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UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

School of Civil Engineering and the Environment

**Soft cliff retreat adjacent to coastal defences, with
particular reference to Holderness and Christchurch Bay,
UK.**

by

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Thesis for the degree of Doctor of Philosophy

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UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

Doctor of Philosophy

SOFT CLIFF RETREAT ADJACENT TO COASTAL DEFENCES, WITH PARTICULAR REFERENCE TO HOLDERNESS AND CHRISTCHURCH BAY, UK.

By Sally Brown

Coastal defences reduce sediment input and modify the sediment budget, usually resulting in a sediment deficit down-drift and an accumulation up-drift. This process results in set-back adjacent to defences. Three types of set-back were identified and these occur due to the:

- *terminal groyne effect*, where defences stop or dramatically reduce erosion, induce a sediment deficit *down-drift* and cause an increase in retreat rate;
- *perceived terminal groyne effect*, where defences stop or dramatically reduce erosion, and *down-drift* retreat rates remain the same or decrease;
- *initial groyne effect*, where defences stop or dramatically reduce erosion, induce sediment accumulation *up-drift* and cause a decrease in retreat rate.

Set-backs are found on defended coasts world-wide, and are complex evolving features dependent on numerous natural and anthropogenic factors.

200 set-back sites were identified in England and Wales, half on cliffed coasts. The terminal groyne effect theory was investigated on 17 sites on the soft cliffs of Holderness, Christchurch Bay and north-east Norfolk, UK, all of which erode naturally at 0.5m/yr-2.0m/yr. Historical shoreline analysis and a history of human intervention was undertaken for each study region and site.

For 13 out of the 17 case studies, a *terminal groyne effect* appeared to have occurred. As time passed and the magnitude of set-back increased, the terminal groyne effect became increasingly apparent. Where increased retreat resulted, the coast was affected for tens to thousands of metres down-drift. For the remaining case studies, a *perceived terminal groyne effect* occurred. An *initial terminal groyne effect* occurred at all sites.

Longshore, the continued set-back caused outflanking of defences prompting emergency works, such as repeated defence extensions up and down-drift. Over several decades of set-back, the defences formed an artificial headland and created a crenulate shaped embayment down-drift. The planform of an embayment expanded rapidly, then reduced to a steadier retreat rate.

As shoreline management evolves from a highly defended to a less heavily managed coast, defence abandonment will result in rapid retreat. Set-backs may be created due to the juxtaposition of maintained and abandoned defences, as illustrated at Happisburgh, Norfolk. In the coming decades, set-backs, artificial headlands and the terminal groyne effect will remain important issues for shoreline management.

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LIST OF ABBREVIATIONS

CAD	Computer aided design.
CCO	Channel Coastal Observatory.
CD	Compact disc.
dp	Decimal place.
DEFRA	Department for the Environment, Food and Rural Affairs.
DGPS	Differential Global Positioning System.
DSAS	Digital Shoreline Analysis System.
ENVI	Environment for Visualising Images.
EPR	End point rate.
ERYC	East Riding of Yorkshire Council.
ESRI	Environmental Systems Research Institute.
GIS	Geographical Information System.
GPS	Geographical Positioning System.
HR Wallingford	Hydraulics Research Wallingford
IPCC	Intergovernmental Panel on Climate Change.
MAFF	Ministry of Agriculture, Fisheries and Food.
N	North.
NE	North-east.
NFDC	New Forest District Council.
NNDC	North Norfolk District Council.
NNE	North-north-east.
NOS T-sheet	National Ocean Service Topographic-sheet.
NTF	National Imagery Transmission Format.
OS	Ordnance Survey.
PC	Personal computer.
SCAPE	Soft Cliff and Platform Erosion
SMP	Shoreline Management Plan.
UK	United Kingdom.
US	United States.
USACE	United States Army Corps of Engineers.
WASA Group	Waves and Storms in the North Atlantic Group.
2D	Two dimensional.
3D	Three dimensional.

LIST OF SYMBOLS

a	Dimensionless coefficient.
b	Dimensionless coefficient determining the bay depth below the x axis.
km	Kilometres.
m	Metres.
mm	Millimetres.
p	Dimensionless coefficient determining bay width.
R ²	Coefficient of determination.
s	Seconds.
t	Time since defence construction.
x	Cross-shore set-back.
y	Longshore distance.
y _s	Longshore component of the shadow zone.
yr	Year.
θ	Angle of the curve.
°	Degrees.
>	Greater than.
<	Less than.
%	Percent.
±	Plus or minus.

1. INTRODUCTION

1.1 Introduction

'The sea hath no king but God alone' (Rossetti, 1890), but man has attempted to be its ruler for thousands of years. Particularly since the mid 19th century, engineers have challenged this sentiment by endeavouring to control shoreline position through a variety of means. On a soft eroding coastline this has meant the building of hard defences, or littoral drift barriers such as a series of shore perpendicular groynes to inhibit longshore drift. Groynes trap sediment enabling a beach to build, thus reducing erosion of the shoreline and wave attack on the cliff base. Defences have many benefits as they slow erosion and whilst they are maintained, generally prevent infrastructure being lost to the sea. However, the coast down-drift is starved of sediment and continues to erode, often at an increased rate for hundreds or thousands of metres longshore (Komar, 1976; Carter, 1988; Viles and Spencer, 1995; Galgano, 1998). In contrast, on the up-drift shoreline, a beach builds due to the sediment trapped the littoral drift barrier(s). It may continue to accrete or stabilise, resulting in reduced erosion. As a consequence, the undefended shorelines adjacent to the defended coast become set-back with respect to its defended counterpart (Bruun, 1995; French, 2001), mimicking a natural headland.

Coastal defences can be advantageous and are well known to reduce land loss and flooding. They attract sediment which attenuates wave energy and increases the amenity value of the coastal zone. Defences also offer protection and access for ports and harbours (French, 2001). However, this thesis investigates the adverse impact of defences on the adjacent undefended coasts. Hence the purpose of this research is to investigate and analyse the impact of artificial littoral drift barriers on soft cliff (sand and clay) coastlines from the mid 19th century to the present day (approximately 150 years), with specific reference to the rate and shape of shoreline evolution down-drift of artificial littoral drift barriers. This will be undertaken by analysing a series of case studies around the UK, investigating the retreat and set-back of the adjacent cliffs on the scale of hundreds to thousands of metres longshore (see Chapters 4, 5 and 6).

1.2 Background

Coastal protection measures date back thousands of years (Brampton, 2002) and by 2004, an estimated 2,300km of the 17,000km UK coast was defended (Eurosion, 2004). But despite these defences, 4,700km (27%) of the coast was reported to be eroding (Eurosion, 2004). When defences are constructed the sediment budget is modified, creating a sediment deficit down-drift.

Consequently, retreat rates increase down-drift and the coastal platform evolves to create a wide, open embayment which is often called a crenulate shaped bay (for further explanation, see Chapter 2). This process is illustrated in Figure 1.1. Set-back is particularly associated with the final groyne (called the terminal groyne), and therefore the phenomenon is referred to as the terminal groyne effect, terminal groyne syndrome or terminal groyne problem (see Chapter 10, Glossary). In this thesis it will be referred to as the terminal groyne effect and it will be investigated (see Section 1.6) in Chapters 4 and 5. French (2001) reported that the terminal groyne effect is a common phenomenon and observed worldwide on soft defended coasts (see Chapter 2 and Table 2.3). An example of the terminal groyne effect is illustrated in Figure 1.2 at Withernsea, Holderness on the east coast of England. After defences were constructed the down-drift coastline became set-back. In practice, it is all defences, and not just the terminal groyne that contributes towards the problem. As the adjacent coast continues to erode, set-back often occurs both down-drift and up-drift, and over decades and centuries the defences stand increasingly seaward of the hinterland and act as a subtle headland or promontory (Valentin, 1954). As time progresses, the headland protrudes and experiences increased wave attack due to deeper water depths and wave refraction. The Futurecoast study (produced by Halcrow, 2002 which provides a prediction of future evolutionary tendencies over the 21st century) reinforces this message, and points towards future engineering and management challenges as emerging coastal features influence large scale retreat, and potentially exacerbate erosion problems. A more detailed review and explanation of the terminal groyne effect and down-drift erosion is found throughout Chapter 2.

Figure 1.3 defines the terminology used in this thesis and in the terminal groyne effect definition (Section 1.6 and Chapter 10, Glossary). The terms up-drift and down-drift relate to the position of the undefended shoreline with respect to the coastal defences. Retreat on the down-drift coast is named down-drift erosion.

Set-back refers to the perpendicular distance between the defended shoreline and the undefended up-drift or down-drift shoreline (with no reference to the rate of erosion). Soft cliffs are defined as those formed of clays, shales, sandstones or unconsolidated sands (Jones and Lee, 1994; Lee and Clark, 2002), which can retreat by significant amounts, especially when protective beaches decline.

There are many natural and anthropogenic forcing agents of coastal erosion (Stive *et al.*, 2002), which makes down-drift erosion an interactive and complex process. The interruption in longshore drift is commonly attributed to being the sole cause of the terminal groyne effect (for example, Russell, 1960), but additional factors that influence coastal erosion need to be considered. These are outlined in Chapter 2 and Figure 2.2 and analysed throughout this thesis.

To date, much research into down-drift erosion and subsequent shoreline evolution has focused on beach erosion and adjacent low-lying land. Many studies (essentially in the United States, for example, Komar, 1983; Bruun, 1995, 2001; Dean, 1996; LaValle and Lakhan, 1997; Galgano, 1998) investigate properties such as beach volume and morphology down-drift of defences, mainly on barrier beaches and islands. Less research into the terminal groyne effect and down-drift erosion has been undertaken on soft cliff coastlines, which provides the unique focus to this study.

1.3 History and problems associated with the terminal groyne effect

Erosion dominates over accretion on most of the world's coastline (Bird, 2000) and has often been amplified by human interference (Hsu and Silvester, 1996) creating localised problems. The terminal groyne effect is not a new phenomenon and by the mid to late 19th century, engineers had a basic understanding of its origins. An early acknowledgement that groynes have an adverse effect on the down-drift beach creating increased beach and cliff erosion was made by Hewitt (1844) from his observations at Trimmingham, Norfolk. Hutchinson *et al.* (1980) assembled evidence from the mid to late 19th century, describing beach depletion down-drift of Folkestone Harbour, Kent. Palmer (1991) also discussed shingle depletion from 1893 due to up-drift defence works at Folkestone (see Section 2.7). Topley (1885) reported that 19th century groynes were often built recklessly, with a disregard for the down-drift

consequences of reduced sediment supply. This was formally recognised by the Royal Commission on Coastal Erosion and Afforestation (1911) who linked the blockage of littoral drift to increased erosion rates down-drift of sea defences. With increased retreat rates and set-back adjacent to defences, headlands form. For example, Ward (1922) noted the growth of a subtle headland at Cromer, Norfolk (Steers, 1964 reported that defences were built at Cromer's predecessor, Shipden, before 1391) and the headland is even more apparent today (Figure 1.4 and Sections 6.3.3 and 7.2.3). Although these first reports were the early warnings of the down-drift erosion problem, the terminal groyne effect has become more prevalent due to an increasing number of defences and longer periods of time since defence construction.

Past coastal management has often taken a local perspective and disregarded broader scale processes and subsequently poor shoreline management has contributed and exacerbated local erosion problems (EuroSION, 2004). For example, the terminal groyne effect is a common occurrence around the UK as coastal defences were frequently terminated at the parish or local authority boundary (for example, Blackpool / Lytham St Annes and Hampshire / Dorset). Today, even with more integrated approaches to shoreline management, down-drift erosion still occurs. For example, Hamer *et al.*, (1998) found that the construction of nine offshore reefs at Sea Palling, Norfolk since 1995 led to beach levels lower than expected on the down-drift coastline.

The terminal groyne effect has created serious engineering and coastal zone planning problems throughout the world in different geomorphic settings, from down-drift of tidal inlets and harbours (Wiegel, 1964; Komar, 1976, 1983; Borah and Balloffet, 1983; Hsu *et al.*, 1993; Bruun, 1995, 2001; Galgano, 1998) to cliffed coastlines (Granja and Carvalho 1991, 1995; French, 2001; Jezard, 2004). Other down-drift problems due to the terminal groyne effect, apart from increased erosion, include the possible outflanking of the protection works and the inadequate design of the terminal groyne to mitigate outflanking (see Section 6.2).

1.4 Reasons and importance of study

An enhanced understanding of down-drift erosion will help coastal managers appreciate shoreline evolution and better incorporate the impact of down-drift erosion into Shoreline Management Plans (SMPs). Shoreline Management Plans were introduced in 1995 covering the 6,000km coastline of England and Wales (Leafe *et al.*, 1998; Cooper *et al.*, 2002; DEFRA, 2003). They aim to improve planning and make coastal protection measures more coherent over a 100 year time scale. SMPs provide guidance over which stretches of coast should be maintained in the future, and present four strategic management policies: (1) hold the existing line of defence, (2) advance the existing defence line, (3) managed realignment, and (4) no active intervention (DEFRA, 2006a). The terminal groyne effect is relevant to study at local (hundreds of metres) and regional (thousands of metres) scales as it has implications for past, present and future forms of defence and shoreline planning. In the past, where the terminal groyne effect occurred, defences were often extended. However, this is only a short term solution as the problem of increased erosion is moved down-drift (Silvester and Hsu, 1997). Defences have contributed to shoreline steepening (Taylor *et al.*, 2004) which leads to deeper water, increased wave attack and the outflanking of the protection. With reduced sediment availability this situation cannot be maintained in the medium to long term future (decades to centuries). Therefore SMPs now advise the selected removal of defences (for example, as already seen at Happisburgh, Norfolk. The Kelling to Lowestoft Ness Shoreline Management Plan, 2006 recommends up to 70% of the defences in north-east Norfolk should be abandoned by 2105). This will result in a temporary period of rapid retreat, restoring equilibrium and increasing sediment availability. However, new forms of the terminal groyne effect will emerge, as set-back and increased erosion due to defence removal will occur down-drift of coastlines that remain protected (see Chapter 6 and 7).

This study is novel as there has been little systematic study of the relative rate of down-drift erosion compared to the pre-defended cliffed coastline or the rate of erosion relative to the undefended coast up-drift of the barrier. The longshore extent that a set-back or embayment will extend down-drift of the barrier on a cliffed coast is also poorly understood.

In 2004, damage due to coastal erosion in England cost £14.4 million per annum (including property, land, infrastructure, and transport disruption or loss) but with climate change and continued development it has been estimated that it could rise to as much as £126 million per annum by the 2080s (Evans *et al.*, 2004). Obtaining an understanding of how the coast erodes and a greater knowledge of the natural and anthropogenic forcing agents of coastal erosion will enhance coastal management and planning. An improved understanding of coastal adjustment and evolution at a local scale is also required (Evans *et al.*, 2004). Consequently an objective of this thesis is to investigate the implications of defences for the adjacent coast over many decades and this is discussed in Chapters 6 and 7. A comparison is also made to natural bay formation systems.

1.5 The investigation and study regions

This study investigates the terminal groyne effect by analysing the retreat on the adjacent cliff before and after defence construction (see Chapters 4 and 5).

Due to the time frame of these studies, site selection was restricted to the UK, where extensive soft eroding cliffs are found mostly along the north-east, East Anglian and south coasts of England (Jones and Lee, 1994; Lee and Clark, 2002). After a national assessment of set-backs adjacent to defences (see Section 3.2), three study regions were selected as follows (see Figure 1.5):

- 1) Holderness, East Riding of Yorkshire;
- 2) Christchurch Bay, Hampshire;
- 3) North-east Norfolk.

These areas were selected because:

- a) They exhibited high rates of retreat (0.5m/yr to 3m/yr) over the historic map evidence (up to 151 years);
- b) There was extensive previous research providing vital information on the environmental conditions for each study region;
- c) Major coastal defences had been constructed mostly during the period of high quality map records, thus providing a quantitative record of cliff top position in response to defence construction;

- d) Suitable data (for example, cliff top positions and records of defence construction and maintenance) was easy to obtain from the relevant local authorities and other organisations.

Retreat rates from study sites in Holderness and Christchurch Bay are analysed in Chapters 4 and 5 respectively. The implications from these sites are discussed in Chapters 6 and 7 with results from north-east Norfolk. It is not possible to analyse north-east Norfolk in detail due to the timing of defence construction and the lack and quality of appropriate data. Studies are undertaken using historical maps, aerial photographs and surveys and mapped on a Geographical Information System (GIS). An explanation of the data and methods used is described in Chapter 3.

1.6 Definition

The terminal groyne effect definition (as illustrated in Figure 1.1) will be investigated using case studies on cliffed sites and is as follows:

Set-backs occur down-drift of defences due to the terminal groyne effect, where defences stop or dramatically reduce erosion, induce a sediment deficit down-drift and cause an increase in retreat rate.

1.7 Study aim and objectives

The aim of this research was to analyse the impact of set-backs, the terminal groyne effect and shoreline evolution due to defence construction on cliffed coasts. Regional scale retreat and case studies were analysed over time scales of decades to centuries and spatial scales in mainly hundreds of metres, but extending to thousands of metres.

The study objectives were:

- 1) To examine the impact of littoral drift barriers and identify sites in England and Wales where the coast is set-back adjacent to defences. This includes

determining the factors which influence retreat and developing a methodology to measure set-back and the terminal groyne effect.

2) To measure down-drift set-back after defence construction to determine if retreat rates subsequently increase, and whether this can be shown unequivocally. Where increased retreat rates do occur, ascertain the longshore distance of coast affected.

3) To evaluate the evolution of set-backs and the terminal groyne effect through the planform shape of the down-drift coast, incorporating recent trends in coastal engineering and shoreline management, such as defence removal and abandonment.

Due to time constraints it was not possible to investigate factors other than defences which affect the rate of cliff erosion such as the cliff morphology, degradation processes and the frequency of coastal storms and erosive events. However, these factors will be mentioned where appropriate throughout this thesis and would make a suitable topic for further research.

Investigation of set-back adjacent to defences has taken place on varying geographical scales, at national (10^5m), regional (10^4m) and local levels ($10^1\text{m} - 10^3\text{m}$). Each objective relates to these scales, and a plan used throughout this thesis is shown in Figure 1.6.

1.8 Summary

The terminal groyne effect occurs when hard defences are built on an eroding coast causing sediment starvation and an increase in retreat rate down-drift. It is a worldwide phenomenon that has been apparent in the literature for at least 150 years and yet remains poorly described, especially on cliffed coasts. The terminal groyne effect and its implications will be analysed nationally, regionally and at numerous study sites. This thesis will investigate the factors influencing coastal erosion and the terminal groyne effect (Chapter 2) and the methodology used to measure it (Chapter 3). The terminal groyne effect will be investigated by analysing retreat rates before and after defence construction (Chapter 4 and 5). Evolution of the terminal groyne effect and subsequent bay formation will

also be studied (Chapter 6). The terminal groyne effect, future shoreline evolution and implications for shoreline management will be discussed in Chapter 7. Chapter 8 provides the conclusions of this research.

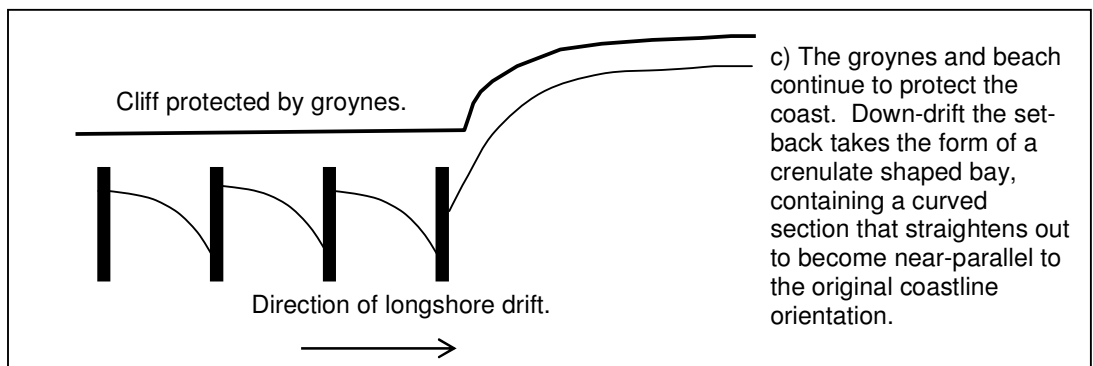
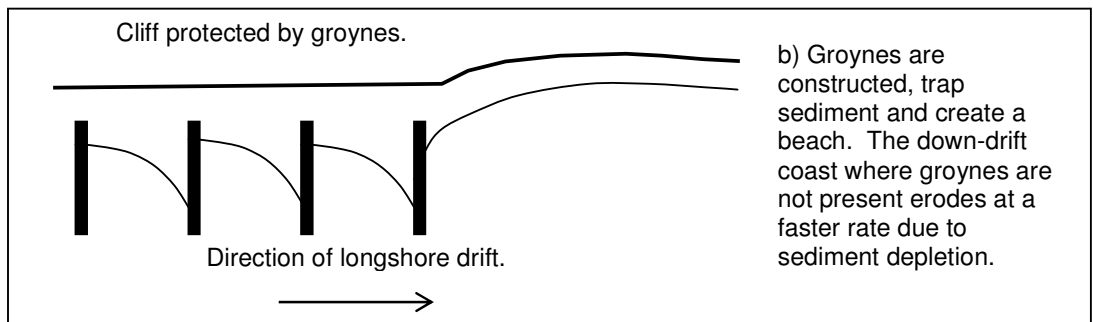
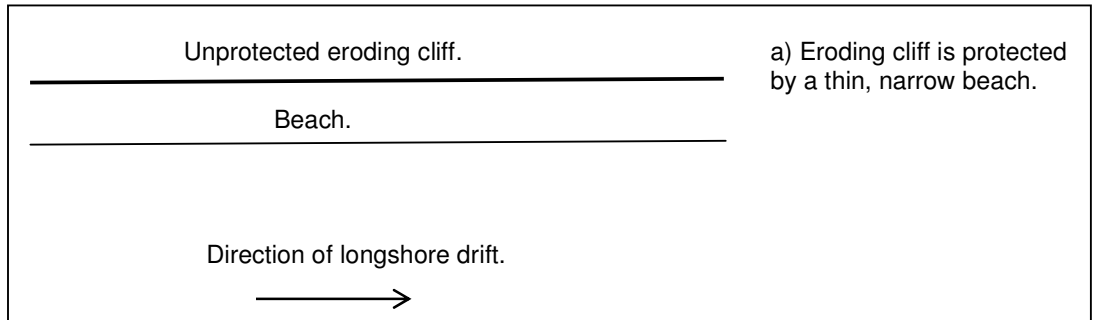


Figure 1.1 – Development of the terminal groyne effect and down-drift erosion on a cliffed coast.

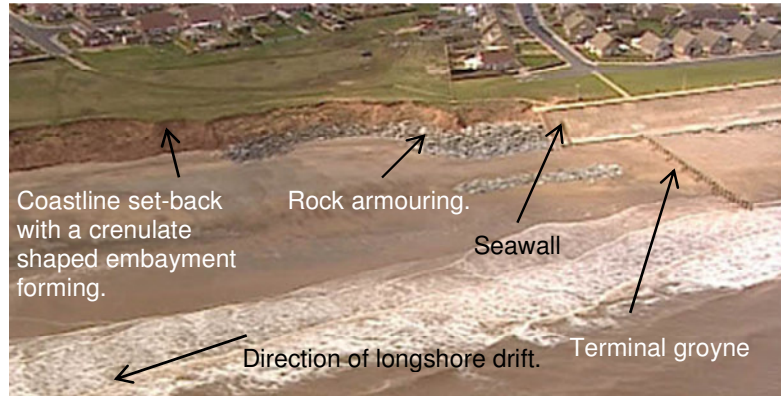


Figure 1.2 – The terminal groyne effect at Withernsea, Holderness. The down-drift coastline is set-back from the terminal groyne, seawall and rock armouring. Down-drift, an embayment is forming. (Photograph from Halcrow, 2002).

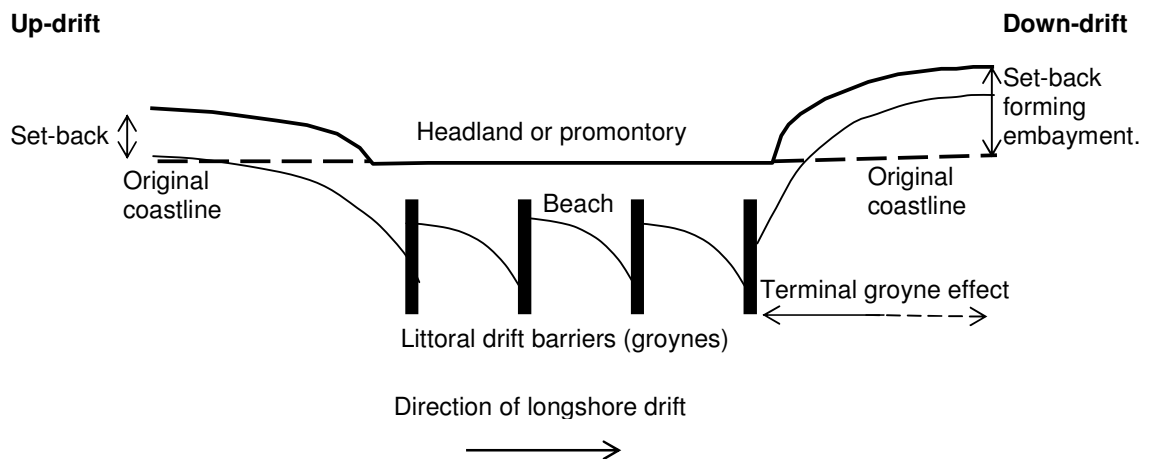


Figure 1.3 – Definition sketch. The bold line indicates the present cliff line position. The dotted line indicates the cliff position when the defences were first constructed. Set-back occurs on the up-drift and down-drift coastlines. The set-back is more extreme down-drift and the longshore extent of the set-back is difficult to define, hence it is represented by a dashed line.

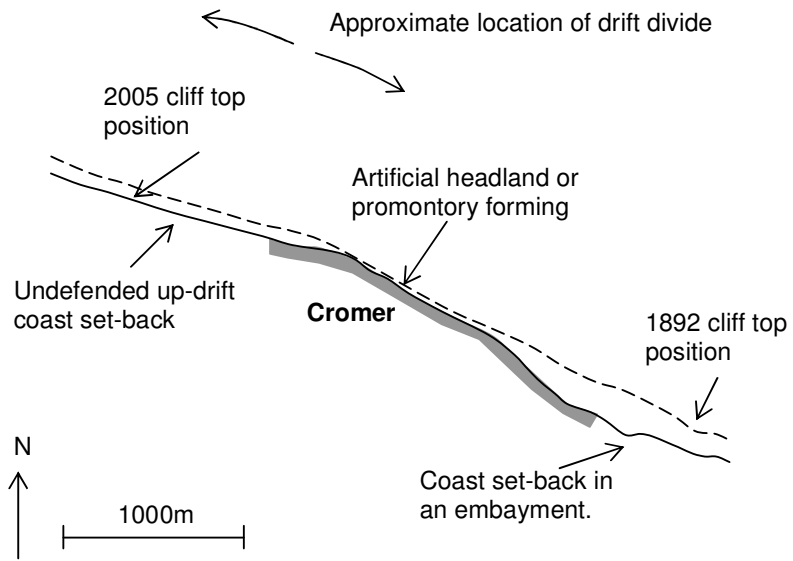


Figure 1.4 – Cromer, Norfolk forming a subtle promontory due to coastal defences maintaining coastline position whilst the adjacent undefended coasts erode. The thick grey line represents the defence position in 2005.

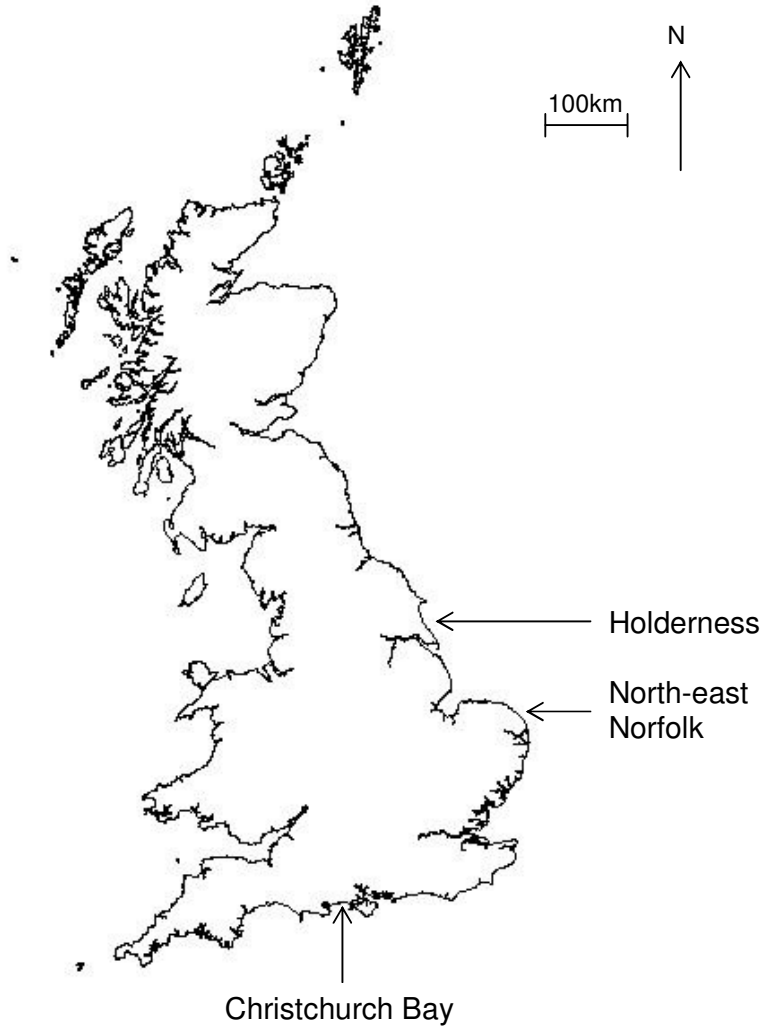


Figure 1.5 – Location of study regions within the UK.

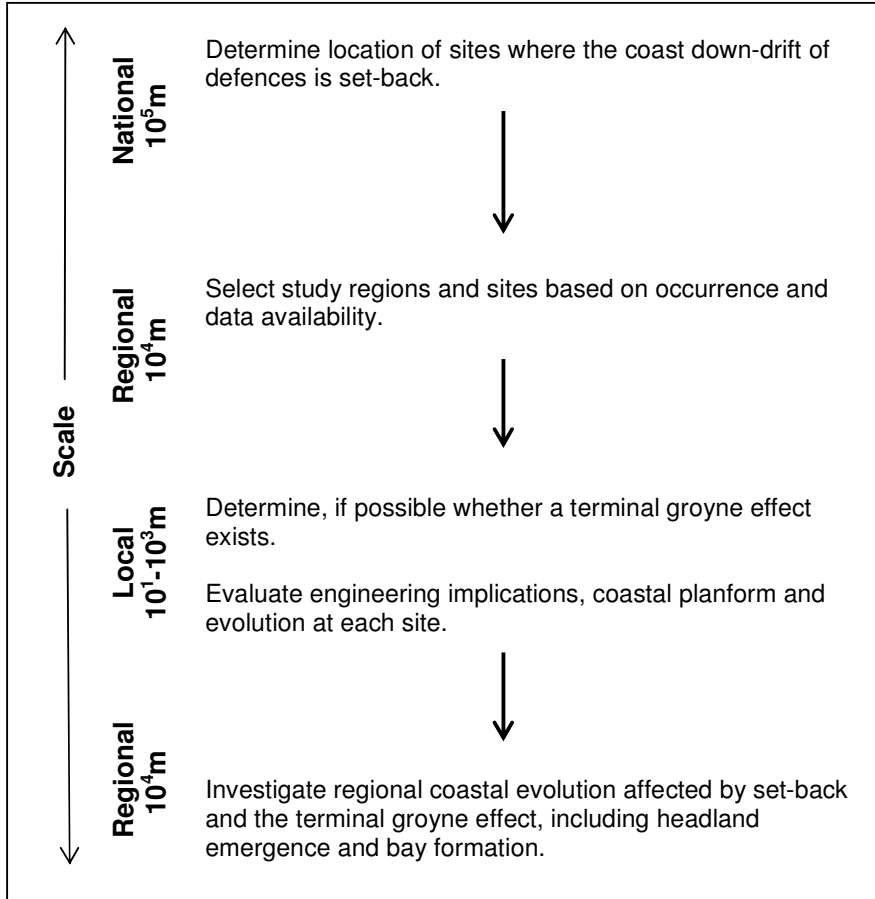


Figure 1.6 – Flow diagram of the methodology within the thesis. An assessment of the terminal groyne effect involves recognition and investigation on national, regional and local scales.

2. DOWN-DRIFT EROSION AND COASTAL SET-BACK

2.1 Introduction

Coastal erosion is an interactive process dependant on many natural and anthropogenic factors. This includes the rate of sediment transport and beach volume, shore platform exposure, cliff and foreshore geology, relative sea levels and wave climate, and the actions of man. Geology is an important control of erosion. In the British Isles, the geology trends from north-east to south-west. Broadly, the oldest, harder, slow-eroding rocks (Precambrian, Palaeozoic and the lower Mesozoic) are found in the upland areas of the north and parts of the west, whilst the younger, softer, faster-eroding, low-lying rocks (upper Mesozoic and Cenozoic) are generally found in the south and east. These conditions give rise to erodable sediments. Eroding cliffs have many benefits; they contribute to the sediment budget (a complex interlinking system of inputs, transfers, stores and outputs within the sediment cell; Carter, 1988; Bray *et al.*, 1995) and form a protective beach, although some of this material is lost offshore. However, erosion has adverse effects including loss of homes and infrastructure meaning that in some cases, protection is required. Hard coastal defences, such as groynes and sea-walls are a beneficial way of stabilising coasts and reducing risk. Frequently defences have been a solution to a local problem, responding to lithological variations, sediment availability and human causes and needs. However, the introduction of coastal defences on any coast alters the sediment budget and disturbs the coast's natural equilibrium, thus redistributing sediment, and influencing retreat rates (Komar, 1976). It can affect the coast from tens to hundreds of metres up and down-drift of the defence structure(s).

Figure 2.1 and Stive *et al.* (2002) indicate that a systems approach is helpful to further understand coastal behaviour, separating natural coastal processes from those caused by man. The interactions and systems of coastal feedbacks are shown in Figure 2.1. Therefore in this chapter, the factors controlling the coastal erosion system and how these factors influence the terminal groyne effect will be investigated (Section 2.2). The impact of littoral drift barriers on the adjacent coast will be examined (Section 2.3), examples presented (Section 2.4) and the effect of these compared to natural systems (Section 2.5). Other factors and

case studies illustrating the impact of defences on the adjacent coast will be discussed in Sections 2.6 and 2.7.

2.2 Factors affecting coastal erosion and their interactions with an artificial barrier

Figure 2.2 illustrates possible interactions of the sediment budget in a cliffed setting in conjunction with an artificial barrier. In this figure, the artificial barrier is a shore perpendicular barrier such as a jetty, breakwater or groyne. Shore parallel defences, such as a seawall also disturb the equilibrium and are discussed in Sections 4.3.1 and 6.2. The interaction of the littoral drift barrier with respect to the sediment budget and factors controlling erosion will be discussed.

2.2.1 Artificial barriers

The purposes of artificial barriers are to improve navigation at inlets and reduce erosion and flooding (Komar, 1976). Artificial barriers include jetties (Figure 2.3), breakwaters (Figure 2.4), groynes (Figure 2.5), seawalls (Figure 2.5), revetments and rip-raps (Figure 2.6). Table 2.1 describes these, with examples. Defences do not stop erosion, but only slow it down. Failure can still occur behind protection areas, for example due to high groundwater levels (see Section 2.2.4). Whilst some defences in the UK are over 100 years old, many have been constructed or re-constructed since the 1950s. Defences are frequently a combination of different artificial barriers depending on the needs and age of the site. For example, Figure 2.4 illustrates the defences at Lyme Regis, UK (for location, see Figure 6.1). The breakwater was constructed in the 13th century and has undergone substantial modification on numerous occasions including a series of groynes and seawalls. In 2006-2007 two beach retaining structures, a new seawall and beach replenishment were added, so that the defences now form a crenulate shape bay (Clark *et al.*, 2000; Fort *et al.*, 2007). All but the most recent modifications have resulted in set-backs and a series of mini embayments down-drift (for discussion of multiple set-backs, see Section 7.2.2). The littoral drift barriers found in the three study regions (Holderness, Christchurch Bay and north-east Norfolk) are breakwaters, groynes, seawalls, revetments and rip-raps.

2.2.2 Longshore movement of sediment

The longshore movement of sediment is one of the most important coastal processes at work, resulting in the accretion and erosion of coastal features (King, 1972; Galgano, 1998). Natural sediment input comes from rivers and cliffs, where sand and gravels can potentially remain to form the beach, whilst lighter clay and mud particles may be washed offshore. Komar (1976) defines longshore drift as the sum of the sediment transport from all individual wave trains from each wave direction. It is driven by longshore currents, which in turn are generated by waves and winds blowing at an angle to the coast (King, 1972). Long term changes (>100 years) to the coastal system and climate variability alter the rate of longshore drift. Longshore drift depends on the wave energy, wave speed, wave breaker angle and the potential longshore transport rate. The true sediment transport rate (the amount of sediment actually moved along the shoreline) is lower than the potential rate as wave climate and storm conditions vary. Therefore measurements are only valid over long timescales (Kamphuis, 2000). Longshore drift is measured in the field and through longshore transport formulae (USACE, 2002). A selection of longshore transport rates are shown in Table 2.2. The example from north-east Norfolk (Clayton, 1989) indicates that defences decrease cliff input, restrict sediment movement and reduce sediment volumes. Hence the terminal groyne effect and down-drift erosion depends on the magnitude of longshore drift and the efficiency of defences to retain sediment.

Figure 2.2 indicates that changes to wave orientation result in reversals of littoral drift allowing sediment to build on both sides of the barrier. Therefore the impact of defence works on the down-drift coast is temporarily minimalised. On some coastlines, such as Cromer, Norfolk a drift divide is a permanent feature, so that the sediment deficit is spread between both adjacent undefended coastlines. On a swash aligned coast Clayton (1989) found groynes were not the best protection method as they do not retain sediment as well as on a drift aligned coast. Hence the direction and magnitude of longshore drift and the type of artificial barrier affect the magnitude of down-drift erosion.

2.2.3 Beaches

A large beach dissipates wave action and helps to protect soft cliffs from erosion. The morphology, size of the beach, water elevation and wave run-up determine whether the cliff toe is protected against marine attack (Ruggiero *et al.*, 2001; Komar *et al.*, 2002). The quantity of beach sediment is partly controlled by the process of longshore drift (discussed in Section 2.2.2) and partly by cliff and river input. River or cliff material feeding into the system may be lost offshore, or contribute to the beach volume (Viles and Spencer, 1995). Bray (1992), working on the West Dorset coast between Black Ven and Golden Cap (a longshore distance of 5km) found that through the addition of cliff material the beach store increased from approximately 25,000m³/km to 85,000m³/km along the shoreline (Figure 2.7). Therefore, down-drift at Golden Cap there is potentially greater protection of the cliff due to this additional beach material.

Beaches evolve at different time and spatial scales (Stive *et al.*, 2002) and are subject to seasonal variations. A greater portion of erosion occurs during the autumn and winter months when storm conditions increase the water elevation and wave attack. Wiegel (1964) found that the beach width was generally higher during the summer months and decreased during the winter months. Over very short time periods (<1 year) storm activity can result in large variations in beach levels, volumes and widths (Galgano *et al.*, 1998). Consequently, it is during these times that the beach and cliff are most susceptible to erosion (Komar *et al.*, 2002).

Understanding long term beach behaviour (both natural and anthropogenic) is important as it can help in the assessment of future shoreline trends and assist in coastal management decision making processes. When establishing medium term trends (>10 years) such as the terminal groyne effect, data must be taken over many decades to determine the real changes rather than it being the result of short term 'noise'. Regular spatial measurements are required but are not always available (see Section 7.2.1). The causes of erosion and geographical change (for example, beach mining) using *a priori* knowledge must be established before any past trends are extrapolated and useful predictions made (Galgano, 1998; Komar *et al.*, 2002).

2.2.4 Cliffs

In the UK, cliffs are a chief contributor to the sediment budget and longshore drift (see Figure 2.1). However, along clay or mudstone cliffs a larger proportion of material is lost offshore rather than from sand or gravel cliffs, where the sediment is retained to form a beach. It is estimated unprotected soft cliffs cover 250km of the English coast (Lee and Clark, 2002). Soft cliffs are vulnerable to erosion (Walkden and Hall, 2005) as they respond more rapidly than cliffs composed of hard materials and result in faster weathering and degradation by mass movement (Bray and Hooke, 1997). Although annual retreat may be small, over many years it leads to significant land and sediment loss (Lee and Clark, 2002). There have been many studies of soft cliff recession (Lee, 2002) producing a range of retreat rates over different periods of time. Rates vary from 0.03m/yr (from 1902-1962) at West Bay, Dorset, reported by Bray (1996), to the more rapidly eroding cliffs between Cromer and Mundesley in Norfolk, where Matthews (1913) recorded an erosion rate of 4.2m/yr to 5.7m/yr (from 1838 to 1861). Regular measurements of retreat rates are essential as they vary over time (see Chapters 4, 5 and 7). Down-drift erosion is influenced by factors other than the defences. These include cliff morphology and lithology, cliff slope evolution and processes, the frequency of storm events and sediment movement. Due to time constraints, there will be no detailed investigation into these factors within this thesis, but they will be discussed.

Hutchinson (1973, 1986) identified three types of clay cliff evolution depending on the rate of toe erosion based on studies of London Clay:

- 1) When the rate of toe erosion is approximately equal to the rate of weathering. This results in shallow slides, such as mudslides, allowing material to accumulate at the cliff toe. For example, at Beltinge, Kent where the London Clay cliffs recede at rates of between 0.3m/yr and 0.8m/yr.
- 2) When the rate of toe erosion is greater than the rate supplied by weathering. This produces higher rates of erosion, steepening the cliff profile and resulting in deep seated rotational landslides with cycles of cliff erosion caused by repetitive over-steepening of the lower cliff. The erosion of the cliff toe controls the rate of the cycle. This occurs at

Warden Point, Isle of Sheppey, Kent where the recession rate has been measured as being from 0.9m/yr to 2.2m/yr.

- 3) When toe erosion is negligible (abandoned cliffs). This occurs where there is no removal of debris from the cliff toe, leading to the accumulation of weathered and degraded material. Over time the slope will reach an equilibrium angle of stability. Defences may reactivate abandoned cliffs by increasing erosion down-drift, for example, at Hordle Cliffs, Christchurch Bay, Hampshire (see Chapter 5).

'Type 1' occurs when erosion is not severe such that a reduction in slope angle does not occur. This is rarely the case in the three study regions.

'Type 2' relates to cliff cycles. The period of a cliff cycle is undoubtedly variable, but is meaningful from a historical context, where the time will be set by the frequency of wave attack. For example, 30 to 40 year cliff cycles are reported at Warden Point, Isle of Sheppey, Kent (Bromhead, 1979; Hutchinson, 1986) and a 19 year cycle at Folkestone, Kent for the previously unprotected shoreline (Muir Wood, 1972). However, cliff cycles are not considered very relevant to regions such as Holderness as wave erosion is frequent and longshore drift is greater in comparison with sites of 'classic' cyclonic modes of evolution. Studies of cliff response within the study regions could prove a useful line of research to augment the classic work undertaken on the London Clay cliffs of Kent and Essex. Pethick (1996), for example, reports on the longshore migration of shallow cliff embayments at Holderness (see Section 4.2.1).

Type '3' occurs at the cliffs within the selected study regions through soft coastal protection, such as replenishment. Cliffs behind hard defences may be subject to artificial earth movement, so cannot fall into this category. Even if the cliff toe is protected by hard defences which may lead to an abandoned cliff, failure can still occur (Clements, 1994; Fookes *et al.*, 2007). For example, this has been seen with the failures at Barton-on-Sea, Christchurch Bay (Reina, 1975; Clark *et al.*, 1976); Sandgate, Kent (Palmer, 1991); Overstrand, Norfolk (Clark *et al.*, 1996); Holbeck Hall, Scarborough, Yorkshire (Clements, 1994; Fort *et al.*, 2000); and Whitby, Yorkshire (Clark and Guest, 1991).

Hutchinson's (1973, 1986) types of cliff are not appropriate to Holderness, as the till (deposited during the Saale and Devensian periods, 10,000 to 250,000 years ago) is softer and more variable than London Clay. Furthermore, the cliffs are lower than London Clay sites and are subject to a higher degree of exposure and wave attack, so colluvium does not provide much protection. Further research between the lithology and the rate of erosion is needed at Holderness (continuing the work of Butcher, 1991 and Pethick, 1996) and in the other study regions.

Due to rapid erosion cycles within study regions (for example, Cambers, 1973 reports a 4 month period of landsliding and talus removal at Holderness) and frequent wave attack on the cliff toe, the random frequency of storm events is an important factor influencing the movement of longshore material and exposure of the cliff toe. For example, a period of years with low pressure and unstable weather conditions will result in higher erosion rates (for example, Richards and Lorriman, 1987; Pethick, 1996).

Cliff retreat can be an uncertain and episodic process, but waves are only one cause of cliff erosion (Steers, 1981; Lee, 2002; Fookes *et al.*, 2007). Apart from variations in geology (such as the type and erodability of material) and beach volume, the rate of retreat is controlled by the exposure of the shore platform (Walkden and Hall, 2005). Erosion rates vary according to site conditions such as topography, geology, hydrology, climatic conditions and historical factors (Muir Wood, 1972; Bird, 2000; Lee, 2002). These factors will be discussed in Section 7.2.1 and Table 7.3.

Water is a dominant factor in landform change, as rainfall of intense duration and volume can significantly influence stability. Hydrogeology is important; landslide activity is associated with the critical pore water threshold being exceeded, and an increased mass of saturated soil (Jones and Lee, 1994; Fookes *et al.*, 2007). Lithological variations cause seepage, for example, where permeable gravels and sands overlie clays, such as at Highcliffe and Barton-on-Sea, Christchurch Bay. High magnitudes and intensity of rainfall lead to high groundwater levels, with an increase in pore pressure and a decrease in effective strength, resulting in a faster rate of physical weathering and potential failure. For instance, analysis of hydrogeological data since 1839 from Ventnor Undercliff, Isle of Wight reveals a close relationship between antecedent rainfall

conditions, groundwater levels and ground movement rates. Ibsen and Brunsden (1996, 1997) found that higher rainfall levels increased the number and size of landslides. They also found that coastal landsliding in Ventnor is closely related to antecedent and seasonal rainfall, and a time lag is frequently found between high precipitation events and subsequent landsliding. Using rainfall records from Ventnor, Moore *et al.* (2007) found an approximate 25% increase in effective rainfall (precipitation minus evapotranspiration) over 170 years, which together with other factors such as mains water supply leakage, has been linked to the increased frequency of landslides and ground movement in the Undercliff. Cliff drainage is a frequent method of cliff protection to reduce instability (for example, Sandgate, Kent; Barton-on-Sea, Christchurch Bay; and Lyme Regis, Dorset (Palmer, 1991; Fort *et al.* 2000; Fort *et al.*, 2007).

Real-time monitoring of rainfall and groundwater can significantly improve the understanding of ground behaviour and landslides (Clark *et al.* 1994, 1996). Periods of heavy rainfall can result in sudden ground movement, and require a quick response. For example, after the 1993 Holbeck Hall landslide in Scarborough, which resulted in more than 1 million tonnes of debris failing in a short time period, piezometers and tiltmeters were installed to monitor groundwater conditions and further movements (Clements, 1994; Clark *et al.* 1996). In 1994, a major landslide occurred on the protected cliffed coast of Overstrand, Norfolk. There was major concern that the landslide would continue inland threatening an increasing number of properties and infrastructure. Tiltmeters were installed, with readings taken at hourly intervals, and the data transmitted to a remote computer, ready for analysis. The transmission of information was vital in monitoring the hydrogeology and landslide potential (Clark *et al.* 1996).

The timing of map surveys or aerial photographs can induce a potential bias in calculation of average erosion rates depending on its proximity to a severe storm event. When investigating long term erosion in the study regions, the retreat data must be recorded over sufficiently long time periods (ideally over several decades) to take account of the frequency of storm events and subsequent sediment movement (see Sections 4.3.3 and 7.2.1). Down-drift of defences relationships over much longer timescales must be taken into account, for example, the relationships between coastal erosion and reactivation of pre-existing landslide systems (Clark and Fort, 2000). Hence, examining cliff retreat

over appropriate time and space scales is essential, and if not undertaken correctly, can create misleading results.

2.2.5 Relative sea levels and wave climate

Cliffs are particularly responsive to wave attack and sea level rise when there is insufficient sediment to form a protective beach. Over decades and centuries, long term variations in the wave climate and sea level rise can influence the rate of cliff erosion. Changes in cliff retreat rates have been wrongly attributed to a changing or increasing wave climate. For example, Clayton (1989) thought a decrease in early 20th century retreat rate occurred due to reduced storminess, whereas the alternative explanation at north-east Norfolk is that the coast was no longer mined for sediment (see Section 6.2.2). Beach mining is frequently ignored in historical cliff retreat studies. Establishing the true cause of retreat rates is essential when analysing down-drift erosion (see Section 7.2.1).

The WASA Group (1998) investigated storm and wave climate in the north-east Atlantic to verify if conditions have worsened over the past 100 years. They found that the storm and surge climate had not roughened along European coasts during the 100 year study period. However empirical models of the wave climate from the past 40 years revealed a roughening wave climate. A roughening wave climate would result in greater wave attack causing erosion to increase. Changes to the wave direction would affect sediment transport (see Section 2.2.2) and thus the efficiency of defences to maintain sediment and therefore retreat rates.

Shennan and Horton (2002) analysed over 1,200 radiocarbon dated sediment samples to produce isostatic change rates and mapped mean relative land and sea level changes in the UK over the past 4,000 years. Woodworth *et al.* (1999) estimated regional sea level rise. The combined results indicated that along the mid-south coast (near to Christchurch Bay) relative sea levels have been rising at 0.5mm/yr and north Norfolk and east Yorkshire are currently experiencing a relative sea level rise of between 0.6mm/yr and 0.8mm/yr.

Throughout the time frame of this study (from 1854 to 2005), the effects of sea level rise and wave climate are of lesser importance compared with other controls of erosion and the terminal groyne effect. However, over long

timescales (>100 years), sea level rise can have significant impacts on the coastal zone. With sea levels rising up to 0.92m by 2099 in the east and south-east of England (DEFRA, 2006b) and with an increase in storminess (IPCC, 2007), defences need to be strengthened to maintain their efficiency (Townend and Burgess, 2004; Brown and Barton, 2007). However, the rate of sea level rise and climate change is a subject of uncertainty and is dependent on future socio-economic conditions and emissions (Zhang *et al.*, 2004; IPCC, 2007).

An increase in sea levels and a changing wave climate results in changes to coastal geomorphology. For example, Pethick (2001) investigated future wave refraction patterns in North Norfolk. Running a model for an extreme 6mm/yr sea level rise over 166 years (resulting in a total rise of 1m), but maintaining the same wave approach and period, he found localities previously in high energy areas were predicted to be replaced by a lower energy environment of mudflats and salt marshes, and vice versa. Therefore coasts that are not presently eroding may do so in the future. These sites may require defending creating new terminal groyne effects. Conversely, elsewhere the defences may no longer be required.

2.2.6 Summary

Many factors affect erosion within the coastal system including longshore drift, beaches, cliffs, the shore platform and relative sea levels. The induction of a littoral drift barrier upsets equilibrium, potentially causing instability and erosion.

2.3 Down-drift response to an artificial barrier

A barrier intercepting littoral drift on an eroding coast upsets the natural equilibrium and can have a major impact down-drift (Komar, 1976; Dean, 1996). Groynes retain sediment up-drift by building beaches and decreasing erosion, resulting in reduced sediment input from the cliff. Both result in sediment deficit down-drift (see Figure 2.2), leading to flatter beach profiles and increased erosion (Dean, 1996). Depending on the length and efficiency of the littoral drift barrier, shoreline orientation, and magnitude and direction of longshore drift, a proportion of sediment may be able to by-pass the barrier (Komar, 1976).

Russell (1960) and Komar (1976) state that the interruption of sediment drift is most severe when the net longshore drift comes from one dominant wave direction (see Section 2.2.2). Komar (1976) also raises the possibility of negligible down-drift erosion if longshore drift is approximately zero. However, he found sediment movement is complex and at Tillamook Bay, Oregon, where longshore drift is minimal, increased erosion still occurred at long distances from the jetty (see Sections 6.2.3 and 7.2.1).

Increased retreat down-drift results in set-back between the defended and undefended coast. Bruun (1995, 2001) and Galgano (1998) found that down-drift of jetties and breakwaters adjacent to harbours and tidal inlets, the beach experiences long and short distance effects (see Figure 2.8). The down-drift beach takes the form of a 'double-s' shape where a short-distance peak of maximum erosion occurs close to the barrier. This moves down-drift at an average rate of 0.3-0.5km/yr (calculated from a number of study sites) compared to a rate of 1.0-1.5km/yr for the long distance effect (Galgano, 1998). Thus the short-distance peak occurs at approximately 20% of the total arc length (Galgano, 1998). Due to drift reversal, sediment is also pushed against the barrier (Bruun 1995, 2001; Galgano, 1998; Kamphuis, 2000). The full down-drift extent of barriers is often omitted from inlet studies (as the 'double-s' shape is ignored) and over many decades can extend down-drift up to 10km. Known as the arc of erosion, it is always mobile and it enlarges at a non-linear rate (Galgano, 1998). When the full arc of erosion is taken into account, Galgano (1998), concluded inlets influence erosion for over 65% of the eastern US barrier beach coastline from Long Island to South Carolina. Sediment accretes up-drift of the jetty with a typical ratio of up-drift accretion to down-drift erosion of 3:7 or 1:2 (Galgano, 1998 calculated this as an average from a number of study sites).

Due to reduced sediment volumes down-drift of inlets on barrier beaches, the shoreline migrates landward. Other geomorphic settings such as cliffs do not have the same freedom to respond to defences. Over several decades on an eroding coast both shore perpendicular and parallel defences create set-back, and this often takes the form of an embayment (see Section 1.2 and Figure 1.3. For discussion on shore parallel defences, see Sections 2.4.4 and 6.2.1). Engineers frequently call an embayment of this planform shape, a crenulate shaped bay. This is because as in nature, it forms down-drift of a hard headland (in this case the defences) and takes the shape of a half heart (Silvester and

Hsu, 1997) as shown in Figure 2.9. It can be divided into three sections: a) a tightly curved section representing a logarithmic-spiral; b) a gently curved section; and c) a tangential coastline parallel to the wave crests (Silvester and Hsu, 1997; Short and Masselink, 1999). Crenulate shaped bays are ubiquitous (Silvester and Hsu, 1997). They comprise 50% of the world's shoreline as well as being created down-drift of man-made littoral drift barriers (Hsu *et al.*, 1993; González and Medina, 2001). This will be discussed in greater detail in Section 2.5.

2.4 Examples of down-drift erosion due to artificial barriers

There have been many studies worldwide into the impact of artificial barriers in different geomorphic settings. A selection of these are shown in Table 2.3 according to the barrier type. There is an abundance of studies into the impact of jetties or breakwaters, whereas research on groynes and shore parallel structures are less plentiful. Generic shoreline responses are shown in Figure 2.10. Specific examples of the impact of the four types of defence are as follows.

2.4.1 Jetties

Jetties built perpendicular to tidal inlets can be found along the barrier beaches of the United States east coast from New Jersey to South Carolina. Ocean City Inlet, Maryland was created after a major hurricane in 1933 (National Research Council, 1990) and was stabilised by two jetties built between 1934 and 1935 (Galgano, 1998). These jetties are presently approximately 600m long (Figure 2.11). The net longshore drift rate at Ocean City Inlet is 153,000m³/yr. Before the jetties were constructed the erosion rate was 0.6m/yr and increased to 9.3m/yr down-drift of the jetty after construction. The down-drift shoreline became set-back from its up-drift counterpart. After 50 years of erosion, the down-drift side migrated landward over 600m, a distance equal to the complete width of the barrier island (National Research Council, 1990) The arc of erosion is mobile and in 1996 the maximum erosion occurred 6.9km down-drift, with increased erosion continuing up to 16.2km. Up-drift, the jetties are nearly filled to capacity allowing material to create an offshore tidal delta and ultimately by-

pass the jetties (Bruun, 1995). Accretion up-drift is relatively stable and occurs up to 4km up-drift of the jetties.

2.4.2 Breakwaters

Breakwaters are built to offer protection to harbours, particularly those built on the open coast. In 1875, Madras, south-east India was located on the open coast and was developed into a port (Komar, 1976, 1983). Net longshore drift, from south to north, was approximately $500,000\text{m}^3/\text{yr}$ (although a small portion of sediment was transported in the opposite direction during the north-east monsoon). Wave period was recorded at 8s to 9s and wave heights at a maximum of 3m. After construction of the first breakwater in 1875, rapid erosion occurred down-drift (Figure 2.12) and was reduced by the placement of groynes. Changes were most rapid immediately after breakwater construction, at $17\text{m}/\text{yr}$ (1876-1898) and reduced to $7.3\text{m}/\text{yr}$ between 1921 and 1950. Increased erosion was reported 5km down-drift of the harbour. On the up-drift side, the shoreline advanced seaward when $1,000,000\text{m}^3$ of sand was retained between 1876 and 1912. To prevent shoaling the breakwaters were subsequently extended and a suction dredger was installed to pump sand past the harbour, thus continuing the movement longshore drift.

2.4.3 Groynes

Groynes are constructed to build a beach and reduce erosion, but have an adverse effect down-drift. At Summerille, on the Potomac River, near Smith Point, Chesapeake Bay, Virginia eight 18m long groynes spaced 18m apart were constructed (Figure 2.13). The groynes reduced erosion but excess retreat occurred immediately down-drift (Anderson *et al.*, 1983). Historically, erosion had been caused by land subsidence and eustatically rising water levels, together with 'northeasters' that created high waves and storm surges. Before defence construction the average site erosion rate was recorded as $1.2\text{m}/\text{yr}$, but after defence construction increased to over $2\text{m}/\text{yr}$. Two years after the groynes were constructed, a 12m set-back in the shape of an embayment was created down-drift. Over 35 years later, the bay forming down-drift is over 100m wide. As the up-drift defended coast continues to erode at a lower rate with respect to the down-drift coast, the defences form a small artificial headland.

2.4.4 Shore parallel defences

Shore parallel defences includes seawalls, revetment and rip-raps (see Table 2.1). Rip-raps are constructed parallel to the shoreline to prevent erosion, in a similar way to a seawall. Terpstra and Chrzastowski (1992) report on a 150m long rip-rap constructed at North Point Marina on the Illinois shoreline of Lake Michigan. Composed of a Holocene beach-ridge plain with fine to medium sand, the area eroded at approximately 3m/yr. Littoral drift was reported to be 70,000m³/yr, and the wave period and height averaged 4s and 0.3m respectively. Commercial development meant that nearby dredged sand was dumped on the beach to form a fan delta accompanied by the construction of the rip-rap. 1.1km down-drift of the rip-rap was a steel sheet pile groyne functioning as a down-drift headland. Immediately after the rip-rap was constructed the down-drift coast started to erode resulting in the formation of a crenulate shaped bay (see Figure 2.14). Over a period of eight months, the bay grew resulting in a set-back of 65m. After this time, to overcome erosion the rip-rap was extended, before it resulted in the disappearance of the marina parking facilities. For further discussion on seawalls and other shore parallel defences, see Section 6.2.1.

2.4.5 Summary

Artificial barriers retain sediment or reduce input to the down-drift coast. The down-drift coast becomes set-back and retreat rates increase. Over many decades this can affect the coast longshore for thousands of metres. Set-back frequently takes the form of an embayment, and this will be discussed in Section 2.5.

2.5 Crenulate shaped bays

The examples presented in Sections 2.3 and 2.4 and Figure 2.10 indicate that down-drift of defences the coast is set-back in the form of an embayment. In nature, a bay of this planform is known as a crenulate shaped bay. An analogy can be made between naturally occurring bays created between alternate layers of soft and harder rock, and coastal defences creating artificial headlands adjacent to soft, erodable material. Both types of headland hinder the

movement of longshore drift. Whereas natural bays have already formed, the formation of man-made bays from an initially 'straight' shoreline can be witnessed at first hand. Hence, studying artificially created crenulate shaped bays provides an insight into how natural bays form (see Chapter 6). This section investigates crenulate shaped bays.

2.5.1 Natural crenulate shaped bays

Sediment movement is hindered around the coast by the presence of natural headlands. Halligan (1906) first observed that on the New South Wales coast, Australia, bays orientated themselves to the predominant wave direction. Silvester and Hsu (1997) stated that beaches curve, orientating themselves predominately transverse to the dominant direction of approaching waves and have been doing so for thousands of years (Figure 2.15). These orientations indicate "Nature's method of balancing wave energy and load of sediment transport" (Silvester and Hsu, 1997, p203), responding to geological and topographical features, sediment type and transport, shoreline geometry and the redistribution of wave energy by refraction or diffraction (Yasso, 1965; McLean 1967). Short and Masselink (1999) estimate that curved beaches and crenulate bays comprise 50% of the world's shoreline.

Crenulate shaped bays form down-drift of a hard headland. They are frequently confined by a second headland down-drift. A prominent example of a crenulate shaped bay is Half-Moon Bay, California (Krumbein, 1944; Bascom, 1951; LeBlond, 1979; Komar, 1976; Silvester and Hsu, 1997). Half-Moon Bay (Figure 2.16) is composed of Quaternary sediment and is sheltered by harder Tertiary sediment in the north, by Pillar Point in the north-west and 10.5km down-drift, by Point Miramontes in the south-east. The curvature is greatest at the up-drift end and diminishes down-drift in the manner of a logarithmic-spiral (Krumbein, 1944) or parabola. The bay contains a sandy beach, backed by a loosely consolidated sand and gravel cliff. Differences in wave height along the bay shoreline are evident due to diffraction controls and distribution of wave energy. With a 12s wave period from the north-west, the waves refract around Pillar Point, the area of lowest wave energy (Komar, 1976). Bascom (1951) found that due to refraction and the distribution of wave energy there is a systematic increase in grain size in the longshore drift direction from Pillar Point to Point Miramontes.

Crenulate shaped bays also occur around the coast of the UK. A selection of bays on the south coast of England are shown in Figure 2.17. These bays form over a variety of time and space scales due to alternating layers of soft and harder rock. At 20km long, Poole Bay, Dorset between Handfast Point and Hengistbury Head is an example of a crenulate shaped bay (Wright, 1981). It formed over thousands of years after the chalk ridge between Handfast Point, at the edge of the Purbecks, and the Needles, Isle of Wight, was breached (see Section 5.2.1). Sea levels rose in the Devensian (10,000-70,000 years ago) allowing the soft sand and clay to be eroded behind it (Wright, 1981). The next major influence on the bay's formation was the sea defences constructed after 1907 (May, 1990). Of the bays mentioned in Figure 2.17, the cliff top position of Poole Bay is now relatively stable, but the other bays are still actively eroding. Bays evolve over time. Headlands erode over time forcing bay systems landwards (Wright, 1981). He also suggested that in the absence of the adjoining headland (Hengistbury Head), Poole Bay and neighbouring Christchurch Bay to the east could be viewed as one bay (Figure 2.18). Equally, this large bay could continue to St Catherine's Point on the Isle of Wight to create a large crenulate bay system. As this does not reflect how this region evolved, the concept of a crenulated form in this case is very hypothetical.

Bays can also occur on smaller spatial and temporal scales. For example, large landslides or mudflows act as a temporary barrier and a barrier to longshore drift, such as at Overstrand, Norfolk (Hutchinson, 1976), Black Ven, Dorset (Bray, 1992) and Senneville-sur-Fécamp, north-west France (Costa *et al.*, 2006).

Russell (1960) and Martino *et al.* (2003) found that the response to barriers was influenced by the beach shape, orientation and the waves and tidal currents acting upon it. Small bays (10^1m , 10^2m , 10^3m) can occur within larger bays (10^2m , 10^3m , 10^4m , 10^5m), and if the wave climate remains consistent it can be hypothesised that they are relatively of the same shape (taking into account the time and space scales) and thus form a fractal coastline (Mandelbrot, 1982; Sapoval *et al.*, 2004). Therefore, the shoreline position of the small bay can potentially be predicted (see Sections 6.3.1 and 6.3.3).

Research on crenulate shaped bays has been presented under many names; zeta bays (Halligan, 1906), spiral beaches (LeBlond, 1972), half-heart bays

(Silvester, 1960), bow-shaped beaches or elliptical shaped beaches (Mashima, 1961), headland bay beaches (Yasso, 1965), headland control beaches (Silvester and Ho, 1972), curved and hooked beaches (Rea and Komar, 1975). In this research, they are referred to as crenulate shaped bays or simply, crenulate bays.

2.5.2 Artificial crenulate shaped bays

Since Halligan's (1906) observations of the New South Wales coast, many geologists and geographers have become interested in crenulate shaped bays, studying their coastal physiography and stable shape (Voisey, 1934; Lewis, 1938; Jennings, 1955; Davies, 1958, 1960; McLean, 1967; Wind, 1994). But it was not until the second half of the 20th century that coastal engineers became aroused by their important role in coastal stability (Silvester and Hsu, 1997). A bay can be stable by maintaining its planform shape and retreating, or by minimal retreat.

Silvester (1960, 1970) found from laboratory experiments that if waves were directed at 45° to a flat coastline with two hard artificial headlands, a half-heart crenulate bay is produced. With time, and constant laboratory or environmental controls the bay forms a stable shape and set-back is reduced. Stable bays are a desired configuration to achieve as they maintain shoreline position, reduce the need for human interference after initial construction, and lower costs. They have been engineered worldwide, including the coast between Hythe and Folkestone in Kent, UK, as shown in Figure 2.19 (Herrington, 2005 and Herrington *et al.*, 2007). When involved in designing the Folkestone bays, Herrington (2005) found there was little data on the application of stable crenulate shaped bays or their use as the solution to coastal erosion in the UK. There is also little information regarding how crenulate shaped bays form down-drift of artificial headlands and this is an emerging topic of research (Hsu *et al.* 2008). Further information regarding bay planform and stability is found in Appendix 1. Crenulate bays, such as Folkestone or Lyme Regis (see Section 2.2.1) were challenging to design and required extensive modelling before the preferred scheme was chosen. Particular challenges in designing bays include modelling of the bathymetry and headland dimensions, appropriate nourishment material and loading, inclusion of changing wave directions and height,

incorporation of the geology, climate change and sea level rise into the design, and anticipation of precipitation and groundwater levels.

Crenulate bays occur in two forms – stable bays (which Silvester and Hsu, 1997 describe as static or dynamic equilibrium for both artificial and natural bays – see Appendix 1) and unstable bays (Silvester *et al.*, 1993 and Klein *et al.*, 2003 describe these as bays with a decreasing sediment supply. Additionally the artificial bays identified in this thesis are caused by a reduction in longshore sediment transport down-drift of defences, which Hsu *et al.*, 2008 termed ‘natural beach reshaping’). Stable bays are well researched and numerous stable crenulate shaped bays have been engineered between headlands (Silvester and Hsu, 1997). Less research has been undertaken about bays in development, and those unwittingly created down-drift of defences. Crenulate bays can form between two headlands, or down-drift of a single headland. Figure 2.20 illustrates a bay between hard defences at Ulrome, Holderness (for location, see Figure 4.1). The age of the defences are not known. Superimposed and scaled upon the photograph is Silvester’s (1960) laboratory test using sand and a wave direction of 45° upon an initially straight coastline with two concrete blocks representing headlands. Despite the bays not being the same shape due to differing levels of wave attack, wave direction, morphology and geology, the figure illustrates the potential of bay formation down-drift of, and between defences on a cliffed coastline.

The combination of refraction, diffraction and to a lesser extent the reflection of waves due to the artificial headland, creates different regions of wave behaviour. Figure 2.21 (González and Medina, 2001) illustrates the regions generated by a barrier. Diffraction is present in Region 1 as the wave front turns around the barrier. Wave height gradients are present in Region 2 as waves suffer from refraction. In Region 3 the breakwater has no effect on the wave field. Factors such as the less dominant wave direction, the beach profile, wave height, period and steepness are of secondary importance (Hsu and Evans, 1989; Silvester and Hsu, 1997).

There are three forms of crenulate bay, known as logarithmic-spiral bays (hereafter known as log-spiral bays), parabolic bays and hyperbolic-tangent bays. Each describes a different bay shape and stability as discussed in Appendix 1. The term log-spiral bay is frequently and incorrectly used by

engineers and scientists as a generic term for crenulate shaped bays. It is incorrect because a log-spiral bay describes a particular bay theory rather than encompassing all types of bay. Log-spiral and parabolic bays are referred to in this thesis.

Crenulate bays are therefore important to study because they provide scientists and engineers with a generic model to predict shoreline position which is useful for coastal planning. In comprehending how shorelines will evolve, an understanding of bay planform and bay development is critical to how bays are engineered (see Section 6.3), and whether bays can be designed to create a stable shape and form down-drift of existing defences on an eroding coast. For example, this may be achieved through the use of headland control and stable bays, as extensively studied by Silvester, Hsu and others (such as Silvester, 1976; Bishop, 1983; Hsu and Evans, 1989; Hsu *et al.*, 1989a,b,c; Silvester and Hsu, 1997 and Moreno and Kraus, 1999).

2.5.3 Summary

Crenulate bays occur naturally between hard headlands and are found on coastlines worldwide. They are recognised for their stable shapes. Man can reproduce crenulate shaped bays by constructing hard headlands and allowing beaches to form between them, or by constructing a single headland and allowing the coast to erode down-drift. Therefore, engineers are interested in bay shape and stability as a method of coastal defence.

2.6 Bay formation – other relevant factors

Krumbein (1944) states that the study of shore processes is complicated by many mutually dependant variables, none of which can be controlled in the field. Russell (1960) believes the terminal groyne effect is solely caused by the cut-off of longshore drift. From laboratory experiments he found that the rate of beach volume accumulation in a newly constructed groyne field is equal to that of the erosion down-drift. Galgano's (1998) research and field data from barrier islands and inlets disagrees with this (see Section 2.3).

Phillips (1985) explained that dominant factors other than the headland, such as the bathymetry, controls the longshore distribution of energy. However he also stated that greater empirical data is required to provide a basis for these ideas. Therefore, although increased recession and crenulate shaped bays down-drift of defences are attributed to the terminal groyne effect and subsequent beach depletion, there may be other unknown factors responsible for the set-back and extent of down-drift erosion. These are discussed in Sections 7.2.1 and Table 7.3.

Muir Wood (1972), Anders and Byrnes (1991), Galgano (1998) and Jezard (2004) state that coastal erosion and shoreline position is a function of natural and anthropogenically induced factors. Natural factors include waves, current and tide processes, sediment size and supply, coastal geology, morphology and permeability, geomorphic setting, topography, offshore bathymetry, and sea level change (see Figures 2.1 and 2.2). Anthropogenic factors include the freedom of the shoreline to respond, length, type and magnitude of the defences and mining. Cliff retreat down-drift of defences is difficult to predict due to a high number of interacting variables (Bray and Hooke, 1997). Analysis of the terminal groyne effect must be taken over long time periods appropriate for the study site (before and after defence construction), using *a priori* knowledge to confirm that defence construction is the real cause of coastal change down-drift.

Many coastal reference books (such as Komar, 1976; Carter, 1988; Viles and Spencer, 1995) associate the terminal groyne effect and down-drift erosion with beach depletion. Carter (1988) found that down-drift of the terminal groyne beach levels can drop by several metres. Data (such as beach profiles and sediment volumes) to prove this on UK coasts is sparse as beach profiles do not go back far enough in time and are not surveyed at frequent temporal and spatial intervals with respect to the littoral barrier. Reliable 1:10,560 maps locating cliff position also do not go back far enough in time to account for all defences (see Chapter 3). Furthermore, there is other human intervention on the coast, such as beach mining (which was particularly acute in the 19th century), as well up-drift disturbances which influence retreat rate.

Potential difficulties encountered in resolving the terminal groyne effect and down-drift erosion include the long history of interference with coastal processes (including protection works further up-drift), problems with determining the time

of barrier construction in comparison to changes in the rate of recession, past mining of beaches, uncertainties over longshore drift rates before and after barrier construction, natural changes in rates of coastal recession, different susceptibilities of the protected and unprotected coasts, change in the degree of exposure to damaging waves and the potential impact of offshore dredging (see Chapter 3, Section 7.2.1 and Table 7.3). In this thesis it has not been possible to examine all the vast number of factors at each study site, and aspects of each region remain unknown.

2.7 Artificial barriers along cliffed coasts

Aside from the three study regions (to be discussed in Chapters 4, 5 and 6), many localities in the UK have a set-back and/or terminal groyne effect. Three areas affected by defences are the Fylde coast (Blackpool), Poole Bay, Dorset and Folkestone Warren, Kent and these are described below.

French (2001) reports on the Fylde coast near Blackpool, where seawalls were first constructed in 1868. By 1937, the whole 11km frontage of the coast was protected, mostly by vertical seawalls, removing the low cliffs which previously eroded at 2m/yr. The movement of sand in this area is complex and sediment moves both north and south. By 2001, at the southern end of the seawall (the local authority boundary) the sand dunes had set-back of approximately 100m. French (2001) attributes this to beach starvation and scour as the sediment source was removed and waves are reflected by the vertical seawalls. It is important to note that seawalls over long distances do create a beach starvation effect (through a reduction in sediment input), although this is not commonly attributed as a down-drift erosion effect (see Section 6.2.1).

On the sandy cliffs of Poole Bay, Dorset (Figure 2.5), the construction and extension of seawalls and groynes since 1907 have created a series of small set-backs progressively around the bay. Similar to Blackpool, the beaches have become starved of sediment and require replenishment approximately every 10 years (May, 1990). Without this, beach levels would continue to lower, leading to groyne failure and seawall scour (Pearce, 2008).

Folkestone Warren, Kent (Figure 2.6) has experienced numerous landslides with one cause attributed to the reduction of the littoral drift (Hutchinson *et al.*, 1980). The Warren, where chalk, Upper Greensand, Gault clay and the Lower Greensand are exposed, has a littoral drift from west to east, and observational accounts have been recorded of beach volume reduction down-drift of the littoral drift barrier. In 1807 a masonry stone wall for the harbour was constructed. Major changes and extensions to the harbour occurred on three further occasions. Large landslides were reported at decreasing time intervals after defence construction. At Sandgate, down-drift of Folkestone, groyne construction and beach mining led to the landward movement of mean low water and mean high water, depleting shingle beaches from 1893. This combined with a period of high rainfall triggered multi-rotational landslides (Palmer, 1991).

2.8 Conclusions

Cliff behaviour is dependant on many interacting factors that control and drive retreat, including geology, precipitation, groundwater levels, beach sediment, longshore drift, relative sea levels and wave climate. The addition of an artificial barrier disturbs the natural equilibrium creating a deficit in the sediment budget down-drift. This leads to lower beach levels, increased retreat and shoreline set-back (see Chapters 4 and 5). Down-drift, set-back often forms an embayment. An analogy has been made between natural and artificial crenulated shaped bays, and this will be examined in Chapter 6.

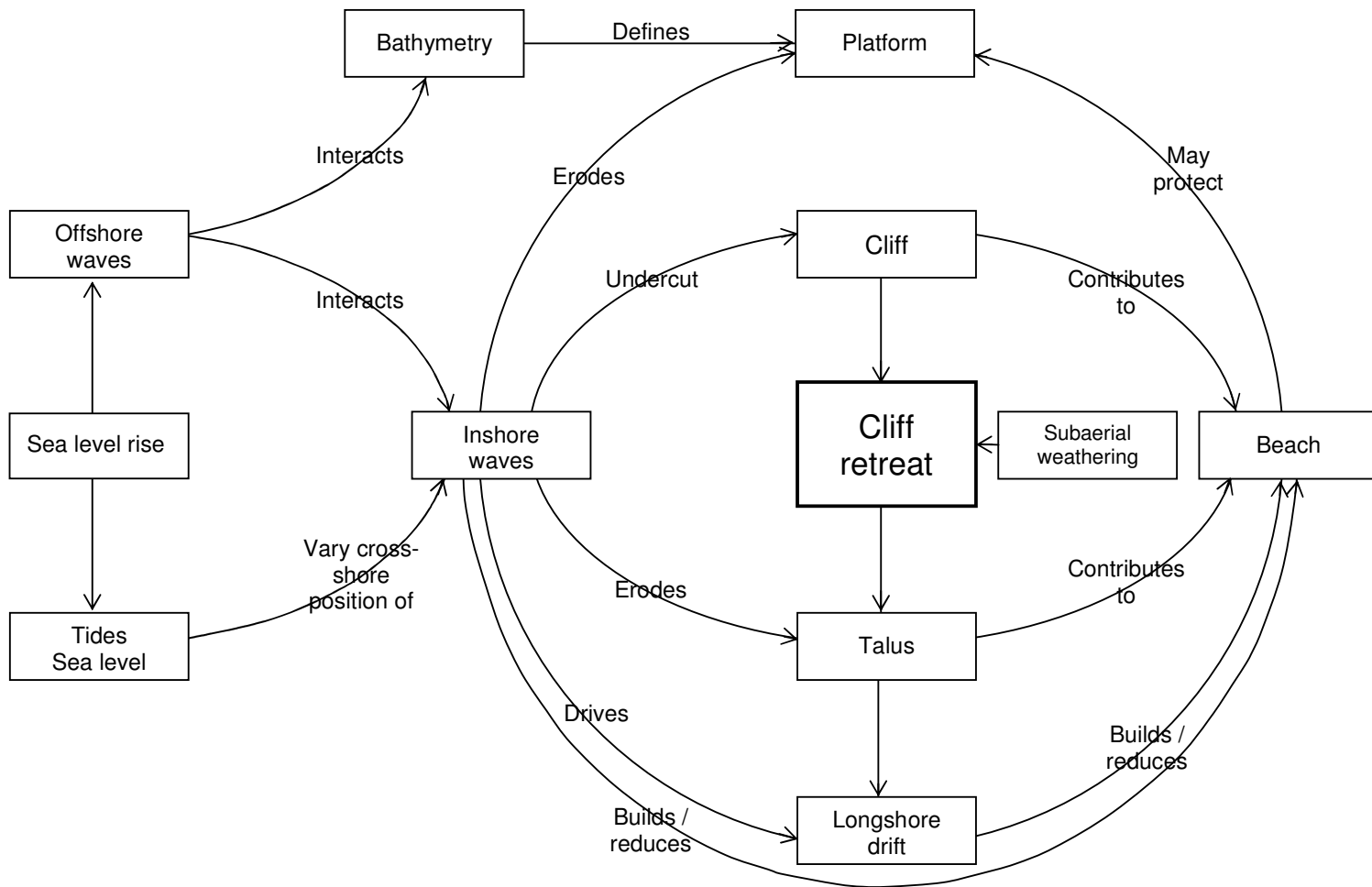


Figure 2.1 - A cycle of cliff retreat interacting with the coastal system and coastal processes. (Adapted from Balsillie and Berg, 1972; Walkden and Hall, 2005; French, 2001). Man-made structures can influence the coastal system at any point depending on the type of structure.

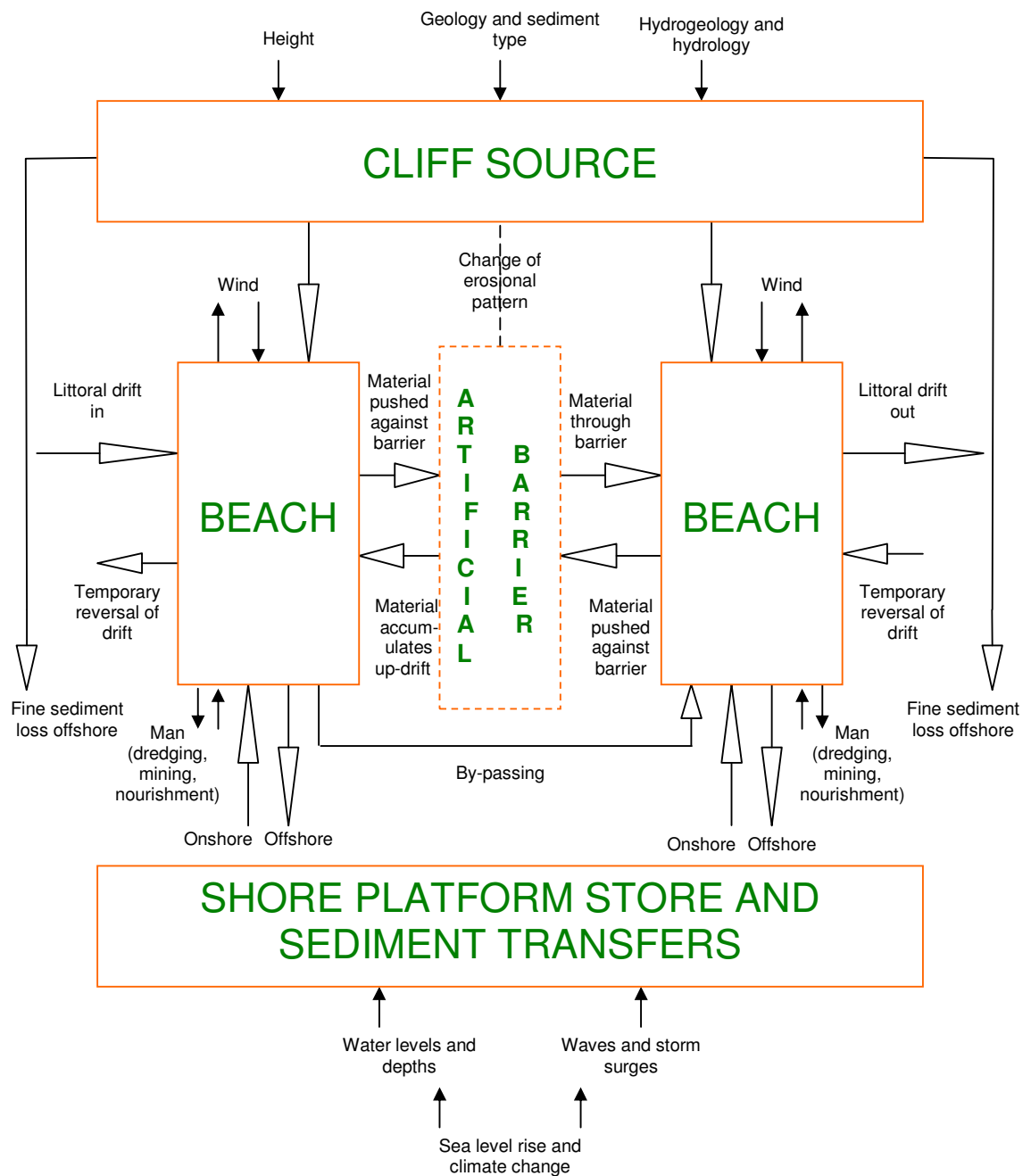


Figure 2.2 - Interactions of the sediment budget system near an artificial barrier.

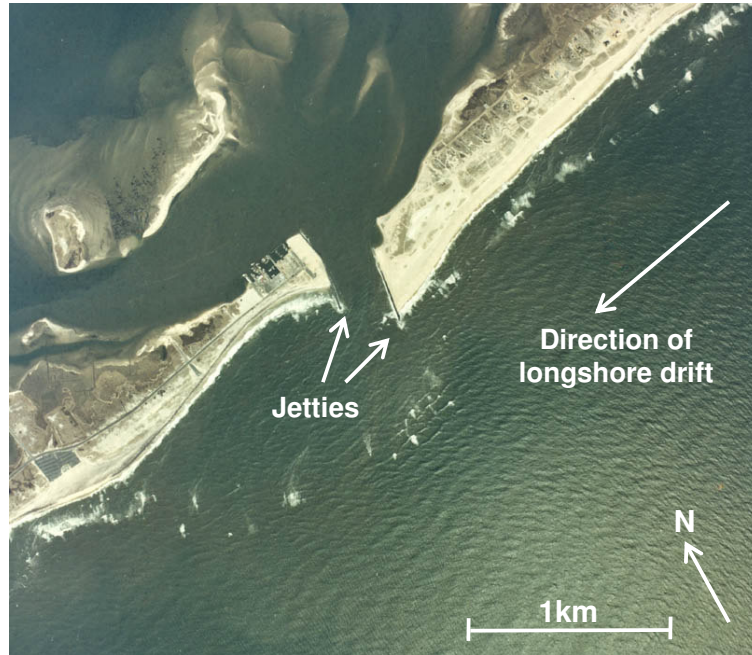


Figure 2.3 - Shinnecock Inlet, New York illustrating the impoundment of sediment up-drift of a pair of jetties, and a sediment deficit down-drift (photograph taken 21st April 1983 by US Army Engineer Research and Development Center, 2007).

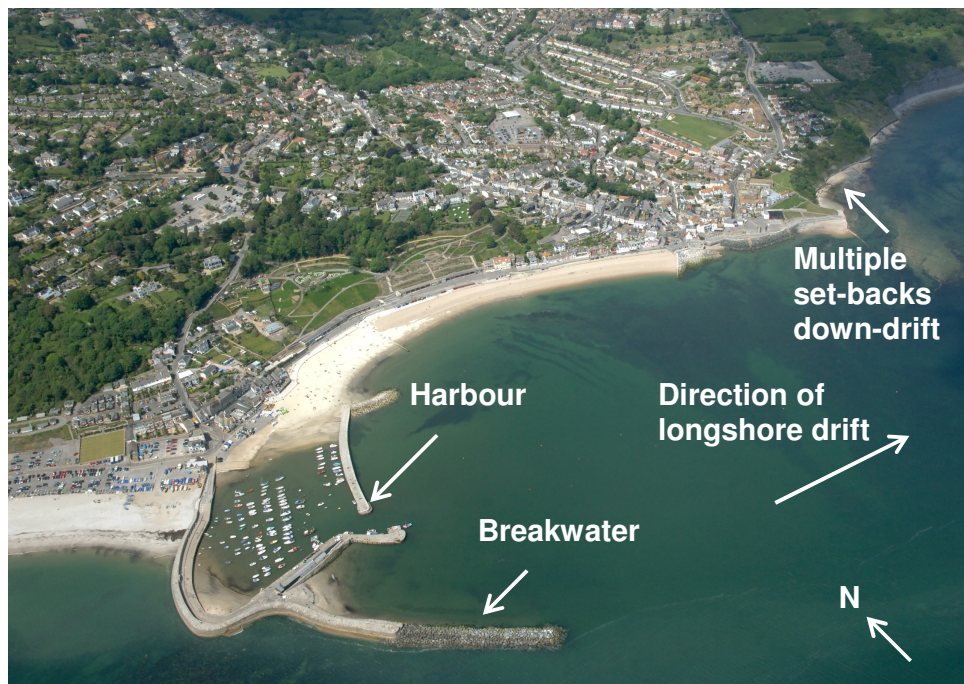


Figure 2.4 - The breakwater at Lyme Regis, Dorset after the 2006/2007 maintenance works (photograph courtesy of Alan Clark). The harbour arm, known as The Cobb (length approximately 250m) has blocked sediment from the west since the 13th century resulting in depleted beaches down-drift. Subsequently groynes were constructed down-drift to protect the town.



Figure 2.5 - Groynes and a seawall at Poole Bay, Dorset prior to beach replenishment in 2006-2007. Longshore drift direction is coming out of the photograph, parallel to the seawall. Note handrail for scale (photograph taken 5th December 2004 by Andrew Pearce).



Figure 2.6 - A rock armoured revetment at Folkestone, Kent (photograph taken in 2002, courtesy of Andrew Pearce).

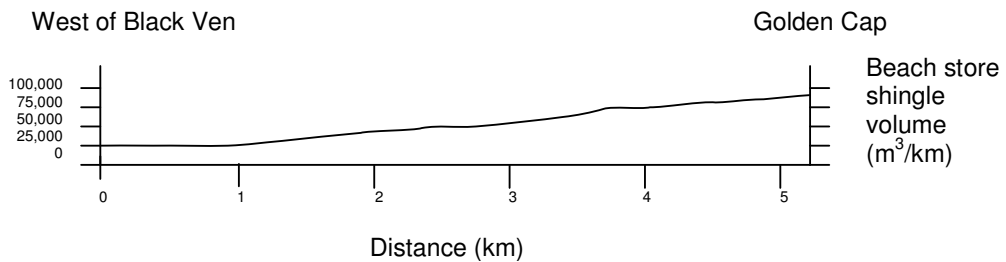


Figure 2.7 – Increased sediment supply down-drift of Black Ven, Dorset. With little human intervention and limited offshore movement, the sediment supply increased down-drift (Bray, 1992).

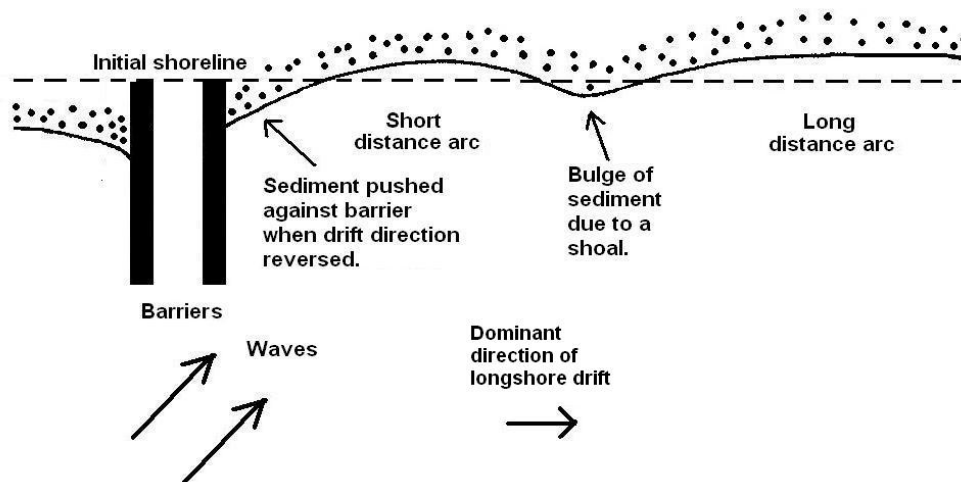


Figure 2.8 - Short and long distant effects of a jetty, creating a 'double-s' shape. Sediment accumulates up-drift, whilst the down-drift coastline is set-back due to sediment deficient. Sediment is pushed against the barrier due to drift reversal and refraction. A bulge due to an ebb tidal shoal occurs and this can migrate down-drift (adapted from Bruun, 1995; Galgano, 1998).

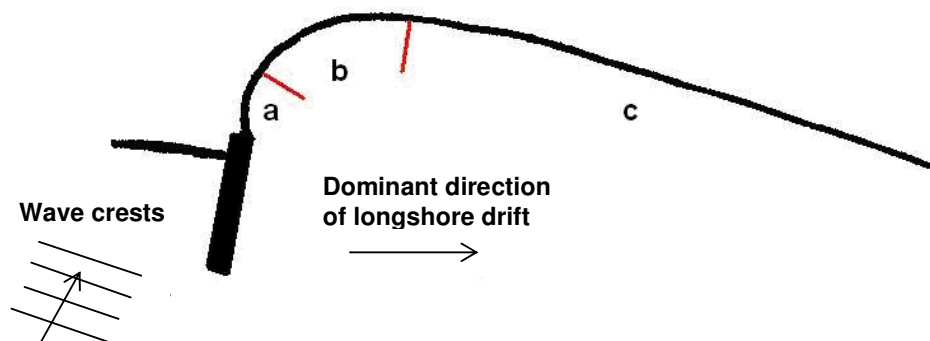


Figure 2.9 - The three components of a crenulate shaped bay include: a) a tightly curved section representing a logarithmic-spiral; b) a gently curved section; and c) a tangential coastline parallel to the wave crests.

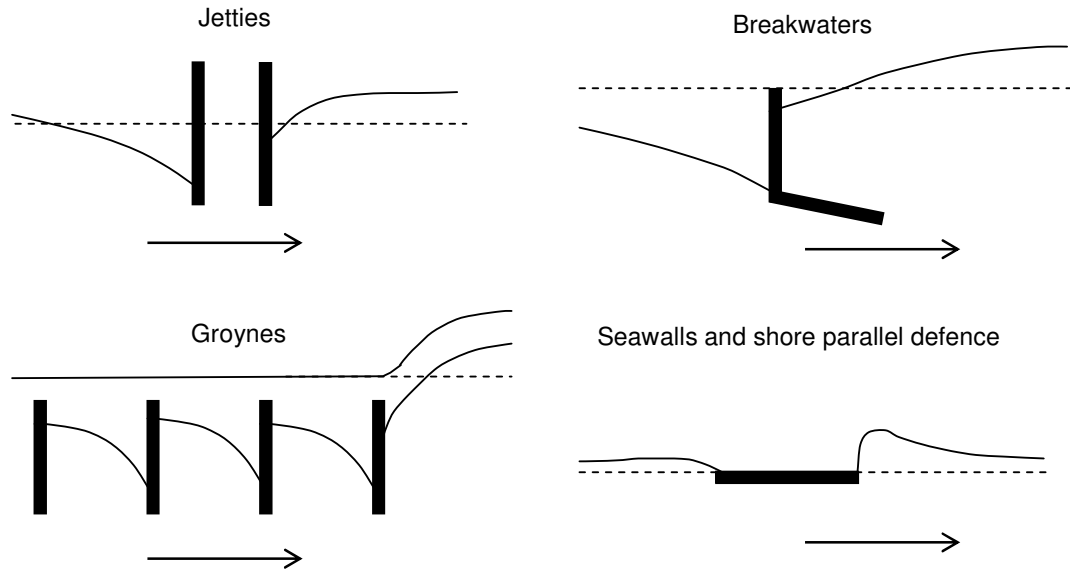


Figure 2.10 – Set-back due to littoral drift barriers (adapted from Komar, 1976; McDougal et al., 1987). The arrows indicate the dominant direction of longshore drift. The solid line represents shoreline after defence construction. The dashed line indicates original shoreline position.



Figure 2.11 - Ocean City Inlet, Maryland. The inlet was stabilised in 1934-1935 and since then, the down-drift coast has been set back over 600m. Erosion increased from 0.6m/yr before jetty construction to 9.3m/yr after jetty construction (photograph from Google Earth, 2007).

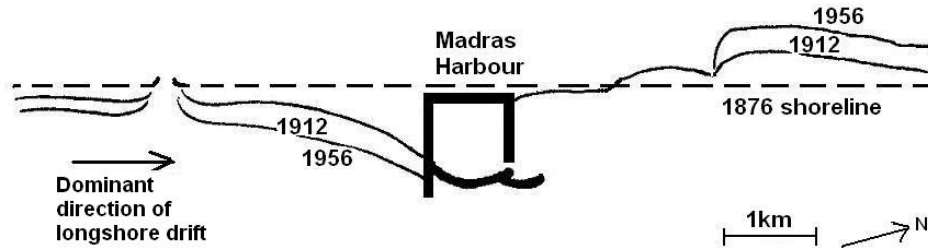


Figure 2.12 - Breakwaters at Madras Harbour, India. Construction of harbour breakwater commenced in 1875. The shoreline set back and increased erosion was reported 5km down-drift. Up-drift, the shoreline advanced seaward (adapted from Komar, 1983).

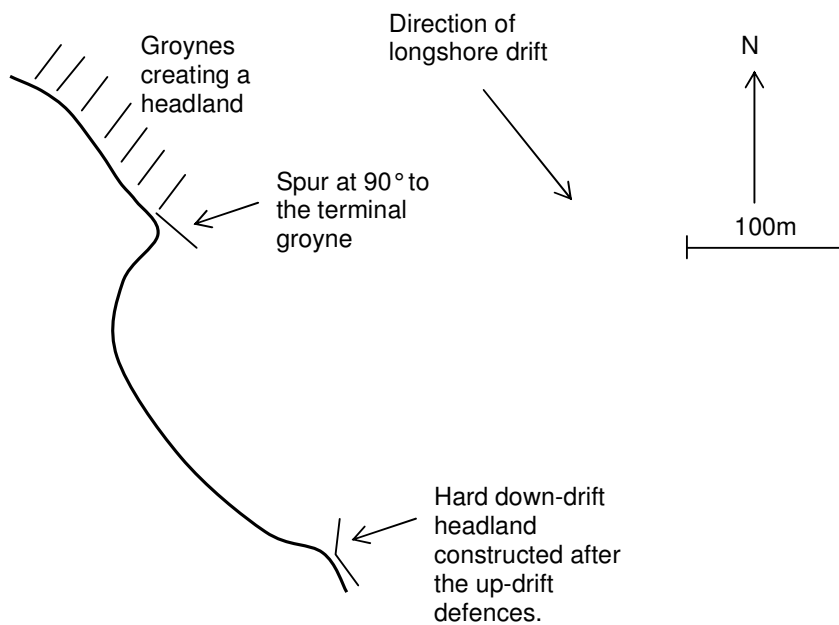


Figure 2.13 – The groynes and spur at Summerille, Smith Point, Chesapeake Bay, Virginia. Due to the continued set back, a spur was added at 90° to the terminal groyne to prevent outflanking. Even so, over 35 years, a 100m wide bay has developed (based on Multimap, 2007).

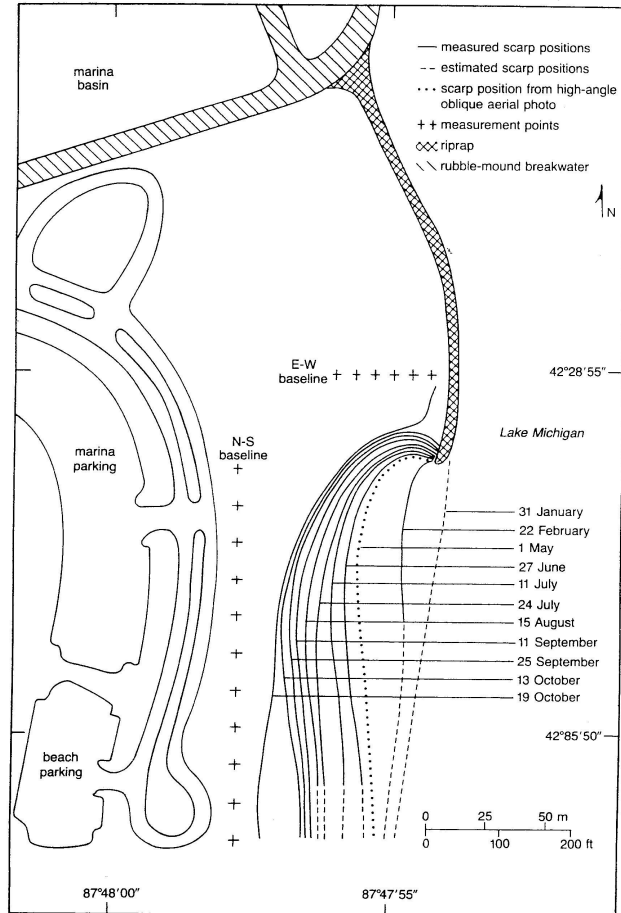


Figure 2.14 - Bay formation at Lake Michigan, Illinois (Terpstra and Chrzastowski, 1992). The bay was formed from January to October 1989 down-drift of a rip-rap on a sandy shoreline. Dominant drift direction is from north to south.

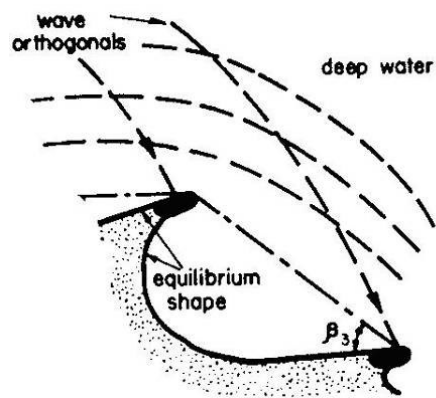


Figure 2.15 - Crenulate shaped bay formation showing curved offshore contours (adapted from Silvester and Hsu, 1997). The down-drift shoreline orientates itself to the incoming waves.

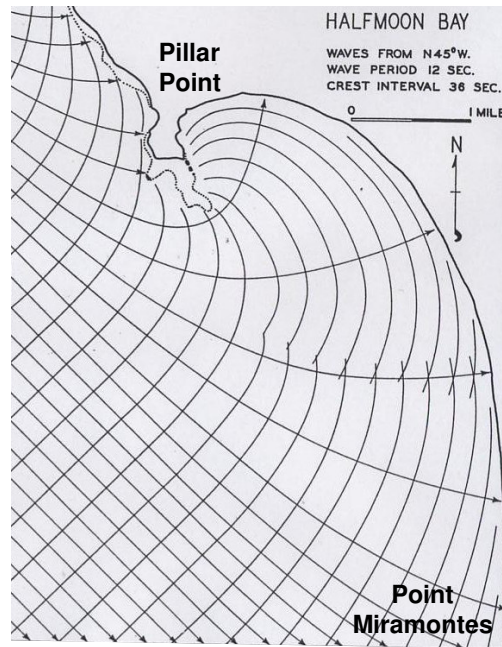


Figure 2.16 – Half-Moon Bay, California (Krumbein, 1944). The curvature is greatest near Pillar Point, the up-drift headland. Wave refraction distributes energy around the bay with an increase in grain size in the longshore drift direction.

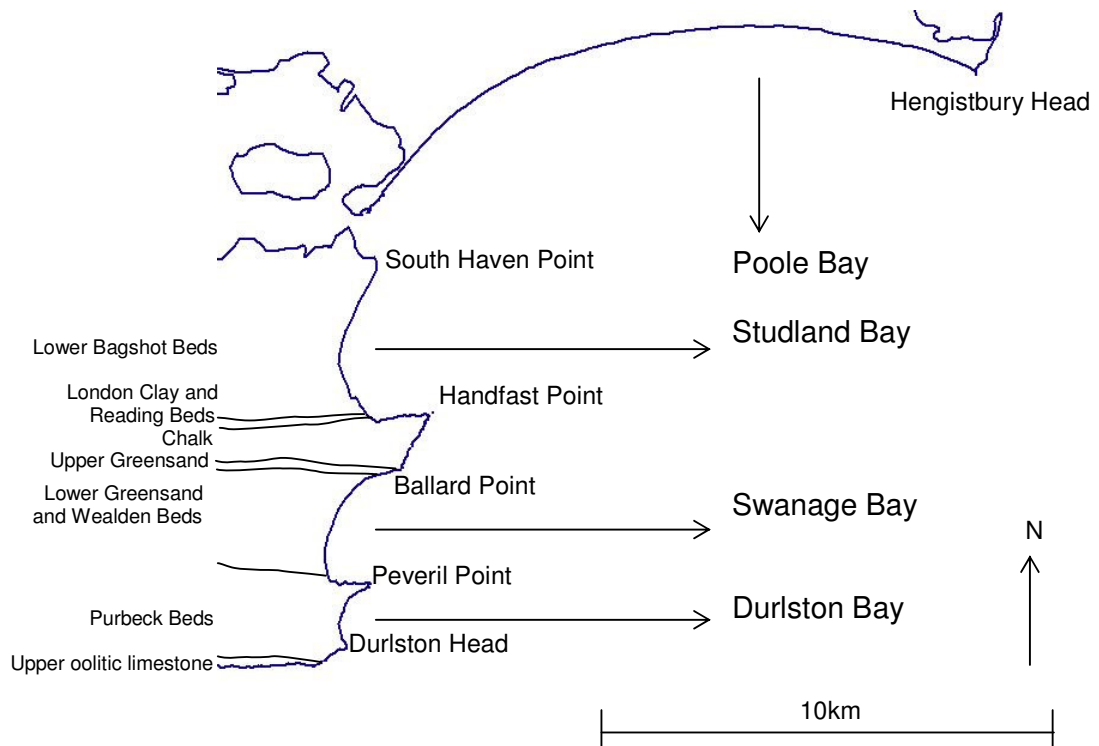


Figure 2.17 - A selection of crenulate shaped bays along the south coast of England. The bays have been created when soft rock has been eroded between harder layers.

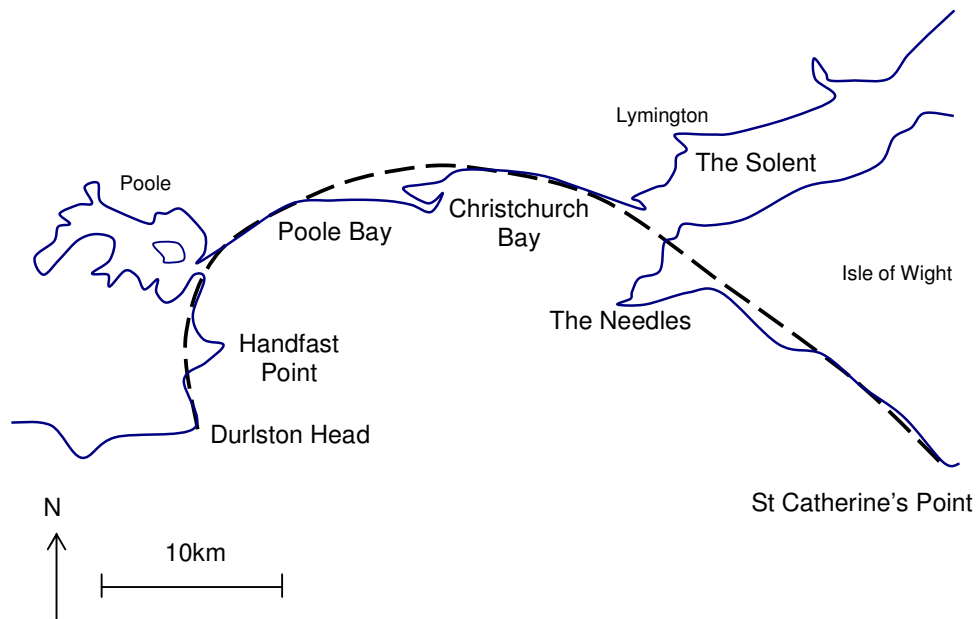


Figure 2.18 – A potential crenulate bay system combining Poole Bay and Christchurch Bay from Durlston Head, Isle of Purbeck to St Catherine's Point, Isle of Wight. It should be noted that this does not relate to how the bays evolved, so the concept of a crenulated form in this case is very hypothetical.



Figure 2.19 – An artificially stable crenulate shaped bay south-west of Folkestone, Kent. Once the headlands were created the beach was nourished. Sediment was designed to be contained within the bay (known as static equilibrium), creating a wide beach protecting the seawall (Channel Coastal Observatory, 2005a).

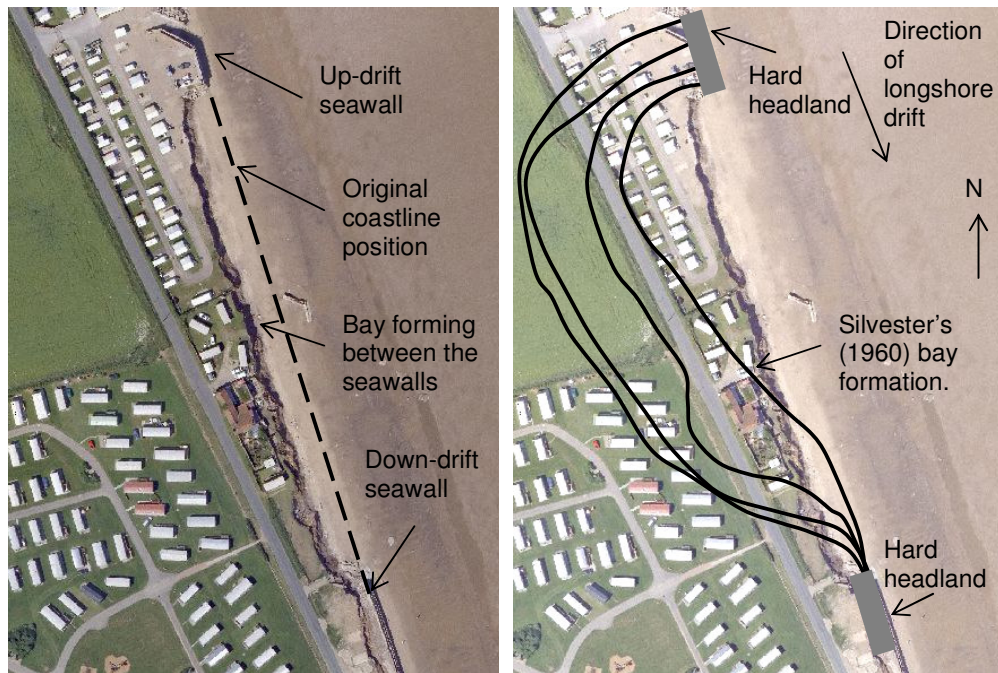


Figure 2.20 – Comparison of an asymmetrical embayment forming at Ulrome, Holderness and through laboratory tests. The left-hand image depicts a small bay forming between two privately constructed seawalls. The right-hand image is superimposed by Silvester's (1960) laboratory tests of bay formation using sand. The lines represent the shoreline position after 8, 24, 56 and 112 hours of wave attack from the north-east, the same orientation as the predominant wave direction on the Holderness coast. Width of photograph is approximately 190m (photograph courtesy of East Riding of Yorkshire Council).

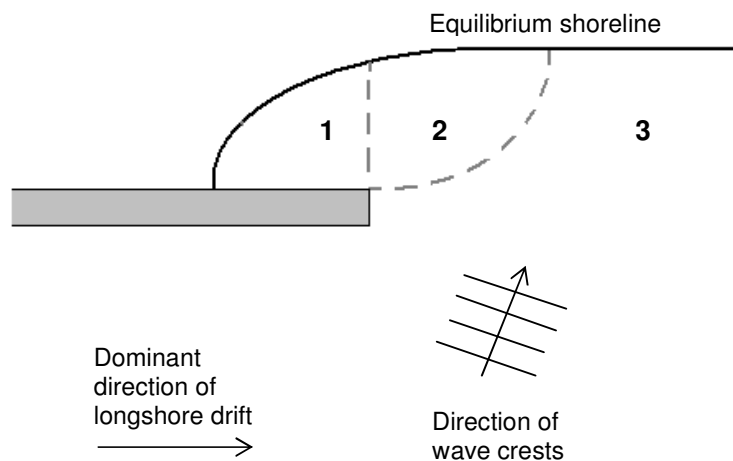


Figure 2.21 - Regions generated by a barrier (Adapted from González and Medina, 2001). Region 1 waves are diffracted around the barrier. In Region 2, refraction occurs and Region 3 displays no effect of the breakwater.

Table 2.1 - Artificial barriers (Komar, 1976; Carter, 1988; Kraus and McDougal, 1996; French, 2001).

Artificial barrier	Purpose	Example
Jetties.	Shore perpendicular littoral drift barriers are often located in pairs at the mouth of a river, tidal inlet, lagoon or estuary to stabilise the channel and to prevent shoaling. Jetties often extend into the breaker zone and can be up to 1 km long, interrupting the supply of longshore drift to the down-drift coastline.	Shinnecock Inlet, New York (Figure 2.3).
Breakwaters.	Shore parallel and perpendicular littoral drift barriers are used to protect the entrance to harbours and provide shelter from the waves. They can be placed at differing orientations to reduce the amount of sediment by-passing.	Lyme Regis, Dorset (Figure 2.4).
Groynes.	Groynes are built to prevent erosion, minimise wave action and to diminish cliff slumping. Constructed of wood or rock armouring they are typically 10m to 200m in length. When several are placed a short distance apart they form a groyne field. This traps a portion of sand and allows for by-passing.	Poole Bay, Dorset (Figure 2.5).
Seawalls.	Vertical or sloping seawalls frequently accompany groynes to maintain shoreline position. Their impact on the beach has generated substantial debate. They do not interrupt longshore drift, but reflect waves which are likely to transport material seaward, creating a drop in beach levels. Seawalls can cause a sediment deficit as cliff input is reduced.	Poole Bay, Dorset (Figure 2.5).
Revetments or rip-raps.	These are constructed on an undercliff or where rock armouring is placed parallel to the shoreline. They frequently provide additional protection to the above defences.	Folkestone, Kent (Figure 2.6).

Table 2.2 - Longshore transport rates. Values included from the three study regions, plus other localities, some of which are discussed in this chapter.

	Location	Littoral drift volume (m ³ /yr)	Source
Study regions	Holderness, Yorkshire.	Up to 90,000	Mason (1985).
	Christchurch Bay, Hampshire.	3,000-20,000	Bray <i>et al.</i> (1995), updated by Carter <i>et al.</i> (2004).
	North-east Norfolk (before defences) (after defences)	333,000 260,000	Clayton (1989).
Other areas	Charmouth, Dorset.	Up to 4,700	Bray (1992).
	Dunwich, Suffolk.	65,000	Vincent (1979).
	Madras, India.	500,000	Komar (1983).
	Ocean City Inlet, Maryland.	115,000	Galgano (1998).
	Port Hueneme, California.	800,000	Savage (1957).

Table 2.3 – A selection of studies on the impact of different artificial barriers.

Type of littoral drift barrier	Location	Source
Breakwaters and causeways.	Nome, Bearing Sea, Alaska. Lagos, Nigera. Hirtshals, Denmark. Madras, India. Ceara, Brazil. Santa Barbara, California. Santa Monica, California. Kakinada, India. Paradip, India. Vishakhapatnam, India. Point Pelee, south-east Canada. Port Hueneme, California. Various harbours, Japan South-east Singapore	Borah and Balloffet (1983). Bruun (1995). Bruun (1995). Komar (1976, 1983). Komar (1976). Komar (1976). Komar (1976). Komar (1983). Komar (1983). Komar (1983). LaValle and Lakhan (1997). Savage (1957). Tanaka (1983). Wong (1981).
Jetties.	Port Canaveral, Florida. Indian River Inlet, Delaware. Managuat River, Turkey. Cape May, New Jersey. Shinnecock Inlet, New York. Moriches Inlet, New York. Manasquan Inlet, New Jersey. Ocean City Inlet, Maryland.	Bruun (1995). Bruun (1995); Galgano (1998). Bruun (2001). Everts (1983); Galgano (1998). Galgano (1998); Galgano and Leatherman (1999). Galgano (1998). Galgano (1998); Galgano and Leatherman (1999). Komar (1976); Everts (1983); Galgano (1998).
Groynes.	Summerille, Chesapeake Bay, Virginia. Barton-on-Sea, Hampshire, UK. Haute Normandy, France. Blackpool, UK. Ofir-Apúlia, north-west Portugal. Oarai, Japan. Brighton, East Sussex, UK. Mappleton, East Yorkshire, UK. Keta, Ghana. Kashimanada coast, Japan. North Point Marina, Illinois, Lake Michigan.	Anderson <i>et al.</i> (1983). Brown and Barton (2007). Costa <i>et al.</i> (2006). French (2001). Granja and Carvalho (1991, 1995). Hsu <i>et al.</i> (1993); Bruun (1995). Jezard (2004) Maddrell <i>et al.</i> (2001). Nairn and Dibajnia (2004). Saito <i>et al.</i> (1996). Terpstra and Chrzastowski (1992).
Seawalls, revetments and rip-raps.	Sylt, Germany. Blackpool, UK. Ofir-Apúlia, north-west Portugal. Norderney, Germany. Sandy Hook, New Jersey.	Dette and Gärtner (1987). French (2001). Granja and Carvalho (1991, 1995). Kunz (1987). Phillips (1985).

3. MEASUREMENT OF SET-BACK

3.1 Introduction

To analyse the terminal groyne effect, past coastal evolution in terms of shoreline positions and the effect of human intervention must be quantified and understood. Quantitative and accurate knowledge of data, together with potential uncertainties are required to gain an understanding of why shoreline changes have occurred (Anders and Byrnes, 1991; Galgano, 1998). There are many methods to calculate shoreline change (Moore, 2000) determined by the temporal and spatial scales required in the investigation. In this thesis, the terminal groyne effect will be investigated over national, regional and local spatial scales (see Figure 1.6). Timescales vary from decades to centuries. To analyse set-backs, the core information required for regional and site studies is the history of defence construction, and shoreline positions to determine the magnitude of retreat.

Figure 3.1 provides an overview of the methodology followed in this research. In this chapter, each part of the figure will be discussed with reference to the terminal groyne effect.

3.2 National assessment of coastal set-back

To determine potential study regions and sites, set-back adjacent to defences were studied nationally, following the procedure outlined in Figure 1.6. Initially a desk study was undertaken using books, reports, journal articles, Ordnance Survey (OS) maps, aerial photographs, and the Futurecoast study. Futurecoast (produced by Halcrow, 2002 for the Department for the Environment, Food and Rural Affairs (DEFRA)) produces a summary of coastal features and behaviour in England and Wales, such as sediment transport, cliff composition, retreat rates and management practices. There is also a video clip of the coastline taken approximately parallel to the cliff. The user can distinguish the main features of any coastal site, including the set-backs adjacent to defences.

In England and Wales, preliminary analysis during this research has estimated there are almost 200 localities which have a set-back adjacent to defences (some with multiple or fossilised set-backs), with half situated on cliffed coasts (Figure 3.2). A list of localities is found in Appendix 2. Approximately 100 sites are situated in the east and south-east regions of England. 50% of the total number of set-backs in England and Wales are on cliffed coasts. Figure 3.2 represents the localities which have set-backs, not the places that have a terminal groyne effect, as it is unknown whether down-drift erosion has increased after defence construction (see definition in Section 1.6). When a terminal groyne effect is present, it may affect the coast for tens and potentially thousands of metres longshore.

To select regions for further study, the coast must be soft, eroding and cliffed. Soft cliffs are predominately found on the north-east, East Anglian and South coast of UK (Jones and Lee, 1994; Lee and Clark, 2002). Figure 3.3 indicates eroding coast in England and Wales (from Jones and Lee, 1994). A comparison between Figures 3.2 and 3.3 indicates set-backs occur even along areas which are not eroding. This is because the coast may have eroded historically, but is presently stable; erosion is localised and too small to indicate on a national scale map; or that set-back occurred adjacent to a breakwater structure at a river mouth (for example, Black Buoy Sands, The Wash Lincolnshire).

3.3 Regional and study site selection

Following a national assessment of set-backs adjacent to defences, Figure 1.6 shows that set-backs are to be investigated regionally. On Figures 3.2 and 3.3, regions where there is a high density of eroding cliff setbacks include north Yorkshire, Holderness, north-east Norfolk, north Kent, east East Sussex, and west Hampshire (Christchurch Bay). These regions and potential study sites were examined in further detail, including geology, littoral drift rates, subjectivity to active erosion, type, age and distribution between defences and availability of data. Frequently, set-backs were fossilised or too old (therefore indicating a lack of data) or too young (indicating set-back is not developed enough), making them inappropriate for detailed study. Consequently, Holderness, north-east Norfolk and Christchurch Bay were chosen for detailed study. Due to data quality and availability, retreat rates in north-east Norfolk were not studied in

detail. Each study region was visited to gain an appreciation of the cliff geology and susceptibility of cliff failure, the nature and size of the beach, and the type and form of defences. Where possible, visits were made to council offices, libraries and other places of interest to obtain information. Study sites were then selected as discussed in Chapters 4, 5 and 6.

3.4 Measurement of shoreline change

The terminal groyne effect definition (see Section 1.6) states retreat rate increases down-drift after defence construction. To measure this, shoreline positions were required before and after defence construction. A technique was required to measure shoreline change and retreat rates (Objective 1). The causes of shoreline change must be understood.

Part b) of Figure 3.1 involves an investigation into other studies of shoreline retreat. Numerous studies are published of shoreline mapping techniques and retreat rates (Moore, 2000). Shorelines are dynamic in nature, and their definition, mapping and subsequent utilisation is a complicated issue (Li *et al.*, 2001). This results in different approaches to shoreline mapping, using a variety of shoreline indicators, and each must be visible on each resource used. Possible shoreline indicators include the high water line, the mean high water line, the low water line, the mean low water line, cliff base and cliff top (Crowell *et al.*, 1991; Boak and Turner, 2005).

Shoreline indicators can exhibit short term variability. For example, storms and tidal cycles potentially obscure short term measurements of the water lines (Crowell *et al.*, 1991; Moore, 2000; Pajak and Leatherman, 2002). However, short term variability becomes noise over longer decadal records (Galgano, 1998). Decadal scales are frequently used when analysing the terminal groyne effect. Nevertheless, water lines can be difficult to map, are associated with many errors and can be misinterpreted from poor quality aerial photographs (Crowell *et al.*, 1991; Moore, 2000).

Some shoreline indicators have a delayed effect in recording the cause of shoreline change. For example, a reduction in beach levels first accelerates retreat at the cliff toe, then at the cliff top (Brown, 2005). The cliff base can be

obscured by landslides and beach levels. Figure 3.4 plots the cliff-beach junction over time taken from a cliff and beach profile located between Barton-on-Sea and Milford-on-Sea, Christchurch Bay (data supplied by the Channel Coast Observatory, see Appendix 3). Over 16 years the cliff base has retreated 13m, but within any one year the cliff base can migrate seaward by 1m to 2m.

Conversely, the cliff top is a permanent feature of shoreline change, only moves landward, is easy to determine and discernible on each aerial photograph, map or survey. However there are some difficulties in locating the cliff edge (Figure 3.5) due to the geometric profile, overhanging vegetation, and cliff undercutting (Gulyaev and Buckeridge, 2004). Fortunately, the majority of the study sites in this research have a clear cliff edge and are free of vegetation, so this does not create a major difficulty. Cliff top retreat is not only influenced by wave action, but also according to its geological and morphological properties, for example height and hardness.

The cliff top has been widely and successfully used in shoreline retreat investigations. Selected studies of historical retreat, cliff characteristics and human influence on the cliff top retreat include Holderness (Valentin, 1954; Richards and Lorriman, 1987; Pethick, 1996), Hunstanton, north-west Norfolk (Drake and Phipps, 2007), north-east Norfolk (Clayton, 1989; Cambers, 1973, 1976), Suffolk (Pile, 2003), Isle of Sheppey (Nicholls *et al.*, 2000; Dixon and Bromhead, 2002), and Christchurch Bay (Barton and Coles, 1973, 1984; Lacey, 1985; Nicholls, 1985; Farquharson, 2006). Hence the cliff top was chosen as the most appropriate shoreline change indicator to measure the terminal groyne effect.

3.5 Data sources

Cliff top position data is derived from historical and modern maps, vertical aerial photographs and repetitive field surveys (Anders and Byrnes, 1991). A combination of these resources from the mid 19th century to the present day were used to assess set-backs and the terminal groyne effect.

3.5.1 Maps

Reliable 1:10,560 and 1:2,500 Ordnance Survey maps were first published in the mid 19th century as part of the County Series, later to become the National Grid (Carr, 1962; Digimap, 2007). Alterations to maps over time include real changes, changes to rule generalisations and deliberate avoidance of strict planimetric accuracy (Oliver, 1996). Errors inherent to cliff mapping that affect the accuracy of cliff positions include inaccurate map sources, careless mistakes, constant instrument error, systematic errors and random errors (Lee and Clark, 2002). Quantifying potential errors involves an understanding of both how and when the survey was carried out (Lee and Clark, 2002; Hanson and Nicholls, 2003). For example, systematic uncertainties in historical shoreline mapping can occur at the time of the survey and throughout the life of the map. Table 3.1 lists some common faults that may have occurred at the time of map production, some more relevant to early maps than their modern counterparts. A quantitative estimation of these errors is not available, but they potentially affect distances over hundreds of metres. Some problems occur with the actual mapping. For example, Oliver (1996) claims some map features were exaggerated (such as Spurn Head from 1818 to 1843), whilst other parts of the coast were displaced from their true position in an attempt to emphasise minor promontories. The geographical scale and extent of this is unknown, but it could be critical to the research as set-backs can result in the growth of subtle promontories.

A further problem is the year of map production. Each map is produced in a certain year or between a number of years, potentially more than a decade apart. From 1888, the OS policy was to date maps from the last time the site was visited (Oliver, 1996). However, it does not mean that the whole site was surveyed or revised in one year. For example, Ordnance Survey (2006a) published the 1:25,000 OS Explorer map for the Norfolk Coast East, which was 'revised' in 1996 and 'revised for selected change' in 2001 and 2006. However, defences constructed between 1986 and 1987 at Overstrand (confirmed from Council records, North Norfolk District Council, 2004) were not included in the 2006 revised edition. Hence maps only provide a guide to the dates of defence construction. A history of defence construction must be accompanied with data derived from other resources (see Section 3.7 and Table 3.7)

Map errors also develop after the time of map production, for example, those caused by storage conditions and extensive map use. These errors are listed in Table 3.2. Crowell *et al.* (1991) undertook an extensive review of the analysis and mapping accuracy of historic shoreline change. Using 1:10,000 NOS T-sheets (National Ocean Service Topographic-sheet) based on maps constructed prior to the use of aerial photography (1888-1930), they estimated that the worst case of the digitised location of the mean high water line using a root mean square method was 8.4m plus sketching error. The factors listed in Table 3.2 would have an additional error dependant on the source. In studies of cliff top retreat at the Isle of Sheppey, Nicholls *et al.* (2000) approximated this to $\pm 10\text{m}$. Hence cliff top change of less than 10m is no evidence of overall change.

3.5.2 Aerial photographs

Aerial photographs have been extensively used in mapping since the Second World War (Anders and Byrnes, 1991; Ordnance Survey, 2007). They are available in two forms; on photographic paper and georectified digitised images. Table 3.3 lists some of the errors associated with aerial photographs. Some can be overcome by georectification. Georectifying is necessary for aerial photographs to correct for spatial location and orientation. They then can be used in a Geographical Information System (GIS) and to take accurate measurements of shoreline retreat. For this research, some imagery had previously been georectified whilst other photographs needed to undergo this process. ENVI 4.1 (Environment for Visualising Images) was used for georectification. For images requiring georectification, ground control points were selected, such as at road intersections and corners of buildings. At times, in rural areas accurate georectification (within $\pm 10\text{m}$) was not possible so data was omitted. Crowell *et al.* (1991) analysed the worst case error estimates of aerial photographs from 1:10,000 aerial photographs. They found a worst case error using the root mean square method of 7.5m-7.7m, plus the position of the shoreline indicator (in this case the inaccurate interpretation of the high water line).

3.5.3 Field surveys

Total stations (Electric Distance Measurement) have frequently been used to measure cliff top positions, but in recent years a greater volume of shoreline data has been available due to advances in mapping technology. This includes differential GPS (DGPS, a Differential Global Positioning System). It has resulted in faster surveys covering larger geographical areas and has millimetre to centimetre accuracy in both vertical and horizontal dimensions. In measuring the cliff top, the greatest error that occurs is safely accessing the cliff edge, thus creating a survey error of $\pm 2\text{m}$.

3.5.4 Data errors

Uncertainties are associated with mapping and locating cliff top positions. Based on Crowell *et al.*'s (1991) and Moore's (2000) analysis of map and aerial photographs (including Tables 3.1, 3.2 and 3.3), errors associated with the maps in this thesis are approximated to $\pm 10\text{m}$. Cliff top position errors from field surveys are approximately $\pm 2\text{m}$. These values do represent extreme values, but testing at the study regions and sites indicate they are plausible bands of error. The $\pm 10\text{m}$ error band was tested by selecting fixed points on a map, such as churches and recording how much they 'moved' with each map addition. This value was found to be representative of map errors. For some maps, if there was greater than $\pm 10\text{m}$ displacement of a fixed object, the error was deemed too high, and the data was not used for quantitative analysis. The $\pm 2\text{m}$ value for field surveys was gained by discussions with surveyors and by evaluating their methods of undertaking surveys. It was tested by checking positions where there is no known set-back, such as along sea-walls and recording the apparent retreat. Where additional cliff retreat data and fieldwork was available (such as fixed measurement points), it was compared with field surveys and aerial photographs. Actual cliff top change may occur within these error ranges ($\pm 10\text{m}$ or $\pm 2\text{m}$), but due to the mapping and methodology errors mentioned, the retreat would not be conclusive evidence of shoreline change. The use of probability bands indicating possible overlap in shoreline retreat is not suitable for the root mean square uncertainties, as it already incorporates the variance of the data. Further research into the probability of errors using the original map sources and survey methods would be advantageous.

3.5.5 Summary

Maps, aerial photographs and field surveys are used to map coastal change. Each are associated with potential errors with $\pm 10\text{m}$ for maps and photographs, and $\pm 2\text{m}$ field surveys, such as a DGPS survey.

3.6 Shoreline change methodologies

The method of determining shoreline change depends upon the data and resources available, accuracy required, level of expertise required to undertake the task, time taken and costs incurred (Moore, 2000). Coastal change happens at different scales and the method used for shoreline change analysis must reflect this. Moore (2000) discusses a selection of shoreline change techniques. One technique used within GIS is the Digital Shoreline Analysis System (DSAS) devised and up-graded by Thieler *et al.* (2003). This creates perpendicular transects from a set baseline, running parallel to the present day coast, and calculates the distance between it and successive shoreline positions. For a detailed methodology see Section 3.8. A disadvantage of using this method is that it requires a high level of expertise to operate, and data preparation and input can take many days or weeks depending on the data type and volume. However, once the system and data is prepared, it is advantageous as it calculates large volumes of cliff top change data quickly, provides a high level of accuracy and is inexpensive to run (Moore, 2000). It is an ideal tool to measure the terminal groyne effect as it can be used at any spatial scales and be repeated at different time intervals.

The accuracy of the rate of shoreline change depends on the precision of shoreline measurements, the temporal variability of the shoreline, number of data points used in calculations, the proximity of each observation to the time of actual change, the time between shoreline measurements, the total time span of the shoreline data and the method used to calculate the rate. Moore and Griggs (2002) and Nicholls *et al.* (2000) found that the longer the time period between measurements, the more representative erosion rates are of the long term rate of change. For cliff top retreat this is important as cliff erosion cycles and the frequency of storm attack on the cliff can create short term effects or noise which obscure long term trends (see Section 2.2.4 and Section 3.4). However,

long term retreat records can not always be used to predict future retreat as controlling conditions change (see Chapters 4 and 5).

Once shoreline change and retreat is produced, the retreat rate can be calculated by differing methods. For example, the end point rate (EPR), average of rates, linear regression and jackknife are popular methods, as described by Dolan *et al.* (1991). In this thesis the EPR has been used. It determines retreat rates by dividing the difference between the most recent and oldest cliff top position, by the time elapsed (see Equations 3.1 and 3.4 in Section 3.9.1). When analysing the terminal groyne effect, this method is advantageous as it is easy to calculate and takes the maximum time period into account, thereby reducing the effect of erosion cycles and other short to medium term changes. However, data uncertainties and errors can have a strong influence on results (Dolan *et al.*, 1991; Galgano, 1998).

A GIS was created with cliff top positions compiled from maps, aerial photographs and field surveys. The DSAS extension was used to create transects perpendicular to the cliff top and retreat rate was measured between successive cliff top positions. Retreat and retreat rate was calculated using the EPR method. The methodology with respect to the study regions will be discussed in detail in Section 3.8.

3.7 Data from study regions

Part c) of Figure 3.1 involves the collection of data. Two data sets are required to analyse terminal groyne effect - the cliff top positions needed to create a GIS, and a history of human intervention, including coastal behaviour.

3.7.1 Cliff top mapping

The main data sources required for creating a GIS are maps, aerial photographs and field surveys. These were available from the relevant local authorities - East Riding of Yorkshire Council (Holderness); New Forest District Council (Christchurch Bay) and North Norfolk District Council (Norfolk). Historical OS maps, landline and raster data were also available from Digimap, an online mapping resource (see Appendix 3). Additional information was obtained from

the Environment Agency and the Channel Coastal Observatory (CCO), Southampton.

Tables 3.4, 3.5 and 3.6 list the resources directly used in each study region. Each table is divided into two parts known as 'main survey years' and 'supplementary survey years'. The 'main survey years' were used to analyse each study site and study region, whereas cliff top data from the 'supplementary survey years' was used only in certain study sites where additional data was required. The table also has two date columns, known as 'publication dates' and 'reference year'. As maps were surveyed over a series of years, it is not known exactly when the cliff top position was mapped. To avoid confusion in data analysis, each series of maps was assigned a reference year relative to the years of map publication. The reference year was selected from when the majority of the maps were published, or alternatively when there was a wide spread of publication dates, the middle year was selected. 1:10,560 or 1:10,000 and 1:2,500 scale maps were used depending on the accuracy and detail of the data required. The difference in years was not taken into account during retreat analysis over time scales of several decades, as the errors were relatively small. Data derived from maps and aerial photographs had potential errors of $\pm 10\text{m}$. Where possible, the 2005 cliff line from aerial photographs was verified using DGPS data, thereby reducing errors to $\pm 2\text{m}$. Field surveys had errors of $\pm 2\text{m}$. Generally prior to 2000, field surveys were undertaken using total stations (Electric Distance Measurement), and after 2000, a DGPS.

Not all data available was required for direct analysis. For example, East Riding District Council's 'erosion posts' data (East Riding of Yorkshire Council, 2004) records measured retreat from fixed points. The posts, on average 500m apart along the cliff edge were used in Holderness to record retreat from 1951 to the present day. This is an excellent data set, but was not appropriate to use to determine set-backs due to temporal and spatial constraints. However, it was used to check and verify map data and other field surveys. Further data verification took place using field surveys, for instance DGPS surveys were undertaken in Christchurch Bay. For historical maps, Digimap (2007) provided an explanation into the storage, processing and digitising of historical OS maps that may be downloaded from their website. This covers the potential problems as outlined in Tables 3.1 and 3.2 and discussed in Crowell *et al.* (1991) and Moore (2000). To check data quality, permanent features were compared

against the modern counterparts. Where large errors occurred ($>\pm 10\text{m}$), data was not used for quantitative analysis (see Section 3.5.4).

3.7.2 Human intervention including coastal behaviour

The measurement of shoreline change and the terminal groyne effect must be accompanied by an understanding of the coastal dynamics within the region and site, and how this has changed throughout time. Without this, other changes to the coast may be misinterpreted (see Section 4.3.3 and Section 7.2.1). This was undertaken by reading books, reports and journal articles, attending talks, together with visits to museums, local libraries, council offices, and each study site. However, some information was difficult to find as the local authority did not retain detailed records of coastal defences older than a few decades. From the available resources, the history of defence construction was ascertained. This was combined with defence details taken from maps and aerial photographs. The locality, length and type of defence were noted in chronological order (see relevant tables for each study site in Chapters 4 and 5). Several difficulties arose when determining a site's defence history as shown in Table 3.7. Defence degradation is recorded for all three regions (see Chapters 4, 5 and 6), but does not significantly influence retreat rate as the defences were mostly aged and inefficient. Defences were only recorded if they were permanent and maintained shoreline position. Where there was disagreement and uncertainties between literature and maps over the time of defence construction, a range of dates are given. Records are not available or kept regarding the dimensions and efficiency of many of the defences. The ability of the defence to retain sediment has a major influence on the severity of the terminal groyne effect. As this information is not available, this thesis has not taken this factor into account during analysis (see Tables 7.2 and 7.3).

3.7.3 Summary

From the data resources, a list of cliff top positions have been collated. Data has been checked for errors. A methodology to determine the history of defence construction and issues surrounding data collection has been described.

3.8 GIS methodology

Data was assembled on a GIS (parts e) and f) of Figure 3.1). A detailed methodology of the GIS process is shown in Figure 3.6. Table 3.8 lists the resources and files used. Cliff top positions were outlined, and distances between successive positions measured.

To measure retreat, the GIS extension DSAS 2.0 was used (see Section 3.6). This process is shown on Figures 3.7 and 3.8. DSAS measures transects from a specified baseline to an approximate parallel shoreline. Figure 3.7 illustrates perpendicular transects extending from the baseline to the cliff top. When perpendicular transects were created, they sliced each successive cliff top and recorded the position. This measured cross-shore retreat between the baseline and each shoreline. Transects were spaced 1m to 20m apart depending on the scale of study site or region. After the retreat was measured by DSAS, the output file for each year was loaded into Microsoft Excel for analysis. Retreat and area of land loss was averaged over set longshore distances according to the scale of the study region or site as shown in Figure 3.8. For example, if transects were measured every 10m, to measure the average retreat over a 50m longshore distance of coast, the average value was taken of 5 transects. Transect width varied according to the size of the site. The area was calculated using the Trapezium Rule, which worked as a good approximation (see Appendix 1). This resulted in cross-shore retreat between successive cliff top positions, relative to the baseline or earliest cliff top position. From here, retreat rates were calculated (see Section 3.9.1, Equations 3.1 and 3.4) using the EPR method.

3.9 Measuring set-back and the terminal groyne effect

The terminal groyne effect definition states that retreat rates increase down-drift after defence construction and Objective 2 was to ascertain if this occurs (see Sections 1.6 and 1.7). Figure 3.9 illustrates a typical set-back after defence construction. It is composed of two parts - a curved section of the bay known as the shadow zone, and a straighter section which extends down-drift. The shadow zone represents a transition from the protected to unprotected coast. It enlarges throughout time, extending up to 200m down-drift over a 45 year period

at the selected study sites (see Section 6.3.2). It does not represent a point of maximum set-back. A maximum point of cross-shore set-back is difficult to define or frequently not seen near to the shadow zone, particularly with sites where there is no down-drift headland to constrain retreat. To ensure the full effect of defences are taken into account, retreat rates before and after defence construction are calculated down-drift of the shadow zone.

3.9.1 Selected retreat parameters

In this thesis, the terminal groyne effect is measured in four ways with measurements taken relative to the cliff top position nearest to the date of defence construction. Four parameters were measured:

1) Retreat before and after defence construction.

$$\text{Cross – shore retreat (m)} = \text{Present cliff top position} - \text{Initial cliff top position} \quad (\text{Equation 3.1})$$

This includes set-back, which is defined as the cross-shore retreat between a shoreline position at the time of defence construction, and subsequent shoreline positions (see Chapter 10, Glossary).

2) Excess retreat.

$$\text{Excess retreat (m)} = \text{Actual retreat} - \text{Predicted retreat} \quad (\text{Equation 3.2})$$

Where:

$$\text{Predicted retreat (m)} = \text{Retreat rate before defences} * \text{Time elapsed since defence construction} \quad (\text{Equation 3.3})$$

And:

$$\text{Retreat rate (m)} = \frac{\text{Cross – shore retreat}}{\text{Time elapsed}} \quad (\text{Equation 3.4})$$

3) Percentage increase in the retreat rate after defence construction.

$$\text{Percentage change (\%)} = - \left(\frac{\text{Difference in retreat rates}}{\text{Retreat rate before defences}} \right) * 100 \quad (\text{Equation 3.5})$$

4) Retreat rates before and after defence construction.

$$\text{Difference in retreat rates (m/yr)} = \text{Retreat rate after defences} - \text{Retreat rate before defences} \quad (\text{Equation 3.6})$$

These parameters were selected because the:

- 1) Retreat (and set-back) provides an absolute value of change;
- 2) Excess retreat measures whether retreat rates have accelerated (and if a terminal groyne effect occurs) in addition to the severity of set-back;
- 3) Percentage increase is a useful comparison between sites;
- 4) Retreat rate comparison is a good measure of change within one site and between sites.

3.9.2 Factors affecting parameter values

Measuring cliff top change presented problems including the variability of longshore retreat due to variable erosion rates (partially due to changes in storm and rainfall levels) and variations of geology or the erodability of the material; the prediction of shoreline position if no defences were constructed (assuming past environmental conditions prevail); uncertainty values within the measurements; and the timespan that the measurements were taken. These will be discussed in Section 7.2 and Table 7.1.

During the taking of measurements, time and spatial scales are essential to define. Timescales must be taken over long intervals (ideally several decades) to minimise short term noise (see Sections 2.2.3, 2.2.4, 3.4, and 3.6). However, due to up-drift interferences the time interval cannot be too long as the historical retreat rate may not be representative of the present conditions (see Section 4.3, 4.4, 5.3 and 5.4). Retreat rates (particularly for excess retreat) must be

averaged over a set longshore distance, proportional to the down-drift coast affected by the terminal groyne effect (see Section 3.8). Averaging retreat is essential as up-drift disturbances (such as old defences) influence the retreat rate spatially throughout time. However, if a down-drift headland is present it constrains longshore growth. This creates a variable retreat rate longshore due to sediment retention, thus protecting the cliffs. This must be taken into account during analysis.

Errors and uncertainties (as mentioned in Section 3.5), must be included in all calculations, extending the measured value to its maximum and minimum extremes. To be certain of a real displacement between two mapped cliff top positions, the positions must be located 20m apart. For a mapped and surveyed position, this decreases to $\pm 12\text{m}$. This value increases when extended throughout time to account for excess retreat.

3.9.3 Summary

Set-back and the terminal groyne effect is calculated by four methods (retreat rates (set-back), excess retreat, percentage increase in retreat rates, and a comparison of retreat rates). Calculations must take into account time and space intervals and data errors.

3.10 Conclusions

After a preliminary study of the terminal groyne effect around the UK coast, three regions were selected for further investigation (Holderness, Christchurch Bay and north-east Norfolk - see Chapters 4, 5 and 6). The cliff top was selected as the shoreline retreat indicator as it is clear and easy to define over many data sources including maps, aerial photographs and field surveys. Uncertainties were deduced as $\pm 10\text{m}$ for maps and aerial photographs and $\pm 2\text{m}$ for field surveys. Using a GIS of cliff top retreat, transects perpendicular to the cliff were taken to measure retreat. Subsequently, retreat and retreat rates were measured and compared to the dates of coastal defence construction.

The results from measuring set-back and determining the terminal groyne effect will achieve Objective 2 listed in Section 1.7. These results derived from the

above equations will be presented in Chapters 4, 5 and 6. The implications of these results will be discussed in Chapters 6 and 7 (covering local and regional scales shown on the flow chart methodology presented in Figure 1.6).

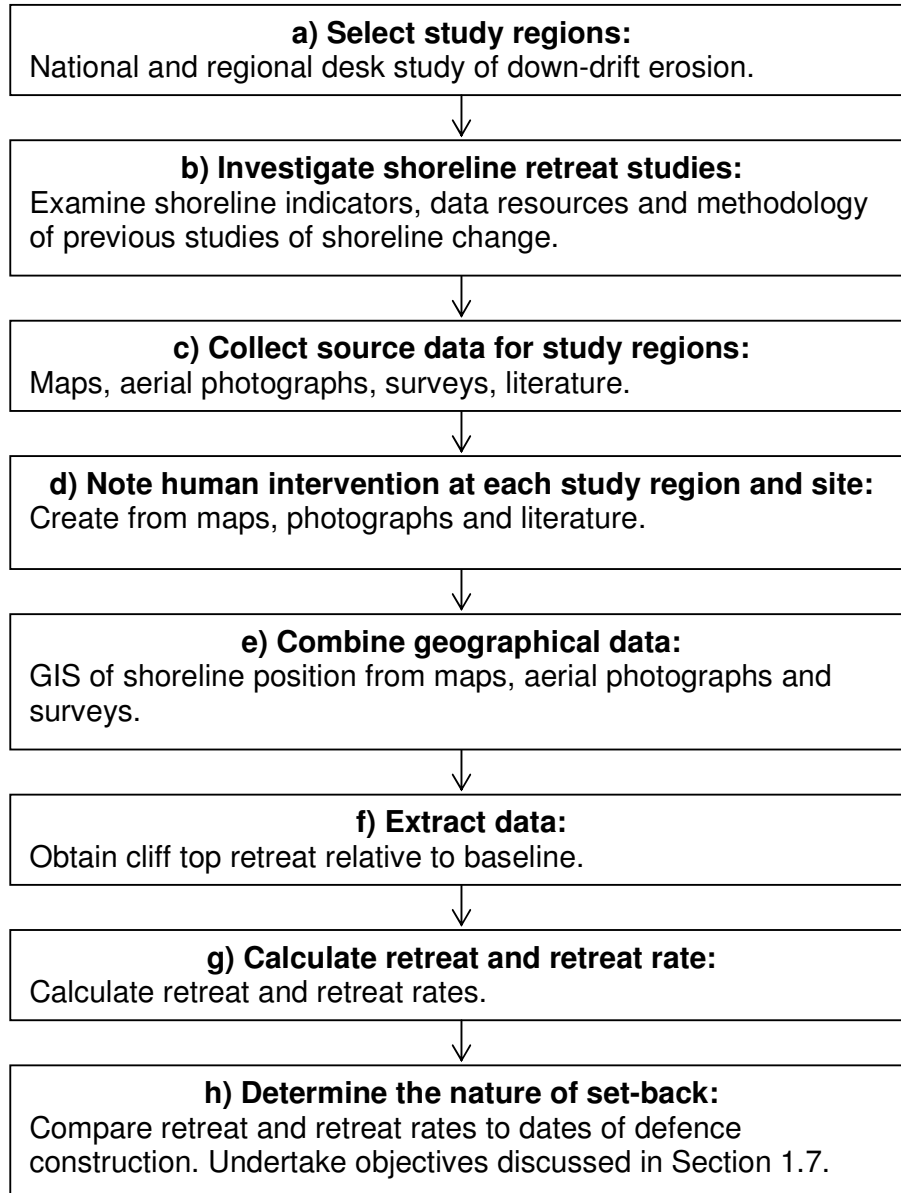


Figure 3.1 - Overview of the methodology used in this research.

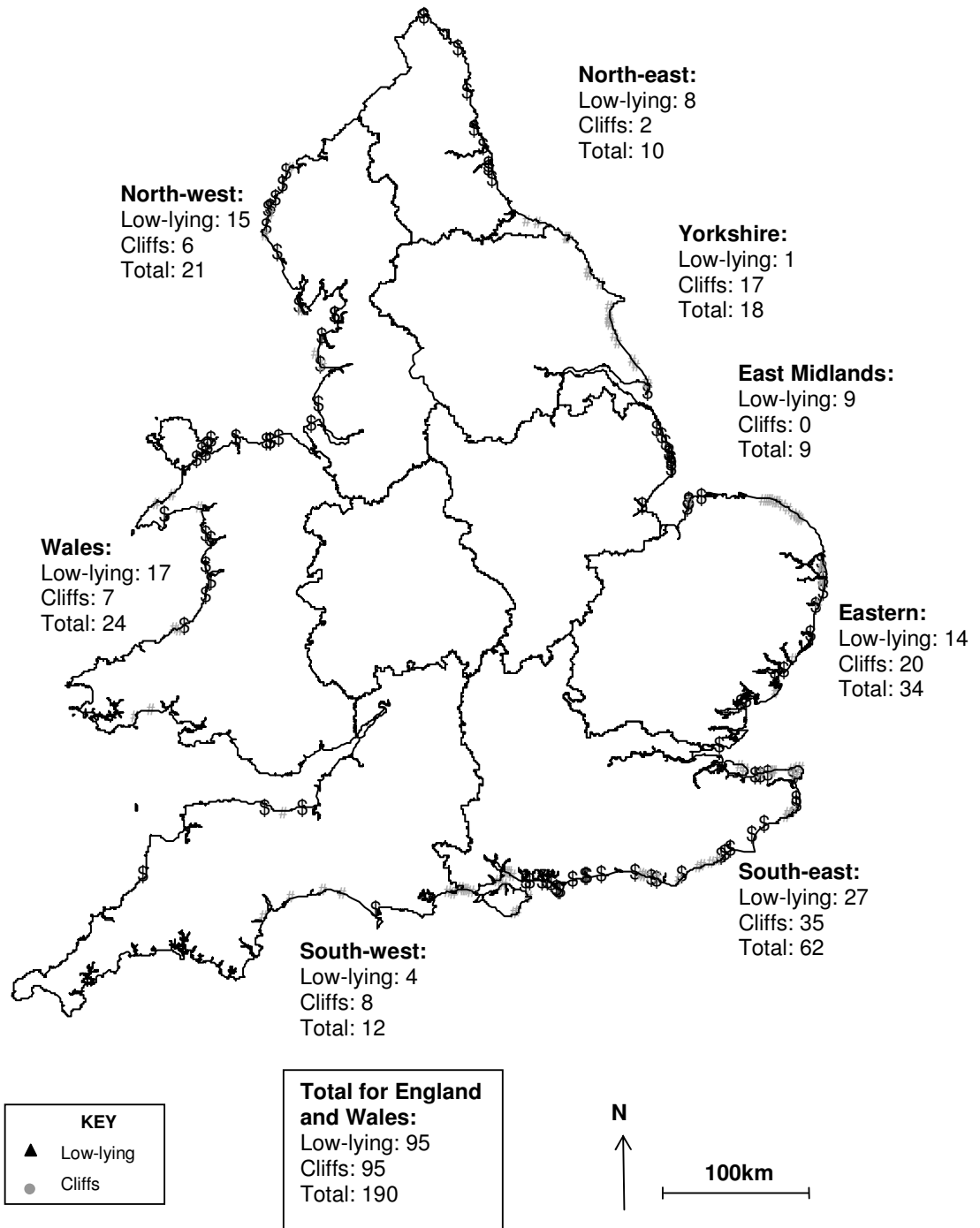


Figure 3.2 – Set-backs associated with defence structures. The number of set-backs for each region is shown. Approximately 200 localities have been identified in England and Wales, some with multiple set-backs. Half of the localities are on cliffed coasts, and around half are situated in the eastern and south-east regions of England.

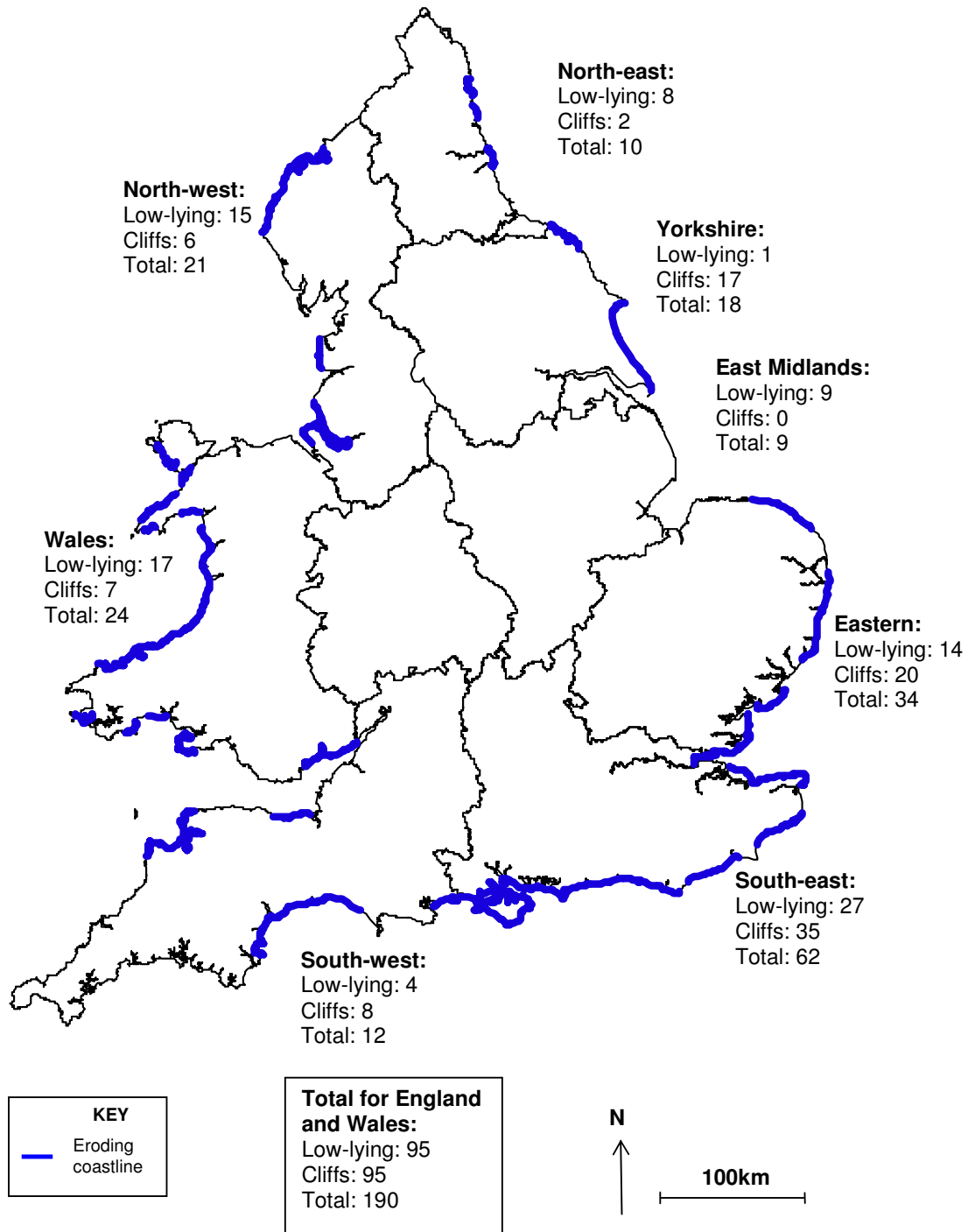


Figure 3.3 – The eroding coastlines of England and Wales (from Jones and Lee, 1994). When compared to Figure 3.2, set-backs occur adjacent to engineering structures, even when the coast is not eroding.

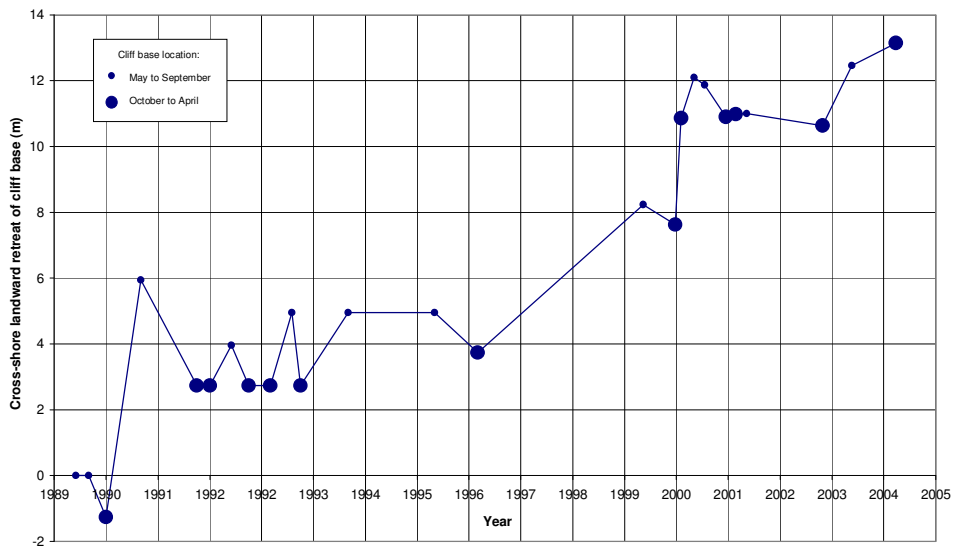


Figure 3.4 – Landward and seaward movement of the cliff-beach junction. The cliff base moves seaward in the winter months (Data from the Channel Coastal Observatory, see Appendix 3).

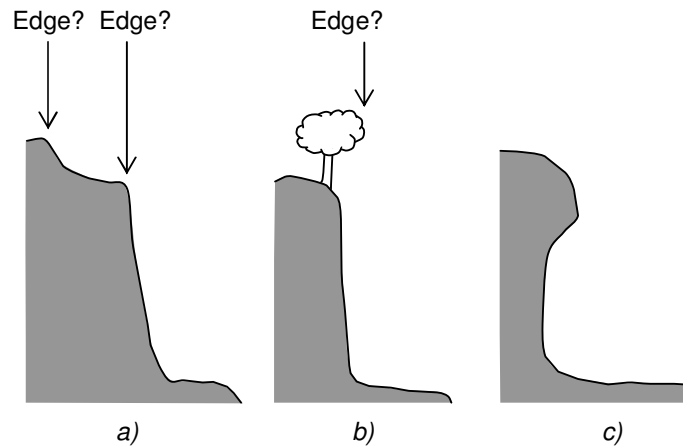


Figure 3.5 – Potential difficulties determining the cliff edge (Gulyaev and Buckeridge, 2004). a) Geometric profile makes the edge uncertain, b) Overhanging vegetation masks the cliff edge, c) The cliff is undercut. The majority of sites in this research have a clear cliff edge and are free of vegetation.

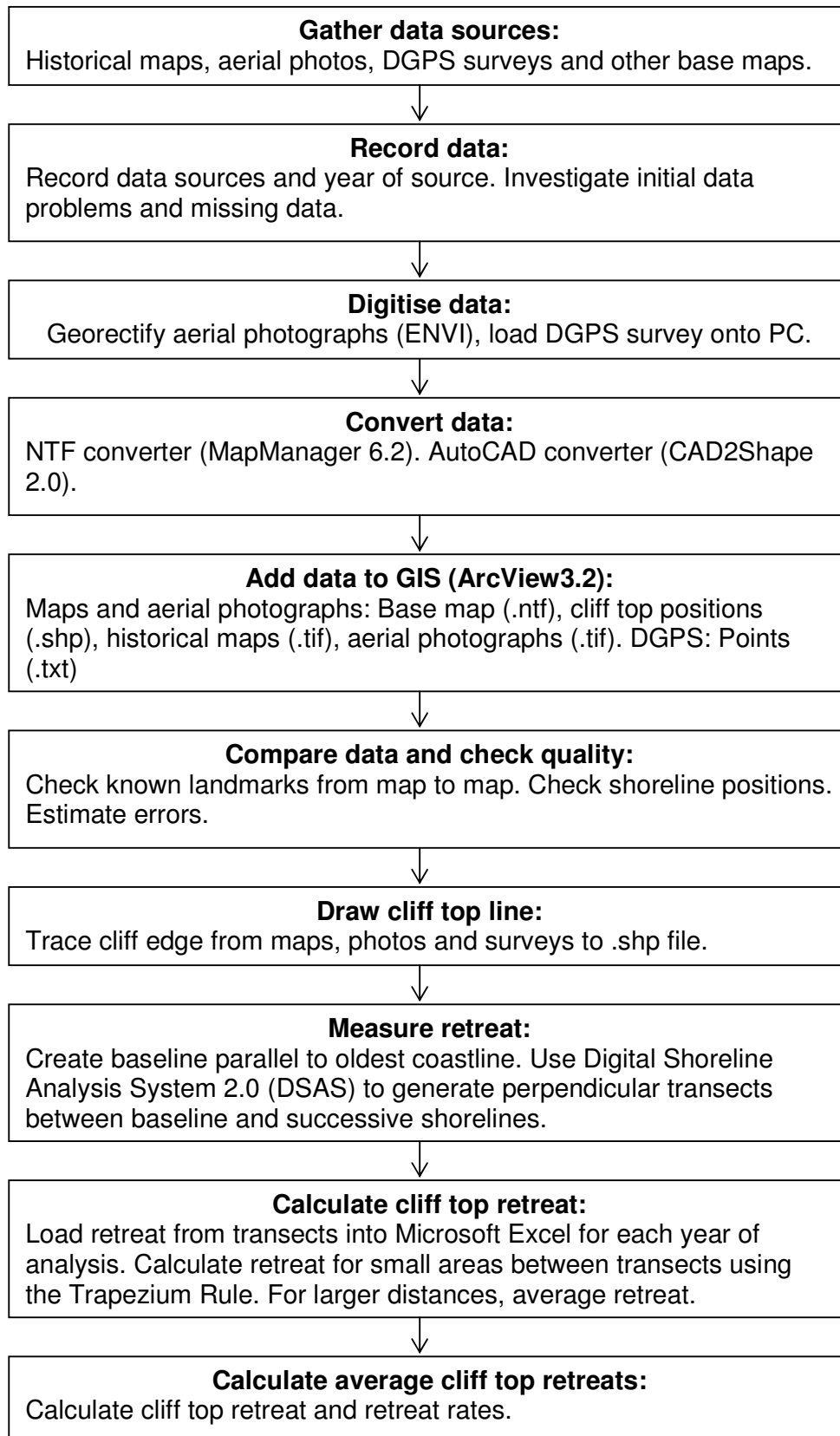


Figure 3.6 – Detailed methodology used for the GIS (parts e) and f) of Figure 3.1).

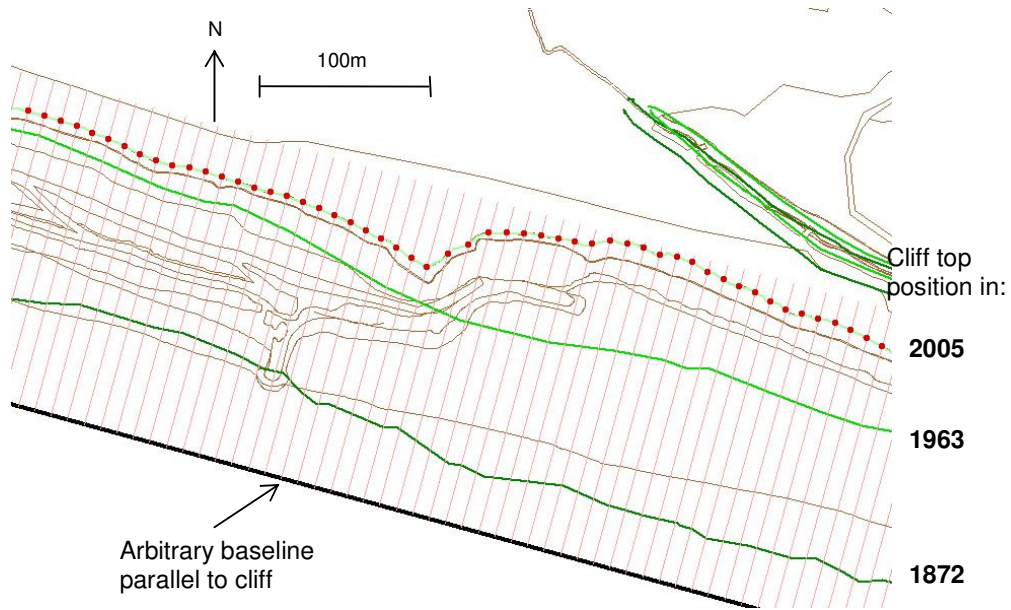


Figure 3.7 – Shore perpendicular transects - an example from Barton-on-Sea, Hampshire. The DSAS was used in ArcView 3.2 to create parallel transects 10m apart approximately perpendicular to the coastline. The bold line indicates the baseline from where all retreat distances were measured. The dots indicate where the transects intersect the 2005 cliff top position.

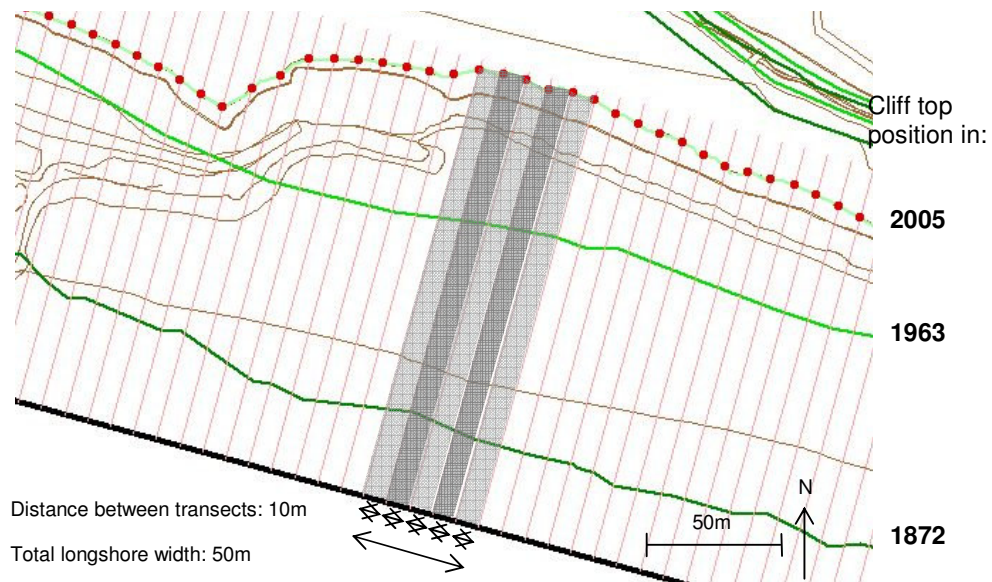


Figure 3.8 - Calculating average retreat. The transects were spaced 1m-20m apart, and the area of land lost between two transects was calculated using the Trapezium Rule. For example, to find the average retreat over 50m, the area of each 10m wide transect was calculated, and summed with the five adjoining areas. The total area was then divided by the total longshore width (50m).

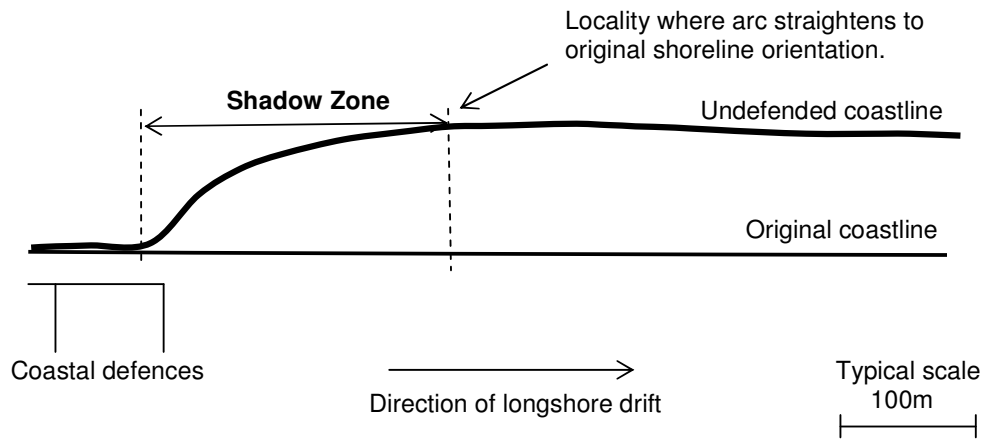


Figure 3.9 – Set-back down-drift after defence construction and the location of the shadow zone

Table 3.1 – Potential map errors occurring at time of production (Carr, 1962; Anders and Byrnes, 1991; Oliver, 1996).

Potential map errors
1. Imprecise copying from one map to another.
2. Map interpretation.
3. Survey methods employed.
4. Misleading cartographic evidence.
5. Accidental errors.
6. Partial revision and mistakes not corrected from one survey to the next.
7. Geographical features not present when map published or vice versa.
8. Misleading dates of survey or publication dates, or a large range of dates.
9. Lack of understanding of changes on maps.
10. Compromise between time spent on mapping and the importance of the area.
11. Difficulty in mapping low tide.
12. Exaggeration of features, displacing true position of coast to emphasise minor promontories.
13. Map irregularity on different scales and transference of maps to different scales.
14. Hachuring (attempting to give a 3D illustration in a 2D medium).
15. Maps systematically rather than planimetrically correct.
16. Maps symbolically rather than architecturally correct.
17. Changes in horizontal datum.
18. Pen thickness and annotation errors.
19. Survey and digitiser error.

Table 3.2 – Potential inaccuracies in maps since time of production (Anders and Byrnes, 1991; Crowell et al., 1991; Moore, 2000)

Potential inaccuracies
1. Scale changes.
2. Stretching and shrinking in different directions.
3. Change in survey standards.
4. Change in publication standards.
5. Change in photographic methods.
6. Map projection.
7. Tears.
8. Folds.
9. Creases.

Table 3.3 – Distortions associated with aerial photographs (Anders and Byrnes 1991; Crowell et al 1991; Moore, 2000; Lee and Clark, 2002).

Image space distortion - lens distortion
1. Radial distortion due to imperfections in the lens element. Distorts image on long radial lines from the principle point.
2. Tangential distortion caused by faulty centring of the camera lens. Distorts image rectangles to radial lines from the principle point.
Image space distortion - film deformation
3. Buckling of film in camera with changes of humidity, temperature or film spool tension.
4. Buckling, shrinking or stretching of film during processing.
5. Instability of photographic media once image has been printed.
Object space displacements - displaced objects from the true position
6. Ground relief - objects above ground level are displayed outwards from the centre.
7. Aerial camera tilt - Near vertical images have a different scale.
8. Atmospheric refraction - depends on flight altitude, camera focus length and direction of optical axes relative to the ground.
9. Scale difference - results in change of altitude, from one photograph adjacent to the next.

Table 3.4 – Data resources used for Holderness. Data available from Digimap and East Riding of Yorkshire Council (ERYC). Generally prior to 2000, field surveys were undertaken using total stations (Electric Distance Measurement), and after 2000, a DGPS.

	Source	Resource	Scale	Resource details	Map revision	Publication dates	Reference year
Main survey years	Digimap / ERYC	Map / Cliff top outline	1:10,560	County Series 1:10,560 1846-1969	1 st edition 1849-1899	1854-1855	1854
	Digimap / ERYC	Map / Cliff top outline	1:10,560	County Series 1:10,560 1846-1969	1 st revision 1888-1914	1888-1894	1888
	Digimap / ERYC	Cliff top outline	1:10,560	County Series 1:10,560 1846-1969	2 nd revision 1900-1949	1905-1912	1905
	ERYC	Cliff top outline				1925-1929	1929
	Digimap / ERYC	Map / Cliff top outline	1:10,560	County Series 1:10,560 1846-1969	3 rd revision 1922-1969	1938-1952	1952
	Digimap / ERYC	Map / Cliff top outline	1:10,000	National Grid 1:10,000 1969-1996	1 st metric edition 1969-1996	1971-1978	1978
	ERYC	Cliff top outline	N/A	Field survey		1989	1989
	ERYC	Cliff top outline	N/A	Field survey		Autumn 2005	2005
Supplementary survey years	ERYC	Erosion posts	N/A	List of retreat at posts		1951 - 2004	N/A
	ERYC	Cliff top outline	N/A	Field survey or map		1968	1968
	ERYC	Cliff top outline	N/A	Field survey		1992	1992
	ERYC	Cliff top outline	N/A	Field survey		Autumn 1994	1994
	ERYC	Cliff top outline	N/A	Field survey		Winter 1995	1995
	ERYC	Cliff top outline	N/A	Field survey		Spring 1998	1998
	ERYC	Cliff top outline	N/A	Field survey		Autumn 2000	2000
	ERYC	Cliff top outline	N/A	Field survey		Autumn 2001	2001
	ERYC	Cliff top outline	N/A	Field survey		Autumn 2002	2002
	ERYC	Cliff top outline	N/A	Field survey		Autumn 2003	2003
	ERYC	Cliff top outline	N/A	Field survey		Autumn 2004	2004
	ERYC	Aerial photographs	N/A	Georectified on CD		Summer 2005	2005

Table 3.5 – Data resources used for Christchurch Bay. Data available from Digimap and New Forest District Council (NFDC).

	Source	Medium	Scale	Resource details	Revision	Publication dates	Reference year
Main survey years	Digimap	Map	1:2,500	County Series 1:2,500 1854-1949	1 st edition 1854-1901	1871-1893	1872
	Digimap	Map	1:2,500	County Series 1:2,500 1854-1949	1 st revision 1893-1915	1895-1898	1898
	Digimap	Map	1:2,500	County Series 1:2,500 1854-1949	2 nd revision 1906-1939	1908-1909	1909
	Digimap	Map	1:2,500	County Series 1:2,500 1854-1949	3 rd revision 1924-1939	1924-1932	1932
	Digimap	Map	1:2,500	National Grid 1:2,500 1943-1995	National Survey 1943-1995	1963-1970	1963
	Digimap	Map	1:10,000	National Grid 1:10,000 1969-1996	1st Metric Edition 1969-1996	1972-1981	1975
	Digimap	Map	1:10,000	National Grid 1:10000 / Latest editions	All latest 1:10,000/10,560 National Grid maps	1985-1989	1989
	CCO	Aerial photo	N/A	Georectified – online resource		May 2001	2001
CCO	Aerial photo	N/A	Georectified – online resource		Aug 2005	2005	
Supplementary survey years	NFDC	Aerial photo	N/A	Georectified on CD		1957	1957
	NFDC	Aerial photo	1:2,500	Original photograph		Mar 1967	1967
	NFDC	Aerial photo	1:2,330	Original photograph		Mar 1977	1977
	NFDC	Aerial photo	1:2,500	Original photograph		Nov 1984	1984
	NFDC	Aerial photo	1:2,500	Original photograph		May 1989	1989
	NFDC	Aerial photo	1:2,500	Original photograph		Aug 1993	1993
	NFDC	Aerial photo	1:2,500	Original photograph		Sep 1997	1997

Table 3.6 - Data resources used for north-east Norfolk. Data available from Digimap and North Norfolk District Council (NNDC).

	Source	Resource	Scale	Resource details	Revision	Publication dates	Reference year
Main survey years	Digimap	Map	1:10,560	County Series 1:10,560 1846-1969	1 st edition 1849-1899	1887-1892	1892
	Digimap	Map	1:10,560	County Series 1:10,560 1846-1969	1 st revision 1888-1914	1907	1907
	Digimap	Map	1:10,560	National Grid 1:10,560 19846-1969	3 rd revision 1922-1969	1946-1951	1951
	Digimap	Map	1:10,000	National Grid 1:10,000 1969-1996	1 st metric edition 1969-1996	1972-1973	1972
	NNDC	Aerial photo	N/A	Georectified on CD		2005	2005
Supplementary survey years	NNDC	Aerial photo	1:2,500	Original photograph		June 1986	June 1986
	NNDC	Aerial photo	1:2,500	Original photograph		July 1992	July 1992
	NNDC	Cliff top outline	N/A	Field survey or aerial photo		Oct 1995	Oct 1995
	NNDC	Cliff top outline	N/A	Field survey or aerial photo		Mar 1996	Mar 1996
	NNDC	Cliff top outline	N/A	Field survey or aerial photo		Sept 1996	Sept 1996
	NNDC	Cliff top outline	N/A	Field survey or aerial photo		Nov 1996	Nov 1996
	NNDC	Aerial photo	1:2,500	Original photograph		Sept 1997	Sept 1997
	NNDC	Cliff top outline	N/A	Field survey or aerial photo		Mar 1998	Mar 1998
	NNDC	Cliff top outline	N/A	Field survey or aerial photo		Mar 1999	Mar 1999
	NNDC	Aerial photo	1:2,500	Original photograph		Aug 2000	Aug 2000
	NNDC	Aerial photo	1:5,000	Original photograph		Aug 2001	Aug 2001
	NNDC	Aerial photo	1:5,000	Photograph scanned to CD		July 2002	July 2002
	NNDC	Aerial photo	1:5,000	Photograph scanned to CD		July 2003	July 2003
NNDC	Aerial photo	1:5,000	Photograph scanned to CD		Sept 2004	Sept 2004	

Table 3.7 – Difficulties encountered when developing a history of coastal defence construction.

Potential difficulties
1. Seawalls and groynes were not constructed simultaneously at one geographical location.
2. Defences, in particular groynes were constructed and later removed.
3. Defences were refurbished and strengthened, thus affecting the longshore drift.
4. No complete record exists for the type or efficiency of groyne or seawall.
5. A large time period may have elapsed between defence construction and map production.
6. Defences were constructed before the earliest map available.
7. The literature and the maps disagree.
8. Dates and map records are not kept on paper or digital form by the local authority - word of mouth used.

Table 3.8 – File types and conversions required to use data sources within ArcView 3.2.

Source / Purpose	File type	File type	File purpose	Conversion required GIS?	Conversion type	File purpose
MAPS						
Historical map	County Series / National Grid tile	filename.tif filename.tfw filename.tab	Image file. ESRI GIS geographical location file. MapInfo co-ordinate information file.	No.		
Basemap	Landline.plus	filename.ntf	Spatial information file.	Yes - Map Manager 6.2.	oslines.dbf oslines.shp oslines.shx	Attribute file. Feature geometry file. Index file.
Basemap	Raster	filename.tfw filename.tif	ESRI GIS geographical location file. Image file.	No.		
AERIAL PHOTOGRAPHS						
Aerial photos	Image file	filename.ecw	Aerial imagery file.	No.		
Aerial photos	Georectified Image	filename.tfw filename.tif filename.hdr filename.pts	ESRI GIS geographical location file. Image file. Header file. Ground control points file.	No.		
FIELD SURVEYS						
Cliff top	Drawing file	filename.dwg	Standard AutoCAD file.	Yes - CAD2Shape 2.0.	oslines.dbf oslines.shp oslines.shx	Attribute file. Feature geometry file. Index file.
Cliff top		filename.dc	Survey controller file.	Yes. Save as .txt In Microsoft Excel.	filename.txt	Table of survey data.

4. HOLDERNESS

4.1 Introduction

The Holderness coast of East Yorkshire is one of the fastest retreating coastlines in the UK at up to 2m/yr (Steers, 1964). Extending 60km from Flamborough Head - the chalk promontory in the north, to Spurn Head spit in the south, Holderness is formed of soft till cliffs. In this chapter, cliff retreat from 1854 to 2005 along 54.6km of coast between Bridlington and Easington (Figure 4.1) is investigated (see Section 4.2). A series of case studies analysing the longshore and cross-shore extent of the terminal groyne effect will be examined (see Section 4.3).

4.2 Holderness

Figures 2.1 and 2.2 illustrates the environmental (Section 4.2.1) and anthropogenic (Section 4.2.2) factors affecting cliff retreat and the interaction of these factors with a littoral drift barrier. In this section these factors will be discussed with respect to Holderness and regional retreat rates analysed.

4.2.1 Environmental setting

Holderness is underlain by synclinal Cretaceous chalk, which outcrops at Flamborough Head (Steers, 1964; Catt, 1987). Overlying the chalk is glacial till 40m-50m thick deposited from ice movement from the north-north-east and north-east (Dosser, 1955; Catt and Penny, 1966; Catt, 1991). Till comprises the Bridlington Member deposited during the Saale Glaciation (100,000 to 250,000 years ago) and the Skipsea and Withernsea Members during the Devensian (10,000-70,000 years old). Sea levels rose after the last glaciation forming the bay. Collectively known as the Holderness Formation these are described in Table 4.1. The till cliffs range in height from approximately 4m (at Barmston) to over 35m (at Dimlington, 2km north of Easington) above mean sea level as shown in Figure 4.2. With a mean height of 15m, Cambers (1973) and Robertson (1990) report that the mean angle of unprotected cliffs is 40°-50°.

Mass failures result in shallow embayments with an average width parallel to the cliff of 26m and a depth of 6m (Pethick, 1996; Balson *et al.*, 1998). Erosion is influenced by the frequency of storm events, the longshore movement of material and erosion of the cliff toe (see Section 2.2.4). Cliff failure is encouraged through changes in hydrostatic pressure, by increasing the risk of undercutting and allowing slip surfaces to develop in unfavourably positioned layers (Robertson, 1990). Seepage is increased by high proportions of sand and gravel lenses (for example, in the Skipsea Member) and erratics. On average, erratics occupy 2%-8% of cliff material, but this can increase to 10%-50% along parts of the coast (Richards and Lorriman, 1987; Robertson, 1990). Dosser (1955) and Balson *et al.* (1998) also attributed instability to sub-aerial weathering. Additionally, beach levels influence the mode of failure. When beaches are low there are a greater proportion of deep seated slips and falls, whilst mudslides and shallow slides are reduced.

Once cliffs fail, the fall, regardless of its size is removed by wave action within 1 to 4 months (Cambers, 1973), indicating the period of an erosion cycle. Sediment supply to the entire coast is estimated as 462,000m³/yr. 33% of this material, notably sand and gravel lenses, remain to form the beach (Scott, 1976; Mason and Hansom, 1988). Other material is lost offshore. Where beaches are present, it is composed of two parts. The upper beach is convex in profile sloping at 4°-7°, and composed of coarse shingle and sand. The lower beach slopes at 0°-2°, and covers the shore platform with a fine to medium grained sand, cobbles and boulders (Mason, 1985). Bars also form (Scott, 1976; Pringle, 1981; Mason, 1985; Robertson, 1990). Beach profiles are illustrated in Figure 4.3 for the defended coast at Hornsea, and adjacent undefended coasts. Note that the defended profile is steeper as it is unable to erode landward.

Beach volume is controlled by longshore drift, estimated to be up to 90,000m³/yr (Mason, 1985) and the presence of irregularly spaced migratory features called ords. Ords are 1km-2km long low sections of beach where the till platform is exposed (Figure 4.4) and migrate down-drift at approximately 0.5km/yr (Phillips, 1962, 1964; Pringle, 1981, 1985). By lowering beach levels, waves remove talus, attack the cliff base and steepen the cliff (Robertson, 1990). Typically 8 to 10 ords are present at any time on the well-developed beaches between Barmston and Spurn (Phillips, 1962; Scott, 1976; Pringle, 1985). As ords are

not found within the coastal defences, they probably do not have an immediate influence on the terminal groynes effect. However, cliff top retreat away from defences must be analysed over several decades to minimise their effect. Mason (1985) found ords were not the sole mechanism for lowering beach levels, and smaller patches of shore platform are intermittently exposed. Pethick (1996) believes ords do not exist and cannot migrate, and are part of sandbar formation during storm conditions. Additionally, he suggests mini-embayments on the cliff top migrate down-drift. The name ord is unique to Holderness, but it is probable that similar features occur on other coasts. For example, Dawson *et al.*, (2007) found their process based model predicted sand waves moving between Sheringham and Winterton, Norfolk from 2000 to 2100 at approximately 0.8km/yr. This changed beach elevations, making parts of the coast more vulnerable to erosion than others. However, unlike ords, the sand waves described by Dawson *et al.* (2007) are promoted by the presence of engineering structures, rather than being a natural feature of the coast, which ords are believed to be.

Flamborough Head and South Smithic Sands shelter the northern quarter of Holderness (Figure 4.5) from the dominant north-north-east and north-east waves as they refract around the headland (Figure 4.6). With fetches of 900km (from the north-north-east) and 650km (from the north-east) and a typical wave period of 6s (Prandle *et al.*, 2001), the central and lower parts of the bay are most exposed. The average tidal range for the bay is 4.0m (Admiralty Chart, 2007). Woodworth *et al.* (1999) estimated regional sea level rise, and together with land subsidence (Shennan and Horton, 2002) historic relative sea level change has been between 0.6mm/yr and 0.8mm/yr (see Section 2.2.5). This is of relatively lower significance over the 151 year study period, as it is not one of the main controls of coastal erosion. In the future, the effect of sea level rise on retreat will be of greater importance.

4.2.2 Anthropogenic influences

Apart from the natural causes of retreat discussed in Section 4.2.1, man has influenced retreat via beach mining and the construction of defences (Reid, 1885; Topley, 1885; Valentin, 1954; Dosser, 1955). Pickwell (1878) and Reid (1885) provide detailed discussions of 19th century retreat rates (including localities), possible causes of the change of erosion rates (including beach

mining) and the consequences of this to the gravel trade and the coast (prohibition and defence construction). Mining was particularly extensive in the mid 19th century. Pickwell (1878) reported that between 1854 and 1869, 203,000 tonnes to 254,000 tonnes (200,000 tons to 250,000 tons) were removed along 3.2km (2 miles) of coast opposite Withernsea. This is an upper record of shingle extraction as other sources estimate the average extraction was 1,260 tonnes/km/yr (2,000 tons/mile/yr). It was not unusual for the beach to be totally depleted, with the shore platform visible. Subsequently, it resulted in severe erosion, and Pickwell (1878) believed retreat rates increased four-fold during this period compared with early 19th century rates. Pickwell (1878) and Reid (1885) reported that shingle was used to repair parish roads and for other building purposes. This was confirmed during a site visit where it was noted that cobbles were used as a building material in the older dwellings and churches. Furthermore, the construction of the Hull and Holderness railway in the mid 19th century provided the impetus for very large quantities of gravel extraction at Bridlington, Hornsea, Withernsea, Kilnsea and Spurn Point (Pickwell, 1878). Mid to late 19th century and early 20th century maps (see those listed in Table 3.4) show the expansion of the towns, villages and the railway. Recognising the detrimental effect gravel extraction and beach mining was having on the coast, the Board of Trade (acting under the Harbour Transfer Act of 1862) prohibited shingle extraction between Hornsea and Spurn in 1869. Even so, high retreat rates would have remained as it would have taken many years for the beaches to recover from mining. Simultaneously, defences were constructed to reduce erosion at Bridlington, Hornsea and Withernsea. Pickwell (1878) describes in detail the construction and dimension of these defences..

Coastal defences at Holderness started in the 12th century, as Bridlington provided a natural shelter for boats (East Riding of Yorkshire Council, 2004). By the mid 19th century stronger defences had been built, but as these degraded they were not always replaced. An early objective of the coastal engineer was to stop cliff retreat, and an emphasis was placed on the construction of seawalls which could withstand wave attack. Little consideration was given to other coastal processes or down-drift erosion (East Riding of Yorkshire Council, 2004). For example, at Bridlington sections of seawalls were built with hundreds of metres of unprotected coastline between them. This created a terminal groyne effect, and only decades later did the intervening coastline gain protection. With piecemeal defences increasing around the bay, the terminal

groyne effect became a common feature and to overcome this, defences were simply extended. Consequently, the total length of defended shoreline within the study region increased from less than 1% in 1854 to 15% in 2005 (Table 4.2). The type and age of defences are shown in Figure 4.7. By 2005, defences included a mix of 19th century structures, up-grades and extensions such as seawalls, groynes, rock armouring (rip-raps or a rock bund), cliff regrading, outfalls and privately constructed and owned defences.

4.2.3 Regional scale retreat

Approximately 670km² (260miles²) of land and at least 30 villages have been lost since Roman times as shown on Figure 4.8 (Sheppard 1912; Ward, 1922; Steers, 1964; Mason and Hansom, 1988). Retreat rates have also been calculated from land ownership information from the Domesday records of 1086 (Pickwell, 1878; Sheppard, 1909), averaging 1.2m/yr to 2.3m/yr for the entire coast. From more recent observations and records, numerous scientists have calculated average retreat rate from 1.34m/yr (Mason, 1985) to 2.7m/yr (Reid and Matthews, 1906). Apart from the precision of measurement, differences in retreat rate arise due to the time period and the length of coastline measured (see Chapters 3 and 7). Pickwell's (1878) measurements from maps, plans, observations and legal documents are associated with large errors (see Table 4.3). Pre 19th century map errors must be accepted if retreat rates are to be judged in a broad context (Bell, 1853). By far the most comprehensive set of measurements over very long periods of time (>100 years) are Valentin's (1954) calculations from maps and ground measurements taken from houses and footpath junctions, which provide an average retreat of 1.20m/yr (1852-1952), with estimated measurement errors of $\pm 6\text{m}$, or a percentage uncertainty of $\pm 5\%$ (Valentin, 1954; Cambers, 1976). Another excellent data set is the East Riding District Council's 'erosion posts' data (East Riding of Yorkshire Council, 2004) described in Section 7.3.1. Retreat measurements only started in 1951 making it inappropriate for analysis over the very long term. With a 50% longer series than in Valentin's (1954) study, plus the construction of new defences which may be responsible for increased erosion down-drift, an analysis of up-to-date retreat rates and a comparison of these with historical rates, are provided in this chapter.

Figure 4.9 illustrates the cliff top retreat between Bridlington and Easington from 1854 to 2005. The cliff top positions in the figure are derived from maps, aerial photographs (1854 to 1989) and other surveys (2005), as detailed in Section 3.7.1 and Table 3.4. Cliff top positions were combined on a GIS and transects calculating the average area of land lost were taken at regular intervals, as described in Section 3.8. The defended coast (see Figure 4.7) is shown in grey. Cliff top positions from 3.6km to 5.1km were omitted due to poor data quality (for reasons, see Section 3.5). The figure is divided into three zones bounded by the defences; Bridlington to Hornsea, Hornsea to Withernsea, and Withernsea to Easington. The first two show marked asymmetry with greater set-back towards the north, and the third zone exhibiting fairly equal retreat. Overall, there has been a variable retreat rate with time, with some areas prone to greater retreat than others. For example, from 5.1km to 12km down-drift there has been a greater amount of retreat compared to the coast between 12km to 18km down-drift. Also, there has been up to 150m of additional retreat at Hornsea compared to Withernsea between 1854 and 2005. There is a sharp peak down-drift of Withernsea (see Section 4.3.4).

Retreat rates derived from Figure 4.9 are shown in Figure 4.10 and Table 4.3. The rates are divided into three approximately 50 year periods based on levels of human intervention (see Section 4.2.2). The results from Valentin's (1954) study, Pickwell's (1878) measurements, uncertainties and standard deviations are shown. Uncertainties are reduced (from $\pm 10\text{m}$ to $\pm 2\text{m}$) with measurements ending in 2005 as a DGPS was used to measure the cliff top position, rather than maps (see Section 3.7.1). Table 4.3 shows retreat varies throughout time, with retreat rates decreasing from 1905 to 1952 in all localities except from Hornsea to Withernsea. Average retreat rates for the entire coast have potentially retained similar levels. Spatially, retreat rates are highest between Withernsea and Easington from 1854 to 1905. This was probably caused by beach mining as Pickwell (1878) believed retreat rates increased four fold between 2.7m/yr-5.5m/yr, compared with his mid 18th to 19th century measurements. Previous retreat rate studies (Valentin, 1954; Doornkamp and King, 1971; Maddrell *et al.*, 2001, 2003) identified the high retreat rate but failed to acknowledge beach mining as a possible cause. Inspection of Figures 4.9 and 4.10 and Table 4.3 indicate that one place of high retreat is at Hornsea, and retreat rates have increased throughout time. Substantial defences were constructed at Hornsea from 1906 (see Table 4.6) and these may be the cause

of the increased rate, particularly as rates are highest nearer to Hornsea compared to Withernsea (see Sections 4.3.2 and 4.4). 19th century defences at Withernsea retained a beach up-drift and decreased retreat rates. Due to mining increasing retreat rates, the standard deviation is higher compared with other parts of the coast that were not subject to human intervention.

Figure 4.9 has a series of undulations between Hornsea and Withernsea in 1888 and 1905, typically 25m in amplitude and 7km apart. Plotting the shoreline retreat with respect to 1888 reveals that some undulations remain in one locality, whilst others disappear, indicating that parts of the coast are more susceptible to erosion than others. Therefore ords (or beach-bar migration), or Pethick's (1996) theory of cliff top migration (see Section 4.2.1) cannot be responsible as both features migrate down-drift. The cause of variations in longshore retreat remains unknown.

4.2.4 Reference profiles

In Section 4.3 cliff top profiles of retreat will be analysed at selected study sites. To assess the magnitude of change these profiles will be compared to profiles located away from defences (Figure 4.11). Five 500m wide profiles were selected (located on Figure 4.7 at the mid-point between major defences). Profile 1 had the least amount of retreat from 1854, with little erosion between 1929 and 1952. However, the latter may be due to map errors as the retreat rate then rapidly increased. Profiles 2, 3 and 4 show approximately 60m of retreat from 1854 to 1929 and diverge thereafter, with retreat at Profile 3 having the greatest magnitude of retreat. Profile 5 had the highest retreat of 110m by 1905 due to mining, and after this date the retreat rate decreased.

4.2.5 Summary

The soft cliffs of Holderness have been eroding for thousands of years, with an average retreat rate of 1.3 ± 0.1 m/yr from 1854 to 2005. Erosion rates were influenced by natural and anthropogenic factors, with some areas having been particularly affected by 19th century mining.

4.3 Study sites

Major changes in retreat occur on Figure 4.9, at Hornsea, Withernsea and Mableton. Therefore these localities have been selected for detailed study. Barmston is also included in the detailed study as set-back has occurred adjacent to defences. Bridlington, Ulrome, Tunstall and Easington are not included for a detailed investigation due to a lack of appropriate data, or because the defences were constructed too recently to have a significant effect on the adjacent coast. For each study site the set-back, excess retreat and percentage increase in retreat rate, and the difference in retreat rate before and after defence construction on the down-drift coast will be analysed (using the equations listed in Section 3.9.1).

4.3.1 Barmston

4.3.1.1 Overview

Defences at Barmston consist of shore parallel rock armouring and tank blocks, protecting a former slipway, road and caravan park. They were first recorded on OS maps in 1978, but were probably present up to 10 years before (see Figure 4.12 and Table 4.4). 660m down-drift of Barmston Caravan Park is Barmston Main Drain. A groyne immediately up-drift of the drain provided protection for it and was first recorded on maps in 1952, but was not present on the next edition in 1978. In the late 1990s, a 180m rock bund and outfall was constructed to reduce sediment accumulation on the up-drift shoreline. Cliff top positions are illustrated in Figure 4.13.

4.3.1.2 Results

Figures 4.14a and 4.14b plot the cliff top retreat for five 100m wide profiles labelled A, B and C. Profiles A and C are situated 200m up and down-drift of the defence respectively and Profile B is located over the armouring. From 1854 to 1952, Profiles A, B and C had similar retreat at 90m to 100m. All profiles flatten after 1929, as did Profile 1 on Figure 4.11, indicating this was due to a natural cause along a long stretch of coast, or a map error. Profile C shows a marked change after 1952, and is confirmed by the analysis of the local authority's 'erosion posts' data (East Riding of Yorkshire, 2004). No evidence

for defences has been found for this time, but the nature of retreat is suggestive that some may have been present. After 1978, the retreat rate at Profile C increased with respect to Profiles A and B, causing a 53m set-back in cliff top position by 2005. The defences now form an artificial headland (Figure 4.15).

To assess excess retreat, cliff top retreat is plotted against the longshore distance down-drift of the defence for 1989 (Figure 4.16) and 2005 (Figure 4.17). This includes the observed set-back and the predicted retreat if no defences were constructed. The predicted retreat is based on the retreat rate from 1929 to 1978 of 1.7 ± 0.4 m/yr. 650m of coast between Barmston Caravan Park and Barmston Main Drain is plotted at 50m intervals and average results (excluding the shadow zone, defined in Section 3.9 and Figure 3.9) are shown in Table 4.5. The down-drift coast exhibited parallel retreat. In 1989, there was 11 ± 15 m of excess retreat, and in 2005 it increased to 15 ± 13 m.

4.3.1.3 Discussion

After defence construction, Profile C was set back more than Profiles A and B. Retreat at Profile A continued at the same rate or slowed after defence construction. The cliff top retreat at Profile B also slowed, but did not stop despite being protected (see cliff abandonment in Section 2.2.4). When first constructed, the shore parallel defence did not retain sediment up-drift. Due to the continued or increased retreat of the hinterland, the armouring later formed a shore perpendicular structure or artificial headland which now retains sediment (Figure 4.15). Taking into account potential data errors, excess retreat in 1989 cannot be resolved with confidence. In 2005, there was only 1m of clear excess retreat, indicating retreat rates have slightly accelerated after defence construction. Even so, the percentage increase in retreat rate is less in 2005 than in 1989.

The shoreline at Barmston will evolve in one of two ways. Firstly, if set-back continues and Barmston Main Drain blocks sediment transport (which it was not designed to), a bay will form between it and Barmston Caravan Park as it will act as a hard down-drift headland. Secondly, if sediment by-passes Barmston Main Drain and the coast continues to set back, the defences at Barmston Main Drain and Barmston Caravan Park will be outflanked if there is no further intervention. Over many decades the planform will reform into a 'straight' coastline.

4.3.1.2 Summary

Barmston Caravan Park is protected by shore parallel rock armour creating an embayment down-drift. Subsequently a headland has evolved and retained sediment up-drift. After 11 years of defence (1989) there was no clear excess retreat and only 1m of clear excess retreat after 27 years (2005). Hence retreat rates down-drift were maintained or slightly accelerated. In the future, with continued erosion the defences may become outflanked.

4.3.2 Hornsea

4.3.2.1 Overview

Hornsea has a complicated history of defence, with the first major defences built between 1869 and 1870 (Pickwell, 1878). Although destroyed in 1876 they held long enough for Pickwell (1878) to note that they had started to create an artificial headland. By 1906 the first substantial seawall was constructed, and since then there have been five major extensions, as documented in Figure 4.18 and Table 4.6. Due to the complex nature of defence construction, only the permanent shore parallel defences are documented. Two major set-backs occurred, firstly in 1930, and secondly in 1977 (Figure 4.19). Due to previous set-backs and outflanking, a specially designed outflanking structure was added in 1977 (Barrett, 1983) and is still present. The structure comprises a wooden groyne and shore parallel rock armouring that is not attached to the main defence (Figure 4.20). For greater discussion on outflanking see Section 6.2. Until 1991, and the construction of a major defence scheme at Mappleton (3.1km down-drift), the shoreline was undefended for 22km down-drift, until Withernsea, except for 320m of shore parallel rock armouring at Tunstall (see Figure 4.7).

4.3.2.2 Results

Figures 4.21a and 4.21b indicate the position and retreat of six 200m wide profiles located in the mid-point of the defence extensions, plus 200m up and down-drift of the undefended coast. From 1854 to 2005 those profiles defended earliest (Profiles B and C), retreated the least. Greater retreat occurred for profiles situated at increasing distances down-drift.

To assess excess retreat after the last defence construction (1977) the retreat rate from 1929 to 1968 ($2.3 \pm 0.5 \text{ m/yr}$) was extrapolated to 1989 and 2005. Although the down-drift coast eroded for a further 10 years, 1968 is the nearest data to defence construction. The predicted and observed cross-shore retreat for a distance of 2km down-drift of the shadow zone is plotted every 100m for 1989 (Figure 4.22) and 2005 (Figure 4.23). Average results for the 2km coast are shown on Table 4.7. If retreat had continued at the pre-defence rate, an average of $4 \pm 21 \text{ m}$ of excess retreat would have occurred by 1989, and $10 \pm 21 \text{ m}$ by 2005. The down-drift coast exhibits parallel retreat. The position of maximum cross-shore set-back remains constant at 800m down-drift.

4.3.2.3 Discussion

Cliff top retreat accelerated after 1905 when substantial defences were constructed (and after 1929 at Profile 3 on Figure 4.11, where the time delay is explained by its greater distance down-drift of the defences). The defences were repeatedly extended, allowing the terminal groyne effect to move and evolve down-drift. As the adjacent undefended coast became increasingly set-back, the defences formed an artificial headland (see Figure 4.18).

Extrapolating the 1929 to 1968 retreat rate to 1989 and 2005 revealed no conclusive evidence of excess retreat, indicating that the terminal groyne effect is not observed. If excess retreat did happen it is more likely to have occurred in 2005 than 1989 as a longer time period would have passed (see Table 4.7). However, if retreat rates are extrapolated from 1905 using the 1854 to 1905 rate of retreat ($1.3 \pm 0.4 \text{ m/yr}$ from Profile F), an excess of $88 \pm 42 \text{ m}$ would have occurred by 2005 (overall set-back is $220 \pm 12 \text{ m}$). Hence over a century, retreat rates have increased creating a terminal groyne effect at Hornsea. Therefore, over a time frame of many decades to a century, the terminal groyne effect is better detected and is larger in size than when measured at shorter timescales or due to defence extensions. However, longer time scales must be used with care, as retreat rates can change over time, caused by factors other than the defence construction.

The terminal groyne effect is seen after initial defence construction, but not after later extensions. Efficient defences retain sediment up-drift and create a

sediment deficit down-drift. Extending defences allows sediment to fill additional beach compartments, but does not retain sediment up-drift or create a significantly larger sediment deficit down-drift. Additionally, the cliffs around Hornsea and other sea-side resorts are often low (less than 10m at Holderness, see Figure 4.2) as villages commonly grew around streams or hithes. Hence building defences and thus reducing sediment input from low cliffs would have a reduced impact on the sediment budget compared to higher cliffs.

Since 1905, the terminal groyne effect has increased retreat rates for over 15km, and potentially up to 22km down-drift of Hornsea. Growth is then constrained by the Withernsea defences (see Figure 4.9). Doornkamp and King (1971) found the relationship between the magnitude of erosion down-drift of Hornsea and the distance from the defence had a correlation coefficient of -0.944 significant at the 99% level. Longshore growth is now limited by the Mappleton defences and retreat rates have reduced (see Figure 4.10). Reid (1885) believed the early Hornsea defences (prior to the 1880s) initiated increased retreat for 3.2km (2 miles) down-drift, whereas Maddrell *et al.* (2001, 2003) calculated the defences increased erosion for just 1.5km down-drift. Hence, when investigating the terminal groyne effect it is essential to investigate cliff top retreat regionally and over as long a time period as possible.

Profile A (Figure 4.21b) shows retreat rate decreased on the up-drift coastline after 1905. Sediment was retained by the groynes (see beach profile data on Figure 4.3), creating a wide beach to protect the cliff toe, and allowing the cliff to become vegetated (Figure 4.24). Figure 4.10 indicates that retreat rates decreased for approximately 3km up-drift. This is a distance of at least 5 times less than the longshore coast affected down-drift. Similar to Galgano's (1998) conclusions, the up-drift and down-drift coast is not equally affected in length (see Section 2.3). Further research is required into the effect of defences and the subsequent retreat rate on the up-drift coast.

4.3.2.4 Summary

Hornsea's first substantial defences were constructed in 1906 and have undergone multiple extensions. The coastline has set-back 220 ± 12 m. Retreat rates (1854 to 1905) have increased from 1.3 ± 0.4 m/yr to 2.6 ± 0.3 m/yr, potentially affecting the entire 22km of coast until Withernsea. The final extension in 1977

did not increase retreat rates down-drift. By referencing the terminal groyne effect to varying baselines, different retreat rates and excess retreat values emerge.

4.3.3 Mappleton

4.3.3.1 Overview

Mappleton, 3.1km down-drift of Hornsea, was protected in 1991 with a 450m defence scheme (see Figure 4.25 and Table 4.8). Cliff top positions are shown in Figure 4.26. Between 1854 and 1989 the coastline was subject to parallel retreat and after defence construction in 1991 a set-back developed down-drift (Figure 4.27).

4.3.3.2 Results

Set-back after 1989 (the nearest cliff top position to defence construction) for three 200m wide profiles positioned 200m up-drift, over and 200m down-drift of defences, are displayed in Figures 4.28a and 4.28b. Profiles A and B retreated 17m and 15m respectively. Prior to defence construction (1952 to 1989) retreat rates were 1.7 ± 0.6 m/yr. After 1989, retreat rates at Profile C on the undefended down-drift coast almost doubled, when the cliff retreated 43m by 2000, and a further 5m by 2005.

To establish the longshore and cross-shore excess retreat, the average retreat rate from 1952 to 1989 was extrapolated to 2005. This time period was selected as Mappleton's retreat rate was influenced by Hornsea's defences (see Section 4.3.2). Measurements down-drift of the shadow zone were averaged every 100m up to 6.2km down-drift. Results are shown in Figures 4.29 and Table 4.9. The set-back is not uniform longshore. Increased retreat occurs until 3.9km-4.4km (within the confidence of the data), and potentially up to 6.2km down-drift, with a maximum cross-shore excess of approximately 50m at 1.6km down-drift. On average, along the 6.2km coast 25 ± 12 m of excess retreat occurred corresponding to a central value of percentage increase of 90%.

4.3.3.3 Discussion

In comparison to Profile 3 on Figure 4.11, the defended profiles, A and B (Figure 4.28b) retreated less and it is believed the defences have been a factor in causing that reduction. Furthermore, Figures 4.9 and 4.10 indicate that there was a reduction in retreat rates for approximately 500m up-drift of Mappleton. Therefore Mappleton's defences retained sediment up-drift, causing a sediment deficit and set-back down-drift.

Retreat rates that can be resolved within the confidence of the data have increased up to 3.9km to 4.4km down drift indicating the terminal groyne effect is observed. This corresponds to an average longshore migration of 280m/yr to 310m/yr. The rate is slightly greater than the longshore migration of the terminal groyne effect at Hornsea of 150m/yr to 220m/yr. If the longshore migration of the terminal groyne effect continues at this rate down-drift of Mappleton, it would take approximately a further 55 years for the effect to be felt at Withernsea, 19km down-drift. It is probable that the longshore migration of the terminal groyne effect is greatest in the years immediately after defence construction (see Section 6.3), so this value may be an underestimate. The rate and expansion of the terminal groyne effect affects those who reside on the coast. With further data or investigation of other study sites, the longshore migration rate of the terminal groyne effect could be explored further.

Mappleton is the site of a well known land tribunal, where in 1999 a local farmer sued the local authority for excessive land loss due to the influence of the defences and down-drift erosion. The landowners, Mr David and Ms Sue Earle, whose tenure was located 1.2km down-drift of Mappleton, claimed that the Mappleton defences had caused retreat rates to increase from 2.0m/yr (from approximately 1977 to 1991) to 4.7m/yr (from 1992 to 1998) after the construction of the protection scheme (Lands Tribunal, 1999; Maddrell and Gowan, 2001).

To investigate their claim from a scientific point of view, cliff top positions between 1989 and 1998 are plotted up to 1.7km down-drift of Mappleton, as illustrated on Figure 4.30. No data was available beyond 1.7km down-drift. The observed set-back and predicted retreat (based on the retreat rate from 1952 to 1989) is shown and results noted in Table 4.9. Figure 4.30 shows retreat rates

had potentially doubled, with an average excess retreat of 23 ± 8 m. At the Earle's farm, the maximum cross-shore excess is 57m from 1989 to 1998. This data indicates that retreat rates increased after defence construction and a terminal groyne effect is present. However, the local authority (with their agents, known as the Compensating Authority) questioned whether the defences were the sole cause of the increased retreat rates. Their evidence resulted in the Earles losing the tribunal as the Council illustrated that retreat rates along Holderness vary throughout time at any one locality. From a legal perspective it could not be proved that the defences directly (whether during or after defence construction) caused an increase in retreat rate or resulted in negligence. Although retreat may have been slower over past decades, one could not expect it to continue at the same rate in the future (Lands Tribunal, 1999).

To clarify the Compensating Authority's claim of variable retreat rates and the need to analyse retreat over long periods of time, Figure 4.31 plots pre-defence (1978 to 1989) and post defence (1989 to 2005) retreat rates up to 6.2km down-drift of the defences. The two rates are mirror images of each other. It can be argued that cross-shore retreat rates have increased up to five times their initial value up to 4.7km down-drift since defences were constructed. While down-drift erosion is a cause of variable retreat rates, another possible reason is the time that defences were constructed with respect to the frequency of erosive events (see Section 2.2.4). When a period of increased wave activity occurs simultaneously to defence construction causing a sediment deficit down-drift, down-drift erosion would be expected to be more severe, but over many decades, the affect of this activity averages out. From a wave buoy located off Hornsea, the tribunal found that there was higher than average wave energy after 1990, but north and north-easterly wind strengths (which would act to increase erosion) were less than average. No indication was given of the difference in wave energy and the affect this had on erosion, nor were any rainfall records analysed. Even so, the Council claimed this partly explained the higher retreat rates after 1991. Whilst this may be one cause, no other short term time period since 1951 analysed by the Compensating Authority had such a high retreat rate (Lands Tribunal, 1999).

The Compensating Authority used computer models to analyse down-drift erosion and predicted that excess retreat should extend no further than 1000m down-drift by 1998, with a maximum set-back occurring at 700m down-drift.

They also modelled retreat down-drift of Mappleton from 1991 to 2030 and 2050 and found cliff top positions were predicted to be virtually the same with and without the protection works (Lands Tribunal, 1999). Although over a shorter time period, Figures 4.9 and 4.29 do not support this as already, Mappleton's defences can be seen as a major disturbance on the coast. Furthermore, the Compensating Authority claimed that Hornsea's defences only increased erosion for 1.5km down-drift (Lands Tribunal, 1999). Figures 4.9 and 4.10 indicate that retreat rates have increased up to 22km down-drift of Hornsea (3.1km up-drift of Mappleton) since defence construction in the late 19th century.

As demonstrated in the Earle's case, over time periods of less than one decade, the terminal groyne effect cannot be proved legally but arguably could be proved scientifically. Comparison of retreat rates between short and long term data is not an ideal method to determine whether there is excess retreat as it is inaccurate or inconclusive, but at times it is the only approach available. Over longer time periods data uncertainties reduce and the terminal groyne effect becomes more apparent.

4.3.3.4 Summary

Mappleton's defences were constructed in 1991 and have resulted in increased cross-shore retreat of up to 50m, extending 3.9km-4.4km down-drift. The frequency of wave attack at the time and after defence construction potentially influences the magnitude and extent of the cross-shore terminal groyne effect with time. This has a bearing on the case presented at the 1999 land tribunal as it was an excellent example of the inability of short term coastal data to prove a long term trend. The data (1991-1998) available to the tribunal was insufficient for them to determine whether the defences were the sole cause of the increase in retreat rate. However, retreat over the medium term (presently 16 years, but ideally more than 20 years) shows the terminal groyne effect has created increased retreat down-drift of Mappleton, affecting the Earle's farm. Other parts of the coast away from Hornsea and Mappleton did not experience the same magnitude of increased retreat rates during the same time period.

4.3.4 Withernsea

4.3.4.1 Overview

Withernsea's first substantial defences were constructed in 1870 (Figure 4.32) and have since been extended down-drift on eight occasions (Table 4.10). The defences have resulted in two major set-backs; firstly, after 1920/1945 due to a seawall and groyne refurbishment, and secondly after 1968 (Figure 4.33). Since 1968, rock armouring and a shore parallel breakwater have been added down-drift (the 1995 breakwater was later removed) with the purpose of reducing outflanking. Figure 4.33 illustrates former cliff top positions down-drift of the 1968 seawall and successive rock armour extensions. The figure includes the position of the 2005 rock armour extension, but this has not been included in analysis as not enough time has passed for the armouring to influence cliff top retreat.

4.3.4.2 Results

Figure 4.34a indicates the location and cliff top retreat of seven 200m wide profiles situated in the middle of each defence extension plus 200m up and down-drift of the defences. Prior to 1888, Profiles A to D had a similar magnitude of retreat (Figure 4.34b). Retreat rate slowed after they were defended. An advance of the coast is shown in Profile D as the seawall was built seaward of the cliff. Profiles E, F and G had a high retreat from 1854 to 1888, and after 1888 decreased.

To investigate excess retreat, Figures 4.35 and 4.36 illustrate the observed set-back and predicted retreat if the defences had not been extended in 1968 (using a retreat rate of 1.6 ± 0.4 m/yr from 1929 to 1978). Although the retreat rate before defence construction partly covers the time when the defences were present, it is the closest date to defence construction and represents a maximum measurement period. Data is plotted in 100m intervals up to 2.2km down-drift of the defences from 1978 to 1989 (Figure 4.35), and 1978 to 2005 (Figure 4.36). Results are shown in Table 4.11. There are longshore variations in the cross-shore set-back along the 2.2km of coast. On average, an excess of -6 ± 15 m of retreat occurred in 1989 and 20 ± 13 m by 2005.

4.3.4.3 Discussion

The 1870 groynes were successful in reducing erosion over the long term. The high retreat rate at Profiles E, F and G was almost certainly caused by beach mining as Pickwell (1878) and Reid (1885) reported the detrimental effect of thousands of tonnes of gravel being removed from the coast and the resulting four-fold increase in retreat rates compared with the early 19th century (see Section 4.2.2). Mining was prohibited in 1869, and this return to previous sediment supply levels, together with the efficiency of the groynes caused them to be buried under shingle by 1876. Retreat continued down-drift, with Profile G set-back $339\pm 12\text{m}$ from 1854 to 2005, causing Withernsea defences to form an artificial headland.

Figures 4.35 and 4.36, and Table 4.11 suggest that excess retreat down-drift due to the last defence extension becomes increasingly apparent with time. Whilst there is no conclusive excess retreat in 1989, retreat rates increased by an average of 45% by 2005. Therefore in 1989 the terminal groyne effect is not seen, but by 2005 a terminal groyne effect is observed.

Calculating the initial erosion rate and presuming environmental conditions will prevail and the rate will continue, is a very important assumption when determining excess retreat. Legal beach mining (reported by Pickwell (1878) and Reid (1885) as stated in Section 4.2.2) continued until 1869 and once it ceased the coast would have taken several decades to regain equilibrium. Between 1854 and 1888 retreat was $3.6\pm 0.6\text{m/yr}$. This rate is unrealistic of natural conditions. A more realistic rate is $1.1\pm 0.4\text{m/yr}$ (see Table 4.3). At Profile G, the coast retreated $217\pm 12\text{m}$ from 1888 to 2005, resulting in $88\pm 49\text{m}$ of excess retreat since 1888. Therefore the terminal groyne effect definition is observed over a 117 year time period.

Profile 5 on Figure 4.11 (located down-drift of Withernsea), is more comparable to Profiles E, F and G, suggesting that there is a change of environmental conditions, and that the coastline is in a transition between lower and higher retreat. In the 19th century, high levels of retreat were believed to be caused by mining (see Section 4.2.2), but its continuation in the 20th century (for these profiles) suggests natural controllers must be involved. As Profiles E and F have a similar retreat to Profile 5 until 1929, they do not appear to be directly

affected by down-drift erosion. Profile 5 is also similar to Profile G, as retreat rates have remained fairly constant since 1888 ($1.9 \pm 0.1 \text{ m/yr}$).

Figure 4.9 shows a sharp peak of retreat at approximately 45km, 1.3km down-drift of the original defence, which Reid (1885) and Pickwell (1878) referred to as increased erosion initiated by the defences. The peak was mainly produced between 1854 and 1888 and did not grow again until after 1952. Due to its distance down-drift of the defence, factors such as beach mining and natural factors are believed to be responsible for its growth rather than being a direct result of defence construction. Previous retreat studies (Valentin, 1954; Doornkamp and King, 1971; Maddrell *et al.*, 2003) state that the exposure and deep water are the principal controls of high historical retreat south of Withernsea. Whilst these factors are very important, 19th century beach mining is also partly responsible for high retreat rates. Doornkamp and King (1971) found no correlation between the distance from the end of Withernsea seawall and the magnitude of erosion down-drift. The research in this thesis agrees that it is not possible to determine the down-drift extent of the terminal groyne effect at Withernsea due to the large number and magnitude of other disturbances.

Attempts have been undertaken at Withernsea to reduce outflanking via the addition of a breakwater and rock armouring, but both failed to reduce erosion (see Table 4.10 and Figure 4.37). Figure 4.38 illustrates the shore platform at the end of the Withernsea defence and groynes. With little beach material extending seaward or down-drift of the defences, additional protection (particularly shore parallel protection) would have had little effect on erosion rates down-drift. The continual build of sediment up-drift since defence construction has greater importance in hindering sediment movement, rather than extending the defences in an already starved system (see Sections 6.2 and 7.2.2).

4.3.4.4 Summary

Withernsea's retreat in the 19th century was controlled by beach mining, and it is difficult to predict a natural rate free from human interference. Even so, the defences have created an excess retreat of $88 \pm 49 \text{ m}$. Extending the defences in 1968 did not increase erosion down-drift (within the confidence of the data) by

1989, but did by 2005. Hence the terminal groyne effect becomes more apparent throughout time.

4.4 Synthesis

4.4.1 Measurement and excess retreat

Four methods of calculation were used to investigate the terminal groyne effect and evaluate excess retreat (see Section 3.9.1, Equations 3.1 to 3.6). The results of excess retreat are shown in Table 4.12. Tables 4.5, 4.7, 4.9, 4.11 and 4.12 indicate that the two most successful methods are a measurement of set-back, and calculation of excess retreat. The success of measuring excess retreat was dependent on the retreat rate prior to defence construction remaining constant. There is no guarantee that this will occur, (particularly due to up-drift influence of defences) and results are therefore a best estimate of what could have happened. The two other methods, consisting of the percentage increase in retreat rates, and a comparison of retreat rates before and after defence construction are not such reliable measures compared with set-back and excess retreat. A high percentage increase does not guarantee shoreline change or excess retreat (for example, Barmston, 1978 to 1989). Retreat rates should only be compared over similarly long time intervals (> ideally 20 years).

A major factor hindering all methods in producing a value of excess retreat is the level of uncertainty associated with measurement. Although errors reduce when measured over long time intervals, not enough time will necessarily have passed since defence construction. Uncertainty values are often a similar magnitude to excess retreat. Surveying with a DGPS reduces measurement uncertainties and has been used since approximately 2000. Therefore the uncertainty in measurements after this date is reduced. This makes excess retreat clearer to deduce.

The first time defences are constructed it is more probable that a terminal groyne effect will be produced rather than after successive defence extensions. The terminal groyne effect becomes more apparent at increasing time intervals. Extending defences down-drift may have little impact in retaining large quantities

of additional sediment once the new groyne compartments are filled. Retreat rates down-drift of the defences exhibit variable behaviour. At Holderness, six out of ten study sites indicated an increase in retreat rates within the confidence of the data, whilst the remaining four, maintained constant retreat or had no conclusive change (disagreeing with the definition). These values fall outside of the range where accelerated retreat can be proved unequivocally. However, at these sites, excess retreat may have occurred as the error range does represent extreme values (further discussed in Section 7.2.2). On the up-drift coast, retreat rates were reduced.

4.4.2 Evolution of the terminal groyne effect

Early terminal groyne effects (prior to the 1920s) observed at Hornsea and Withernsea were predominately caused by seawalls rather than groynes. Seawalls created shoreline set-back through continued retreat of the undefended down-drift coast. As groyne design improved through the 19th and 20th centuries, they caused sediment to accumulate, thus leading to excess retreat. The terminal groyne effect is a dynamic effect, and is constantly evolving. It is a combination of all defences, not just the terminal structure as described in Section 1.2. For example, at Hornsea and Withernsea continued set-back is caused by multiple extensions. Therefore the terminal groyne effect must be clearly referenced in space and time.

4.4.3 Longshore extent of the terminal groyne effect

Predicting the longshore extent of the terminal groyne effect is dependent on predicting the correct retreat rate and whether it has longshore variability if defences were not constructed. Hence defining the longshore extent of the terminal groyne effect is accompanied by uncertainty. Where defences are less efficient and other natural processes dominate, the longshore coast is only affected for hundreds of metres or its extent is not detectable. Elsewhere, when defences have been present for over one hundred years, and the coast is free to respond, the terminal groyne effect potentially affects long distances down-drift (for example, Hornsea). Until 1991, Hornsea's terminal groyne effect was constrained in growth by Withernsea's defences 22km down-drift. As the coast continued to set-back between defences, shallow embayments formed, for example, between Hornsea and Mappleton, and Mappleton and Withernsea,

where Hornsea, Mablethorpe and Withernsea act as hard headlands. Embayments form by increasing or continuous erosion down-drift of a hard headland and by sediment accumulating up-drift of a second hard headland located down-drift. It is believed the defences are responsible for this between Hornsea and Withernsea because:

- a) The coast between Hornsea and Withernsea was, up to 1991, uninterrupted by shore perpendicular defences and has similar exposure and bathymetry (see Figure 4.5);
- b) The initial shoreline undulations between Hornsea and Withernsea (see Section 4.2.3 and Figure 4.9) reduced as the defences became more developed and efficient in retaining sediment;
- c) The phenomenon was first identifiable in 1929 after the Hornsea defences became more substantial (see Figure 4.9);
- e) A new longshore migratory effect restarted after the Mablethorpe defences were constructed (see Figures 4.9 and 4.10).

It will take many decades or centuries for the embayments to become stable, whether through a reduced retreat rate or in planform shape (see East Riding of Yorkshire Council, 2004), but this would require significant strengthening of defences (Brown and Barton, 2007) and is discussed in Chapters 6 and 7. Valentin (1954) was one of the first scientists to recognise this new physiographical feature of headlands and bays developing on the Holderness coast. He understood that defences would become increasingly difficult to maintain within a few centuries due to lowering beach levels. However, difficulties have already emerged as beaches steepen (see Figure 4.3) and rock armouring is required to protect the seawalls (for example, at Withernsea). For further discussion of headlands, see Section 7.2.3.

4.4.4 Other factors

The geography and geomorphology of any coast depends on many factors including bathymetry, exposure, wave action and orientation, tidal forces, underlying geology, sub-aerial erosion, sediment transport, the water table, slope stability and the influence of man as described in Figures 2.1 and 2.2. All these factors and mapping uncertainties must be taken into account when assessing excess retreat. When comparing sites, where possible, the same

time period must be analysed to ensure the factors that control erosion are the same. There is no indication that the position in the coastal cell or changes in the volume of sediment transport affect the cross-shore or longshore extent of the terminal groyne effect as other controlling factors dominate.

Set-back and the terminal groyne effect is influenced by and influences the frequency and magnitude of storm activity. Retreat before and after defence construction must be taken over long time intervals to take this into account (> 20 years). Hence excess retreat rates taken from 1978 to 1989 (an 11 year period) are potentially biased as a longer time period is required to calculate average erosion rates (Barmston and Withernsea).

Over the short term (< 10 years), the impact of storms can be severe, particularly when beach levels are low, such as immediately down-drift of defences. However, a very large storm may have a similar impact on a beach, and thus on cliff erosion, regardless of the beach volume. These changes could have a similar effect for the whole of the Holderness coast over a set period of time, so geographical changes become more important. Over several decades, the effect of storms and wave action on the cliff toe average out.

4.5 Conclusions

The Holderness coastline is eroding at approximately $1.3 \pm 0.1 \text{ m/yr}$ (1854-2005), and its retreat has been influenced by human intervention. The following conclusions are drawn from the study region:

- 1) Building defences has created set-back of the adjacent undefended coasts. Set-back is greater on the down-drift coast than the up-drift coast.
- 2) Set-back increases throughout time making the terminal groyne effect more apparent. Set-back down-drift frequently evolves into the shape of an embayment.
- 3) Variable cliff behaviour is observed down-drift. Retreat rates do not always increase, partly as relatively large data uncertainties indicate no conclusive excess. However, with advanced survey methods such as DGPS, uncertainties reduce over the longer term.

- 4) On a sediment starved coast, extending the defences will have minimal effect on erosion rates down-drift.
- 5) The terminal groyne effect can increase shoreline retreat for hundreds to thousands of metres down-drift.
- 6) The terminal groyne effect is complicated by the influence of beach mining, which has generated increased retreat rates on the Holderness coast during the measurement period. The effect of mining is under acknowledged and undervalued in previous studies of retreat at Holderness.
- 7) The terminal groyne effect is influenced by the frequency of storm and erosion events. Over short time scales it is not always possible to deduce if the defences are the sole cause of increased retreat. Ideally retreat rates need to be measured over at least 15-20 years.
- 8) With continued set-back, the defences are outflanked leading to defence extensions. Extending and refurbishing defences allows the terminal groyne effect to evolve. The terminal groyne effect can be measured from multiple baselines for each stage of defence evolution.
- 9) With continued retreat of the adjacent coast, the defences form artificial headlands. Seawalls (or other shore parallel defences) produce set-back even though they do not block sediment movement. With time, seawalls protrude seaward creating an artificial headland.
- 10) Over hundreds of years and continued set-back, shallow embayments form between headlands even if situated tens of thousands of metres apart.

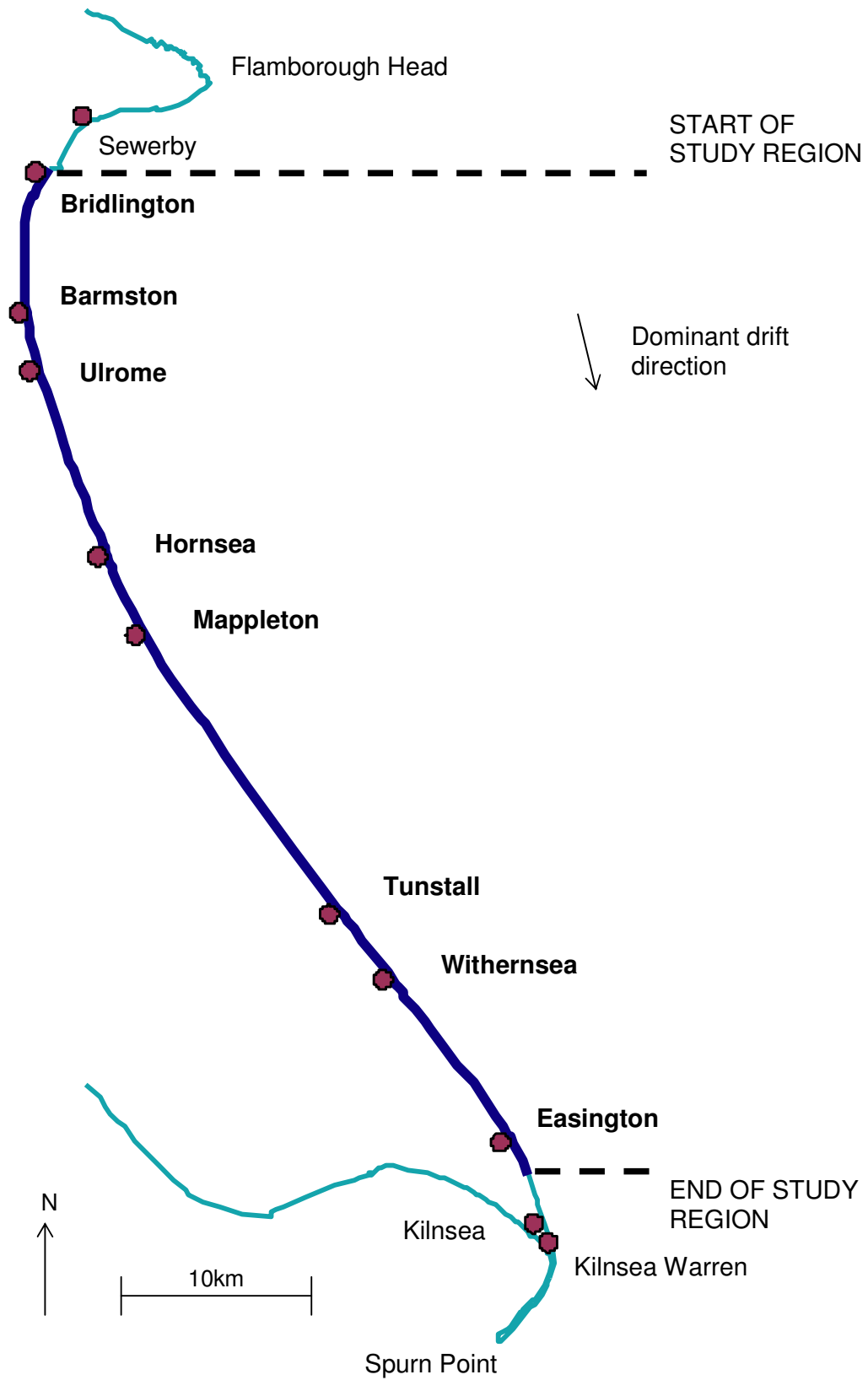


Figure 4.1 – The Holderness Coast. The study region extends 54.6km from Bridlington’s harbour arm to south of Easington. The defended localities within the study region are shown in bold.

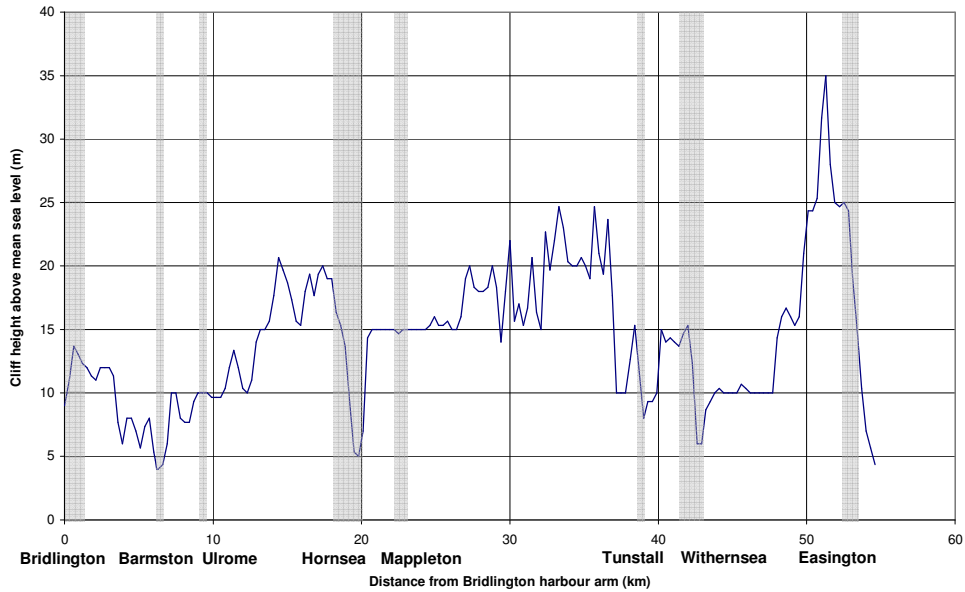


Figure 4.2 – Cliff height from Bridlington to Easington. The cliffs range from 4m at Barmston to over 35m above mean sea level near Easington. Data extracted from Ordnance Survey (2006b,c) to $\pm 2m$. The grey areas indicate the location of defences in 2005.

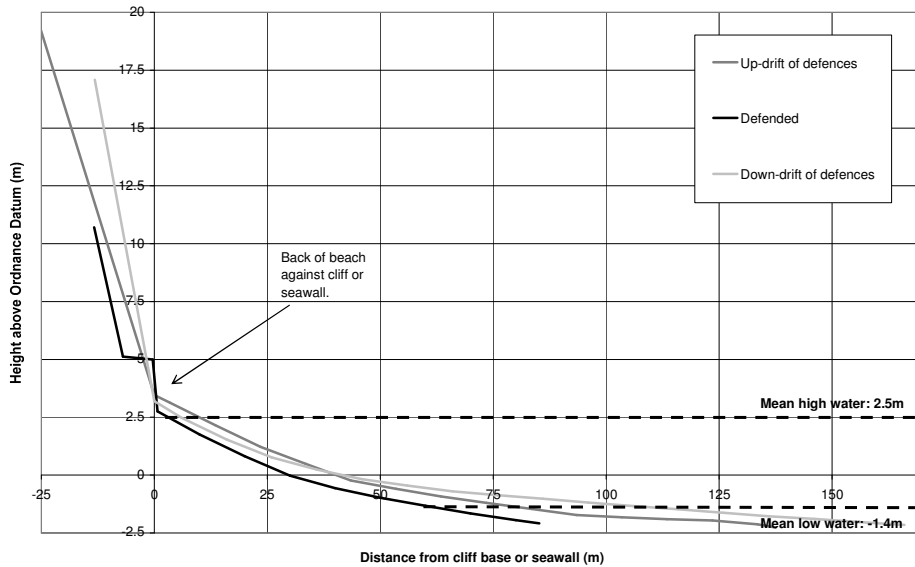


Figure 4.3 – Beach profiles at Hornsea, up-drift and down-drift of the defences (maximum distance of 1km from the defence) and within the defences. Mean high and low water is shown for Hornsea. Beach surveyed in September 2005 (available from East Riding of Yorkshire Council, see Appendix 3).

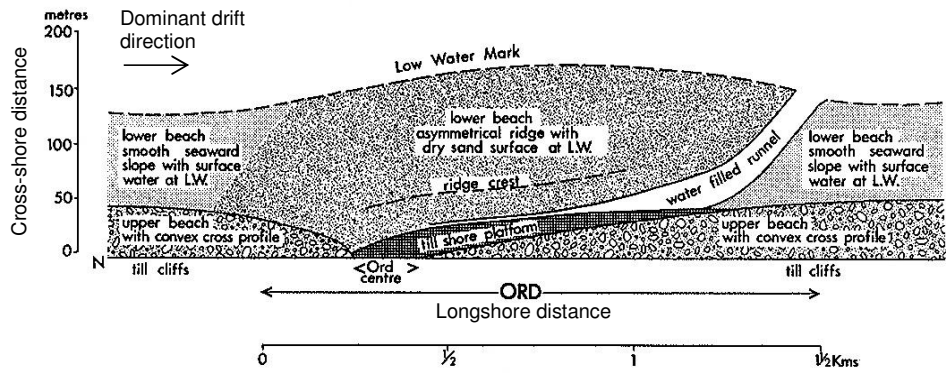


Figure 4.4 – A generalised planform of an ord (Pringle, 1981). The lower beach exposes the till platform and cliff base to erosion. Pringle (1981) found the ord migrates by the northern (up-drift) upper beach pushing shorewards during storms. Other scientists doubt ords exist and believe they are part of the beach-bar system.

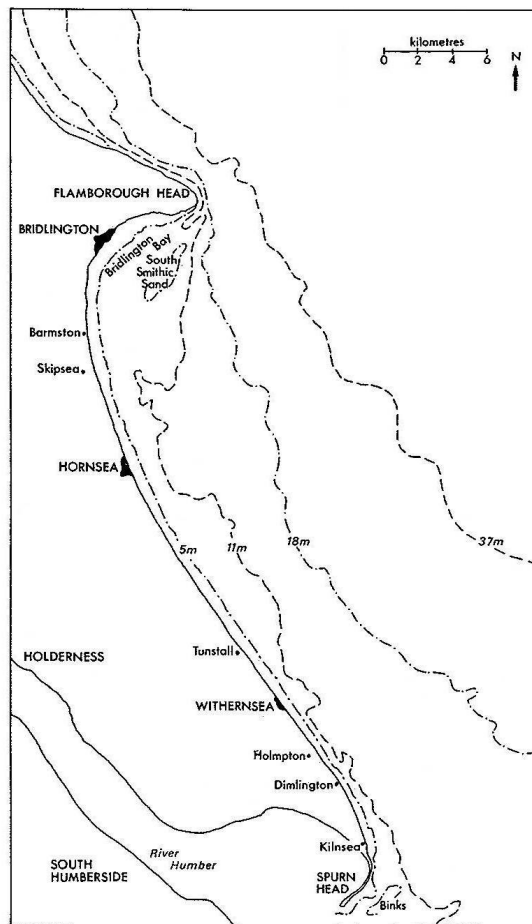


Figure 4.5 – The bathymetry of Holderness (after Pringle, 1981). The northern quarter is protected by Flamborough Head and South Smithic Sands. The southern quarter is most exposed and the 11m contour reaches its closest position (at 600m) to the shore.

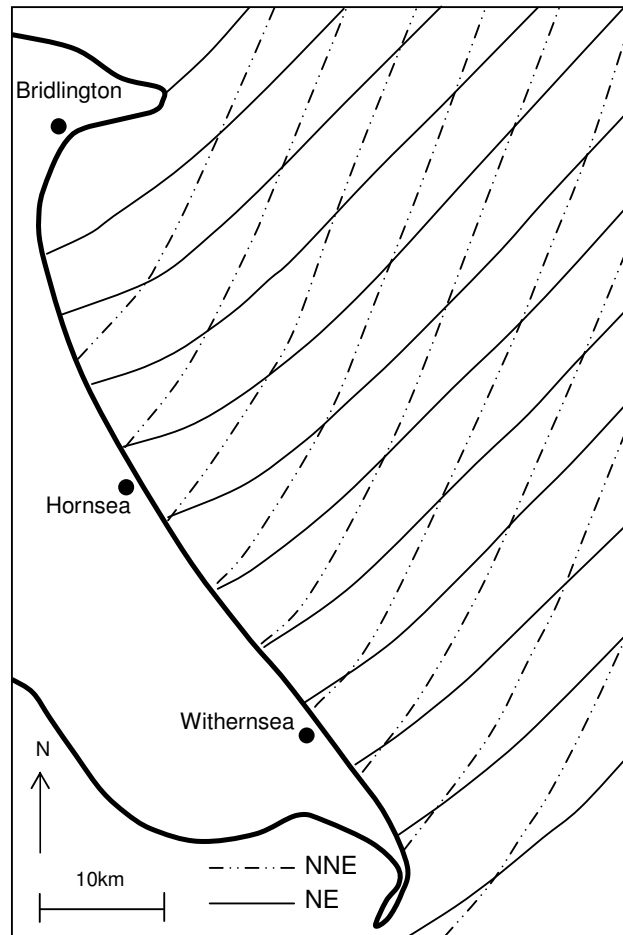


Figure 4.6 – Wave refraction orthogonals on the Holderness coast due to changes in bathymetry. Refracted wave rays propagate from the dominant wave directions of the north-north-east (NNE) and north-east (NE). Adapted from Scott (1976).

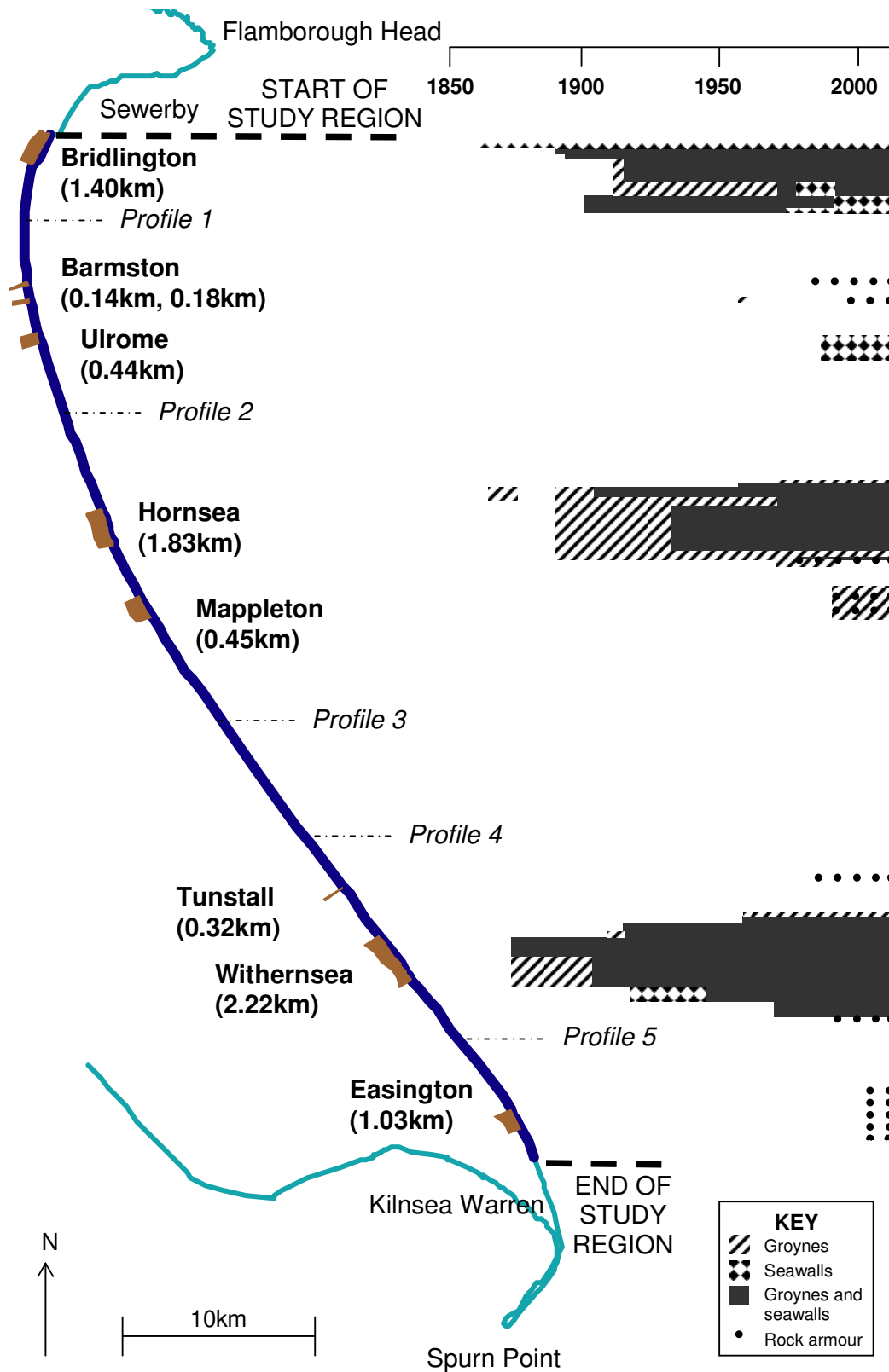


Figure 4.7 – Defences at Holderness (Bridlington to Easington). The defended sections are shown in bold with the length of defences in brackets. The bar chart (stretched x2 vertically) indicates defence type over time. Additionally rock armouring may be in front of seawalls. The thin dashed lines indicate the position of the five 500m wide retreat profiles plotted on Figure 4.11. Bridlington's defences also extend 2.2km further up-drift.



Figure 4.8 – The lost villages of the Holderness coast. Approximately 670km² (260miles²) of land and at least 30 villages are estimated to be lost since Roman times (Sheppard 1912; Ward, 1922; Steers, 1964; Mason and Hansom, 1988). Image from Steers (1964).

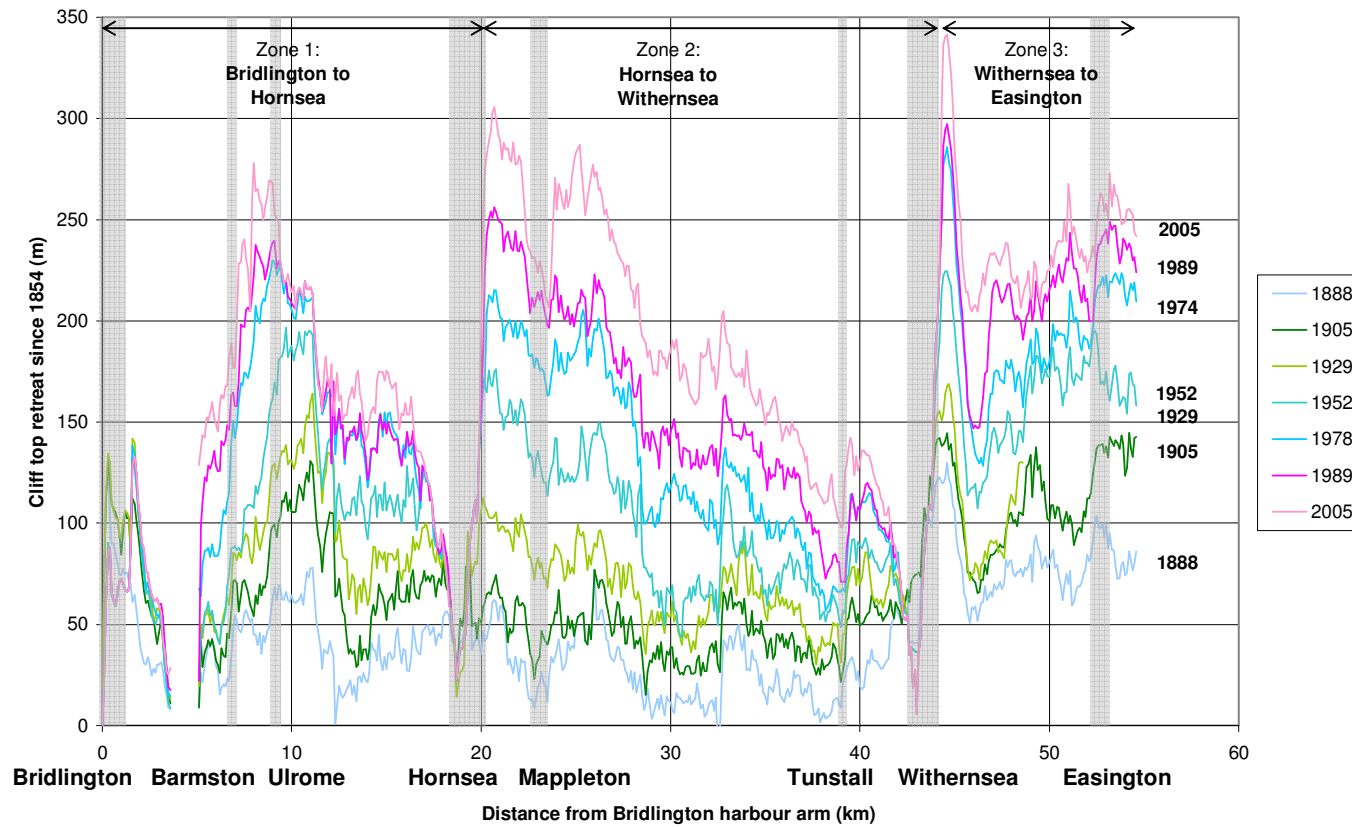


Figure 4.9 – Cliff top retreat at Holderness from 1854 to 2005 using all study years. For origin of data, see Section 3.7.1 and Table 3.4. The figure is divided into three zones based on defence location; Bridlington to Hornsea, Hornsea to Withernsea, and Withernsea to Easington. Areas defended in 2005 are shown in grey.

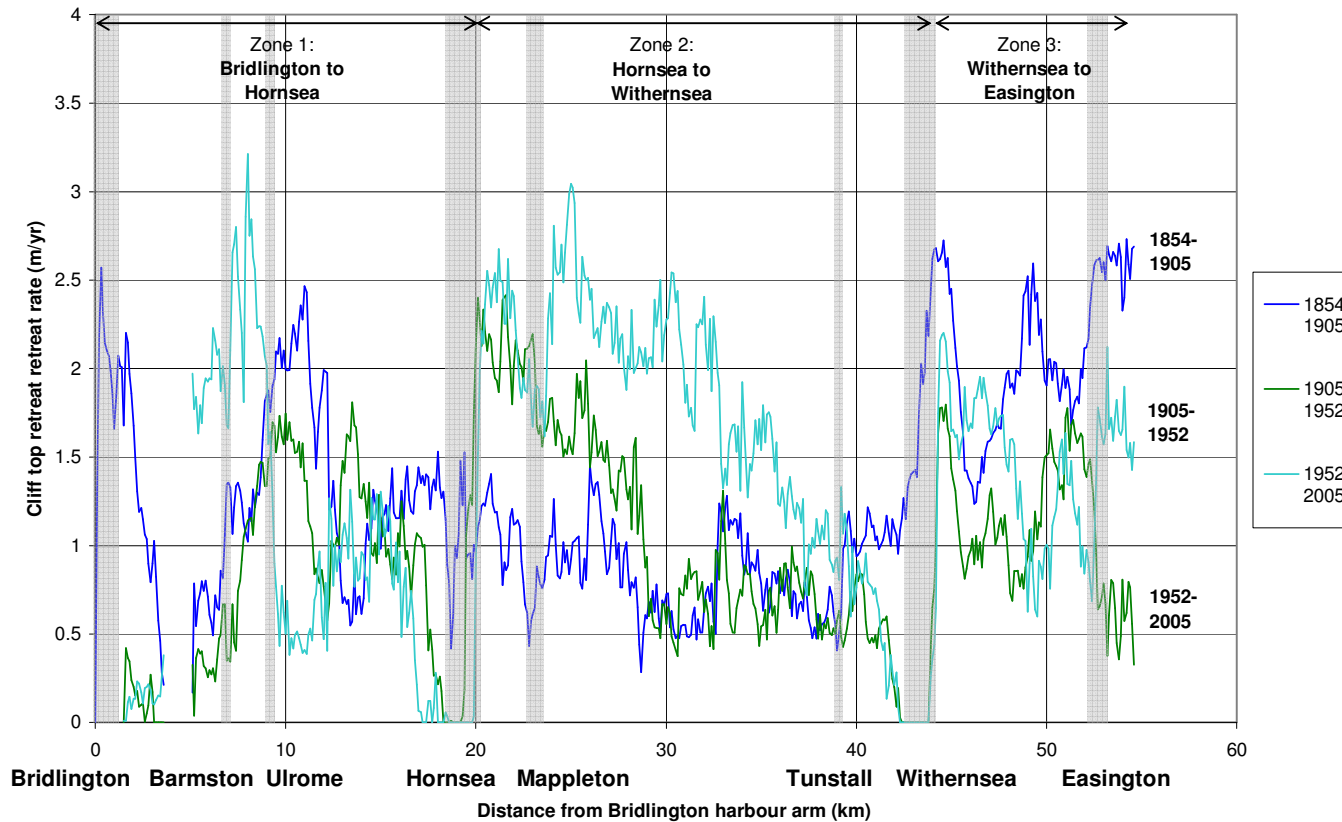


Figure 4.10 – Cliff top retreat rates at Holderness calculated in three approximate 50 year periods. The data is derived from Figure 4.9. Table 4.3 displays a summary of these rates. Areas defended in 2005 are shown in grey. Retreat rates vary within each zone.

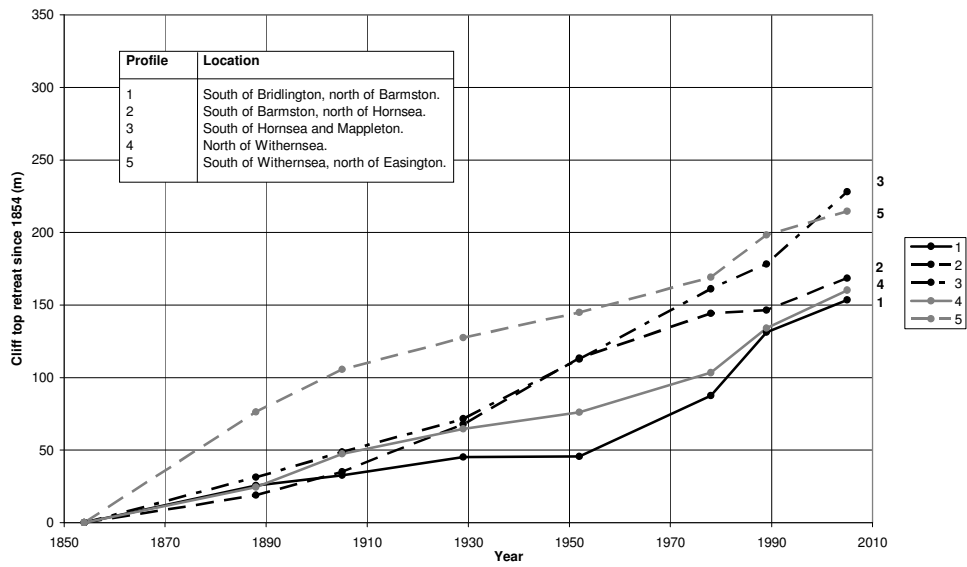


Figure 4.11 – Five undefended retreat profiles situated well away from the defences (see Figure 4.7). These profiles are to be compared to those situated on or near defences (Section 4.3).

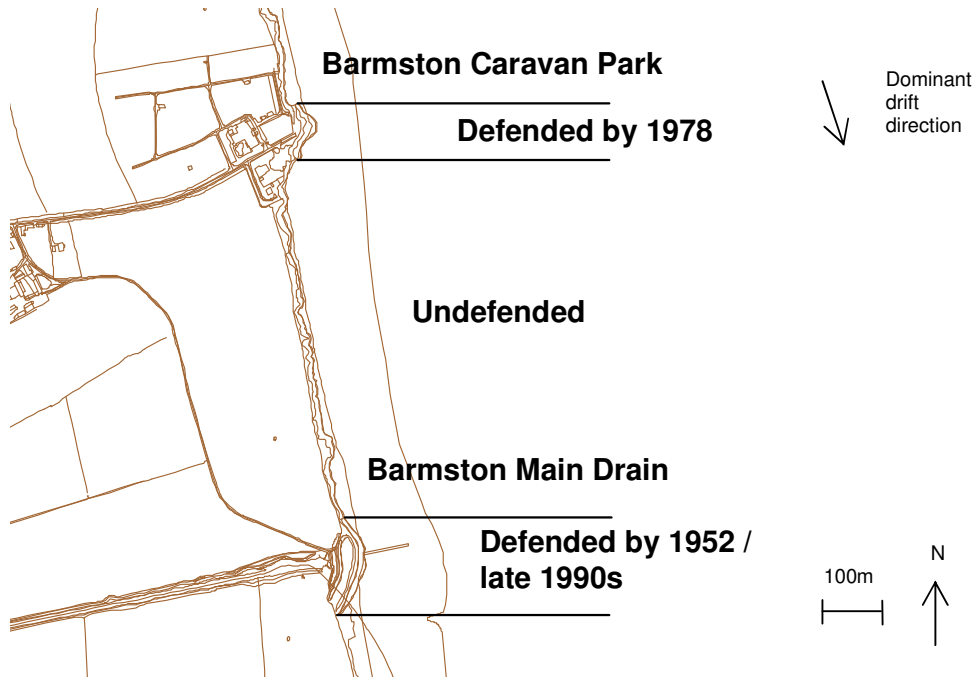


Figure 4.12 – Earliest records for defence construction at Barmston. See Table 4.4 for further details. The defences at Barmston Main Drain have not significantly interfered with the coastline up-drift, but can potentially limit Barmston Caravan Park’s set-back down-drift.

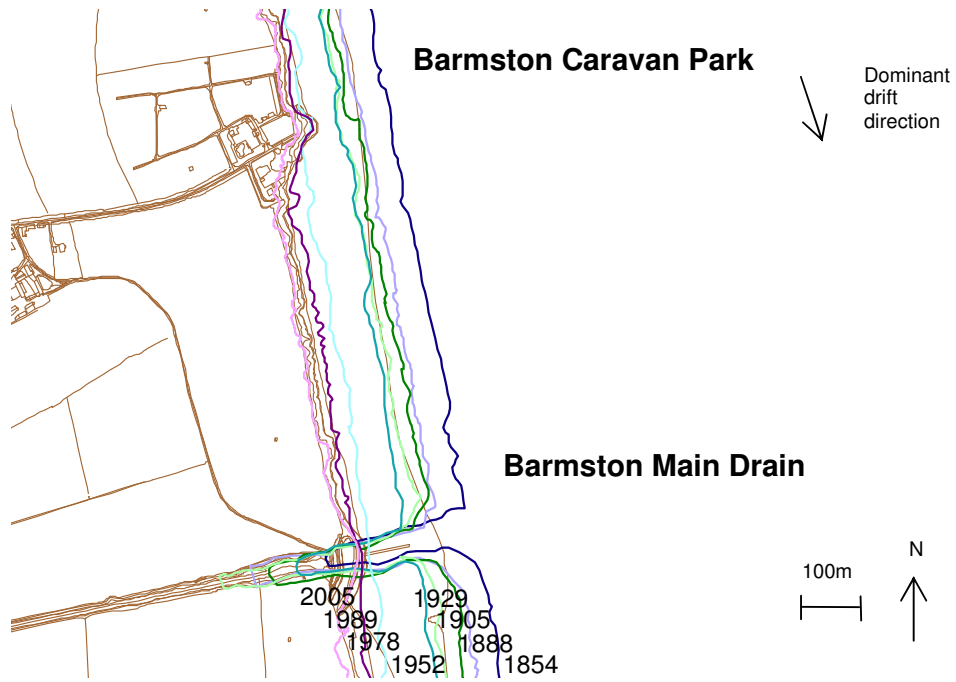


Figure 4.13 –Cliff top positions from 1854 to 2005 at Barmston.

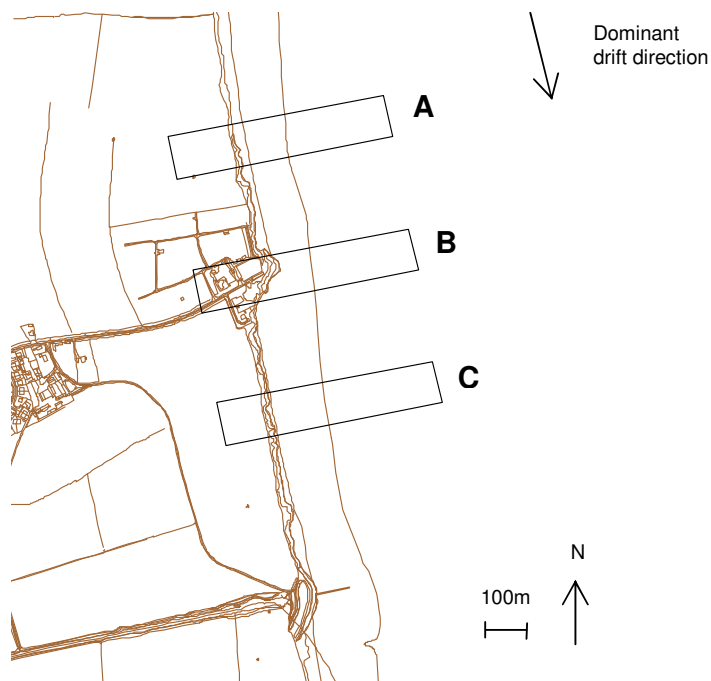


Figure 4.14a – Position of average retreat profiles at Barmston. Profiles are 100m wide. Profile B is situated over the Barmston Caravan Park defences, and Profiles A and C are located 200m up-drift and down-drift of the defence.

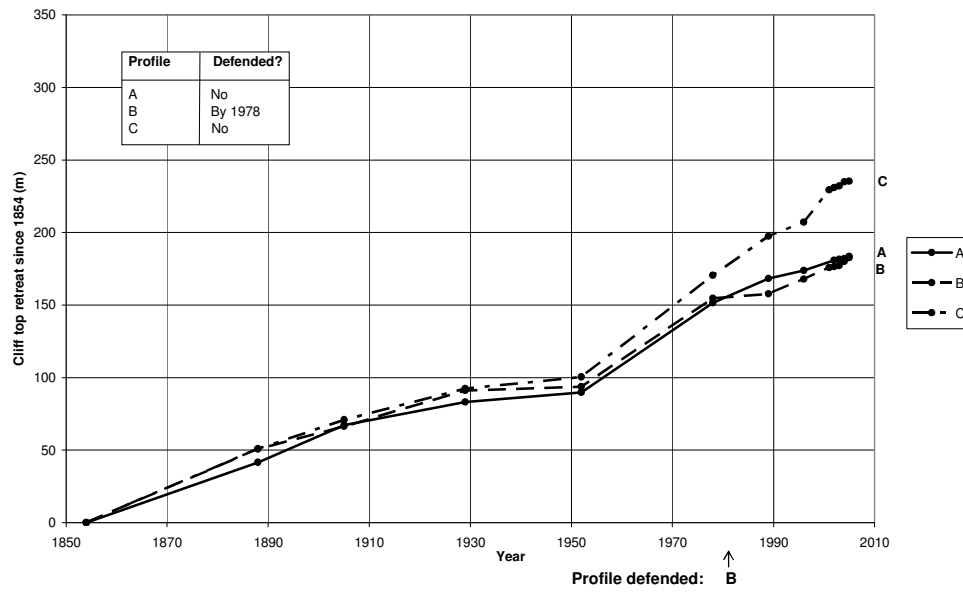


Figure 4.14b – Retreat profiles at Barmston. For profile location, see Figure 4.15a. Profiles had a similar magnitude of retreat until 1952 and after the known defence construction first recorded in 1978.



Figure 4.15 – The bay forming between Barmston Caravan Park and Main Drain. Barmston Caravan Park defences can be seen in the distance. The bay is 660m long and an average of 60m deep (photograph taken 10th August 2006).

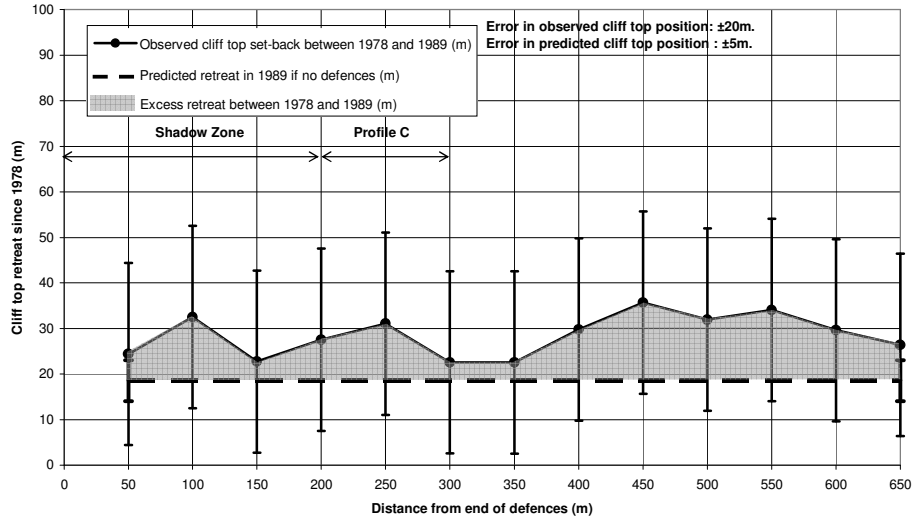


Figure 4.16 – Predicted and observed retreat down-drift of Barmston from 1978 to 1989. Retreat rates before and after defence construction remained at similar levels, but have relatively large values of uncertainty. Average excess retreat is $11 \pm 15\text{m}$.

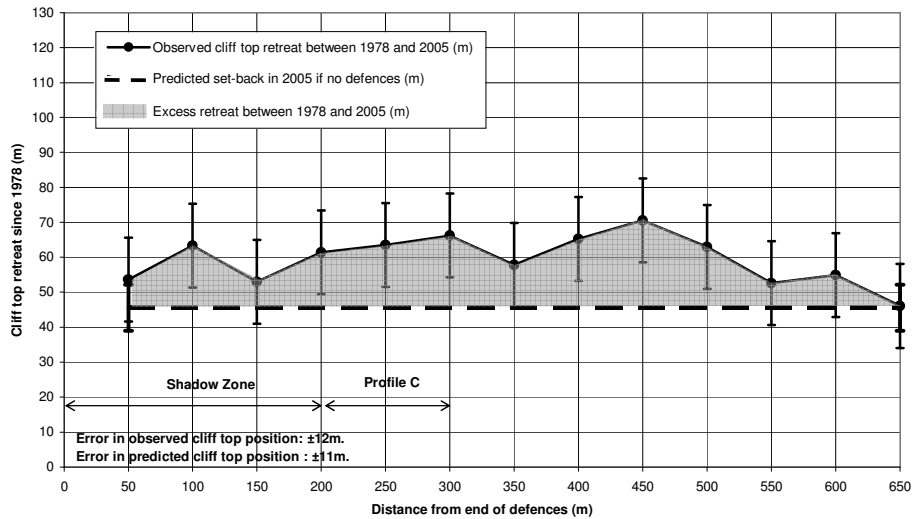


Figure 4.17 – Predicted and observed retreat down-drift of Barmston from 1978 to 2005. An embayment has formed down-drift, with average excess retreat of $14 \pm 13\text{m}$.

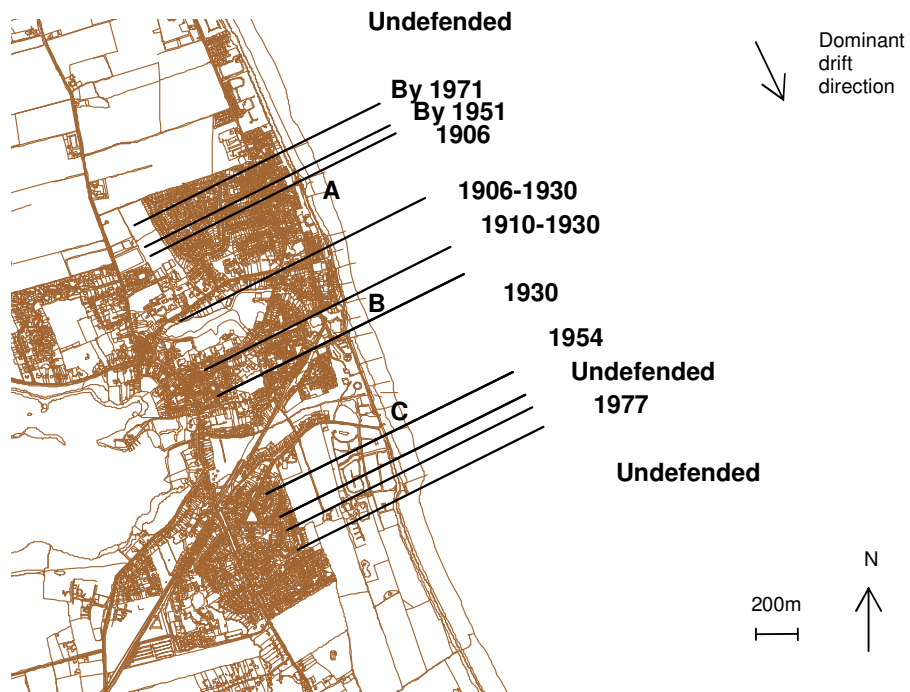


Figure 4.18 – Defence construction at Hornsea. Dates relate to defence extensions between adjacent parallel lines. See Table 4.6 for further details. A – Morrow Avenue, B- Sands Lane, C – Hornsea Burton Road.

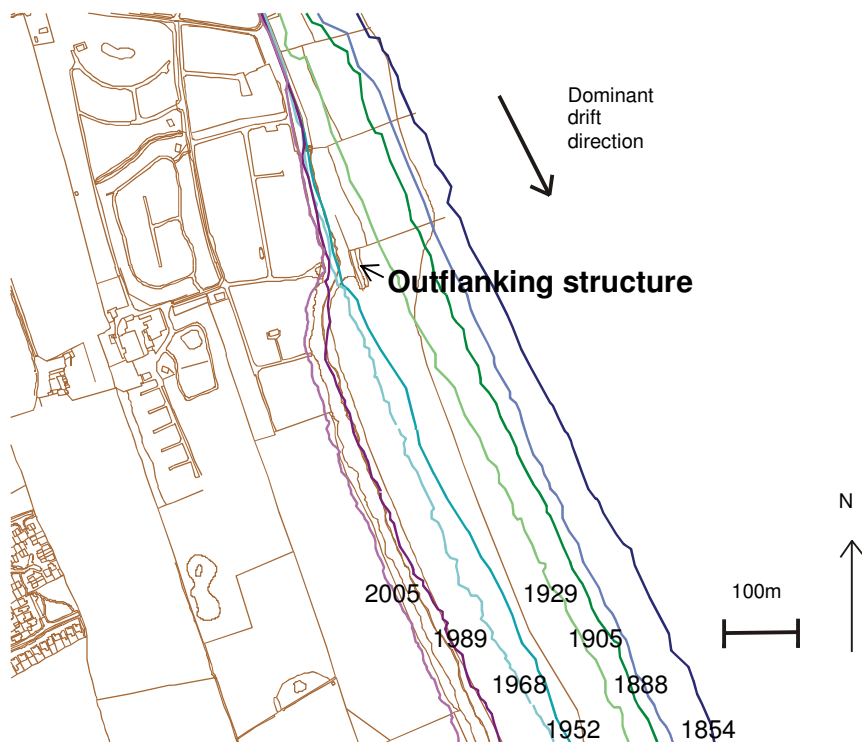


Figure 4.19 – Cliff top positions from 1854 to 2005 at Hornsea. The outflanking structure was constructed in 1977 and the down-drift coastline set-back



Figure 4.20 – The outflanking structure at Hornsea. Composed of rock armouring, this T-shaped structure is not connected to the seawall, allowing outflanking and erosion to continue behind the structure. Photograph taken 9th August 2006.

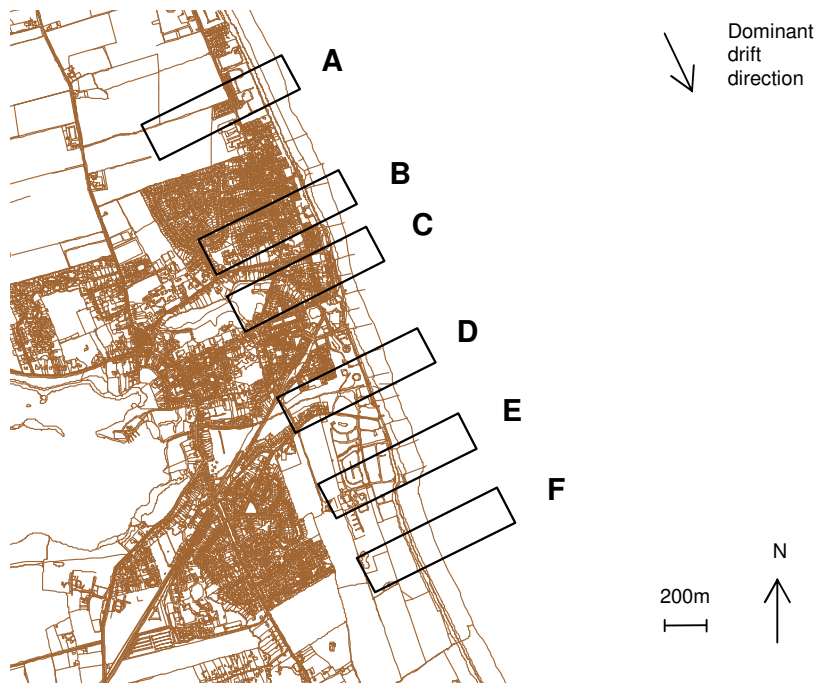


Figure 4.21a – Position of average retreat profiles at Hornsea. Profiles are 200m wide and located in the middle of each defence extension, plus 200m up-drift and down-drift of the defences.

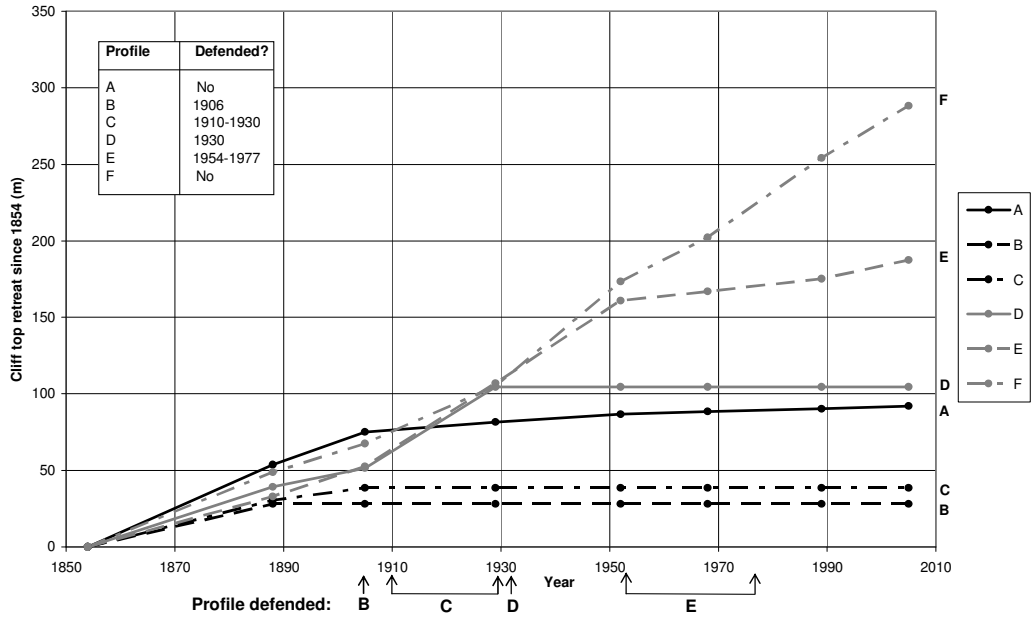


Figure 4.21b – Retreat profiles at Hornsea. Retreat is greatest for the profiles which were defended later in time.

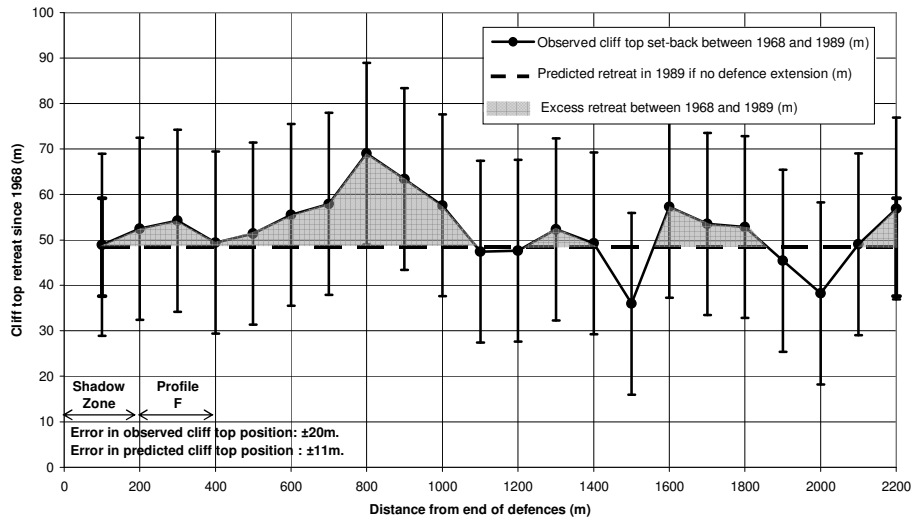


Figure 4.22 – Predicted and observed retreat down-drift of Hornsea from 1968 to 1989. Retreat rates prior to and after defence construction remained at similar levels due to the uncertainties in cliff top position. Average excess retreat is $4 \pm 21\text{m}$.

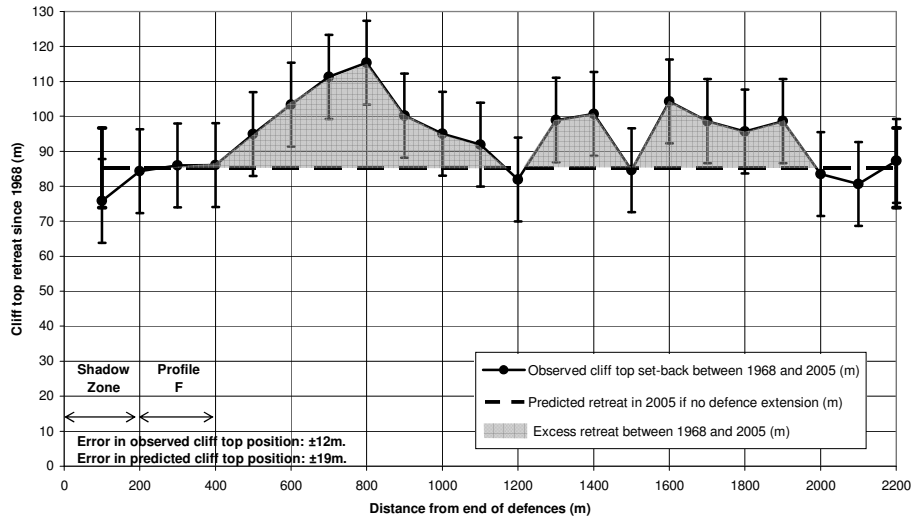


Figure 4.23 – Predicted and observed retreat down-drift of Hornsea from 1968 to 2005. Excess retreat occurs around 800m, and then decreases down-drift to similar levels to before defence construction. Average excess retreat is $10\pm 21\text{m}$.



Figure 4.24 – Hornsea's up-drift groyne. Sediment has accumulated up-drift of the defences, creating a wide, high beach protecting the cliffs from marine attack. (Photograph taken by Max Barton on 1st October 2007).

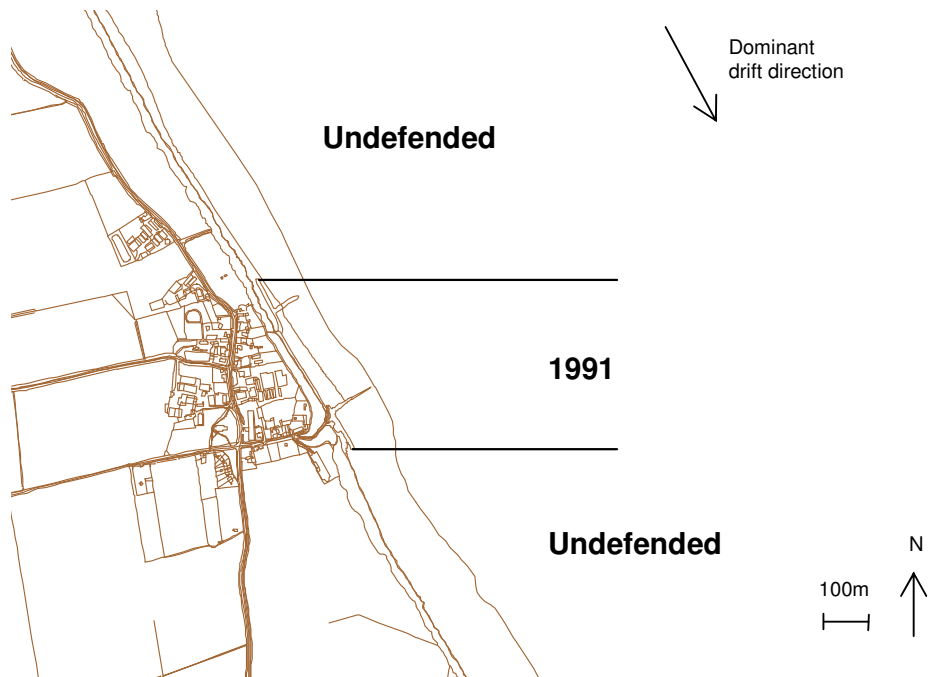


Figure 4.25 – Defence construction at Mappleton. The defences comprise rock groynes, revetment and cliff regrading. See Table 4.8.

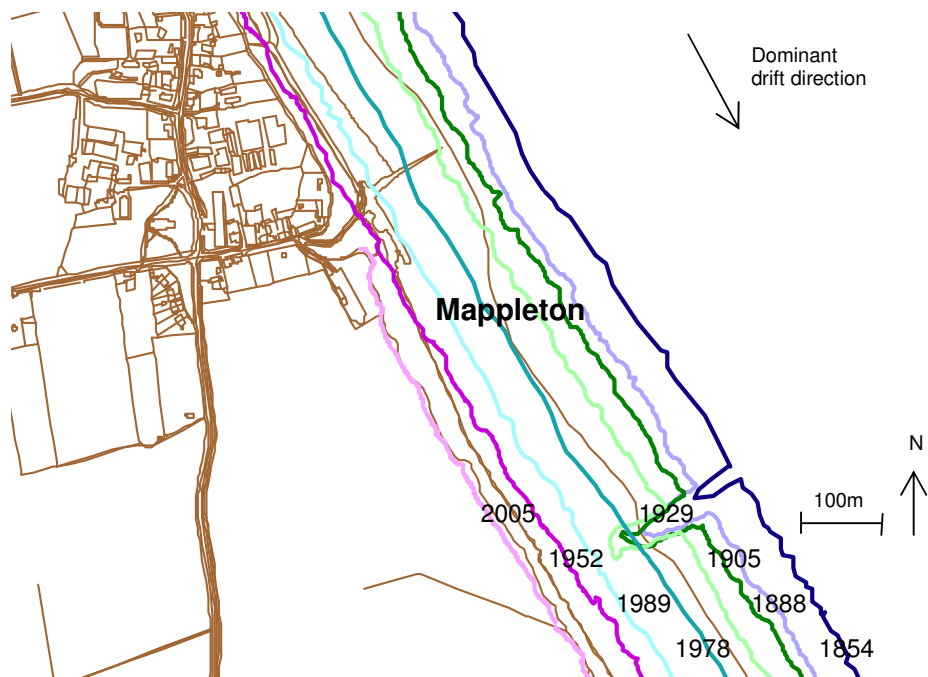


Figure 4.26 – Cliff top positions from 1854 to 2005 at Mappleton. Until 1989, the shoreline exhibited parallel retreat and after defence construction in 1991 the down-drift coast set back.



Figure 4.27 – Cliff set-back down-drift of Mappleton. Photograph taken 10th August 2006.



Figure 4.28a – Position of average retreat profiles at Mappleton. Profiles are 200m wide. Profile B is situated in the middle of the defence, and Profiles A and C are located 200m up-drift and down-drift of the defence.

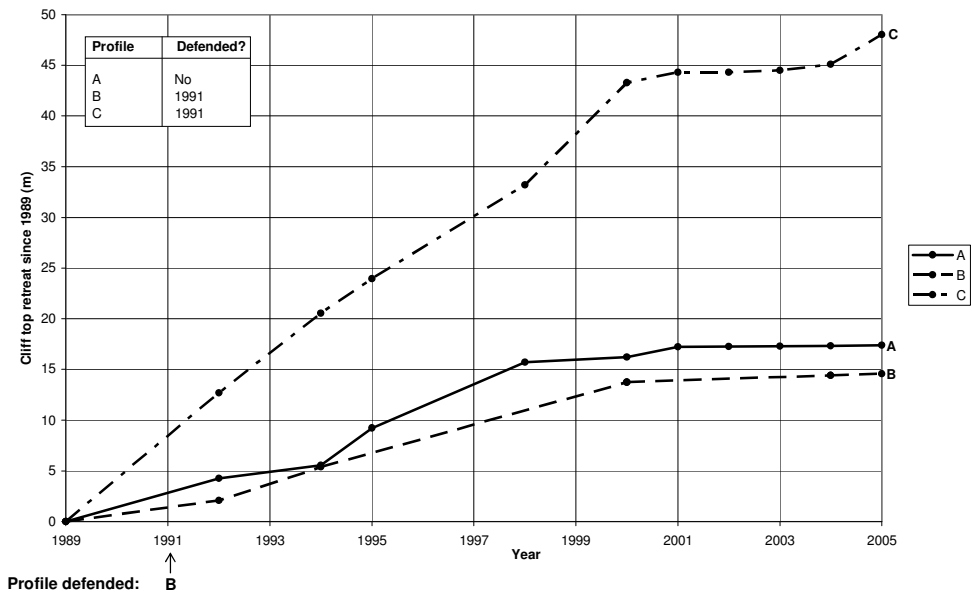


Figure 4.28b – Retreat profiles at Mappleton. The undefended coast had high retreat rates after defence construction in comparison to the defended and undefended up-drift coast.

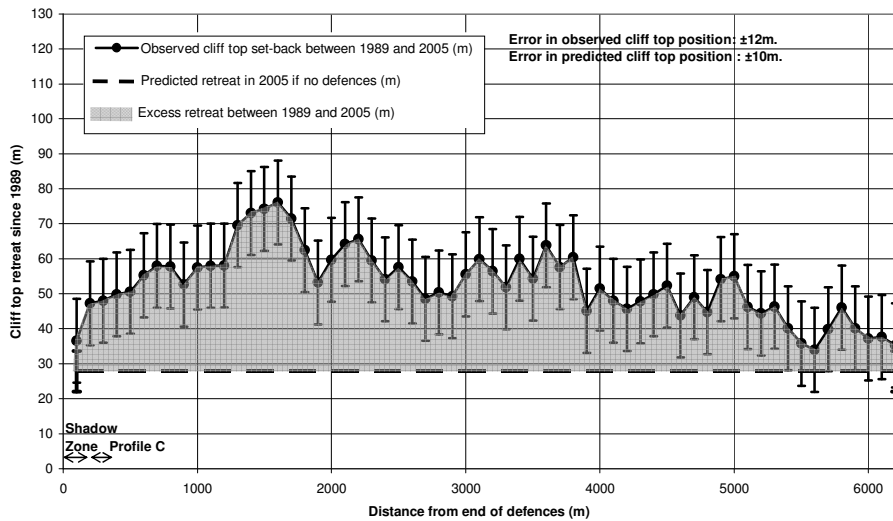


Figure 4.29 - Predicted and observed retreat down-drift of Mappleton from 1989 to 2005. Excess retreat peaks at 1.6km, and extends for 3.9km to 4.4km down-drift.

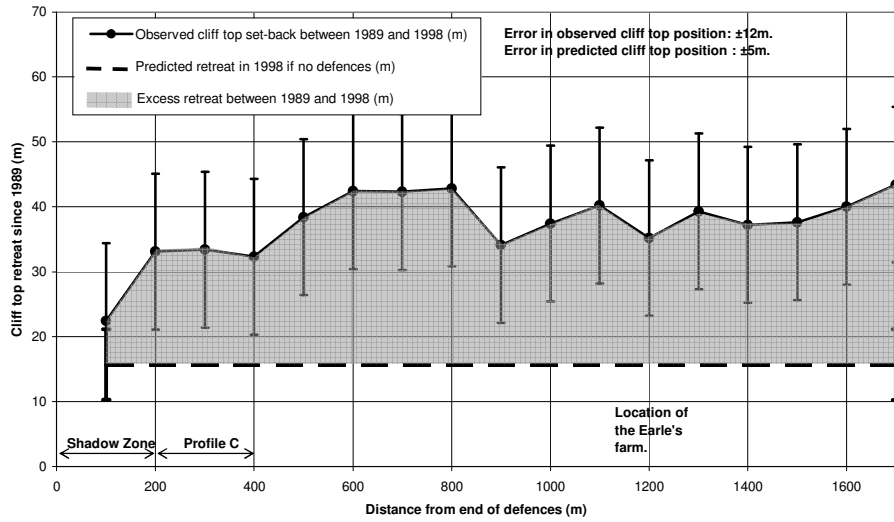


Figure 4.30 - Predicted and observed retreat down-drift of Mappleton from 1989 to 1998. Retreat rates increased, and $23\pm 8\text{m}$ of excess retreat was recorded over 9 years.

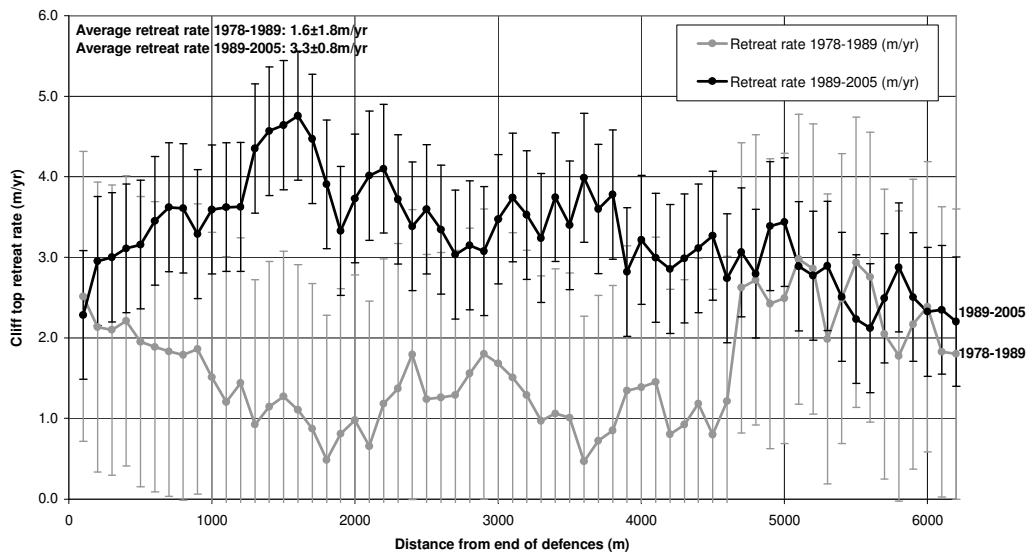


Figure 4.31 – Comparison of retreat rates before (1978-1989) and after (1989-2005) defence construction at Mappleton. Excess retreat extends to approximately 4.7km down-drift.

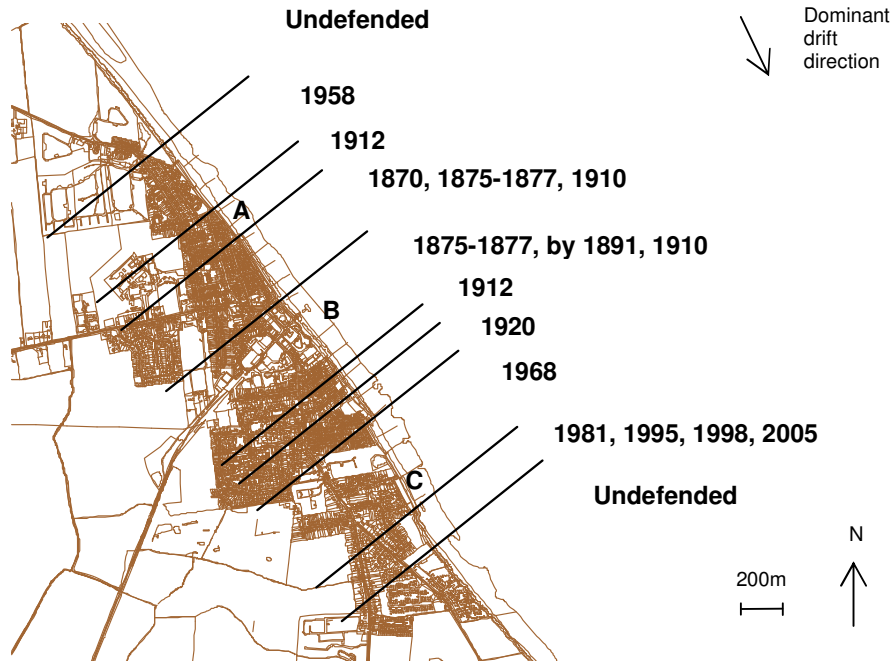


Figure 4.32 – Defence construction at Withernsea. Dates relate to defence extensions between adjacent parallel lines. See Table 4.10 for further details. A – Seathorne Road, B – Pier and Pier Road, C – Louville Avenue.

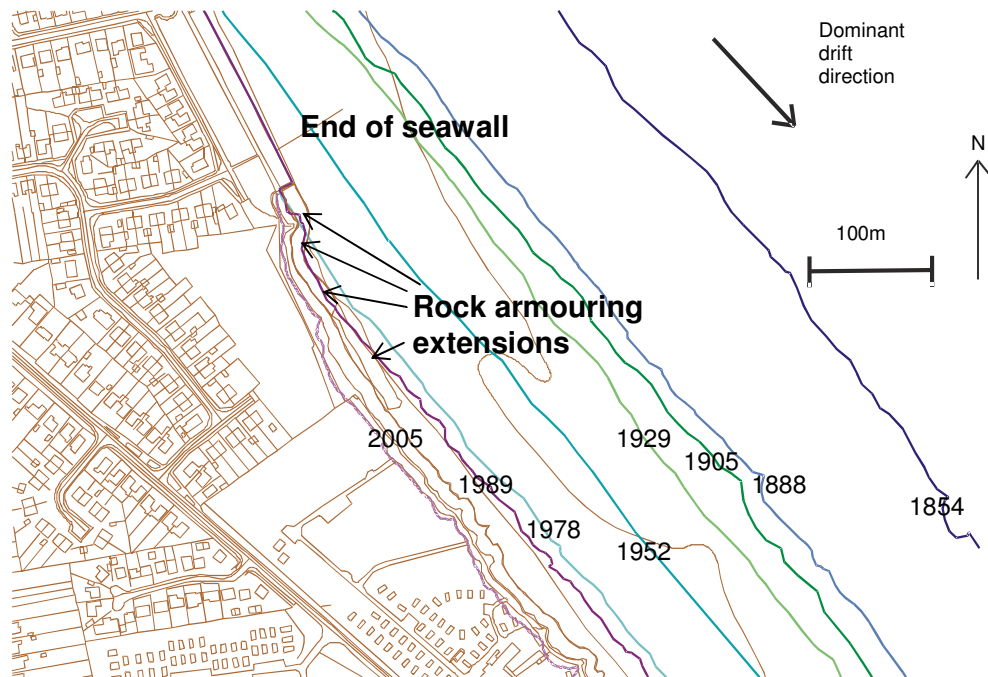


Figure 4.33 – Cliff top positions from 1854 to 2005 at Withernsea. Rock armouring was added in 1981, 1995, 1998 and 2005.



Figure 4.34a – Position of average retreat profiles at Withernsea. Profiles are 200m wide and located in the middle of each defence extension, plus 200m up-drift and down-drift of the defences.

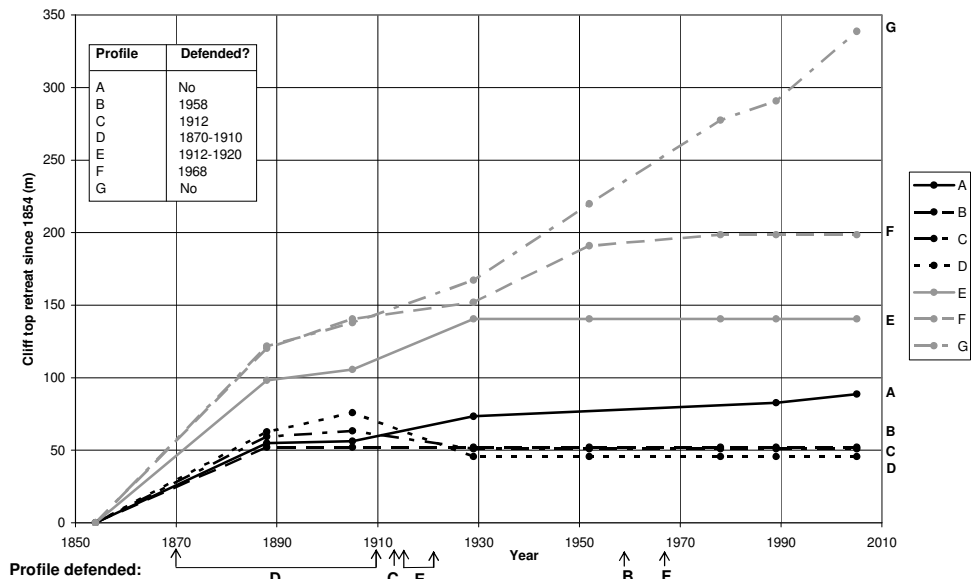


Figure 4.34b – Retreat profiles at Withernsea. Retreat has continually been high for Profiles E, F and G compared to Profiles A, B, C and D suggesting transition in longshore coastal behaviour between low and high retreat.

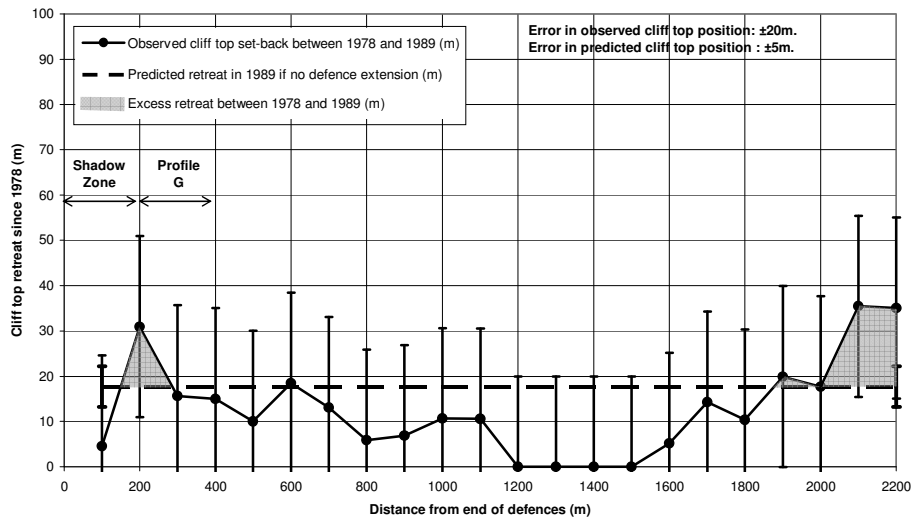


Figure 4.35 - Predicted and observed retreat down-drift of Withernsea from 1978 to 1989. Excess retreat cannot be resolved with any confidence.

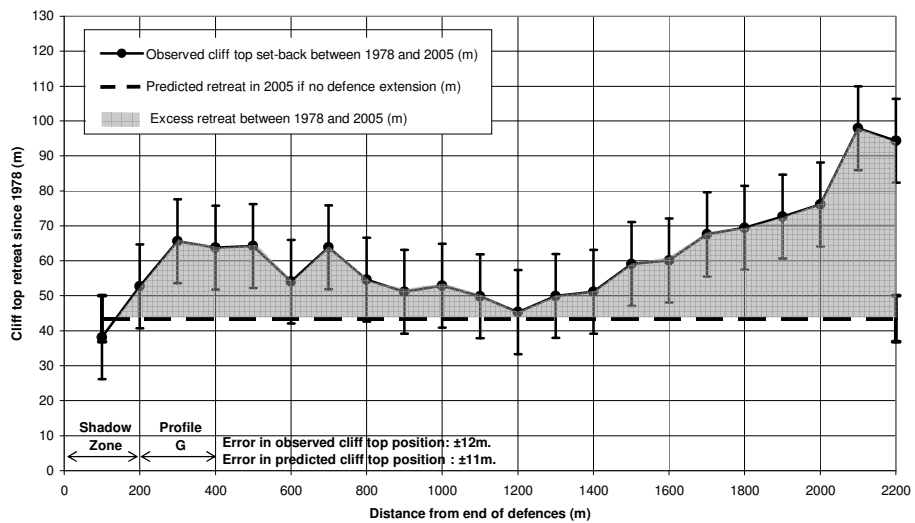


Figure 4.36 - Predicted and observed retreat down-drift of Withernsea from 1978 to 2005. Note the increased observed retreat down-drift of 1,400m, representing the peak on Figure 4.9 at approximately 45km down-drift of Bridlington.



Figure 4.37 – The rock armour extensions at Withernsea and subsequent shoreline set-back. Photograph taken 9th August 2006.



Figure 4.38 – Wooden groynes and a seawall at Withernsea. At the seaward end of the groynes, there is very little sediment and the shore platform is exposed. Photograph taken 10th August 2006.

Table 4.1 – The glacial tills of the Holderness Formation. Compiled from Catt and Penny (1966), Madgett and Catt (1978), Catt (1991) and Lewis (1999).

Lewis (1999)	Madgett and Catt (1978)	Catt and Penny (1966)	Age	Locality	Description
Withernsea Member	Withernsea Till	Purple Till	10,000 to 70,000 years.	Mappleton to Easington, over 20m in thickness at Dimlington (2km north of Easington).	A dark, reddish brown massive, fine grained diamict till. Greater silt content than the Skipsea Till.
Skipsea Member	Skipsea Till	Drab Till	10,000 to 70,000 years.	Varies in thickness from less than 6m to greater than 12m and exposed along cliff base for nearly the entire coast.	Chocolate-brown fine grained till containing approximately equal amounts of chalk, red Triassic silt, sandstone, grey shales, limestones and coal erratics. Sand and gravel lenses make it susceptible to erosion.
Bridlington Member	Basement Till	Basement Till	100,000 to 250,000 years.	Intermittently exposed on the foreshore and cliff base at Bridlington, and between Kilnsea and Holmpton (located mid-way between Withernsea and Easington).	Uniformly stiff till, dark grey-brown with a green tinge. Contains erratics including chalk, flint, limestone, and igneous and metamorphic rocks from Scotland and Scandinavia.

Table 4.2 – The length and percentage of defended coastline from Bridlington to Easington from 1854 to 2005 as reported on 1:10,560 or 1:10,000 OS maps (see Table 3.4, no map data is available for 1929). A decrease is seen in 1952 due to groyne degradation/removal. Total length of study region is 54.6km. The distribution of defences is illustrated in Figure 4.7.

Year		1854	1888	1905	1952	1978	1989	2005
Length	km	0.04	2.2	4.1	3.8	5.4	6.2	8.0
Percentage	%	<1	4	8	7	10	11	15

Table 4.3 – Retreat rates on the Holderness coast. The data was derived from Figures 4.9 and 4.10. The results found in this research are compared with Valentin’s (1954) and Pickwell’s (1878) studies. *Known as Earl’s Dike in Valentin’s (1954) work. All results shown to 1dp. **Extends 4.5km south to Kilnsea Warren. ^ As cited in article, but using map error estimates discussed in Section 3.5, this could potentially increase to ± 0.2 m/yr.

Locations	Distance km	Results from this study					Valentin (1954)	Pickwell (1878)
		1854-1905 m/yr	1905-1952 m/yr	1952-2005 m/yr	1854-2005 m/yr	1854-1952 m/yr	1852-1952 m/yr	Mid 18 th - 19 th century m/yr
Sewerby to Barmston Main Drain*	8.1						0.29	
Bridlington to Hornsea	17.1	1.3	0.8	1.0	1.0	1.1		1.5
Barmston Main Drain* to Hornsea	10.6	1.5	1.1	0.9	1.1	1.3	1.10	1.7
Hornsea to Withernsea	21.7	0.9	1.1	1.8	1.3	1.0	1.12	1.8
Withernsea to Easington	8.1	2.1	1.2	1.4	1.6	1.7	1.75**	1.1
Entire coastline								
Bridlington to Easington	54.6	1.3	1.0	1.4	1.3	1.2		1.5
Sewerby to Kilnsea Warren	72						1.20	
Retreat rate errors		± 0.4	± 0.4	± 0.2	± 0.1	± 0.2	± 0.1 ^	$> \pm 0.5$
Retreat rate standard deviation		± 0.6	± 0.3	± 0.3	± 0.4	± 0.5	± 0.5	± 0.8

Table 4.4 – Defence works at Barmston. To be read in conjunction with Figure 4.12 (Compiled from data sources listed in Table 3.4 and Barmston Beach Caravan Park, pers. comm., 2006).

Year	Location	Description of works	Parallel Frontage (m)	
			New	Total
By 1978	Barmston Caravan Park.	Slipway.	6	6
Late 1980s / early 1990s	Barmston Caravan Park.	Slipway removed. Armouring around base of former slipway parallel to the cliff, including tank blocks.	140	140
2005	TOTAL LENGTH OF DEFENCES			140

Table 4.5 – Summary of the results for Barmston averaged for the length coast. *from reference shoreline, the closest to defence construction. Error value represents the extremes. The figure in brackets for the percentage increase indicates the maximum value.

	1929-1978	
Retreat rate prior to defences used to predict retreat (m/yr)	1.7±0.4	
	1978-1989	1978-2005
Observed set-back after defence construction* (m)	29±20	60±12
Observed retreat rate after defence construction (m/yr)	2.7±1.8	2.2±0.4
Predicted retreat after defence construction* (m)	19±5	46±11
Excess retreat (m)	11±15	15±13
Percentage increase (%)	58 (188)	32 (68)

Table 4.6 – Defence works at Hornsea. To be read in conjunction with Figure 4.18 (Compiled from data sources listed in Table 3.4 and Pickwell, 1878; Sheppard, 1912; Steers, 1964; Whittaker, 1990; Southwell, 1995; Easdown, 1996; East Riding of Yorkshire Council, 2004).

Year	Location	Description of works	Seawall Frontage (m)	
			New	Total
19 th century		Minimal defences		
1869-1970	Morrow Avenue.	Two groynes and breastwork, destroyed in 1876.		
1878-1880	Sands Lane.	Pier constructed.		
By 1892	South from Morrow Avenue.	Groynes spanning 1.72km.		
1906	South from Morrow Avenue.	Seawall constructed.	422	422
1910	Sands Lane.	Pier removed (part remained until 1929).		
1910-1930	New Lane to Sands Road	Seawall extended south	447	869
1911	South from Morrow Avenue.	Groyne field length reduced to 1.6km		
1930	Sands Lane to Hornsea Burton Road.	Seawall extended south.	545	1414
By 1951	North of Morrow Avenue.	Groynes extended 70m north, spanning 0.8km.		
1954	South of Hornsea Burton Road.	130m long revetment.	130	1544
By 1971	Start 190m north of Morrow Avenue.	Groynes extended north and south.		1544
By 1971		Shore parallel defence down-drift of seawall.	175	1719
1977		Outflanking structure added down-drift.	115	1834
1970s		General seawall maintenance.		
1980s		Upgrade and strengthening of seawalls, groynes and terminal structure.		
1990s		General seawall and groyne maintenance.		
2000s		Increased height and maintenance of seawalls. Groyne maintenance.		
2005	TOTAL LENGTH OF DEFENCES			1834

Table 4.7 – Summary of the results for Hornsea averaged for the length coast. *from reference shoreline, the closest to defence construction. Error value represents the extremes. The figure in brackets for the percentage increase indicates the maximum value.

	1929-1968	
Retreat rate prior to defences used to predict retreat (m/yr)	2.3±0.5	
	1968-1989	1968-2005
Observed set-back after defence construction* (m)	52±20	95±12
Observed retreat rate after defence construction (m/yr)	2.5±1.0	2.6±0.3
Predicted retreat after defence construction* (m)	48±11	85±19
Excess retreat (m)	4±21	10±21
Percentage increase (%)	7 (87)	11 (54)

Table 4.8 –Defence works at Mappleton. To be read in conjunction with Figure 4.25 (Compiled from data sources listed in Table 3.4 East Riding of Yorkshire Council, 2004).

Year	Location	Description of works	Seawall Frontage (m)	
			New	Total
1991	Mappleton village.	450m of cliff parallel rock armouring, two rock groynes and cliff regrading.	450	450
2005	TOTAL LENGTH OF DEFENCES			450

Table 4.9 - Summary of the results for Mappleton averaged for the length coast. *from reference shoreline, the closest to defence construction. Error value represents the extremes. The figure in brackets for the percentage increase indicates the maximum value.

	1952-1989	
Retreat rate prior to defences used to predict retreat (m/yr)	1.7±0.6	
	1989-1998	1989-2005
Observed set-back after defence construction* (m)	38±12	53±12
Observed retreat rate after defence construction (m/yr)	4.2±1.3	3.3±0.8
Predicted retreat after defence construction* (m)	16±5	28±10
Excess retreat (m)	23±8	25±12
Percentage increase (%)	144 (239)	90 (180)

Table 4.10 – Defence works at Withernsea. To be read in conjunction with Figure 4.32 (Compiled from data sources listed in Table 3.4 and Pickwell, 1878; Reid, 1885; Sheppard, 1912; Steers, 1964; Whittaker, 1990; Easdown, 1996; East Riding of Yorkshire Council, 2004).

Year	Location	Description of works	Seawall Frontage (m)	
			New	Total
Before 1850s		Minimal defences.		
1870, 1875-1877	Pier Road.	New pier and five groynes. Seawall constructed 140m north of pier.	364	364
By 1891	600m north and 450m south of Pier Road.	4 groynes. 3 groynes south of pier.		
1903		Pier severely damaged - only 15m (50 feet) remained.		
1910	Pier Road.	Central prom constructed near pier, joining 1875-1877 seawall.	314	678
1912	Terminates at Seathorne Road.	North Gate Prom constructed.	161	839
1912	Terminates 300m south of pier.	Central Prom extended down-drift to Cheverton Avenue.	107	946
1920	Terminates 610m south of pier.	Central Prom extended down-drift to South Cliff Road.	270	1216
1945		Whole groyne field refurbished.		
1958	Extends 300m north along Seathorne Road.	Seathorne Prom built.	305	1521
1956-1978		Groyne extensions.		
1968	Terminates at Louville Avenue.	South Revetment constructed south.	486	2007
1970s		Seawall repaired.		
1980a		Upgrading of groyne field.		
1981		Rock armour extended south.	29	2036
1992-1995		Strengthening of rock armouring, extension of defences and breakwater.	25	2061
1990s		Seawall and groyne repaired.		
1998		Rock armouring extended.	60	2121
2000s		Seawall and groyne repaired.		
2005		Rock armouring extended.	100	2221
2005	TOTAL LENGTH OF DEFENCES			2221

Table 4.11 - Summary of the results for Withernsea averaged for the length coast. *from reference shoreline, the closest to defence construction. Error value represents the extremes. The figure in brackets for the percentage increase indicates the maximum value.

	1929-1978	
Retreat rate prior to defences used to predict retreat (m/yr)	1.6±0.4	
	1978-1989	1978-2005
Observed set-back after defence construction* (m)	12±20	63±12
Observed retreat rate after defence construction (m/yr)	1.1±1.8	2.3±0.4
Predicted retreat after defence construction* (m)	18±5	44±11
Excess retreat (m)	-6±15	20±13
Percentage increase (%)	-31 (172)	45 (80)

Table 4.12 – Summary of excess retreat results from the Holderness study sites.

	Study sites									
	Barmston		Hornsea			Mableton		Withernsea		
	1978-1989	1978-2005	1905-2005	1968-1989	1968-2005	1989-1998	1989-2005	1870-2005	1978-1989	1978-2005
Measurement period (years)	11	27	100	21	37	9	16	135	11	27
Average observed set-back (m)	29±20	60±12	220±12	52±20	84±12	38±12	53±12	217±12	12±20	63±12
Average predicted retreat (m)	19±5	46±11	133±40	48±11	85±19	16±5	28±10	129±47	18±5	44±11
Excess retreat (m)	11±15	15±13	88±42	4±21	10±21	23±8	25±12	88±49	-6±15	20±13
Relative retreat rates within confidence of data	Maintained / no conclusive change	Accelerated	Accelerated	Maintained / no conclusive change	Maintained / no conclusive change	Accelerated	Accelerated	Accelerated	Maintained / no conclusive change	Accelerated
Longshore influence down-drift	Up to 650m	Up to 650m	Up to 22km	Not detectable	Not detectable	At least 1.7km	3.9km - 4.1km	Not detectable	Not detectable	Up to 700m

5. CHRISTCHURCH BAY

5.1 Introduction

Christchurch Bay located in central southern England extends 14km from Hengistbury Head, a 36m high sandy headland in the west, to Hurst Castle Spit protruding 2.1km into the Solent (Figure 5.1). Behind Hengistbury Head is Christchurch Harbour, whose entrance is bounded by double spits. The bay is formed largely of sand and clay cliffs and when undefended, eroded at approximately 0.5m/yr to 1m/yr (see Section 5.2.3). Discharging into the bay are two small streams at Chewton and Becton Bunnies. Following the approach of Chapter 4, cliff retreat from 1872 to 2005 along 10.6km of coast between Mundeford and Milford-on-Sea is investigated. Man's intervention and the effect this has on retreat rates will be investigated regionally and through a series of case studies.

5.2 Christchurch Bay

Natural and anthropogenic factors affecting cliff retreat and the impact of littoral drift barriers are illustrated in Figures 2.1 and 2.2. In this section, these factors will be investigated and retreat rate analysed.

5.2.1 Environmental setting

The geology of Christchurch Bay forms part of the Hampshire Basin, an asymmetrical syncline orientated east-west surrounded by Chalk (Allen and Gibbard, 1993). The unlithified sand and clay Palaeogene deposits (65,000,000 to 23,300,000 years ago) outcrop in the cliffs include members of the Bracklesham and Barton Groups (the latter composed of Boscombe Sands, Barton Clay, Chama Sand and Becton Sand), and the lower part of the Headon Formation (Bristow *et al.*, 1991). Figures 5.2 and 5.3 show the geology of Christchurch Bay. The eastward flowing former Solent River and its tributaries, deposited extensive Pleistocene (10,000 to 1,640,000 years ago) gravel terraces (up to 4.7m), particularly in the eastern and central parts of the bay

(Allen and Gibbard, 1993; Velegarakis *et al.*, 1999). As sea levels rose in the late Devensian (10,000-70,000 years ago), or possibly earlier Devensian (Wright, 1981), the chalk ridge between Handfast Point, Purbeck and the Needles, Isle of Wight was breached (for locations and map see Figure 2.18). The rise in sea levels submerged the Solent River valley and allowed Christchurch Bay to evolve.

Hengistbury Head is composed of Boscombe Sands underlying Barton Clay (including the Warren Hill Sand), with intervening layers of ironstone nodules (Bristow *et al.*, 1991). The low lying coast between Hengistbury and Mundeford is composed of Branksome Sand from the underlying Bracklesham Group. East of Highcliffe Castle (1km west of Chewton Bunny), the Barton Clay outcrops for 4.8km (Figure 5.2 and 5.3) with a true dip of 0.75° to the east-north-east (Barton, 1973) to Becton Bunny, where the Lower Headon beds are exposed. This trend continues with the exception of two very small anticlines either side of the main palaeochannel west of Taddiford Gap (not noted on Figure 5.2). The cliffs range in height from 35m at Naish Farm to beach level at Saltgrass Lane (extracted from Ordnance Survey, 2002 with heights relative to mean sea level) and are shown in Figure 5.4.

At Highcliffe, Barton (1973) and Barton and Coles (1984) attributed cliff degradation to marine toe erosion and five other key processes - bench sliding, scarp slumping, scarp spalling, mudflows and stream erosion. In 1976, the cliff typically had three benches, an average slope of 19° , with a typical cliff top slump 1m to 5m in length and 2.7m in breadth (Barton *et al.*, 1983; Barton and Coles, 1984). Present observations found one to two benches between East Barton and Becton Bunny. On the eroding cliff (between Becton Bunny to 250m east of Taddiford Gap), two to three benches form at any one time. The average cliff angle is 29° . 250m east of Taddiford Gap, the cliffs are covered in vegetation and are protected by a wide shingle beach.

Christchurch Bay is a contained sediment circulation system with two fixed partial boundaries at Hengistbury Head and Hurst Castle Spit (Bray *et al.*, 1995). Sediment circulates eastwards in a clockwise direction (Figure 5.5) and is estimated to be between $3,000\text{m}^3/\text{yr}$ and $20,000\text{m}^3/\text{yr}$. Offshore sediment losses occur at Hengistbury Head, West Barton, Hordle and Hurst Castle Spit (Nicholls, 1985; Carter *et al.*, 2004).

Extensive gravel deposits provide a regionally important sediment source (Allen and Gibbard, 1993; Bray *et al.*, 1995). Lacey (1985) estimated that in the early part of the 20th century, the cliff input 136,000m³/yr of sediment, with 63,000m³/yr remaining stable on the beaches. Due to increased cliff defence, particularly since the 1960s (see Table 5.1), sediment supply decreased to 84,000m³/yr in the latter part of the century (Lacey, 1985). Additional beach material was supplied by major replenishment schemes (see Section 5.2.2). Beach material of sand and shingle coarsens eastwards due to the increased exposure (Nicholls and Webber, 1987). Typical beach profiles at and adjacent to Barton-on-Sea, are shown in Figure 5.6. They indicate the profile up-drift of defences has the greatest beach volume, followed by the down-drift profile, which has partially recovered from the sediment deficit due to the defences. A sandbar extends from Milford-on-Sea and has grown westward in recent decades (Nicholls, 1985) and presently terminates a few hundred metres west of Taddiford Gap.

Figure 5.7 illustrates the bathymetry of the bay. With a dominant wave direction from the west-south-west, the maximum fetch (east of Barton-on-Sea) is thousands of kilometres across the Atlantic Ocean, providing large storm waves (Henderson, 1980; Lacey, 1985; New Forest District Council, 2003). Hengistbury Head and Christchurch Ledge offers protection to the western half of the bay as wave refraction channels low energy waves to those sheltered parts in the west, and higher energy waves to the east, potentially causing greater cliff erosion (Figure 5.8). The mean significant wave height and period was calculated as 0.6m and 4.2s respectively near Milford (Channel Coastal Observatory, 2005b). The mean tidal range for the bay is 1.2m (Admiralty Chart, 2007). Sea level rise is estimated at 1mm/yr to 2mm/yr (Woodworth *et al.*, 1999) and Shennan and Horton (2002) report land subsidence as 0.5mm/yr (see Section 2.2.5). However, this is of relatively lower significance during the 133 year study period compared to man's actions (described in Section 5.2.2).

Due to wave direction, refraction (Figure 5.8), bathymetry (Figure 5.7) and geology (Figures 5.2 and 5.3) Christchurch Bay has formed into a crenulate shape. The relatively harder up-drift headland of Hengistbury Head is also the down-drift headland for neighbouring Poole Bay, which also forms a crenulate shape (see Figure 2.18). However, Wright (1981) stated that the evolution and planform shape of the bay is not totally due to wave refraction and diffraction,

but also partly due to Flandrian sea level rise and variations in the lithology. Therefore geology is critical to the formation of crenulate bays.

5.2.2 Anthropogenic influences

Aside from natural causes of retreat (see Section 5.2.1 and Figures 2.1 and 2.2), the retreat at Christchurch Bay has been heavily influenced by man through beach mining and defence schemes.

Large scale mining in Christchurch Bay commenced in the mid 19th century at Hengistbury Head (see Table 5.2). Mining peaked between 1848 and 1865 when 45,400 tonnes (50,000 tons) of ironstone nodules or doggers were removed from the cliff, beach and foreshore, including Beerpan Rocks and Christchurch Ledge (Lavender, 1985; Powell, 1995; Hoodless, 2005). The mining removed a natural groyne protecting Christchurch Bay which sheltered it from large storm waves and retained sediment in Poole Bay. Due to the high commercial value of ironstone, mining continued into 1870 (a similar time to Holderness, see Section 4.2.2) despite it being recognised as a major problem some 16 years earlier and associated with increased erosion of the headland (West, 1885; Powell, 1983; Pepin, 1985; Popplewell, 1986).

Ironstone and shingle were also removed from the beaches at Barton and Milford and within the bay until the early 20th century (Heygate, 1916; Burton, 1925; Cole, 1926, 1948; May, 1966). Septarian nodules were dredged from a 2.4km to 3.2km (1.5 mile to 2 mile) long ledge between Chewton and Becton Bunny, and from near Hurst and Hengistbury Head until approximately 1878 (Woodd, 1910; Burton, 1925; Cole, 1926).

To replicate nature at Hengistbury Head, a 200m long artificial breakwater, known as Long Groyne was constructed around 1938 (Stopher and Wise, 1966). Sediment built up-drift of the breakwater, but down-drift, sediment movement and beach levels reduced (Figure 5.9). Over the next 20 to 30 years beach levels decreased around Christchurch Bay. By the early 1960s retreat rates had increased, and subsequently parts of the coast were protected with wooden and rock groynes and revetments (Stopher, 1963; Stopher and Wise, 1966; Summers and Maddrell, 1978; HR Wallingford, 1991). Together with hard engineering, from the mid 1970s major replenishment schemes were

undertaken at Highcliffe, Hurst Castle Spit and neighbouring Poole Bay, and minor projects at Hengistbury Head, Mundeford, Barton and Milford (Summers and Maddrell, 1978; Tyhurst, 1985; May, 1990). The growth and location of defences are shown in Figure 5.10, with approximately 57% of the study region protected in 2005 (see Table 5.1). Note that before 1932 less than 4% of the region was defended, but this increased to over 25% by 1963 and 50% by 1975. Therefore since the 19th century man has influenced retreat rate in Christchurch Bay, firstly through mining, then through defence construction.

5.2.3 Regional scale retreat

Sections 5.2.1 and 5.2.2 demonstrate a multitude of factors causing and controlling retreat at different spatial and temporal scales. The retreat of the cliffs from 1872 to 2005 between Mundeford and Milford-on-Sea is shown on Figure 5.11. The cliff top positions in the figure are derived from maps, aerial photographs (1872 to 2005) and other surveys (2005), as detailed in Section 3.7.1 and Table 3.5. Cliff top positions were combined on a GIS and transects calculating the average area of land lost were taken at regular intervals, as described in Section 3.8. Defences present in 2005 are shown in grey (for further details of defences, see Figure 5.10 and Table 5.1). The figure is divided into three zones based on defence positions and the location of the bunnies; Mundeford to Chewton Bunny, Chewton Bunny to Becton Bunny, and Becton Bunny to Milford-on-Sea. Zone 2 indicates a marked increase in retreat compared to the adjacent zones. There has been a variable retreat rate with time, as shown in Figure 5.12 and Table 5.3 (this data has been derived from Figure 5.11). Figure 5.12 divides retreat rates into multi-decadal time periods based on the level of human intervention described in Section 5.2.2. Retreat rates were greatest from 1872 to 1932, despite sediment release from mining at Hengistbury Head. The zone with lowest retreat is Mundeford to Chewton Bunny.

Nicholls (1985) found there is no simple relationship between sediment supply, beach stability and growth, and cliff erosion around the bay. In part this is due to the influence of man, in particular mining. Mining at Hengistbury Head was initially beneficial to Christchurch Bay as sediment was released extending the harbour's southern spit 2.3km towards Highcliffe Castle (Robinson, 1955). The spit forced a channel (known as The Run) between it and the cliffs. Whilst the spit protected the coast from storm waves, stream erosion prompted the building

of defences at Highcliffe Castle around 1880 (see Section 5.3.1 and Table 5.5). Until approximately 1935 (and the building of Long Groyne around 1938) the spit breached and reformed on at least five occasions (Table 5.4). Each breach released sediment around the bay and potentially caused the growth of the large beach at Hordle (Nicholls, 1985) reducing erosion (Lacey, 1985 estimated this sediment growth as $1,300\text{m}^3/\text{yr}$ from 1932 to 1968).

Table 5.3 shows an average retreat rate of $1.0\pm 0.3\text{m}/\text{yr}$ between Chewton Bunny and Becton Bunny between 1872 and 1932. Although a time of sediment abundance, exposure and in particular shingle and septarian nodule mining made the cliffs susceptible to erosion (see Section 5.2.2). 1932 to 1963 was a transition between sediment abundance and lowering beach levels due to the construction of Long Groyne around 1938. Beach levels reduced and coastal defences were constructed from the 1960s (see Section 5.2.2, Figure 5.10 and Table 5.1). Constructing defences locally reduced sediment input, inhibited sediment movement and created local zones of intense retreat down-drift of Highcliffe, Barton-on-Sea, Becton and Milford-on-Sea (Lacey, 1985; Nicholls, 1985; Nicholls and Webber, 1987; Bray *et al.*, 1995; Dixon *et al.*, 1998; Farquharson, 2006). Despite building defences, retreat continued in some of the protected areas. For instance, at Barton-on-Sea the permeable (predominantly clay) Middle Barton Beds allowed a partly contained aquifer to form due to infiltrating precipitation in the overlying (predominantly sand) Upper Barton Beds (Fort *et al.*, 2000). This resulted in numerous localised failures since the 1970s (see Section 5.3.2). From 1870 to 1965, the movement of the low water mark, high water mark and cliff top was calculated as $1.24\text{m}/\text{yr}$, $0.72\text{m}/\text{yr}$ and $0.98\text{m}/\text{yr}$ respectively, suggesting foreshore steepening (Hooke and Riley, 1991).

5.2.4 Summary

Christchurch Bay formed during the Devensian sea level rise which created and eroded the sand and clay coast. Since the mid 19th century coastal processes have been heavily influenced by cliff, beach and nearshore mining, altering the sediment budget. Average retreat for the bay from 1872 to 2005 was $0.5\pm 0.1\text{m}/\text{yr}$.

5.3 Study sites

Figure 5.10 indicates major defences at Mudeford, Highcliffe, Barton and Milford. High retreat rates from 1963 to 2005 are recorded at Naish (down-drift of Highcliffe) and Barton (Figure 5.12), and these localities have been selected for detailed study. Becton is also selected as a study site as an outfall has resulted in a large set-back down-drift. For the three study sites, the set-back, excess retreat, percentage increase in retreat rate and the difference in retreat rates before and after defence construction, on the down-drift coast will be analysed (using the equations listed in Section 3.9.1). A maximum value of the percentage increase is not shown in the results tables (Tables 5.6, 5.8 and 5.10) as the values become meaningless (see Section 7.2.1 and Table 7.1).

Since at least the mid 19th century, Christchurch Bay has not been free from human intervention. Predicting retreat if no defences were constructed is a very difficult task as the natural rate is unknown. Modelling shoreline positions would be beneficial, but may not improve results due to potential data errors. Therefore the values for excess retreat are a best estimate based on the conditions immediately before defence construction.

5.3.1 Highcliffe

5.3.1.1 Overview

Highcliffe and its castle were first protected in the 19th century (see Section 5.2.3 and Table 5.5). After a period of low retreat, substantial protection works and beach replenishment were undertaken at Highcliffe from the 1960s (Figure 5.13 and Table 5.5). The protection works resulted in a set-back of the down-drift coast 1.25km until Barton-on-Sea (Figures 5.14 and 5.15).

5.3.1.2 Results

Figures 5.16a and 5.16b illustrate the position of four 200m wide profiles located equidistance over the defences and 200m up and down-drift. After defence construction, Profile A up-drift of the defences retreated approximately the same distance as Profiles B and C located over the defence. Retreat at Profile D accelerated creating a 62 ± 12 m set-back down-drift by 2005.

To assess excess retreat after defence construction (and the building of Long Groyne), the retreat rate from 1932 to 1963 ($0.6\pm 0.6\text{m/yr}$) is extrapolated to 1989 (Figure 5.17) and 2005 (Figure 5.18). Predicted and observed longshore retreat is measured every 50m for the 1.25km of coast at Naish. Figure 5.17 shows that there was greater set-back nearer to Highcliffe than West Barton, with clear excess retreat within the shadow zone. If the 1932 to 1963 retreat rate had continued to 1989, average excess retreat is predicted of $18\pm 26\text{m}$. By 2005 clear cross-shore excess retreat of up to 28m and up to 400m down-drift would have occurred. This created an average excess retreat of $17\pm 29\text{m}$ for the coast between Highcliffe and West Barton. A summary of results are shown in Table 5.6.

5.3.1.3 Discussion

Profiles A, B, and C indicate that over several decades the defences have been successful in reducing retreat. Initially timber groynes (constructed between 1967 and 1971) failed to attract a beach, but a timber revetment maintained cliff position (Tyhurst, 2003). Although sediment input from the cliff was reduced causing a deficit down-drift, a replenishment scheme provided additional sediment input. Furthermore, beach levels were influenced by offshore sediment movement (Bray *et al.*, 1995; Carter *et al.*, 2004, see Figure 5.5). Therefore the continued erosion of the down-drift coast created a set-back. The conversion of timber to rock groynes probably more effectively inhibited sediment movement, creating excess retreat down-drift. The percentage increase is a poor measure of excess retreat as the value decreased in 2005 despite excess retreat staying approximately the same.

The results suggest defence construction at Highcliffe accelerated retreat down-drift, but not for the entire 1.25km of unprotected coast. Averaging the excess retreat along the 1.25km Naish frontage suggests no excess retreat that may be resolved within the confidence of the data (see Table 5.6). However, excess retreat can be resolved, but only for 200m down-drift. Average excess retreat is only a useful metric when the down-drift coast exhibits parallel retreat. At Naish there is greater set-back and excess retreat than at West Barton (see Figures 5.17 and 5.18). This could occur because:

- a) The Highcliffe defences have a decreasing influence on the retreat further down-drift, resulting in reduced erosion;
- b) The Barton-on-Sea defences reduce littoral drift, thus maintaining higher beach levels at West Barton than immediately east of Chewton Bunny.

The down-drift cliffs are set-back and have developed into a crenulate shaped embayment with the defences acting as hard headlands. Therefore bay growth and excess retreat down-drift is constrained by the Barton defences.

Unlike other study sites, the maximum excess retreat occurs within the shadow zone (Figures 5.17 and 5.18). There are two explanations for this, the first being the feature known as Lob's Hole, an approximately 200m long section of cliff located 300m down-drift of Chewton Bunny. It has greater set-back than the adjacent unprotected cliff and is created through local geological influences (Barton, 1973). Erosion here was severe until 1963 (see Figure 5.14), but since then retreat rates have reduced compared to the immediately adjacent undefended coast. The second explanation is that Chewton Bunny and the bastions effectively cut off a portion of the shadow zone, leaving a shallow curve. Silvester and Hsu (1997) report this as a common occurrence with man-made bays.

5.3.1.4 Summary

Highcliffe's defences have been effective in maintaining cliff top position and creating set-back down-drift. Excess retreat has occurred near to Highcliffe and increased with time, creating an approximately 28m cross-shore excess up to 400m down-drift by 2005. Growth is constrained down-drift by the Barton-on-Sea defences, creating a crenulate shaped embayment at Naish Farm.

5.3.2 Barton-on-Sea

5.3.2.1 Overview

Barton-on-Sea was first defended in the 1930s and later in the 1940s and 1950s by a wooden groyne field (Phillips, 1974). The groynes attracted a beach, but failed to stop cliff top erosion. A large stabilisation scheme was constructed over the initial defences after 1964 and was extended down-drift on two

occasions (see Figure 5.19 and Table 5.7). In the 1980s and 1990s, the defences were up-graded, and converted from wooden to rock groynes, and rock armouring placed at the cliff toe. The down-drift coast is now set-back (Figure 5.20) until the Becton Bunny former sewage outfall which acts as a partial sediment barrier 450m down-drift of the armouring (Figure 5.21).

5.3.2.2 Results

Figures 5.22a and 5.22b indicate the position of four 100m cliff profiles, located over, and 150m up and down-drift of the defences. Between 1872 and 1963, Profiles A, B and D retreated between $69\pm 20\text{m}$ to $83\pm 20\text{m}$. Profile C retreated $110\pm 20\text{m}$ and is located in a 'peak' of erosion in the central zone of Figure 5.11. This may be due to the translational failures on the Barton Clay at the F1/F2 interface (Fort *et al.*, 2000). After 1963 retreat rates at Profile D accelerated creating a set-back of $72\pm 12\text{m}$ by 2005. The dipping geology and benches significantly influence retreat down-drift.

To investigate excess retreat, Figures 5.23 and 5.24 illustrate the observed and predicted set-back and retreat (based on a retreat rate of $0.5\pm 0.6\text{m/yr}$ from 1932 to 1963) from 1963 to 1989, and 1963 to 2005 respectively. Data is plotted in 50m intervals down-drift of the defences eastwards until Becton Bunny. The 150m of coast between Becton Bunny and the outfall is omitted as Becton Bunny debouches at approximately 45° to the coast and has migrated westward during the study period (see Figure 5.20). In 1989, $21\pm 27\text{m}$ of excess retreat occurred, decreasing towards Becton Bunny. By 2005 there was a percentage increase of 205%, causing $41\pm 29\text{m}$ of excess retreat. Table 5.8 summaries the results.

5.3.2.3 Discussion

Barton-on-Sea's 1964 defence scheme and upgrades have been successful in reducing retreat over several decades (see Profiles A, B and C on Figure 5.22b). However, failures occurred at the defended area of Barton Court in 1974 and 1975 causing problems to local infrastructure. A number of other smaller failures occurred in 1987/1988, 1993, 1998, 2001, 2003, 2004 (Reina, 1975; Clark *et al.*, 1976; Fort *et al.*, 2000). This led to extensive ground investigations and monitoring (Fort *et al.*, 2000). Due to continued set-back down-drift, a rock

armoured extension was added to the revetment. This temporarily overcame the outflanking problem, but a further extension was required in the early 1990s. Storm waves still attack the cliff base behind the armouring (Figure 5.25). This created a double set-back and crenulate shape on the cliff top over a longshore distance of 100m. For further discussion of outflanking at Barton, see Sections 6.2.1 and 6.2.3. Due to the extensions, the shadow zone has increased in length longshore.

At Profile A (Figure 5.22b), located up-drift of the defences, retreat reduced after defence construction probably due to sediment being retained up-drift (see beach profiles on Figure 5.6). This supports the discussion of Highcliffe's terminal groyne effect and limitations in longshore growth (see Section 5.3.1). Little is known about the effect defences have on the up-drift shoreline and their role in bay formation.

By 2005 the down-drift coast had set-back 72 ± 12 m. However, in planform the set-back would appear less as the undefended coast initially stood seaward of the up-drift coast. This is because defence construction terminated at a natural promontory (for an aerial photograph, see Figures 6.5a and 6.5b). Therefore it cannot be assumed cross-shore set-back is the distance between the defences and the present cliff top position. The terminal groyne effect must be measured with respect to the initial cliff top position.

Retreat rates and excess retreat have increased throughout time, with a percentage increase in 2005 of 205%. Excess retreat has been measured within the confidence of the data in 2005 and probably also occurs in 1989. Hence the terminal groyne effect is more apparent at Barton in 2005 than in 1989. At Highcliffe, retreat rates decreased with time as sediment was probably retained by the Barton defences (see Section 5.3.1). The Becton outfall acts only as a partial sediment boundary. It is overtopped during storm conditions and allows for greater passing than a groyne field, explaining the increased rates.

Excess retreat is not uniform longshore and decreases down-drift. Analysis of beach profiles from 1989 to 2005 (for details, see Appendix 3) indicates that beaches are larger and wider nearer to the outfall than to Barton. Field visits and surveys confirmed this result. Like Highcliffe, the undefended coast has

formed a crenulate shaped embayment between the two defences which act as headlands. Maximum set-back within the embayment occurred approximately one third of the distance between Barton and the outfall due to defence sheltering, recovery of sediment levels, drift reversals and accumulation of sediment near the outfall (Brown and Barton, 2007). Therefore a key process in crenulate shaped bay formation is the presence of a down-drift headland (whether natural or artificial) which retains sediment up-drift. If the outfall was removed, sediment would migrate down-drift creating lower beach levels and increasing erosion rates between Barton and Becton Bunny (see Section 6.2.3).

5.3.2.4 Summary

Major defences were constructed at Barton-on-Sea after 1964 and have undergone several upgrades. The defences have slowed retreat, but a number of small failures continue to occur in the defended area. Set-back has resulted down-drift of the defences. Down-drift retreat rates and excess retreat have increased over time. The terminal groyne effect is constrained down-drift by the outfall, which acts as a partial sediment barrier, leading to an embayment forming between Barton-on-Sea and the Becton outfall.

5.3.3 Becton

5.3.3.1 Overview

Becton is a former sewage outfall 450m down-drift of Barton. It is protected by rock armouring and acts as a partial sediment barrier (see Figures 5.26 and Table 5.9). It was constructed between 1971 and 1972 and had a major upgrade between 1994 and 1997. Shoreline positions are shown in Figure 5.27. The down-drift coast is set-back a greater distance compared to the up-drift undefended coast (Figure 5.28). The coast is undefended for 2.8km until Milford-on-Sea (Figure 5.10), with minimal retreat down-drift between Taddiford Gap and Hordle, approximately 700m to 1.5km down drift respectively (see Figures 5.11 and 5.27).

5.3.3.2 Results

Figure 5.29a and 5.29b illustrate the position and retreat of three 50m wide profiles located up-drift, over and down-drift of the outfall. Between 1872 and 1975, Profiles A, B and C retreated between $71\pm 20\text{m}$ and $80\pm 20\text{m}$. After 1975 the retreat rate at Profiles B and C accelerated. Unlike other studies sites, the greatest retreat occurred over the defences (Profile B), where the cliff set-back is $79\pm 12\text{m}$ (1963-2005).

To examine excess retreat, the retreat from 1932 to 1963 ($0.2\pm 0.6\text{m/yr}$) was extrapolated to 1989 (Figure 5.30) and 2005 (Figure 5.31) and plotted with the observed retreat. Data is plotted every 50m to 650m down-drift until the retreat is minimal. Set-back and excess retreat was not uniform longshore and decreased away from the outfall. In 1989, the average excess retreat is recorded as $18\pm 27\text{m}$ for the 650m coast, indicating no definite excess. However excess retreat does occur up to 150m down-drift, and potentially extends up to 550m down-drift (see Figure 5.30). In 2005, average excess retreat is recorded as $33\pm 29\text{m}$. A summary of results is shown in Table 5.10. Excess retreat occurred with certainty up to 350m down-drift.

5.3.3.3 Discussion

The retreat rate at Becton until 1963 had a comparable magnitude to the retreat rate at Barton, suggesting similar environmental conditions prevailed longshore. The retreat at Becton since 1963 is under the combined influence of Hengistbury Head Long Groyne and the up-drift protection works, particularly those at Barton. Hence it is difficult to deduce how much excess retreat is solely due to the outfall, and how much is due to other anthropogenic causes.

Profile A on Figure 5.29b exhibits lower retreat compared to Profile B and C, as sediment was retained up-drift of the outfall (see Section 5.3.2). The maximum retreat occurred over the outfall (Profile B), rather than down-drift as with all other study sites. The outfall acts only as a partial sediment barrier and the adjacent coast continued to set back after the outfall's construction. This caused outflanking and by 1994 defences were moved landward to retain their effectiveness (Figure 5.32). This created a zone of intense retreat (Brown, 2005) and will be discussed further in Section 6.2 and Figure 6.6. After defence

construction, retreat accelerated down-drift at Profile C. The geology significantly influences retreat as 2 to 3 benches form on the cliff at any one time. These create a wide cliff, and with help of a protective shingle beach, it can take many years for the cliff top to retreat.

Figures 5.30 and 5.31 indicate that the terminal groyne effect migrates down-drift with time. Jezard (2004) concluded protection works had influenced beach volumes up to 750m down-drift. Cliff top results from this thesis suggest that by 2005 excess retreat is recorded as being between 350m and 650m down-drift. A limited length of coast is affected because beach levels are high, the cliff is wide containing 2 to 3 benches and the sand bar offers additional protection. When averaged longshore, there is no excess retreat within the confidence of the data, but clear excess is recorded up to 650m down-drift. Therefore the longshore average excess retreat is only a useful metric when there is parallel retreat down-drift.

Reliable beach profiles are only available from 1989 (from the Channel Coastal Observatory, see Appendix 3) with six profiles spaced at irregular intervals between Becton and Milford. Between 1989 and 2005 beach volume and width (from the cliff base to mean low water spring tide) doubled at a profile located 365m down-drift of the outfall, but the foreshore volume and width remained constant. The cause of this is unknown. Towards Taddiford Gap beach volume and width reduced after 1989 whilst the foreshore volume and width remained constant. This trend continued and was particularly severe at Hordle where beach volumes and widths halved between 1989 and 2005. This is contrary to Bray *et al.*'s (1995) finding that the small foreland at Hordle is accreting. The beach profile data agrees with observational evidence (from 2003 to 2008), as east of Taddiford Gap ex-situ siderite nodules on the beach and the shore platform are frequently exposed. West (2008) reports that siderite nodules have been exposed at Taddiford Gap since 1998, indicating that the coast is in a transition phase from a relatively stable coast to an eroding one. This is also visible on aerial photographs (listed on Table 3.5), as previously vegetated cliffs (indicating a stable shoreline) are now eroding. Offshore sand losses occur at Hordle (Nicholls, 1985; Bray *et al.*, 1995; Carter *et al.*, 2004, see Figure 5.5) but would have minimal effect on cliff erosion.

These changes may not be directly related to the terminal groyne effect. Over the medium term (several decades) the excess retreat from the protection works may merge with the recently induced erosion at Taddiford Gap, giving a false impression of the down-drift extent of the terminal groyne effect. Therefore understanding how, why and what controls coastal erosion and the terminal groyne effect is important.

5.3.3.4 Summary

The Becton outfall was constructed between 1971 and 1972, and together with the up-drift protection works, it created a set-back and excess retreat down-drift. Excess retreat increases cross-shore and longshore with time. In 2005 the terminal groyne effect increased retreat up to 650m longshore, but was limited in growth by a large beach. Approximately 1.5km down-drift, the cliffs are subject to minimal retreat, but since at least 1989 beach volumes and widths have been decreasing.

5.4 Synthesis

5.4.1 Measurement and excess retreat

The terminal groyne effect has been measured by recording the set-back down-drift after defence construction, the excess retreat after defence construction, the percentage increase in retreat rates, and the difference in retreat rates before and after defence construction (see Section 3.9.1) based on the conditions immediately prior to the protection works (see Section 5.3).

The difficulty in assessing if excess retreat has occurred is establishing baseline change, that is, the cliff top position if no defences were constructed. In addition to protection works, Hengistbury Head Long Groyne had an additional impact on the retreat around the bay. The true anthropogenic impact on the sediment levels and retreat is unknown. In this thesis, excess retreat is based on previous environmental and anthropogenic conditions, which may not continue in future. Hence the results in Section 5.3 provide a best estimate. They include a combination of the defences at Hengistbury Head Long Groyne, and protection works immediately up-drift.

A summary of results for the excess retreat is shown in Table 5.11. Excess retreat occurred unequivocally for 2 out of the 6 case studies indicating that retreat rates have accelerated down-drift after defence construction. As time progresses, the terminal groyne effect becomes more apparent providing there are no barriers down-drift limiting the longshore growth. For 4 out of the 6 cases, the average excess retreat cannot be resolved within the confidence of the data. This suggests retreat rates have been maintained or excess retreat is limited longshore. An inspection of the predicted and observed retreat longshore (Figures 5.17, 5.18, 5.23, 5.24, 5.30, 5.31), indicates set-back and excess retreat decreases at greater distances away from the defence. For 3 out of the above 4 cases (the exception being Barton, 1963 to 1989 - Figure 5.23), clear excess retreat occurred, but only within a few hundred metres of the barrier. For these three cases, after a short distance of excess retreat, an area of reduced retreat followed. The reduced retreat is believed to occur because defences down-drift limit longshore drift and cause sediment accumulation, thus protecting the cliff.

With low retreat rates (For example, 0.2 ± 0.6 m/yr at Becton), it is difficult to record cliff top change after defence construction within the confidence of the dataset. Retreat rates can double over a period of several decades, but this can not be resolved as actual cliff top change within the confidence of the data. Therefore, the percentage increase in retreat rate can be misleading.

5.4.2 Evolution of the terminal groyne effect

Prior to the 1950s, defences had minimal measurable effect in reducing cliff top retreat. Set-back between adjacent defended and undefended cliff top positions was minimal. Therefore in Christchurch Bay factors other than a large beach, such as the hydrogeology, water erosion and subaerial weathering make the cliffs susceptible to retreat (Barton, 1973; Barton and Coles, 1984; Tyhurst, 2003). Measurement of the terminal groyne effect ideally requires beach volumes, but these are not available. Since the 1960s more substantial defences have been constructed and 5 out of the 6 case studies have excess retreat, some just for a few hundred metres down-drift. Over longer distances excess retreat cannot be resolved with confidence (see Section 5.4.1 and Table 5.11).

The defences have been modified throughout time allowing the terminal groyne effect to evolve. Where there have been no down-drift constraints to growth, the terminal groyne effect has become more apparent with time. As set-back continued, the ends of the defences have become ineffective and outflanked. Defences were extended or moved landwards (for example, Barton and Becton, see Tables 5.7 and 5.9 respectively and Figures 5.19, 5.26 and 5.32). Moving defences landwards creates an intensified zone of set-back. Extending the rock armouring provides greater protection as waves refract around the barrier. Hence extending and moving rock armouring alters set-back and the terminal groyne effect. This impact is recorded on the cliff top, particularly when it is left as an abandoned cliff (see Section 2.2.4).

With continued or increased set-back the defences form artificial headlands. Where defences are present either side of an undefended coast, an embayment forms. Silvester (1960) reports that between headlands, the retreat rate should reduce due to sediment retention allowing the bay to form into a stable platform. At Highcliffe retreat is reduced over time, but this is partly obscured by data uncertainties. However down-drift of Barton, retreat rates have increased with time, as the Becton outfall is only a partial sediment barrier.

5.4.3 Longshore extent of the terminal groyne effect

Table 5.11 indicates the longshore extent of the terminal groyne effect at each study site. The longshore influence of the terminal groyne effect is defined as the zone at which the observed set-back exceeds the predicted retreat. Determining this is difficult as shorelines with low retreat rates (<0.5m/yr) erode less (even over several decades) than the error of the measurement ($\pm 10\text{m}$ or $\pm 2\text{m}$, see Sections 3.5 and 5.4.1).

At the three study sites, set-back and excess retreat decreases down-drift. At Highcliffe and Barton this is due to defences (at Barton and Becton respectively) blocking sediment transport. As sediment accumulates excess retreat reduces and an embayment forms. Hence over longer periods of time, the length of longshore coast affected by the terminal groyne effect can potentially be reduced. The effect of the Barton defences probably propagates further than the Becton outfall. It has not been possible to determine what excess is due to the outfall and what is due to the Barton defences. At Becton, the longshore

extent of the terminal groyne effect on the cliff top migrates down-drift with time. The migration is slower than other sites due to lower longshore transport rates, beach recovery and increasing cliff width. If longshore drift and the terminal groyne effect is not constrained down-drift by defences or high beach levels, excess retreat increases longshore throughout time.

A study of beach profiles would be beneficial to determine the longshore extent of the terminal groyne effect but these are not available for comparison before and after defence construction. If available, they could potentially reduce ambiguity. An analysis of beach volumes from 1989 to 2005 down-drift of Becton was inconclusive. The longshore extent is also influenced by onshore and offshore sediment movement (see Figure 5.5), such as at Hordle, but this probably has minimal effect on cliff top retreat.

5.4.4 Other factors

The terminal groyne effect is affected by many factors other than the defences. Although a change may not be recorded on the cliff top, sediment levels may have reduced and are not uniform around the bay. However, a decline in beach volume may not result in increased erosion because as long as the cliff base remains protected, the cliff top is subject only to the slower processes of subaerial weathering and slope degradation. Therefore defences do not stop retreat, as seen at the numerous small landslides in protected areas, such as at Barton-on-Sea (Reina, 1975; Clark *et al.*, 1976; Fort *et al.*, 2000), and others listed in Section 2.2.4. Hence erosion of the cliff top represents changes due to processes affecting the cliff, beach and shore platform.

In common with Holderness, cliff, beach and nearshore mining has been a common cause of artificially high retreat rates. Mining has had an adverse affect on retreat by lowering Christchurch Ledge, the shore platform and beach levels within the bay, making the coast more susceptible to storm waves and erosion (see Section 5.2.2). Mining has also reduced retreat by releasing sediment during mining at Hengistbury Head, creating artificially high beach levels around the bay (Lacey, 1985; Nicholls, 1985). Artificially high beach levels were also created through replenishment schemes, such as at Highcliffe (see Section 5.2.2 and Table 5.5). Although successful in increasing beach

levels within the groyne compartments, it is unclear how this has affected erosion rates and the terminal groyne effect down-drift.

The geology, sediment input, longshore drift rate (and the effectiveness of defences to reduce this), bathymetry and exposure all vary around the bay (see Figures 5.2, 5.3, 5.5, 5.7 and 5.8, and Section 5.2.1). With a lower drift rate, increased sediment input, harder geology and lower exposure, set-back and the terminal groyne effect would be reduced in cross-shore and longshore directions. Field observations suggest that geology and the presence of benches down-drift of Becton have a greater importance in determining the magnitude of retreat and morphology than the Becton outfall. However in this chapter, these relationships have not been proved or investigated in detail as many factors other than the defences influence down-drift erosion and the terminal groyne effect.

5.5 Conclusions

Retreat rates around Christchurch Bay average 0.5 ± 0.1 m/yr (1872 to 2005) and have been influenced by man since at least the middle of the 19th century through mining and protection works. The following conclusions have been drawn:

- 1) Constructing defences resulted in set-back of the adjacent coast. Set-back is greater on the down drift coast compared to the up drift coast. An embayment forms down drift.
- 2) Within each study site variable behaviour is observed down drift. Excess retreat occurred, frequently for only a few hundred meters. Providing there was no growth constraints down-drift, set-back and excess retreat increased with time, making the terminal groyne effect more apparent.
- 3) Set-back and the terminal groyne effect is complicated by and constrained by defences or a large beach down drift. The defences act as headlands and block sediment transport enlarging the beach and reducing retreat.
- 4) In Christchurch Bay, map errors and set-back were often of similar magnitude. Determining excess retreat is limited by the confidence of the data. With DGPS surveys, uncertainty levels are reduced.

- 5) The terminal groyne effect is complicated by mining around Christchurch Bay as it is not possible to determine retreat rates free from human interference. Retreat rates were reduced by sediment release at Hengistbury Head. Retreat rate also increased due to increased wave attack due to shore platform and beach lowering throughout the bay.
- 6) Factors other than defences affect the cross-shore and longshore extent of the terminal groyne effect. This includes the beach, the shore platform, sediment transport, exposure, frequency of wave attack, geology and other defences.
- 7) The cliff top can take many years to respond to defence construction and a reduction in longshore drift. Measurement of beach volumes (when and where available) may provide a great insight.
- 8) The percentage increase in retreat rate is not a good measure of the terminal groyne effect as it can be misleading. Excess retreat and retreat rates are a useful comparison, but are limited by data uncertainties. Measuring set-back provides the best metric for recording change.
- 9) With continued set-back, defences are outflanked. Extending defences creates a record of set-back on the cliff top. Upgrading and extending defences allows the terminal groyne effect to evolve.
- 10) Crenulate shaped bays form between headlands leading to reduced retreat. Defence maintenance upgrading and extensions are essential to retain artificial headlands and reduce defence outflanking.



Figure 5.1 – Christchurch Bay. The study region runs for 10.6km from Mudeford to Milford-on-Sea. The defended localities within the study region are shown in bold.

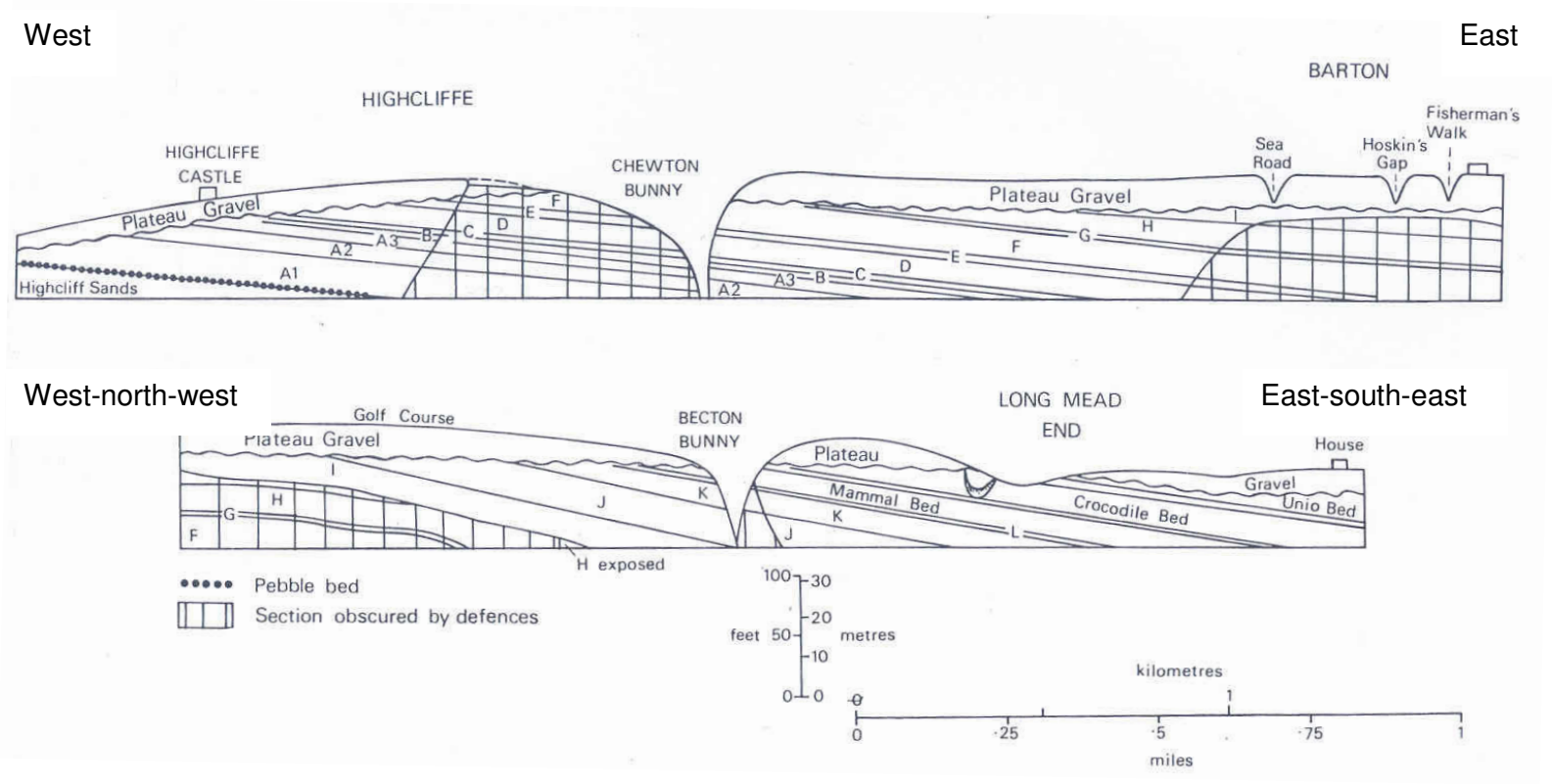


Figure 5.2 – Geology of part of Christchurch Bay (Melville and Freshney, 1982). For details, see Figure 5.3.

		metres		
Lower Headon Beds, or Hordle Member	Rodent Bed	1.5	Pale brownish marl. <i>Lymnaea</i> , <i>Theridomys</i>	
	Unio Beds	5.2	Laminated pale and dark grey clays with sandy layers. <i>Unio solandri</i> , <i>Viviparus lentus</i> , seeds of water plants	
		5.5	Pale blue and green clays with seams of lignite, thin limestone near base	
	Chara Beds	1.2	Laminated sandy clays with pockets of <i>Chara</i> nucules	
	Crocodile Beds	3.7	Brown sand with white sil; at top. <i>Erodona gregarea</i> , <i>Potamides vagus</i> , fish scales, remains of crocodiles, turtles and mammals.	
	Leaf Bed	0.9	Purple sands and laminated clay with pockets of leaves and seeds.	
	Mammal Bed and basal clays	5.2	Pale green clays, layers of white sand with <i>Viviparus lentus</i> . Mammals rare, Ironstone nodules in basal clays.	
Upper Barton Beds, or Becton Member	L	1.2	Black clays, crushed shells	
	K Long Mead End Bed	6.0	Pale sands with brackish-water shells at top. <i>Batillaria concava</i> , <i>Bayania fasciata</i> , <i>Corbicula</i>	
	J Becton Bunny Bed	8.0	Grey-brown clays with both marine (<i>Olivella</i> , <i>Pollia</i> , <i>Nucula</i> , <i>Pitar</i>) and estuarine shells (<i>Potamides</i> , <i>Corbicula</i> , <i>Bayania</i>). <i>Callianassa</i> in soft concretions	
	I	8.0	Sands, unfossiliferous	
	H Chama Beds	5.5	Sandy clays. <i>Chama squamosa</i> , <i>Crassatella tenuisulcata</i> , <i>Glycymeris delata</i> , <i>Cardita oblonga</i> , <i>Conorbis dormitor</i> , <i>Hemiconus scabriculus</i> , <i>Pollia lavata</i>	
Middle Barton Beds, or Naish Member	G Stone Band	0.3	Limestone made of comminuted shells. <i>Turritella</i> , <i>Tellina</i>	
	F	6.0	Brownish grey clay. <i>Turritella</i> , <i>Corbula</i>	
	E Earthy Bed	1.5	Glauconitic sandy clays, septaria at top. Large shells (see text)	
	D	6.0	Glauconitic clays	
	C	1.8	Glauconitic sandy clay, septaria at top and bottom. <i>Athleta suspensus</i> , <i>Clavilithes longaevus</i> , <i>Callista belgica</i>	
	B	1.2	Grey clays. <i>Pholadomya</i>	
	Lower Barton Beds, or Highcliff Member	A3 Highcliff Sands	3.0	Stiff grey clay with beds of grey sand. <i>Scolecis ambigua</i> , <i>Bartonie canaliculata</i> , <i>Dientomochilus bartonensis</i>
		A2	4.0	Glauconitic clays. <i>Turricula lanceolata</i> , <i>Athleta athleta</i> , <i>Nummulites rectus</i> , otoliths, sharks teeth.
		A1	6.0	Glauconitic sandy clays. <i>Nummulites prestwichianus</i> at base
			3.0	Clay Bed of flint pebbles

Figure 5.3 – Stratigraphy of the Barton Formation (Melville and Freshney, 1982). For geographical locations, see Figure 5.2.

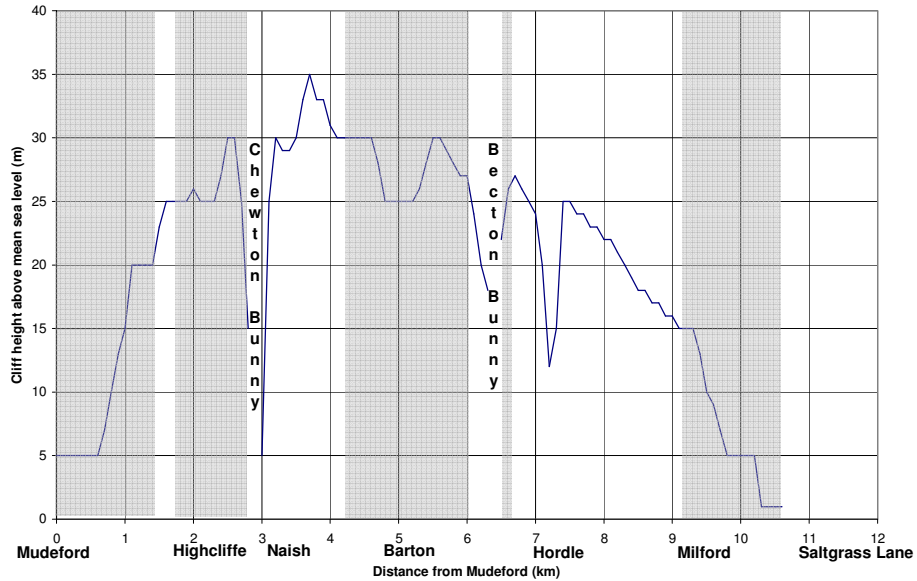


Figure 5.4 - Cliff height from Mudeford to Saltgrass Lane relative to mean sea level. Data extracted from Ordnance Survey (2002) to $\pm 2m$. The maximum cliff height occurs at Naish, and diminishes to the extremities of the study region. The grey areas indicate the location of defences in 2005.

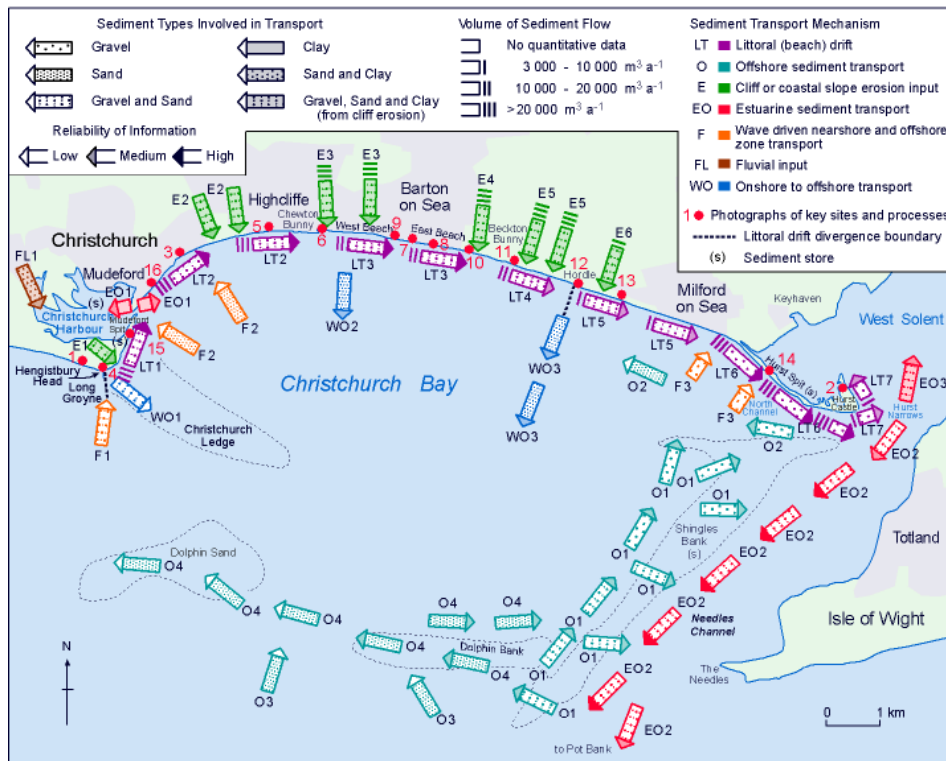


Figure 5.5 – Sediment pathways in Christchurch Bay (Carter et al., 2004). Predominant sediment circulated is clockwise. Sediment is lost offshore or deposited on the Shingles Bank, Dolphin Bank or Dolphin Sand.

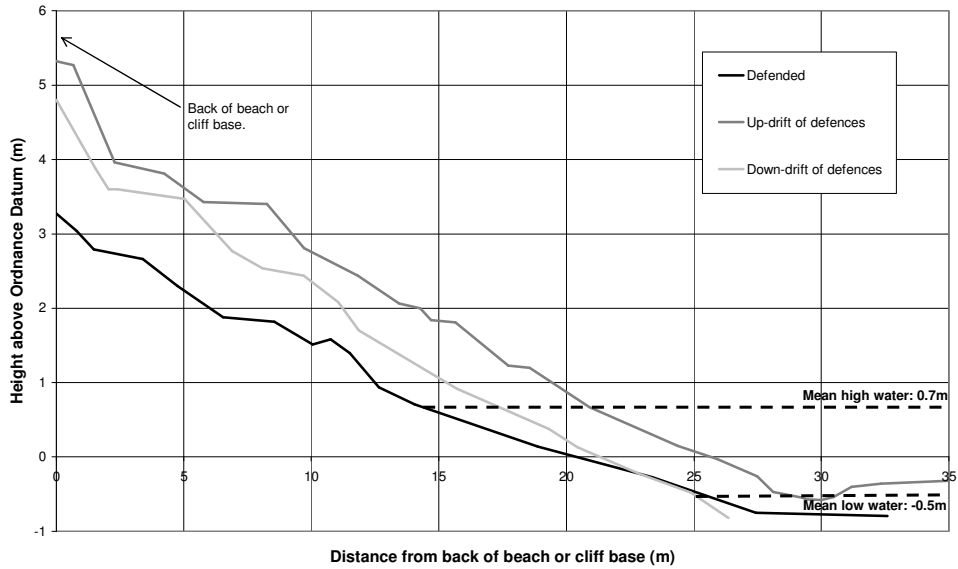


Figure 5.6 – Beach profiles at the centre of Christchurch Bay, approximately 150m up-drift and down-drift of the Barton defences and within the defences. Mean high and low water is shown for Barton. Beach surveyed March to September 2005 (available from the Channel Coastal Observatory, see Appendix 3).

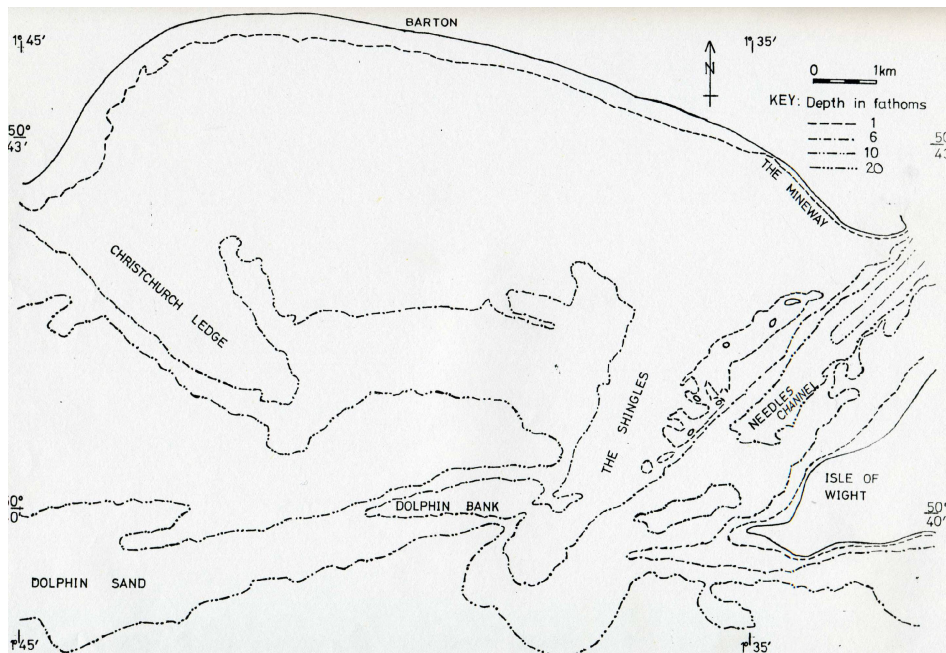


Figure 5.7 – The bathymetry of Christchurch Bay (Lacey, 1985). Christchurch Ledge helps protect the bay from large south-westerly waves.

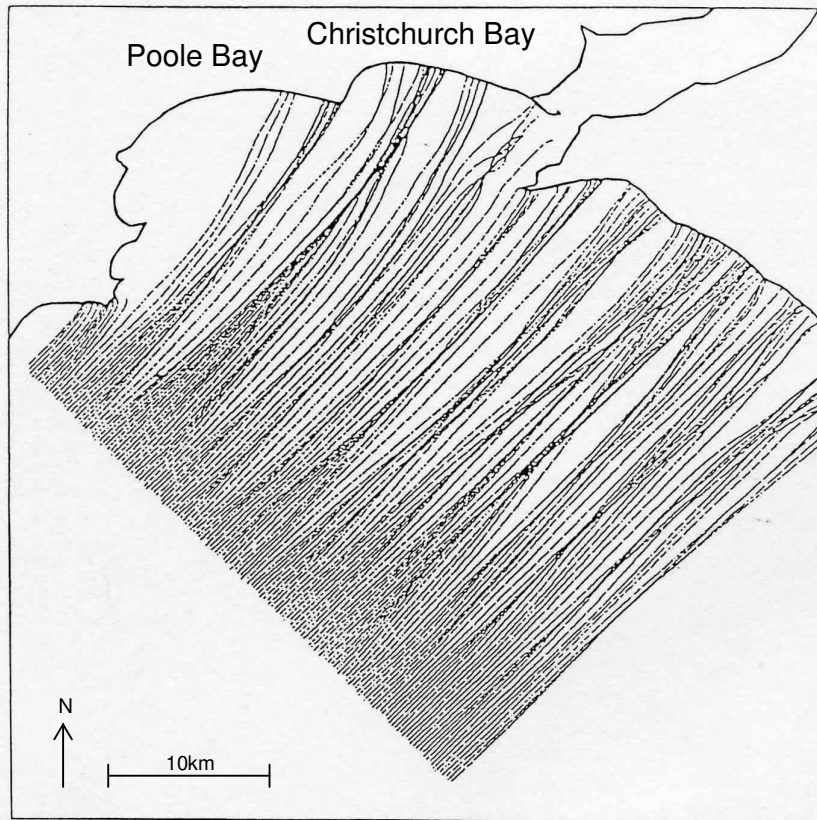


Figure 5.8 – Wave refraction around Christchurch Bay. Refraction curves (from model data) showing the wave track are from the south-west, with a wave period of 9s (Henderson and Webber, 1979). Note that Christchurch Bay is more exposed than neighbouring Poole Bay.

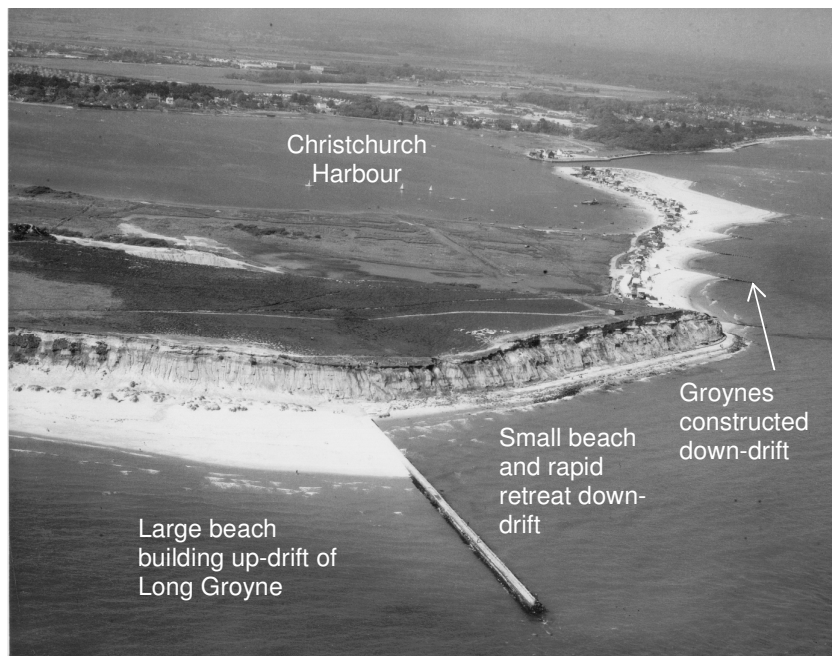


Figure 5.9 – Hengistbury Head Long Groyne looking towards Christchurch Harbour in 1955. Sediment movement is inhibited up-drift of the groyne, creating a wide beach. Due to rapid erosion, additional groynes were constructed down-drift to hold shoreline position. Photograph taken by Messrs. Aerofilms, now Messrs Simmons Aerofilms.

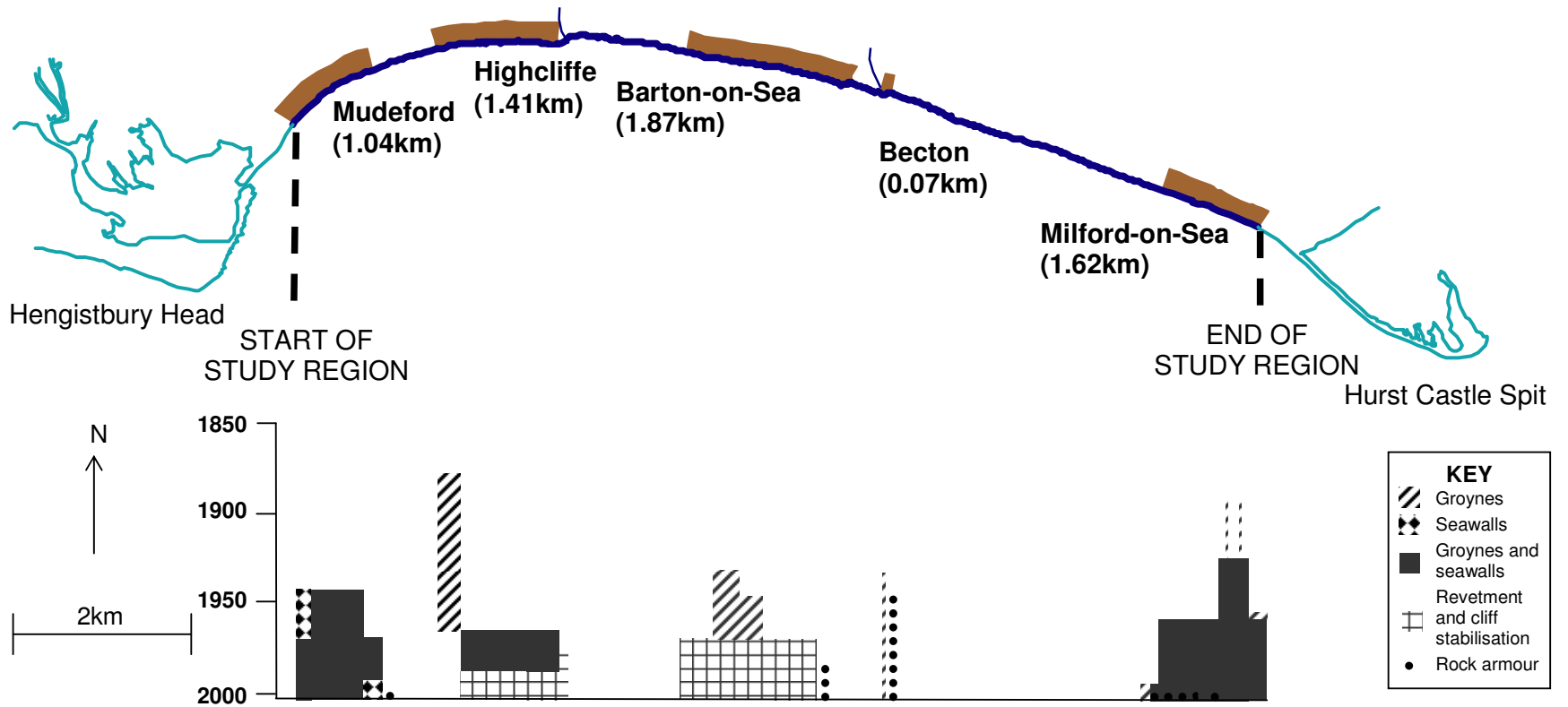


Figure 5.10 – Defences at Christchurch Bay (Mundeford to Milford-on-Sea). The defended sections are shown in bold with the length of defences in brackets. The bar chart indicates defence type over time. The revetment and cliff stabilisation includes groynes and rock armour.

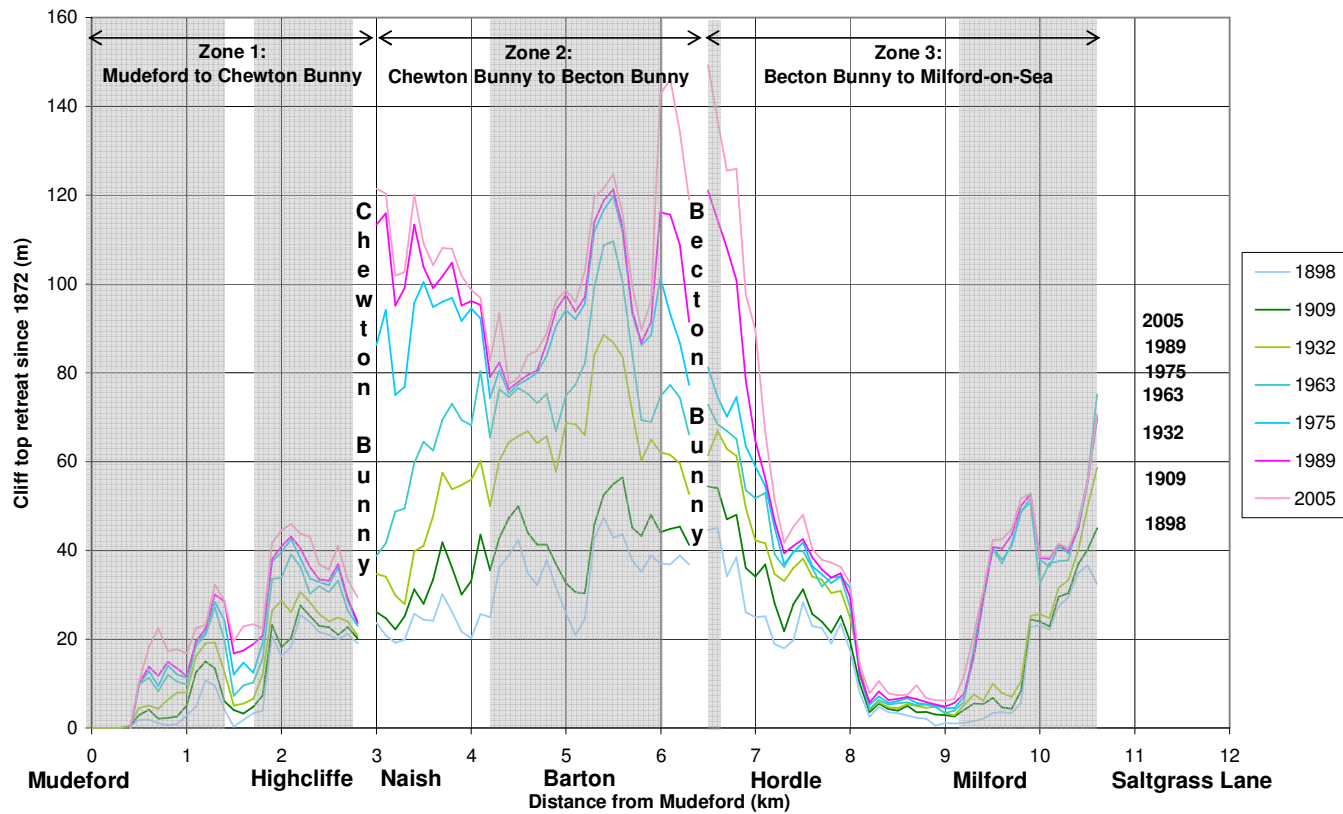


Figure 5.11 – Cliff top retreat at Christchurch Bay from 1872 to 2005 using all survey years. For origin of data, see Section 3.7.1 and Table 3.5. Zone 2 has retreated by the greatest distance since 1872, and retreat has slowed due to defences, particularly after 1963.

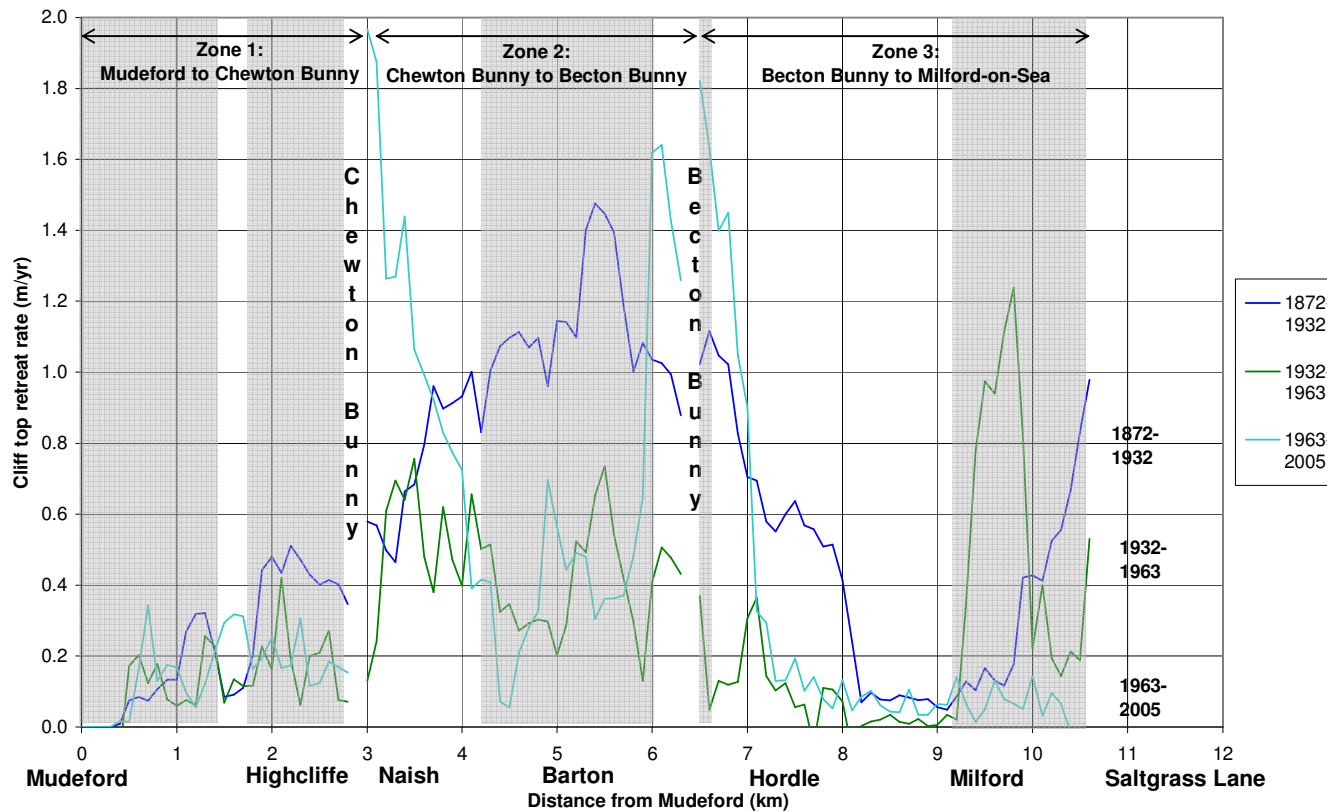


Figure 5.12 – Cliff top retreat rates at Christchurch Bay using multi-decadal time periods based on human intervention on the coast. The data is derived from Figure 5.11. Table 5.3 displays a summary of these rates. Areas defended are shown in grey. Retreat rates have varied due to mining, defence construction and changes in longshore drift.

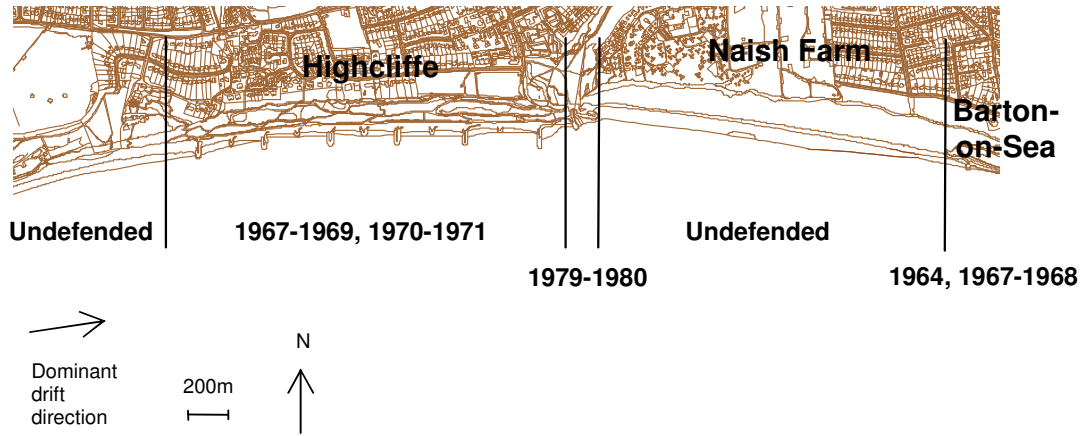


Figure 5.13 – Defence construction at Highcliffe. Dates relate to defence extensions between adjacent parallel lines. Ongoing maintenance works since the 1970s include the conversion of timber to rock groynes. See Table 5.5 for further details.

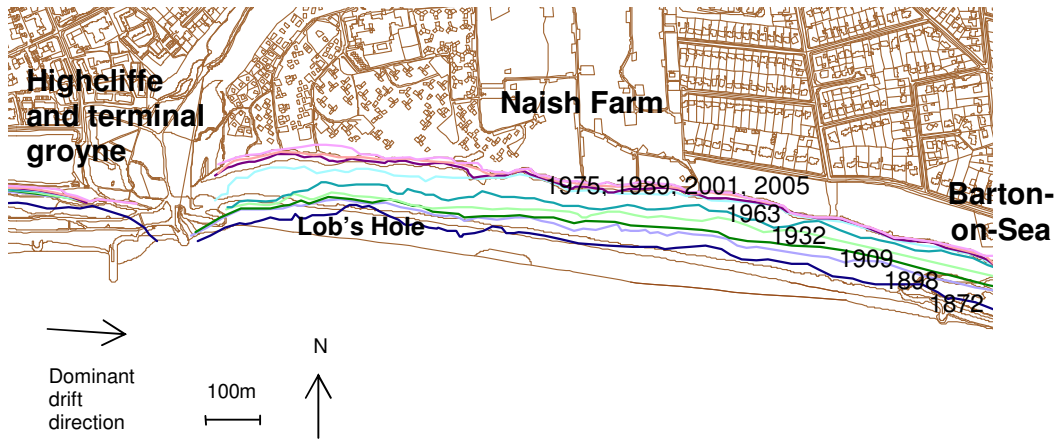


Figure 5.14 – Cliff top positions from 1872 to 2005 at Highcliffe. Set-back is reduced down-drift towards Barton-on-Sea due to its defences (constructed after 1967).



Figure 5.15 – Down-drift of the Highcliffe defences. The Chewton Bunny bastion acts as the terminal groyne with the cliff set back down-drift. Longshore drift is eastwards, into the photograph (photograph taken 26th December 2007).

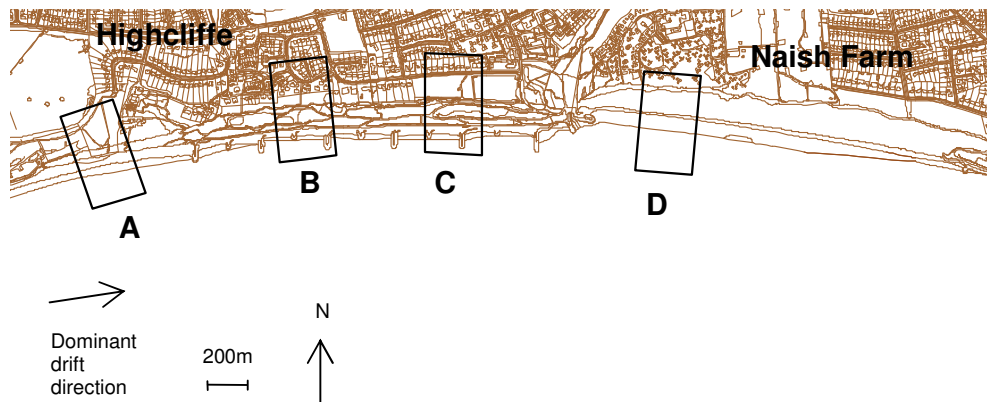


Figure 5.16a – Position of average retreat profiles at Highcliffe. Profiles are 200m wide, with Profiles A and D located 200m up and down-drift of the defences and Profiles B and C situated over the 1967-1969 and 1970-1971 defences.

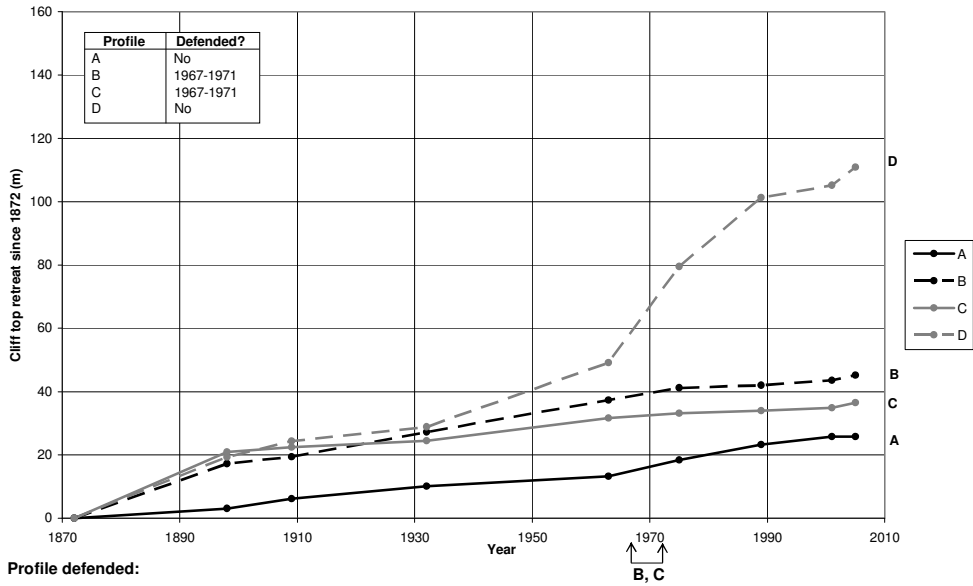


Figure 5.16b – Retreat profiles at Highcliffe. For profile location, see Figure 5.16a. The undefended down-drift coast (Profile D) shows the greatest retreat since 1963, whilst cliff retreat is greatly reduced for the defended profiles.

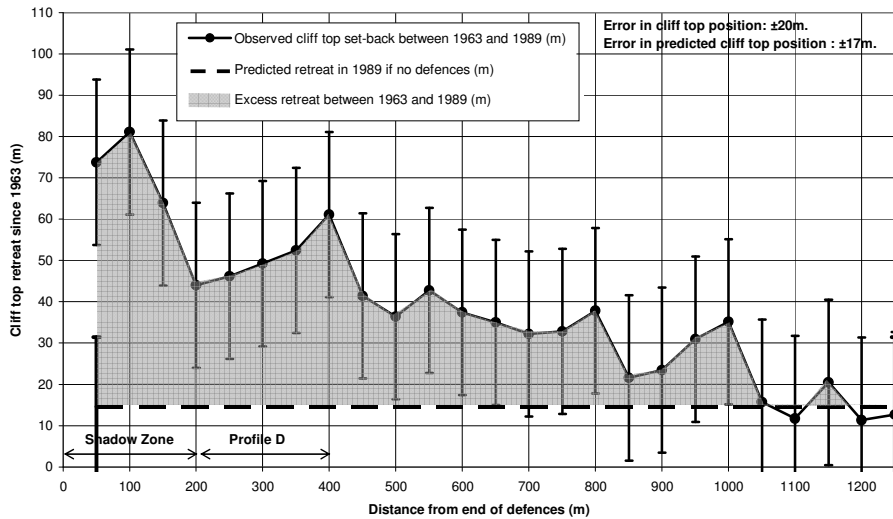


Figure 5.17 – Predicted and observed retreat down-drift of Highcliffe from 1963 to 1989. West Barton is to the right of the figure. Retreat rates increased down-drift after defence construction, with at least 200m of longshore coast having excess retreat.

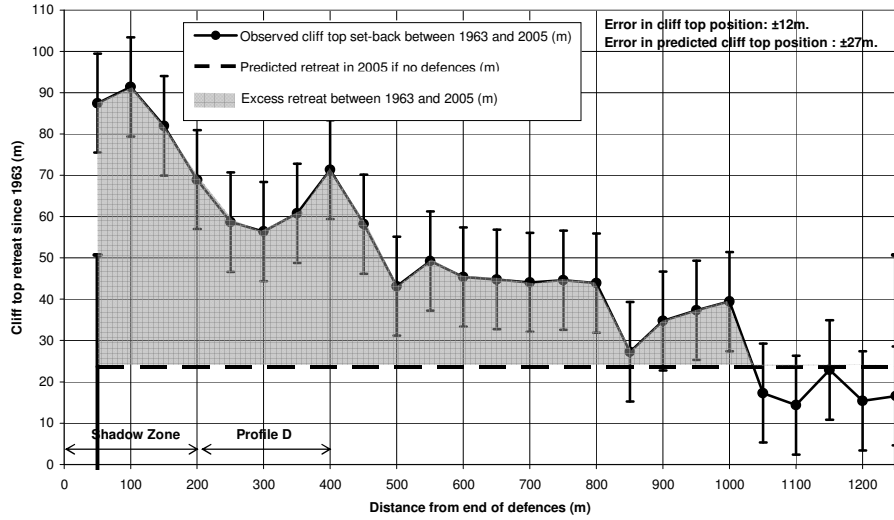


Figure 5.18 – Predicted and observed retreat down-drift of Highcliffe from 1963 to 2005. West Barton is to the right of the figure. The retreat rate decreases down-drift with the Highcliffe and Barton defences being jointly responsible for changes in the retreat rate after defence construction.

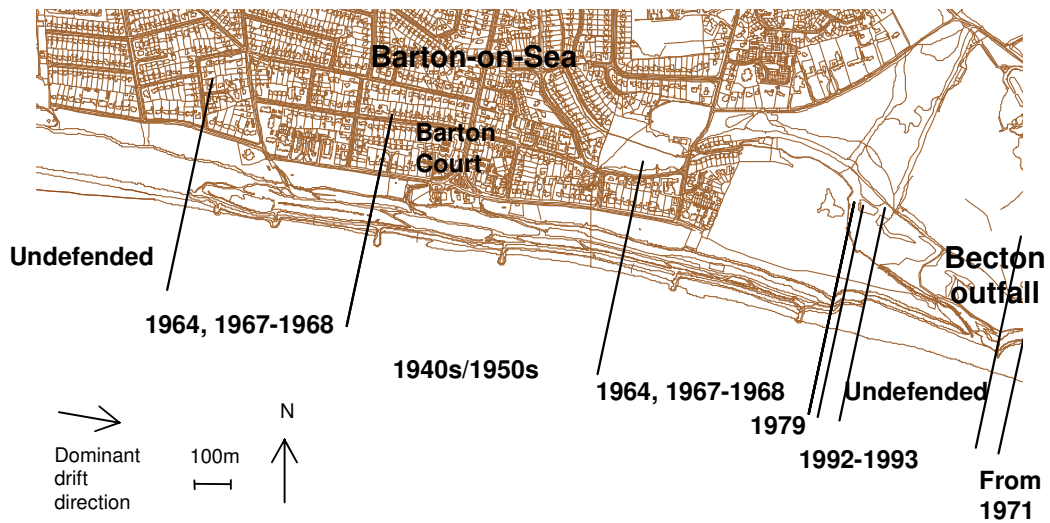


Figure 5.19 – Defence construction at Barton-on-Sea. Dates relate to defence extensions between adjacent parallel lines. Defences were up-graded from wooden to rock groynes, and rock armour toe protection added. Undefended shoreline down-drift of Barton-on-Sea constrained by the Becton outfall, constructed between 1971 and 1972. See Table 5.7 for further details.

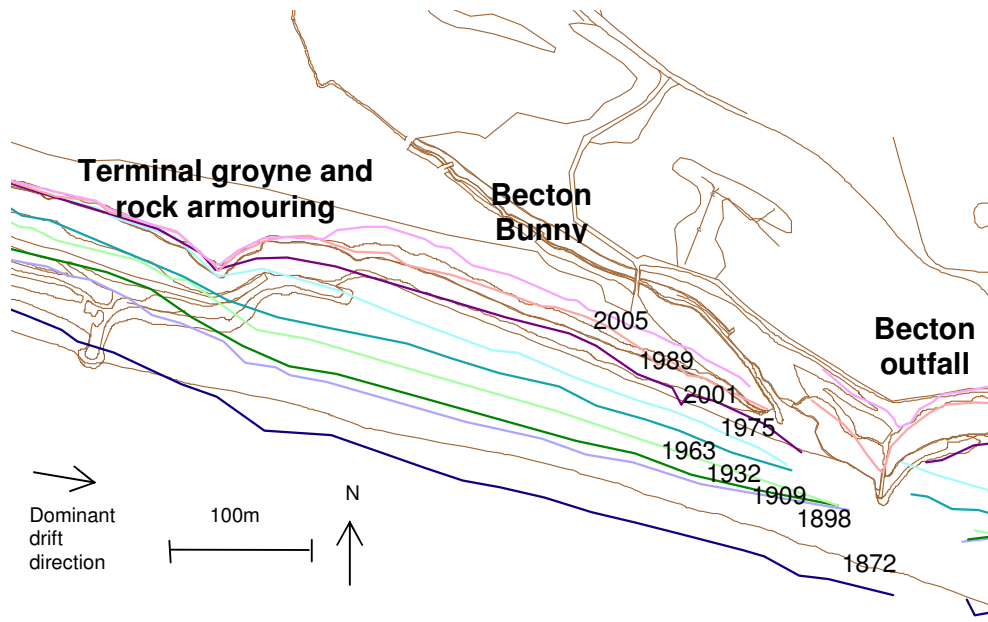


Figure 5.20 – Cliff top positions from 1872 to 2005 at Barton-on-Sea. The terminal rock groyne was completed in 1979 and armouring extended in 1992-1993. The outfall at Becton Bunny is situated approximately 300m down-drift of the rock armouring.

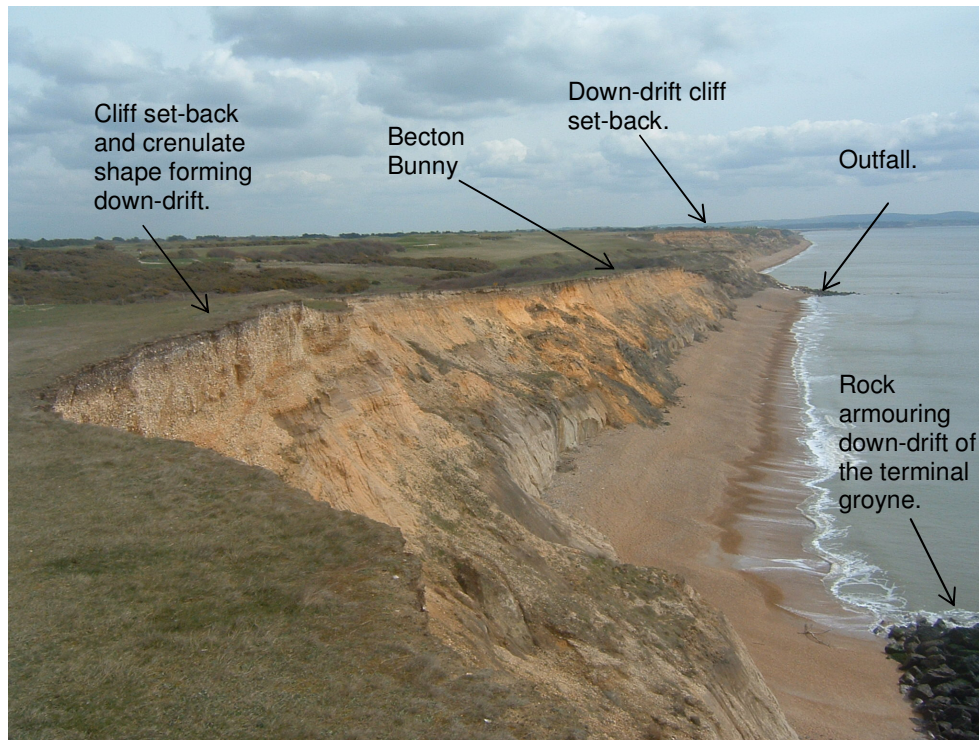


Figure 5.21 – A crenulate shaped embayment forming down-drift of Barton-on-Sea. Photograph taken 4th April 2006.

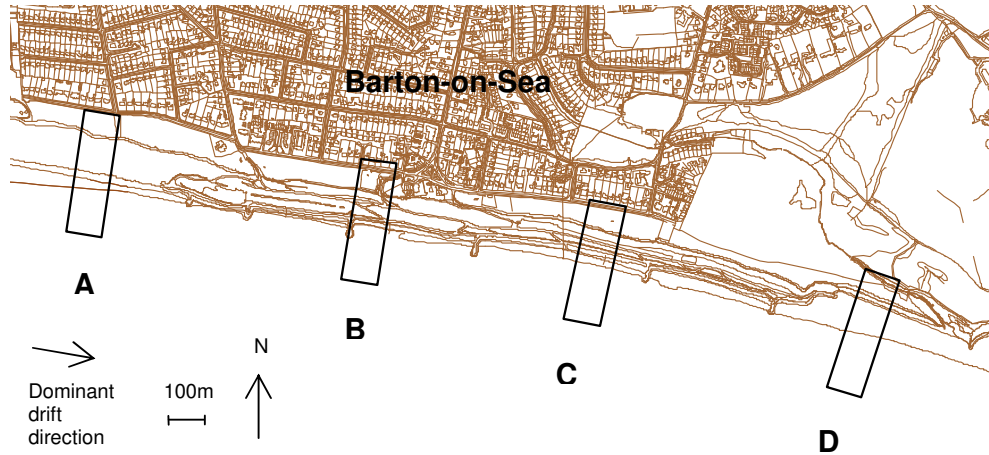


Figure 5.22a – Position of average retreat profiles at Barton-on-Sea. Profiles are 100m wide, with A and D located 150m up and down-drift. As the early defences do not create a terminal groyne effect, Profiles B and C are situated over the 1964 to 1967-1968 defences.

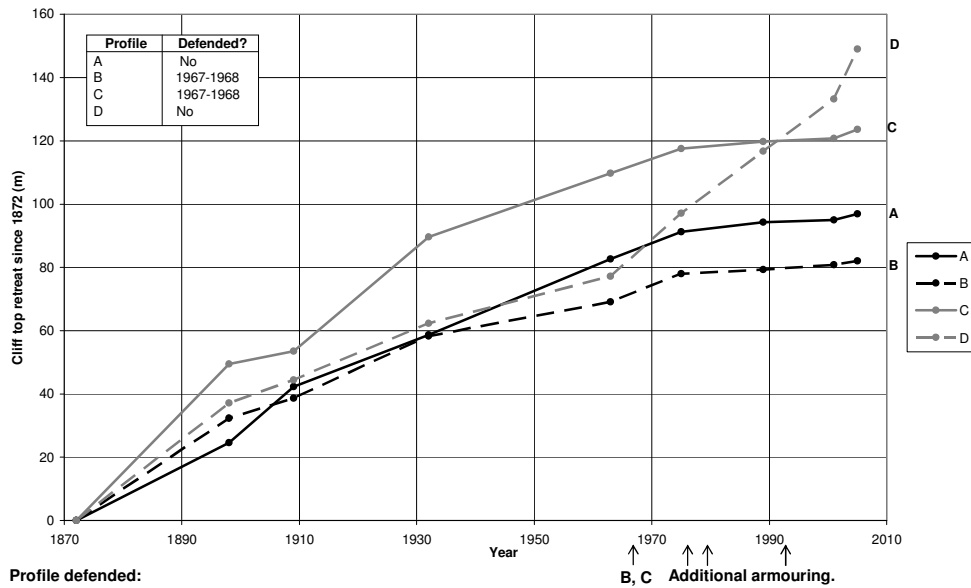


Figure 5.22b – Retreat profiles at Barton-on-Sea. For profile location, see Figure 5.22a. Profiles A, B and D have a similar retreat until 1963 and the construction of defences. It is unclear why Profile C is higher prior to 1963. Since 1963, retreat rates have increased down-drift of the defences.

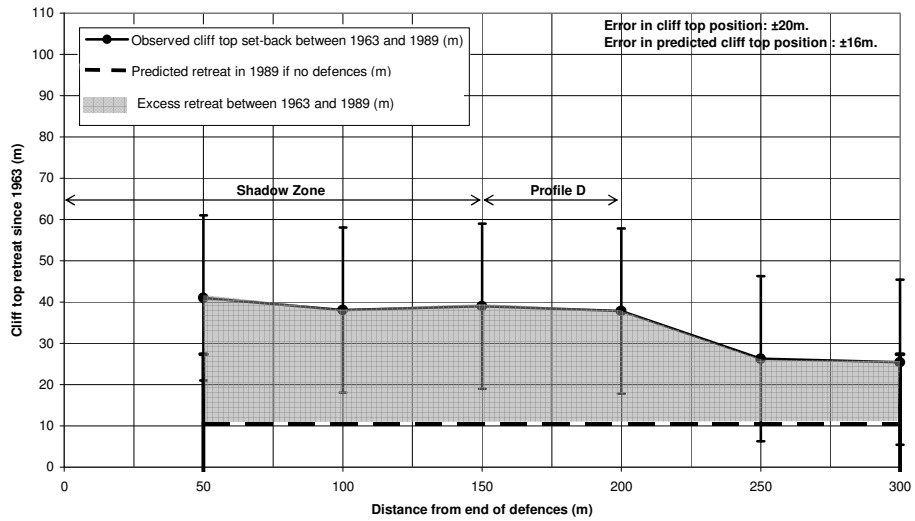


Figure 5.23 – Predicted and observed retreat down-drift of Barton from 1963 to 1989. Sediment is retained by the outfall creating $21 \pm 27\text{m}$ of excess retreat.

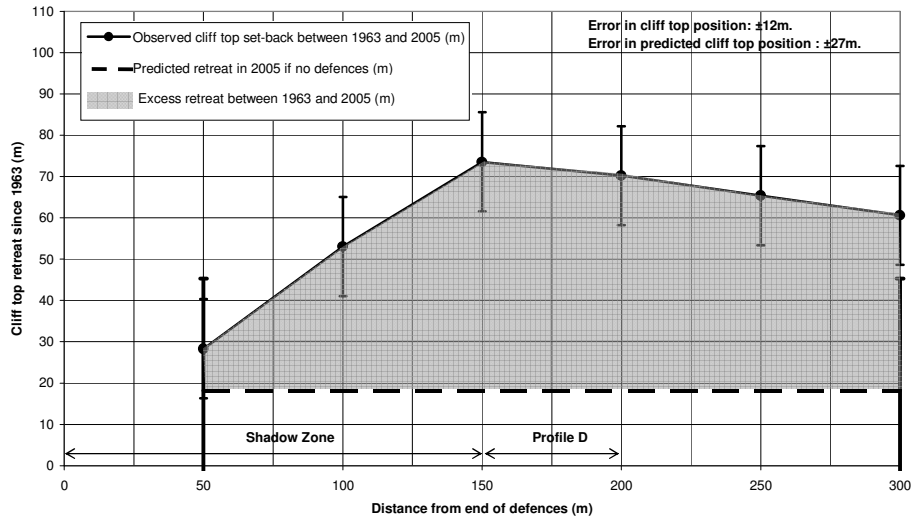


Figure 5.24 – Predicted and observed retreat down-drift of Barton from 1963 to 2005. Excess retreat is greater than in 1989 at $41 \pm 29\text{m}$, indicating there has been a definite increase in retreat rate once potential errors are accounted for.



Figure 5.25 – Wave attack on the cliff base behind the rock armouring at Barton-on-Sea. The armouring was originally placed against the cliff base to protect it from erosion. The cliff continued to erode and in 2005 there was a distance of 22m between the cliff base and the armouring as it became outflanked. Photograph taken 31st March 2006.

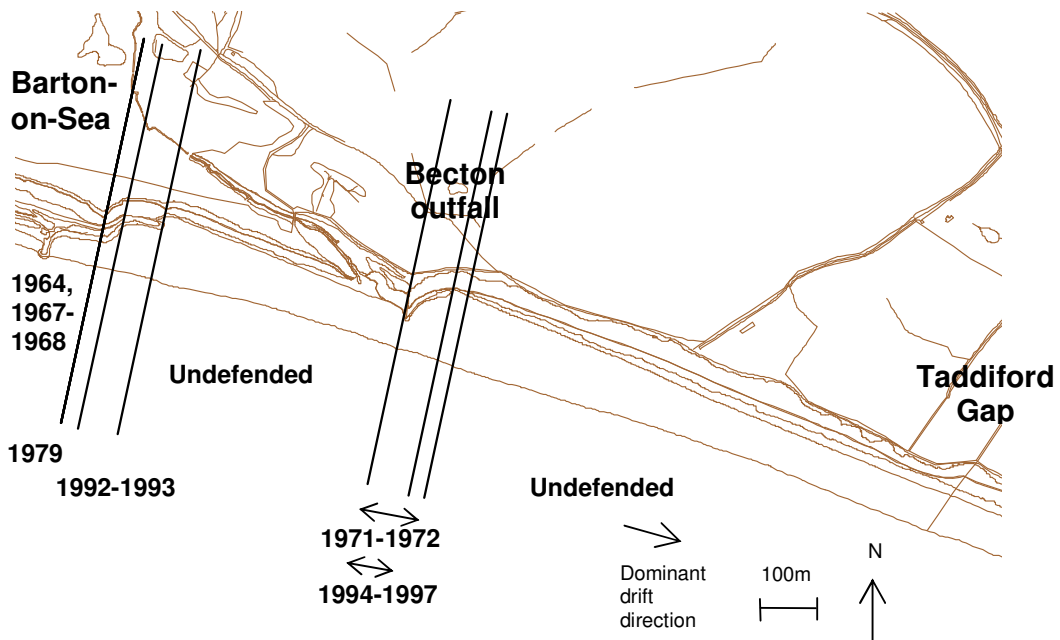


Figure 5.26 – Defence construction at Becton. Dates relate to defence extensions between adjacent parallel lines. The rock armouring surrounding the outfall reduced in longshore length between 1994-1997 (see Table 5.9 for further details). The shoreline is undefended for 2.8km down-drift to the Milford-on-Sea defences.

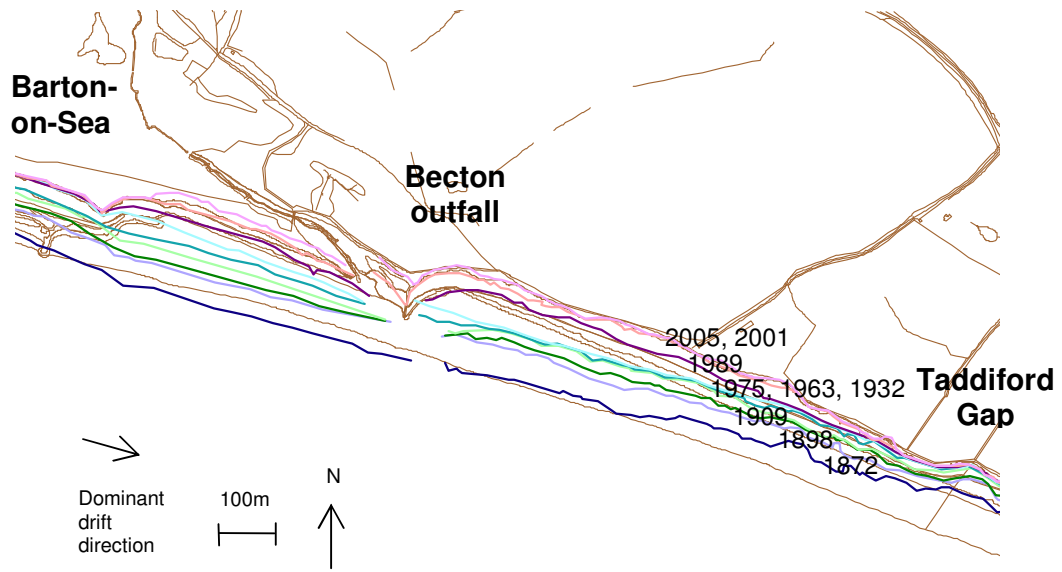


Figure 5.27 – Cliff top positions from 1872 to 2005 at Becton.

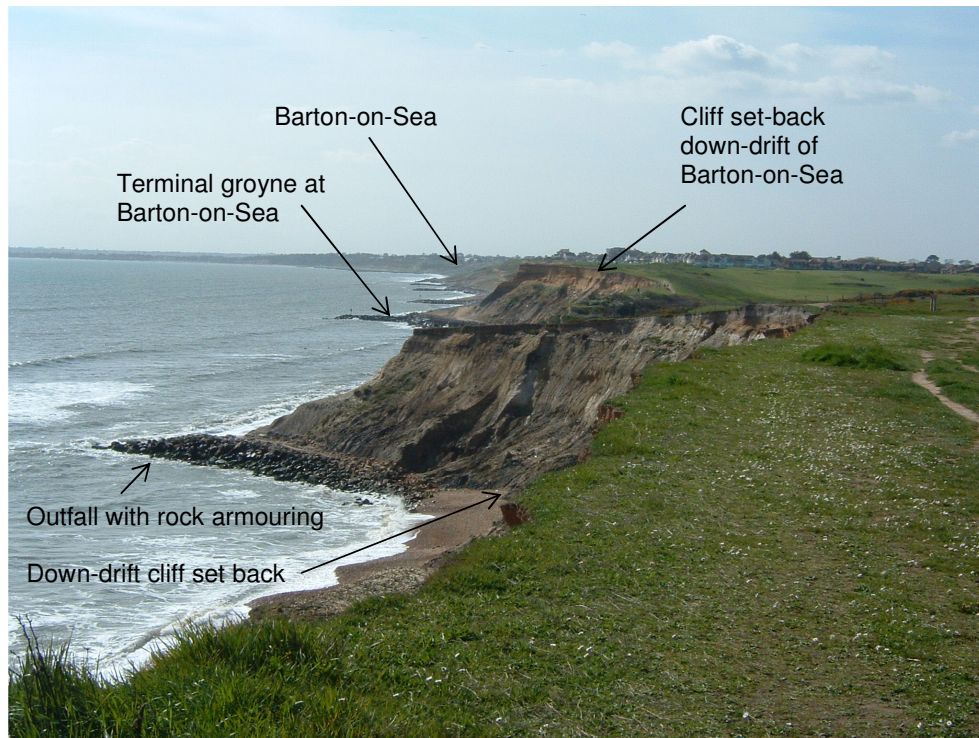


Figure 5.28 – The Becton outfall and subsequent shoreline set-back. Barton-on-Sea can be seen in the distance. Photograph taken 23rd April 2004.

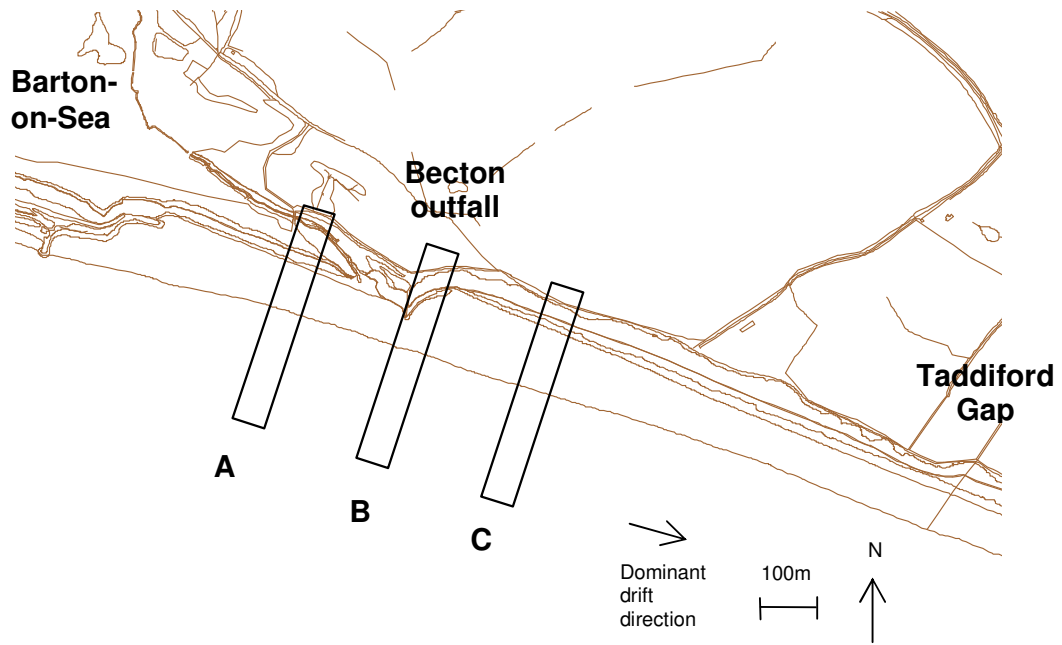


Figure 5.29a - Position of average retreat profiles at Becton. Profiles are 50m wide, spaced 150m apart, with Profile B situated on the defence.

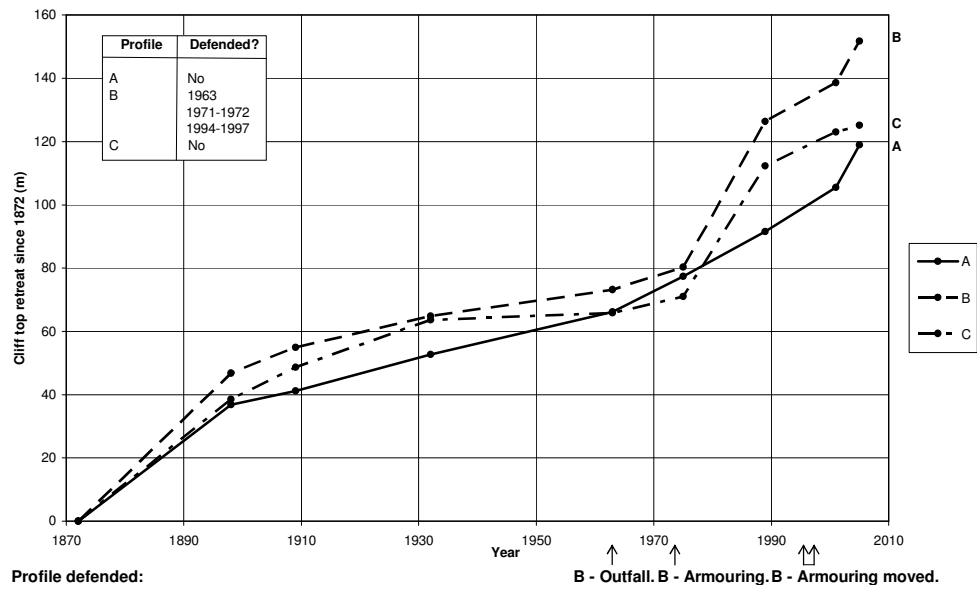


Figure 5.29b - Retreat profiles at Becton. For profile location, see Figure 5.29a. Profile B retreated greater than Profiles A and C due to the landward movement of armouring (see Table 5.9) and beach recovery.

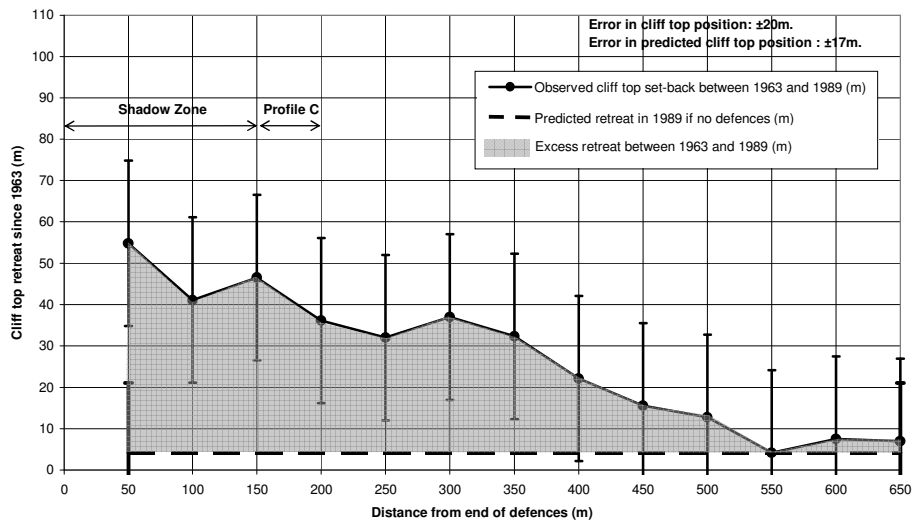


Figure 5.30 – Predicted and observed retreat down-drift of Becton from 1963 to 1989. An increase in observed retreat rate is particularly noticeable up to 150m down-drift.

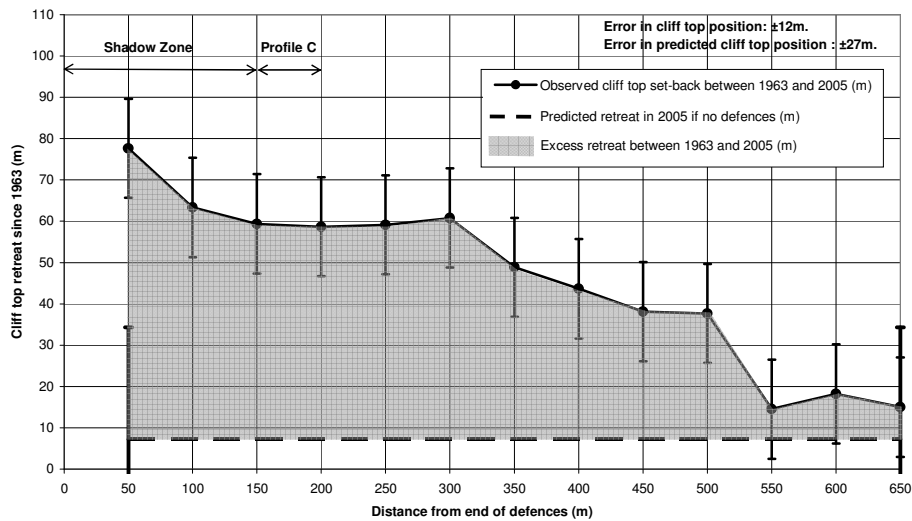


Figure 5.31 – Predicted and observed retreat down-drift of Becton from 1963 to 2005. Compared to Figure 5.30, the excess retreat has increased in both cross shore and longshore directions. Average excess retreat is 33 ± 29 m, indicating that retreat rates have increased down-drift.

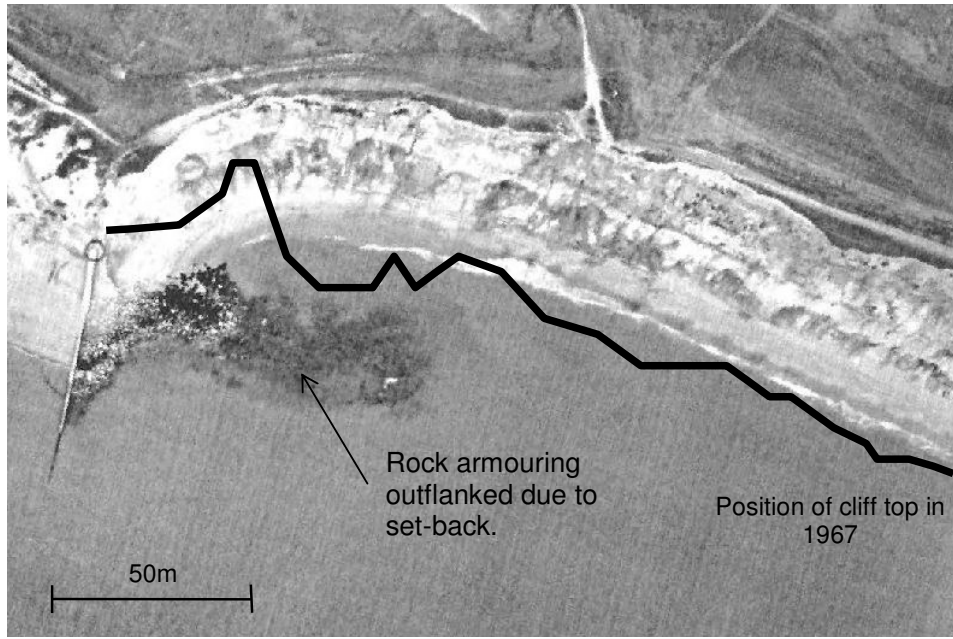


Figure 5.32 – Outflanking around the outfall and the rock armouring at Becton in 1993. The solid black line indicates the cliff top position in 1967. Photograph taken 14th August 1993 (Available from New Forest District Council, see Table 3.5).

Table 5.1 – The length and percentage of defended coastline from Mundeford to Milford-on-Sea from 1872 to 2005 as reported on 1:10,560 or 10,000 OS maps (see Table 3.5). Total length of study region is 10.6km. The distribution of defences is illustrated in Figure 5.10.

Year		1872	1898	1909	1932	1963	1975	1989	2005
Length	km	0	0.02	0.02	0.4	2.9	5.36	5.98	6.01
Percentage	%	0	0.2	0.2	3.8	27.4	50.6	56.4	56.7

Table 5.2 – Description of works at Hengistbury Head (Burton, 1931; Robinson, 1955; Wise, 1963; Stopher and Wise, 1966; Lavender, 1985; Tyhurst, 1985; Powell, 1995).

Year	Description of works
1848	Hengistbury Head Mining Company formed. Around this date mining commenced on the headland, beach and offshore.
1856	Mining of ironstone below high water ceased.
1870	Mining of ironstone on beach and headland ceased.
Around 1938	Hengistbury Head Long Groyne (200m long) constructed.

Table 5.3 – Retreat rates around Christchurch Bay. The data was derived from Figures 5.11 and 5.12. *Greater distance than each zone as width of bunnies also included. Map errors indicate extreme values. All results shown to 1dp.

Locations	Distance km	1872-1932 m/yr	1932-1963 m/yr	1963-2005 m/yr	1872-2005 m/yr
Mundeford to Chewton Bunny	2.9	0.2	0.1	0.2	0.2
Chewton Bunny to Becton Bunny	3.4	1.0	0.5	0.8	0.8
Becton Bunny to Milford	4.2	0.4	0.2	0.3	0.3
Entire coastline					
Mundeford to Milford	10.8*	0.5	0.3	0.6	0.5
Retreat rate errors		±0.3	±0.6	±0.3	±0.1
Retreat rate standard deviation Mundeford to Milford		±0.4	±0.2	±0.5	±0.2

Table 5.4 – Growth and breach of Christchurch Harbour's southern spit. Highcliffe Castle is located approximately 500m to the east of Steamer Lodge and 1km west of Chewton Bunny (Compiled from data sources listed in Table 3.5 and Burton, 1931; Robinson, 1955; Wise, 1963; Lavender, 1985; Tyhurst, 1985; Powell, 1995).

Year breached	Spit extent prior to breach
Prior to 1870	Growth due to mining - unknown extent and probable breach.
1883	Extended to Highcliffe Castle.
1895 or 1896	Extended to Steamer Lodge, but was covered at high water.
1911	Extended to Highcliffe Castle.
1924	Probably extended to Highcliffe Castle.
Around 1935	Extended to Steamer Lodge.

Table 5.5 – Defence works and events at Highcliffe. To be read in conjunction with Figure 5.13 (Compiled from data sources listed in Table 3.5 and West, 1885; Burton, 1931; Wise, 1963; Stopher and Wise, 1966; Phillips, 1973; Christchurch Borough Council, 1985, 2004, 2007a,b; May, 1990; HR Wallingford, 1991).

Year	Location	Description of works and events	Frontage (m)	
			New	Total
1880	1km west of Chewton Bunny.	Groynes and other protection at Highcliffe Castle due to stream erosion.		
1960		Severe erosion occurred when storms washed beach away.		
1963		From 1962-1963, beach levels lowered by 1.2m-1.5m (4 feet-5 feet), revealing cliff base in same position as 1936.		
1967-69, 1970-71	Highcliffe frontage.	Revetment stage 1 and 2: Permeable defences, including a steel pile and flexible wooden revetment and groynes.	1280	
1973	Highcliffe frontage.	Cliff drainage.		
1979-1980	Chewton Bunny.	Chewton Bunny bastions added.	130	1410
1984-86	Highcliffe frontage.	Two stage cliff stabilisation works and defence up-grading.		
1985-87	Highcliffe frontage.	Sediment replenishment (75,000 tonnes of gravel) to provide protection for wooden revetment and groynes. Conversion of two wooden groynes to rock groynes.		
1990-93	Highcliffe frontage.	Emergency works and drain improvements. Conversion of wooden groynes to ten alternate long and short rock groynes. Replenishment top-up.		
2005	LENGTH OF DEFENCES:			1410

Table 5.6 - Summary of the results for Highcliffe averaged for the length coast. *from reference shoreline, the closest to defence construction. Error value represents the extremes.

	1932-1963	
Retreat rate prior to defences used to predict retreat (m/yr)	0.6±0.6	
	1963-1989	1963-2005
Observed set-back after defence construction* (m)	33±20	40±12
Observed retreat rate after defence construction (m/yr)	1.3±0.8	1.0±0.3
Predicted retreat after defence construction* (m)	15±17	24±27
Excess retreat (m)	18±26	17±29
Percentage increase (%)	124	70

Table 5.7 - Defence works and events at Barton-on-Sea. To be read in conjunction with Figure 5.19. (Compiled from data sources listed in Table 3.5 and Stopher and Wise, 1966; Phillips, 1974; Reina, 1975; Clark et al., 1976; Summers and Maddrell, 1978; Wright, 1998; Fort et al., 2000).

Year	Location	Description of works and events	Frontage (m)	
			New	Total
1935-1939		Groynes		
1940s/1950s	West of Barton Court.	18 groynes constructed, later in dis-repair.	700	700
1964	Barton Court.	Filter drain, outfalls and 4 groynes over 300m of already protected cliff.	300	700
1967-1968	Whole frontage.	16 timber groynes and a rock fill timber revetment, with 1.3km of drainage works overlapping with protected frontage.	1800	1800
1969-70, 1972	Whole frontage.	Drainage and maintenance works to cliff and timber revetment.		
1972/1975	Various groynes and terminal structure.	Conversion of some timber groynes to rock groynes. Rock armouring added to wooden revetment at end of groynes.		
1978	East of Barton Court.	Shingle nourishment with 30,000 tonnes of material within penultimate strongpoint compartment.		
1979	Terminal groyne.	Conversion of timber groyne to rock groyne. Revetment extension by rock armouring.	10	1810
1982-1984	West of Barton Court.	Conversion of timber groynes to rock groynes.		
Early 1990s	Barton frontage and down-drift of terminal groyne.	Rock armour placed along entire frontage as toe protection, including rock armour extension down-drift.	60	1870
2005	LENGTH OF DEFENCES:			1870

Table 5.8 - Summary of the results for Barton-on-Sea averaged for the length coast. *from reference shoreline, the closest to defence construction. Error value represents the extremes.

	1932-1963	
Retreat rate prior to defences used to predict retreat (m/yr)	0.5±0.6	
	1963-1989	1963-2005
Observed set-back after defence construction* (m)	33±20	61±12
Observed retreat rate after defence construction (m/yr)	1.3±0.8	1.5±0.3
Predicted retreat after defence construction* (m)	13±17	20±27
Excess retreat (m)	21±27	41±29
Percentage increase (%)	167	205

Table 5.9 - Defence works and events at Becton. To be read in conjunction with Figure 5.26 (Compiled from data sources listed in Table 3.5 and Phillips, 1973; Bialas, pers. comm. 2004; Wright, pers. comm., 2004).

Year	Location	Description of works and events	Frontage (m)	
			New	Total
1957	Becton Bunny.	Pipe at Becton Bunny		
1963		Outfall installed.		
Late 1960s (1969?)		New outfall installed.		
1971-1972	At outfall.	Tripod armouring around outfall, creating a strongpoint.	90	90
1975		Wooden piles constructed around strongpoint.		
Early 1990s		Failure of original rock armour – additional rock armouring placed around pipe.		
1994-1997		Due to outflanking, rock armouring moved nearer to cliff and parallel to shoreline.		65
2002		Outfall demolished. Further rock armouring placed on beach.		65
2005	LENGTH OF DEFENCES:			65

Table 5.10 - Summary of the results for Becton averaged for the length coast. *from reference shoreline, the closest to defence construction. Error value represents the extremes.

	1932-1963	
Retreat rate prior to defences used to predict retreat (m/yr)	0.2±0.6	
	1963-1989	1963-2005
Observed set-back after defence construction* (m)	23±20	41±12
Observed retreat rate after defence construction (m/yr)	0.9±0.8	1.0±0.4
Predicted retreat after defence construction* (m)	5±17	8±27
Excess retreat (m)	18±27	33±29
Percentage increase (%)	366	418

Table 5.11 – Summary of excess retreat results from the Christchurch Bay study sites.

	Study sites					
	Highcliffe		Barton		Becton	
	1963-1989	1963-2005	1963-1989	1963-2005	1963-1989	1963-2005
Measurement period (years)	26	42	26	42	26	42
Average observed set-back (m)	33±20	40±12	33±20	61±12	23±20	41±12
Average predicted retreat (m)	15±17	24±27	13±17	20±27	5±17	8±27
Excess retreat (m)	18±27	17±29	21±27	42±29	18±27	33±29
Relative retreat rates within confidence of data	Maintained, with some excess / no conclusive change	Maintained, with some excess / no conclusive change	Maintained / no conclusive change	Accelerated	Maintained, with some excess / no conclusive change	Accelerated
Longshore influence down-drift.	Up to 1,250m	Up to 1,250m	Not detectable	Greater than 300m	Up to 550m	Up to 650m

6. BAY EVOLUTION AND PLANFORM

6.1 Introduction

In Chapter 2 a comparison was drawn between natural bays and artificial bays. Natural bays form down-drift of a headland, where as artificial bays form down-drift of a groyne. Natural coastlines consist of a series of bays and headlands which are built transverse to the wave direction and refraction (Lewis, 1938; Davies, 1958). Headlands are composed of relatively hard rock (Flamborough Head on the Holderness coast or Hengistbury Head in Christchurch Bay) or mobile beach deposits (Dungeness, Kent or Orfordness, Suffolk) compared with the adjacent coast. Between headlands, beaches, cliffs and other coastal features form. Small bays can form within larger bays, for example, the 85km wide bay between the headlands of Start Point in Devon and Portland Bill in Dorset contains Start Bay, Tor Bay, Babbacombe Bay and Lyme Bay (Figure 6.1). Bays are evolving and can be ephemeral features, for example, Pile (2003) reports of the battle of Sole Bay, Suffolk in 1672. Today the bay has disappeared leaving only a shallow indentation on the coast.

Monitoring natural bay formation and planform is difficult as data is required over many centuries and millennia and such information is not available. However, analogies can be made between natural and artificial bay formation. Similar to natural bays, artificial bays develop between an up-drift and down-drift headland (although the down-drift headland may be at a very long distance down-drift). Natural and artificial bays form at different spatial and temporal scales (see Chapters 2, 4 and 5). Therefore bays in different stages of evolution have different features. The spatial and temporal evolution of artificial bays in Holderness and Christchurch Bay are shown in Figure 6.2. To envisage future artificial bay development the heavily defended coast of north-east Norfolk has been studied and will be presented in this chapter. Although coastal defences underwent a massive expansion during the 1950s and 1960s, parts of the north-east Norfolk coast have been defended for over 100 years. Therefore defences are of a similar age or older than those in Holderness, but they are geographically located closer together as in Christchurch Bay. Hence north-east Norfolk represents how defences evolve and how they potentially impact on the

adjacent cliffs in Holderness and Christchurch Bay in many decades and centuries time. However, coastal evolution is not only effected by defences, but also controlled by many natural factors, such as geology and the frequency storms and toe erosion.

Objective 3 (Section 1.7) is to evaluate the evolution of set-backs and the terminal groyne effect. Therefore the purpose of this chapter is to establish the stages in artificial bay evolution through studying cliff set-back, defence outflanking and abandonment, and planform shape using examples from Holderness, Christchurch Bay and north-east Norfolk.

6.2 Outflanking and defence removal

As shown in Chapters 4 and 5, set-backs and the terminal groyne effect evolve over time. Littoral drift barriers inhibit longshore drift and reduce sediment input, leading to a diminished sediment supply down-drift (see Chapter 2). The continued or increase set-back down-drift can threaten the stability and effectiveness of the defences, triggering extensions and maintenance (for example, Hornsea and Withernsea in Holderness, and Barton and Becton in Christchurch Bay).

6.2.1 Outflanking

Down-drift erosion is caused by a combination of all defences, not just the terminal groyne effect, as described in Section 1.2. The down-drift effect of seawalls (and other shore parallel defences) affect sediment transport and its effect is not traditionally associated with the terminal groyne effect.

Seawalls are used as a method of coastal protection, but knowledge of the short and long term effects of the beach and nearshore (and therefore the effects down-drift) are limited (Griggs *et al.*, 1990; Tait and Griggs, 1990; Miles *et al.*, 2001). Seawalls create wave reflection and diffraction (Silvester, 1976; Griggs, 2005), and when situated on an eroding coast, reduce sediment input. This leads to scour, reducing levels down-drift (Powell and Whitehouse, 1998) and is referred to as 'end effects' (or flanking, terminal or lateral scour). It has a similar

effect on erosional processes and the down-drift planform as the terminal groyne effect.

End effects have two components. Firstly, there is a tendency for localised deeper water adjacent to the seawall, caused by reflective waves coinciding with incident waves, reducing the backwash wave component. Typically this extends 50m to 150m down-drift (Griggs and Tait, 1989; Griggs *et al.*, 1990; Plant and Griggs, 1992; Dean, 1996; Griggs, 2005). It can be seen at Barton-on-Sea at the end of the shore parallel rock armour (Figure 6.3). Griggs *et al.* (1990) and Kraus (1988) noted that a rip current trough frequently runs perpendicular to the seawall, but this was not seen at Barton. Secondly, there is a long distance down-drift erosional component caused by sediment reduction and continued erosion of the hinterland, leading to set-back in the planform of a log-spiral or crenulate shape, as shown in Figure 6.4 (Silvester, 1978; McDougal *et al.*, 1987; French, 2001). Figure 6.4 shows that the set-back progressively erodes landward behind the barrier, removing the support of the structure leading to outflanking and failure (Carter, 1988; French, 2001).

Griggs and Tait (1989), Griggs *et al.* (1990) and Griggs (2005) concluded that defence outflanking and retreat is a function of wave height, period and angle, stage in tidal cycle, geomorphology and permeability and length of seawall. For example, Birkemeier (1980) reported that down-drift of a 579m seawall at Lake Michigan, the erosion of sand bluffs increased by 380% in comparison to the up-drift side. McDougal *et al.* (1987), and Griggs and Tait (1989) estimated that down-drift outflanking effects are in the order of 70% and 50% respectively of the length of the seawall. They suggest there is an absolute limit with time of end effects, but research from this thesis suggests end-effects and down-drift erosion can potentially expand and evolve continuously. For example, continued erosion at Barmston (Section 4.3.1) has caused the shore parallel rock armouring to become a groyne. This retains sediment up-drift, which can potentially affect erosion longer distances down-drift. Galgano (1998) noted that arcs of erosion from jetties are always evolving and can continue to affect shorelines down-drift. This can also apply to seawalls. For example, Walton and Sensabaugh (1979) found that the length of the seawall and the longshore distance of excess erosion followed a logarithmic relationship. This was concluded by studying beach elevation and scour after Hurricane Eloise in 1975 at Panama City Beach, Florida. At Ulrome and Barmston, Holderness, set-back

continues down-drift of the seawalls, allowing the defences to form an artificial headland (Figures 2.20 and 4.15), thus blocking sediment up-drift, and potentially extending end effects further down-drift. Therefore shore parallel and perpendicular defences can result in a similar form of set-back.

Using a time series of aerial photographs, outflanking was studied at Barton-on-Sea and Becton in Christchurch Bay (for defence details see Figure 5.19 and Table 5.7 for Barton, and Figure 5.26 and Table 5.9 for Becton). At Barton-on-Sea, a major defence scheme was completed by 1968 and terminated at a natural promontory, so the down-drift undefended coast stood seaward of the adjacent defended coast (see Section 5.3.2) as illustrated on Figure 6.5a,b. During the next decade, this natural promontory eroded rapidly (1.7m/yr at Profile D on Figures 5.22a and 5.22b), but at first sight in Figure 6.5b, the defence appears not to be set-back compared to its defended counterpart, suggesting that there was no terminal groyne effect. The rock armouring was extended in 1979 due to outflanking problems, thus encouraging the enlargement of the crenulate shaped bay (Figure 6.5c). In the early 1990s the armouring was extended again. By 2001 this had created a double crenulate shape on the cliff top (Figure 6.5g,h) and a 22m set-back (see Figure 5.25). Similar examples of multiple extensions and double crenulate shaped cliff tops are seen down-drift of Withernsea, Holderness (Figures 4.33 and 4.37) and Lyme Regis, Dorset (Figure 2.4) which has had multiple defence works since the 13th century (Fort *et al.*, 2007).

The Becton outfall was installed on an initially unprotected 'straight' shoreline in the late 1960s (see Figure 6.6a). In 1971 rock armouring was added to protect the outfall, but resulted in increased set-back down-drift (Figure 6.6b). As waves eroded the cliff behind the rock armouring (Figures 6.6c,d), the bay widened leaving the defence ineffective (as seen in Figure 6.6e). Subsequently between 1994 and 1997, the armour was moved closer to the cliff, providing protection for the outfall. Therefore at Barton and Becton retreat has continued down-drift leading to erosion and outflanking behind the defence.

Outflanking of defences has prompted defence extensions and other maintenance works as noted in Chapter 4 and 5 at Holderness and Christchurch Bay. This will be discussed in Section 6.2.3.

6.2.2 Defence removal

During the 20th century, Britain's low-lying and soft, erodable coastline has become increasingly protected by hard defences to reduce erosion and flooding. Defences have decreased sediment input and availability in some areas, intensifying erosion and making it increasingly difficult to maintain defence levels (French, 2001). Climate change and rising sea levels create additional strains on maintaining defences (Nicholls and Klein, 2005). The introduction of Shoreline Management Plans (SMPs) in 1995 presented four strategic management policies: (1) hold the existing line of defence, (2) advance the existing defence line, (3) managed realignment, and (4) no active intervention (DEFRA, 2006a). Managed realignment involves controlling or limiting shoreline movement (both backwards and forwards) to benefit erosion or flood risk. No active intervention is where there is no investment in coastal defences or operations, which can lead to defence degradation (DEFRA, 2006a). As the perils of extensive hard protection became apparent, the school of thought shifted from hard to softer approaches of coastal management, such as realignment and no active intervention (Leafe *et al.*, 1998; French, 2001). Abandoning defences leads to the release of beneficial sediments to protect the coast. These policies are reflected in the second round of SMPs and in adopting this strategy the aim is to create a long term, affordable and sustainable plan to protect the coast. This is not without problems, as difficult decisions need to be made over what land and which communities remain protected, and which parts of the coast are abandoned.

No active intervention involves a lack of defence maintenance and upgrades, and without this, the defences become outflanked and ineffective. This can lead to defence removal such as at Happisburgh, north-east Norfolk (Figures 6.7 and 6.8). North-east Norfolk is underlain by Chalk and during the Pleistocene glaciation (10,000-1,640,000 years ago) complex weak glacial tills composed of layers of sand and clay were deposited (Owen, 1976; Hart, 1999; Ohi *et al.*, 2003). Along the Norfolk coast the largest waves arrive from the north and north-east, where the fetch exceeds 500km (Dickson *et al.*, 2005). Landslides are a major sediment input into the system (Cambers, 1976) and a drift divide is present west of Cromer (see Figure 6.7). Clayton *et al.* (1983) and Clayton (1989) state longshore transport is 260,000m³/yr to the south-east towards Eccles on Sea, whilst 60,000m³/yr is transported north-west of Cromer towards

Sheringham. Before coastal defences, the cliffs, regionally up to 40m high retreated at approximately 1m/yr (Clayton, 1989; Thomalla and Vincent, 2003).

As with Holderness and Christchurch Bay, north-east Norfolk saw a substantial increase in the number and length of coastal defences constructed in the 20th century. In the early 1950s, less than 20% of the coast from Sheringham to Cart Gap was defended, but by 2005 this increased to approximately 70%, resulting in a sediment deficit and lower beach levels (Cambers, 1976; Clayton, 1989). Happisburgh's 10m high cliffs were defended with wooden revetments in 1958 and groynes in 1968. Routine maintenance of defences was undertaken until the 1980s when the local authority concluded that major investment was required to preserve the sea defences over the longer term (Coastal Concern Action Group, 2005). By 1991, defence failure led to partial defence removal (Figure 6.8) on safety grounds (HR Wallingford, 2001). Defences not removed were outflanked. Subsequently after 33 years of reduced retreat due to protection, erosion was re-initiated along a 900m stretch of coast (until a sheet pile seawall down-drift). In 14 years it created a 100m deep embayment in the shape of a parabola (Figures 6.9 and 6.10). With continued costs, objections and legislation, no defence plan could be agreed (with the exception of emergency works in 2002 and 2007 reported by Coastal Concern Action Group, 2005, 2007).

Figures 6.11a, 6.11b and 6.11c illustrate the retreat of four 100m profiles. Prior to defence construction (1892 to 1951, the nearest cliff top positions to the date of defence construction) the cliff eroded 0.5 ± 0.4 m/yr (Figure 6.11b). Clayton (1989) attributed the high retreat rate prior to 1907 to a changing wave climate. Another plausible explanation is beach and nearshore mining or rapid erosion as the coast adjusts to its equilibrium profile once the mining ceased. Ward (1922) reports of shingle removal since the mid 18th century for road building and the exportation of sediment to Staffordshire for pottery manufacture. As at Holderness and Christchurch Bay (see Sections 4.2.2 and 5.2.2) it is probable that beach sediment was also a building source for buildings and railways. Another possible reason for a decreased retreat rate after 1907 is early defences. For example, Matthews (1913) records a seawall at Ostend 2.7km up-drift (for location, see Figure 6.7).

With the degradation of defences after 1991, retreat rates rapidly increased (Profiles B and C of Figures 6.11b and 6.11c) to an average of 3.0m/yr to 5.5m/yr (1986 to 2005), with a maximum retreat rate occurring between 1995 and 2005. Retreat is initially greatest at Profile C, as defences failed here first, but retreat rates then slowed as the coast benefited from sediment retained by the down-drift seawall. This rapid retreat was caused by a denuded beach allowing larger waves to attack the cliff toe. This caused a relative change in the level of the shore platform level (and cliff toe), causing rapid retreat as the cliff profile tended towards dynamic equilibrium (Dickson *et al.*, 2007). The set-back and embayment formed due to the juxtaposition of defended and undefended coast. Retreat extended down-drift to a seawall and scoured behind it creating an 'initial groyne effect' (Figure 6.12, and see Section 7.2.3 and Glossary). This feature will continue to grow and indicates the beginning of outflanking problems.

The degradation and removal of defences is responsible for the large retreat rates and to the coastal planner, knowledge of when retreat rates will decrease to previous levels is essential. Table 6.1 documents previous retreat rates (1892 to 1951) and the predicted and observed retreat based on this rate, for 2005. With Profiles B and C excess retreat is not recorded within the confidence of the data.

6.2.3 Discussion

Section 6.2.1 indicates that defences, if not maintained are outflanked. Solutions have been proposed to overcome outflanking problems including seawall extensions, additional groynes (particularly permeable and shorter and lower groynes) in front and down-drift of the seawall, and nourishment (Galgano, 2004). Solutions in Holderness and Christchurch Bay are noted in Table 6.2. At Hornsea, after successive defence extensions an outflanking structure was constructed in 1977 (Barrett, 1983). Composed of a shore parallel and perpendicular defence and not connected to the main seawall, its design allowed for cliff erosion and outflanking behind the structure (see Figure 4.20). By 2005 an 86±12m set-back formed down-drift (see Figure 4.21b, Profile F). Although the defence has required reinforcement since its construction, it has been more effective in coping with the outflanking problem than solutions at the other study sites, as repeated extensions have not been required.

Defence outflanking at Barton-on-Sea and Becton is caused by the continued retreat of the adjacent coastline. At Barton-on-Sea, there have been two extensions of rock armouring in 38 years. Each extension has provided further protection for the original defences as it has allowed for dissipation of wave energy behind the armouring (except during the storm conditions when waves overtop the armouring – see Figure 5.25). This also occurred at Withernsea (see Figure 4.33 and Tables 4.10 and 6.2).

At Becton, moving armouring nearer to the cliff rather than extending it down-drift created an area of intense scour (noted as a scour hollow in Brown, 2005). How defences are managed and maintained today will determine how the coast will look in the future. For example, maintenance of the outfall adjacent to Becton Bunny, which is no longer in use, remains the responsibility of the local water company. However, it may be wise for the local authority to maintain the outfall as it retains sediment between the Barton and Becton defences, and slows cliff erosion (Brown, 2005). If the outfall is not maintained outflanking will continue and the armouring will again become ineffective. With time, it will form an artificial island with shingle acting as a temporary causeway between the armouring and the land. Beach levels down-drift of Barton will reduce, set-back and outflanking will increase and the Barton and Becton bays will merge forming a single wide bay. In a natural headland bay system, set-back occurs down-drift of a headland until a deep bay forms. Simultaneously the headland protrudes increasingly seaward and becomes thinner, the equivalent of outflanking in an artificial system. Over many thousands of years, the headland will become a stack or island, creating a wide bay between adjacent headlands. The beginning of headland thinning is seen at Flamborough Head (albeit extremely slight as the headland doubles-back on itself towards the north, before the coast orientates south). It is seen not at Hengistbury Head, presumably due to mining reducing the headland's size, and some sediment by-passing the headland, creating Christchurch Harbour's southern spit. Whilst set-back is widely recognised, there are few references in the reviewed literature that connect outflanking and how crenulate shaped bays erode and form. LeBlond (1972), modelled bay formation and found outflanking a necessary step towards achieving spiral shape.

At Happisburgh abandonment has allowed waves to engulf the defences (Figure 6.13). Abandoned defences lead to other issues such as how defences are

physically and safely removed and the coast realigned. Safety issues are very important, as legal action can be taken against a local authority whose degraded defences create unseen dangers. For example, already there are dangers for beach users, such as children playing bare-foot, or sharp metal objects buried just below the surface. Similarly surfers, swimmers and those using inflatables would be unaware of objects extending up from the shore platform where the water is cloudy with sediment or too deep to be seen clearly. With more defences abandoned small pleasure craft may experience navigation problems. Abandoned defences could become widespread such as with defunct World War 2 defences, for example as illustrated at Milford-on-Sea, Christchurch Bay (Figure 6.14). Although beaches are checked and cleared for dangerous objects by local authorities, some councils do provide warning signs of these hazards, but others do not for fear of deterring those who use the coastal zone. With defence abandonment and realignment, defences will have to be systematically removed and the environment monitored to avoid these dangers.

Table 6.3 reports alternative solutions to outflanking of seawalls and groynes in other localities. Extending the defences is a common practice, but it has a knock-on effect as it magnifies the problem and moves it down-drift (Viles and Spencer, 1995; Silvester and Hsu, 1997). At Norderney, Germany and Ofir-Apúlia, Portugal, extending defences and nourishing the beach was partly required to protect the growing tourist industry. This was also noted at Bridlington, Hornsea and Withernsea in the UK.

With a multidirectional wave environment and strong seasonal shifts in net longshore drift, groynes do not always provide the best solution to reduce coastal erosion. For example, Sandringham, Melbourne, Australia is located within a cliffed crenulate bay within the natural harbour and nourishment may be the preferred defence option (Stephenson, 2007). With a marina on the adjacent bayed coast requiring frequent dredging, the sediment could be recycled as beach material providing protection to the eroding coast. Hence, the terminal groyne effect can sometimes be beneficial to those who provide solutions to coastal erosion problems (Stephenson, pers. comm., 2008). The multidirectional wave environment at Smith Point, Virginia (as described in Section 2.4.3 and Figure 2.13) caused sediment to infill behind the outflanked terminal groyne when the spur provided extra sheltering. Silvester and Hsu (1997) reported that this configuration could also form a stable beach. The

effects of multidirectional or minimal littoral drift is discussed in Sections 2.2.2, 2.3 and 7.2.1.

On an eroding coast, the defence will become outflanked, regardless of whether the rate of down-drift erosion has remained constant or increased. A number of different solutions have been sought, but no single solution provides total satisfaction (see Tables 6.2 and 6.3). Each solution is specific to each site. As with the terminal groyne effect, end effects of seawalls evolve with time, and are frequently set-back, forming an embayment. Not until recent decades was outflanking incorporated and monitored in coastal defence schemes in the study regions, for example, sites include Hornsea, Holderness in 1977, Mablethorpe, Holderness in 1991, Sea Palling, Norfolk since 1995, and Easington, Holderness in 1999.

Defence removal leads to new coastal configurations and a new type of terminal groyne effect as the juxtaposition of coastlines will be an intermediate stage between defence removal, rapid retreat and a fully responded and aligned coast (as proposed for north-east Norfolk in the Kelling to Lowestoft Ness Shoreline Management Plan, 2006). Happisburgh provides a new form of terminal groyne effect due to defence removal rather than the addition of defences. However, abandonment and removal is not a new practice and has occurred for hundreds of years. For example, groynes have previously degraded south of Hornsea (1892-1911), north of Overstrand (1907-1938) and south of Overstrand (1888-1907). Sheppard (1912) found that after the destruction of the short lived Hornsea pier in 1880 (Easdown, 1996), rapid erosion resulted down-drift. This represented a temporary period of increased retreat as the long term retreat rate remained unaffected. However, the impact of groyne degradation and removal in the 21st century will be greater than in previous decades because of longer periods of defence and mid to late 20th century defences generally being more substantial and efficient than 19th century and early 20th century structures. With many people residing and using the coastal zone, and an expectation that the coastal position will be held, adequate modelling of future shoreline position and response to the communities affected by abandonment, is crucial. Shoreline Management Plans must choose appropriate policies based on technical, environmental, social and economic factors. They are required to address current legislation, but should be flexible enough to adapt to future legislation, politics and social attitudes (DEFRA, 2006a).

Future coastal response to abandonment will depend on how the coastal defences fail. For instance, if the up-drift defences are abandoned first, beneficial sediment would be provided for the down-drift coast, reducing the short term impact of the accelerated retreat (see Section 7.2.3). Furthermore, coastal set-back from defence removal depends on prior erosion rates and the length of time protected. Although on a sediment starved coastline, Happisburgh was defended for only 33 years before defences were removed. If other areas are abandoned that had been defended for longer periods of time (for example, Overstrand has been defended since at least 1907), retreat and retreat rates could be greater than already seen at Happisburgh. Abandoning defences will also result in increased retreat up-drift as the cliffs become more vulnerable to wave attack and retained sediment is transported down-drift resulting in lower beach levels. The remaining defended coast will form artificial headlands where the adjacent soft coast continues to erode (see Section 7.2.3). The artificial headlands will suffer from outflanking and greater wave attack, already noted at Cromer and Overstrand (Ward, 1922; Craig-Smith, 1973). Appropriate engineering solutions into up-drift and down-drift defence terminations need to be sought with long term management and maintenance of the whole coastal cell an essential consideration.

6.3 Bay shape, development and equilibrium

Silvester and Hsu (1997) stated that stable bays in static or dynamic equilibrium (when there is no cross-shore retreat) develop a common planform shape such as a logarithmic spiral, parabola or hyperbola (see Section 2.5 and Appendix 1). However for bays still under formation there is little research documenting how, and at what rate bay planforms evolve and grow into these shapes. Factors that affect bay formation and planform outlined in Chapter 2 include direction of wave approach, wave energy, geometry, outflanking and the presence of other artificial structures (Phillips, 1985; Terpstra and Chrzastowski, 1992; LaValle and Lakhan, 1997). One difficulty in monitoring bay formation in nature is that planforms need to be measured over years, decades, centuries and millennia and such data is not available for any coast. With artificial bays developing in the time frame of years to decades, data is available and similarities and differences can be seen between natural and artificial bays.

6.3.1 Bay shape

Figure 6.15 illustrates the regional planform of the Holderness coast and the artificially formed embayments studied in Chapter 4. They are compared to a parabola, a common shape for a one headland bay system (see Section 2.5 and Appendix 1). The results indicate that the artificial bays have similar planforms to each other and the entire bay, regardless of their age, size or defence type. Figure 6.16 illustrates the planform of Christchurch Bay and the artificial bays. Again, the artificial bays resemble each other and Christchurch Bay in planform.

6.3.2 Bay growth

Silvester (1960), Wright (1981), Terpstra and Chrzastowski (1992), and LaValle and Lakhan (1997) found that as artificial bays evolve they maintain a similar planform shape provided that there are no other disturbances to the system. Section 3.9 and Figure 3.9 described a crenulate shaped bay forming in two parts - a shadow zone, representing the curved portion of the bay and a straighter section extending down-drift. An objective was to measure the cross-shore and long shore termination of the shadow zone throughout time by analysing the change of angle of the curve (θ) for smoothed bay planform for study sites in Holderness, Christchurch Bay and Norfolk (Figure 6.17). Transects were taken every 10m and the angle calculated between successive transects. A 10m distance between transects was selected as it accounted for large landslides within the smoothed planform. When the change in angle became constant or zero, this signified the termination of the shadow zone. The cross-shore (Figure 6.18) and longshore (Figure 6.19) termination point was then measured at successive time intervals and distances from the terminal groyne. Hornsea, Withernsea (prior to 1998), Barton and Becton are not plotted on Figures 6.18 and 6.19 because these are complex sites to measure due to outflanking, defence extensions and modifications, and longshore limits to bay growth (see Table 6.2) which makes data extraction subjective.

Figure 6.18 shows an approximately linear trend of cross-shore retreat throughout time, although retreat rates at Mappleton and Highcliffe later decrease. Variations in retreat occur due to potential map errors (see Section 3.5), and changes in cliff height resulting in fewer larger landslides compared to multiple smaller landslides within a set time period. In addition to defence

efficiency, rainfall and groundwater levels, the frequency of storms, erosion cycles, and the time for the cliff top to respond to sediment disequilibrium may explain why there are high retreat rates immediately after defence construction.

Figure 6.19 plots the longshore growth of the shadow zone with time. The growth follows a natural logarithmic trend and regression lines were fitted to each curve (Figure 6.20). The longshore growth is subject to the same errors as the cross-shore retreat. With errors potentially shifting the data set $\pm 10\text{m}$, this provides an explanation into why data points vary from the regression line. The equations of these are displayed in Table 6.4, together with the coefficient of determination (R^2). The plots can be described by the generic equation:

$$y_s = a \ln(t) + 2a \quad (\text{Equation 6.1})$$

where: y_s is the longshore component of the shadow zone (m),
t is the time since defence construction (years),
a is a dimensionless coefficient.

Happisburgh, Norfolk is the only exception to Equation 6.1 due to the rapid retreat after defence removal. Subsequently, the final term increases from '+2a' to '+2.4a'. Table 6.4 shows R^2 varies between 0.91-0.99, but Figure 6.20 illustrates that the best fit line is ill fitting for the first 10-20 years of data, depending on the size of the shadow zone. Therefore in coastal engineering this relationship is only useful for predictions once retreat rates become steadier, in these examples it is over several decades. Aside from potential map errors explaining this variation, a lack of data points in the initial measurement period could be responsible. These errors limit the validity of the predictions if the curves are extrapolated for future years (to at least $\pm 10\text{m}$).

6.3.3 Discussion

Figures 6.15 and 6.16 illustrate that Holderness and Christchurch Bay and most artificial bays develop in the shape of parabola. This agrees with Moreno and Kraus (1999) as double headland bays form in the shape of a log-spiral, whereas single headland bays form a parabola. Parabolic and log-spiral equations (see Appendix 1) can be fitted to crenulate bays (for example, Wright, 1981; Hsu *et al.*, 1989a,c; Silvester and Hsu, 1997), and describe bay

characteristics and stability. Typically bays, and subsequently their equations are defined between two fixed control points, but frequently the down-drift control point is difficult to locate. There are also difficulties taking into account the wave obliquity, diffraction and defining the log-spiral or parabola centre (Silvester and Hsu, 1997). With bays in formation a down-drift headland or control point is frequently not present or does not constrain bay growth. Therefore, traditional log-spiral or parabolic equations cannot be applied. Wang *et al.* (2008) proposed using the set-back distance as a reference line to measure planform and stability instead of the down-drift headland. This is a simple measure and further research is required into this new method.

The parabolic equation was first applied to describe various bow-shaped bays forming between two headlands in Japan (Mashima, 1961). Building on Mashima's (1961) theory, and taking into account the absence of a down-drift headland, a parabolic bay is shown in Figure 6.21 and described by:

$$y = px^2 \quad \text{(Equation 6.2)}$$

where: y is the longshore distance (m),
 x is the cross-shore set-back (m),
 p is a dimensionless coefficient determining the bay width.

When applied to Holderness and Christchurch Bay, and the artificial bays, Equation 6.2 did not work well. It does not take account of outflanking (as demonstrated in Section 6.2.1 and also recorded at Flamborough Head), and so omits the extremity of the headland. With no down-drift control point it was difficult to define bay shape. There were also problems in describing the bay width, in addition to scaling and age difficulties when comparing bays described in this thesis. To overcome this, Equation 6.2 was modified to (see Figure 6.21):

$$y = px^2 - bx \quad \text{(Equation 6.3)}$$

where: y is the long shore distance (m),
 x is the cross-shore set-back (m),
 p is a dimensionless coefficient determining the bay width,
 b is a dimensionless coefficient determining the bay depth below the x axis.

Equation 6.3 is an improved fit to Equation 6.2, as the equation takes account of the whole headland and outflanking. However, a common characteristic of artificial bays is a constant bay width, which Equation 6.3 still fails to describe. Difficulties with bay scales and age also remain. The results indicate that artificial bays within one region have similar values of p and b , yet these differ from the larger natural bay in which they reside, even when scaling factors were taken into account. Hence whilst artificial bays appear in a similar planform shape to the bay in which they reside, they have different characteristics. This indicates that parameters other than the wave direction control bay shape. Further research is required into the controlling parameters of bay formation, planform growth, together with the comparison of artificial and natural bay platforms.

The orientation of the artificial bays is approximately the same as the bay in which they reside. The principal drivers to bay formation include wave climate, bathymetry, the shore platform and sediment supply. Therefore, these drivers must be similar for natural and artificial bays and they interact and influence each other as depicted in Figures 2.1 and 2.2. Additionally, Phillips (1985) concluded that the shadowing effects of the headland were also important. However, natural bays and artificial bays develop in different ways as a natural bay evolves around a hard headland, whereas with an artificial bay, a hard headland (the groyne) is suddenly created (see Section 6.1). Furthermore, Phillips (1985) determined that bathymetry reflected shoreline configuration for a considerable distance offshore.

Groynes impede longshore drift which initiates increased erosion down-drift of the shore platform, beach and cliff. Once the groyne compartments are filled, longshore drift regains an equilibrium and the shore platform and its retreat then becomes the long term controller of cliff set-back. In turn, this is eroded by waves which define the bathymetry - the same drivers as natural bay formation. This helps explain why the artificial embayments align themselves in the same direction as the initial coastal orientation. With shore parallel defence (such as at Barmston, Holderness, see Figure 4.12 and Table 4.4) longshore drift is not inhibited by the seawall, but with continued set-back of the adjacent cliff the seawall progressively becomes a headland or groyne (Figure 4.15) inhibiting a greater volume of sediment movement as time progresses. Therefore, both natural and artificial bay formations are controlled by the same principal drivers,

but individual bay configurations are derived in different ways, assigned by factors such as defence efficiency, sediment availability and longshore drift. These factors also determine the growth of the shadow zone.

All the artificial bays studied, except Highcliffe and Barton, Christchurch Bay and Happisburgh, Norfolk have one headland positioned up-drift allowing the down-drift shoreline to freely respond and align itself in a parabolic shape. A second artificial headland may be present, but positioned a very long distance down-drift so has minimal effect on retreat. Artificial bays with one headland also formed in north-east Norfolk at Mundesley, Bacton and Ostend (see Figure 6.7 for locations) and are illustrated in Figure 6.22. They are also of the parabolic shape despite the convex shape of Norfolk's coast. This suggests that all artificial bays without a down-drift headland, or a very distant one, form in the shape of a parabola rather than forming a replica of the bay in which they reside. Therefore, bay planforms could be partially predicted on the wave direction (Klein *et al.*, 2003 found that wave period and height had minor influence on bay planform), regardless of the large scale coastline shape.

Naturally forming bays with a single headland are difficult to define, as frequently a second headland is present down-drift, albeit at a long distance. One example of a double headland bay is Filey Bay, (Figure 6.23), located immediately north of Holderness. The bay is confined up-drift by Filey Brigg, a limestone and grit promontory and down-drift by Flamborough Head, which act as sediment boundaries allowing sediment and erosion to be contained within the bay. The same principle applies to artificial bays bound between two headlands (see Highcliffe and Barton, Christchurch Bay in Chapter 5). If the up and down-drift headlands are located relatively close to each other (for example in Norfolk, headlands form when erosion is approximately 1m/yr over a 100 year time span with headlands 2km apart), the otherwise straight section of the bay (defined in Figure 3.9) reduces in size, so the overall bay planform resembles a log-spiral. These conditions are found in north-east Norfolk, where parts of the coast have been defended for many centuries (Ward, 1922), and where defence construction has been particularly expansive since the end of the 19th century. Between Cromer and Overstrand, the continued retreat has formed a bay (Figure 6.24) allowing the defences to form a subtle promontory. This was first noted by Ward (1922). Overstrand's defences form a greater promontory than Cromer's as it has a higher retreat rate due to Cromer's terminal groyne effect.

Also, the drift divide west of Cromer prevents beach material building up-drift of Cromer. Therefore headlands are more pronounced when the coast is equally set-back either side of the defences (see Section 7.2.3 and Table 7.5).

Detailed analysis of the terminal groyne effect could not be undertaken in Norfolk as defences were constructed prior to the first map publication around 1892, so a retreat rate free of human intervention cannot be determined. Between 1892 and 2005 the retreat rate has remained approximately constant ($0.8 \pm 0.2 \text{ m/yr}$), but in the future, erosion rates could decrease as sediment is retained between the headlands (as described in Section 2.5.2). If defences are maintained at Holderness and Christchurch Bay and the coast continues to erode, headlands will become prominent, much like north-east Norfolk. Therefore, once down-drift erosion extends to a down-drift headland, it is that headland, which has the dominant control of set-back and bay planform. If the headland is an efficient defence, it retains sediment up-drift and reduces cliff erosion between the headlands allowing a bay to form (see Figure 6.24).

The parabolic model is a useful tool for coastal planners to estimate future shoreline position, bay shape and planform down-drift of existing defences. It is of added importance when considering future defence configurations under different management scenarios. The size of the bay and the shadow zone are important features to study and a greater understanding of the growth is useful to coastal management. One way of predicting bay growth is by calculating 'a' (the dimensionless coefficient of Equation 6.1) for each site as described in Section 6.3.2. However defences already need to be constructed or abandoned before 'a' can be determined. Its calculation for each site by other methods before down-drift erosion commences would be a valuable tool. However, calculating 'a' for each site is complicated by defences further up-drift retaining sediment, thus increasing retreat rate down-drift. It is further complicated by wave refraction and diffraction effects caused by the natural headland up-drift, plus additional sediment input from the cliffs. Tests for each region indicate that 'a' has a proportional relationship to the retreat rate prior to defence construction and the wave approach with respect to the shoreline orientation. These two factors are also proportional to each other within each study region. Parameter 'a' would also depend on defence type and efficiency. For example, Barmston's defences consist of a shore parallel revetment, which when first constructed did not retain sediment up-drift in the same way as a groyne. Also, the extensive

groyne field at Hornsea stores greater sediment than the groynes at Mableton, and thus the set-back at Hornsea is more severe.

On studying barrier beaches, Galgano (1998) found that the arc of erosion is a mobile feature that enlarges down-drift at a nonlinear and often exponential rate, with the change of area per year conserved. Although restricted by data availability, no evidence could be found of this relationship at the Holderness and Christchurch Bay study sites, or any relationship between the length of the shadow zone and the longshore length of coastline affected by increased erosion. In part this is due to a lack of suitable data, but even if this were available it would remain difficult to prove as there are many other disturbances and factors influencing retreat (as discussed in Chapters 4, 5 and 7). Laboratory experiments of this, together with a detailed study of shadow zone growth with time, may be more revealing.

6.4 Synthesis

Figure 6.25 illustrates the connections between the building of defences and subsequent outflanking, abandonment, bay growth and headland formation. The upper part of the figure represents no engineering intervention after defence construction, and the lower part relates to monitoring, decision making and intervention after defence construction. Although Figure 6.25 applies to artificial bays these interconnected factors can apply to natural bay formation over thousands of years. Predictions of the shape and rate of retreat are required for shoreline planning and management, and these are related to the defences and how the set-back is caused. The longshore growth of the shadow zone can be predicted in simple cases once retreat has been initiated, but complex cases are common, providing frequent exceptions to the natural log rule (Equation 6.1) and bay predictions.

There is a greater difficulty in predicting set-back where defences are abandoned compared to where set-back occurs down-drift of existing defences. Although models can predict shoreline retreat and planforms, including when and how it will occur, it is still open to uncertainty. Over the coming decades, with potential increasing abandonment of defences in the UK there will be a transition period between a defended and a semi-defended coast. Bays will only

form after abandonment if there is the correct configuration of defences, that is, protected coastlines located up-drift of unprotected coastlines. This creates a new form of terminal groyne effect. Over longer timescales the remaining coastal defence will form artificial headlands. Further research and engineering solutions are required into how much stronger these defences will need to be to withstand wave attack, avoid outflanking and how the defended coast will interact with the adjacent undefended shoreline over the long term (>100 years).

6.5 Conclusions

Coastal defences result in set-back of the adjacent coastline and the following points can be concluded about retreat, bay planform and evolution.

- 1) The building of seawalls and groynes result in similar planforms of down-drift set-back and embayment. With continued set back, a shore parallel defence forms into a shore perpendicular defence.
- 2) Continued set-back leads to erosion and outflanking of the defences.
- 3) The removal and degradation of defences also leads to rapid retreat. At Happisburgh, Norfolk the combination of defended and undefended coast has led to set-back and a new form of the terminal groyne effect.
- 4) Where one headland is present, natural and artificial bays form in the shape of a parabola. Present understanding of natural bays does not take account of bays in formation or outflanking, as theory is based on natural equilibrium planforms after thousands of years.
- 5) The longshore growth of the shadow zone with time is defined by a natural logarithmic relationship.
- 6) Natural and artificial bays have the same principal controls of formation but individual bay planform is controlled by local influences.
- 7) A defended coast will form into an artificial headland if the adjacent coast continues to set-back or defences are selectively abandoned.
- 8) Defences are often extended due to outflanking, creating an artificial headland. This is not seen in natural headlands as the harder rock protrudes inland. However headland thinning does occur.

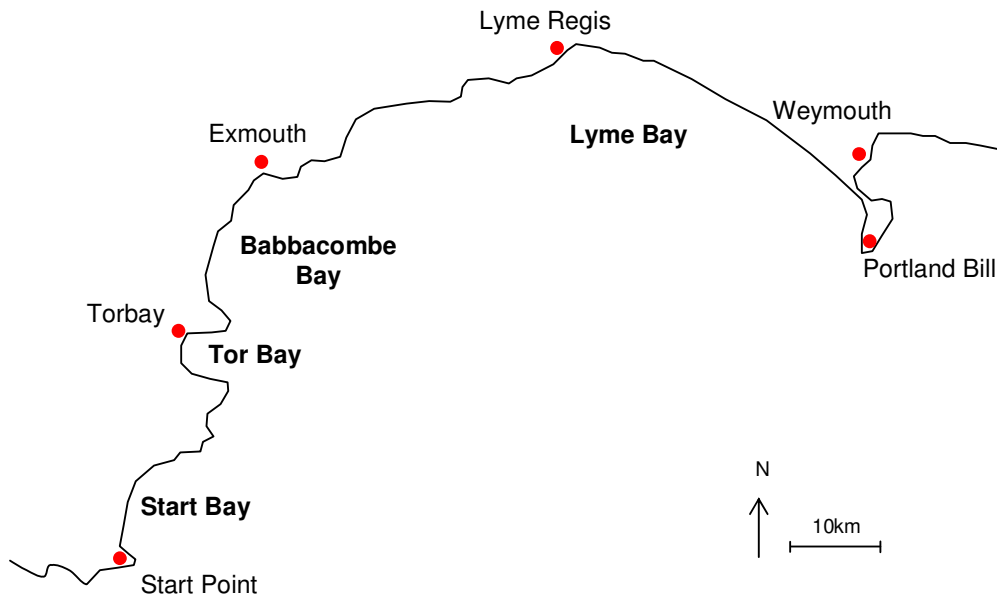


Figure 6.1 – Bays developing within a large headland bay system. Start Bay, Tor Bay, Babbacombe Bay and Lyme Bay form between Start Point, Devon and Portland Bill, Dorset.

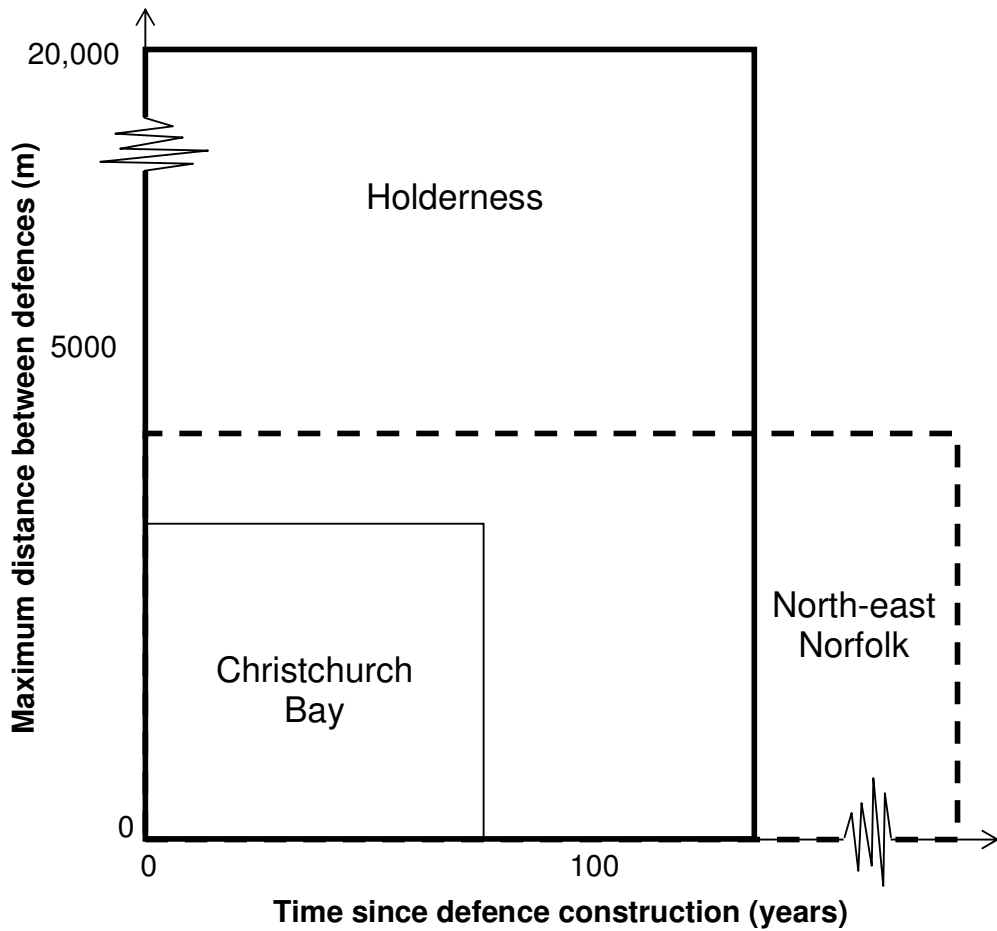


Figure 6.2 - Spatial and temporal spacing of artificial headlands at Holderness, Christchurch Bay and north-east Norfolk. This indicates possible relationships in defence evolution between the study regions.

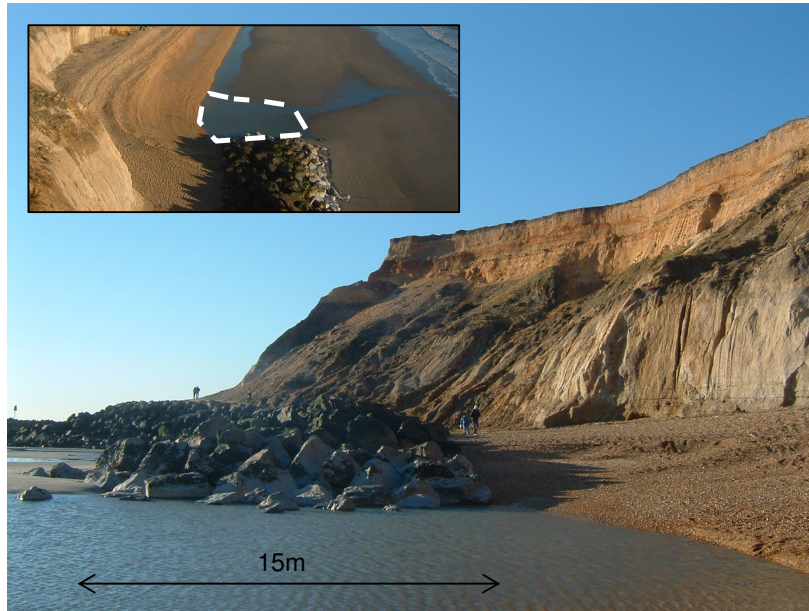


Figure 6.3 – Scour at the end of the rock armoring at Barton-on-Sea. Inset photo: As viewed from the cliff top (circled by bold dashed line). Although a 2m wide trough of water extended down-drift, it was much smaller in size than the pool at the end of the rock armoring. Photographs taken 29th January 2006.

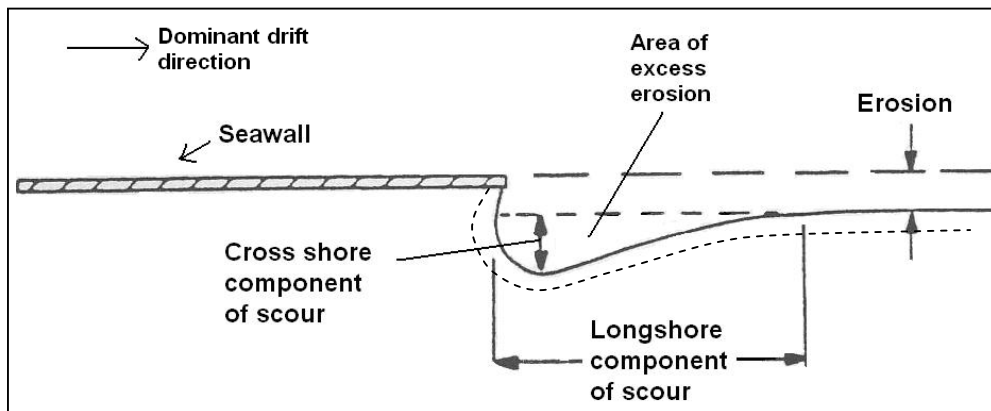
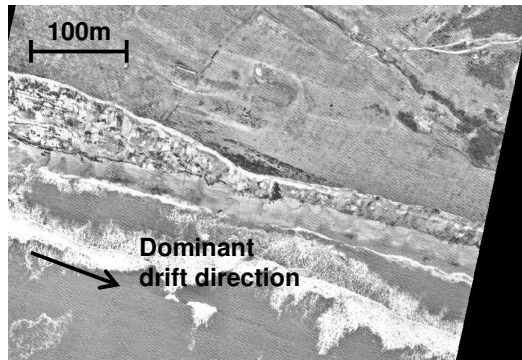


Figure 6.4 – The spiral form of erosion down-drift of a seawall (adapted from McDougal et al., 1987). The dotted line indicates possible future shoreline position, with outflanking behind the barrier.



a) 1967

- Unprotected shoreline
- Shoreline has formed a natural promontory due to geology.
- This is where the defences will terminate.



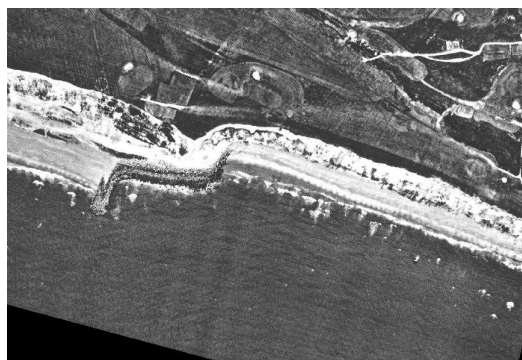
b) 1977

- Coastal defences comprising a terminal wooden groyne and rock armouring.
- Coastline starting to set back at end of rock armouring. As the up-drift shoreline was originally set-back, the excess erosion down-drift does not yet appear to be in a crenulate form. Set-back is therefore relative to its starting position.
- Some scour behind the armouring.



c) 1984

- Terminal groyne now rock groyne, known as a strong point.
- As there was a risk of outflanking the original defence, the armouring was extended landward.
- Some scour starting at the tip and behind the armouring.



d) 1989

- Crenulate shaped bay has formed down-drift of the armouring.
- Scour behind the armouring.

Figure 6.5 (i) – Four of eight photographs (Panels a-d) showing outflanking and the growth of a crenulate shaped embayment down-drift of Barton-on-Sea from 1967 to 2005 (Aerial photographs from New Forest District Council and the Channel Coastal Observatory, Southampton, see Table 3.5).



e) 1993

- Rock armouring extended 60m down-drift in early 1990s.
- The initial crenulate shaped bay has enlarged.



f) 1997

- A set-back is seen on the cliff base at the end of the armouring, but no crenulate shaped bay has started to form on the cliff top.



g) 2001

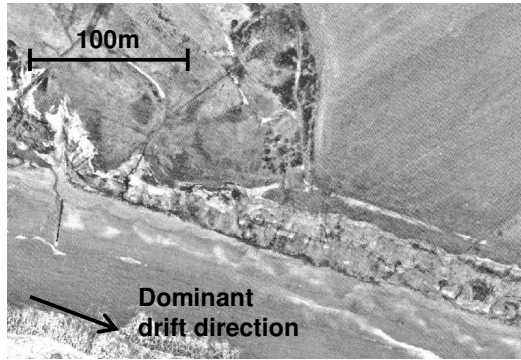
- A second crenulate shaped bay has formed on the cliff top down-drift of the rock armour extension.
- Scour has started to occur behind the rock armouring.
- This new crenulate shaped bay has enlarged and migrated up-drift.



h) 2005

- Set-back and crenulate shaped embayment has continued to enlarge inland.
- Scour and erosion has continued at the cliff base.

Figure 6.5 (ii) – Four of eight photographs (Panels e-h) showing outflanking and the growth of a crenulate shaped embayment down-drift of Barton-on-Sea from 1967 to 2005 (Aerial photographs from New Forest District Council and the Channel Coastal Observatory, Southampton, see Table 3.5).



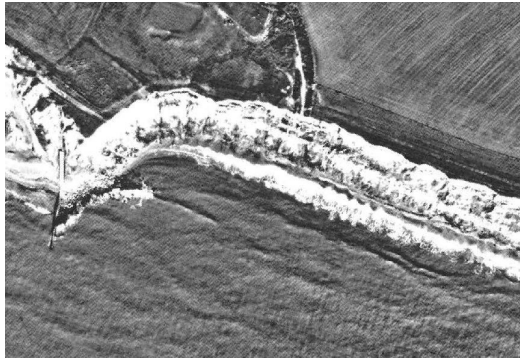
a) 1967

- Unprotected pipe at Becton Bunny.
- Straight shoreline.



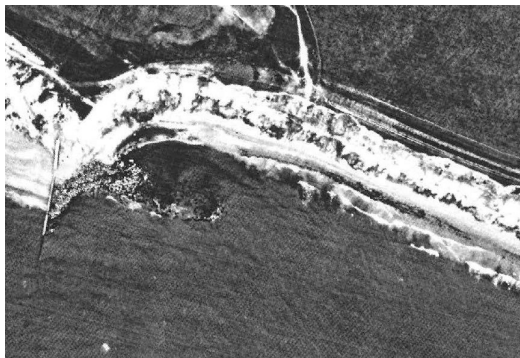
b) 1977

- Pipe replaced and rock armouring placed parallel to the coastline for 90m.
- Coastline set-back at end of rock armouring, the first sign of a crenulate shaped bay.



c) 1984

- The crenulate shaped bay at the end of the rock armouring has enlarged.
- Scour has started to occur behind the rock armouring enlarging the crenulate shaped bay up-drift. The original crenulate shape can still be seen.



d) 1989

- Scour has continued behind the rock armouring, enlarging the crenulate shaped bay.

Figure 6.6 (i) – Four of eight photographs (panels a-d) showing outflanking and the growth of a crenulate shaped embayment down-drift of Becton from 1967 to 2005 (Aerial photographs from New Forest District Council and the Channel Coastal Observatory, Southampton, see Table 3.5).



e) 1993

- Set-back and embayment has enlarged behind the rock armouring.
- Distance between the rock armouring and cliff base stands at approximately 30m.
- If cliffs had continued to erode, the outfall would have been outflanked.



f) 1997

- Rock armouring has moved against cliff.
- Small indentation on cliff base due to scour and lower beach levels.



g) 2001

- Erosion at cliff base has enlarged at end of armouring.
- Scour has started to occur behind the rock armouring.
- This was at a slower rate than 1977.



h) 2005

- Scour and erosion has continued at the cliff base.
- The cliff top has started to erode as the crenulate shape has enlarged and migrated down-drift.

Figure 6.6 (ii) – Four of eight photographs (panels e-h) showing outflanking and the growth of a crenulate shaped embayment down-drift of Becton from 1967 to 2005 (Aerial photographs from New Forest District Council and the Channel Coastal Observatory, Southampton, see Table 3.5).

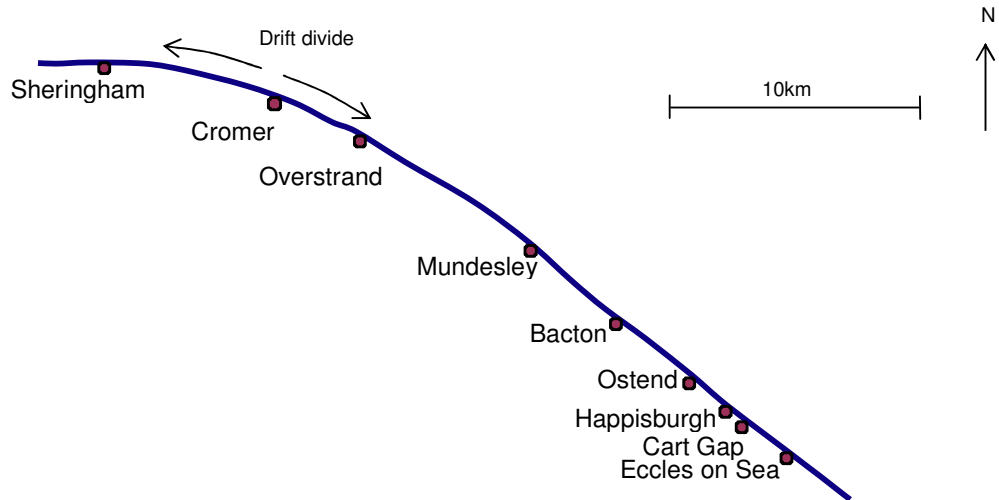


Figure 6.7 – Localities in Norfolk. The drift divide west of Cromer is also illustrated.

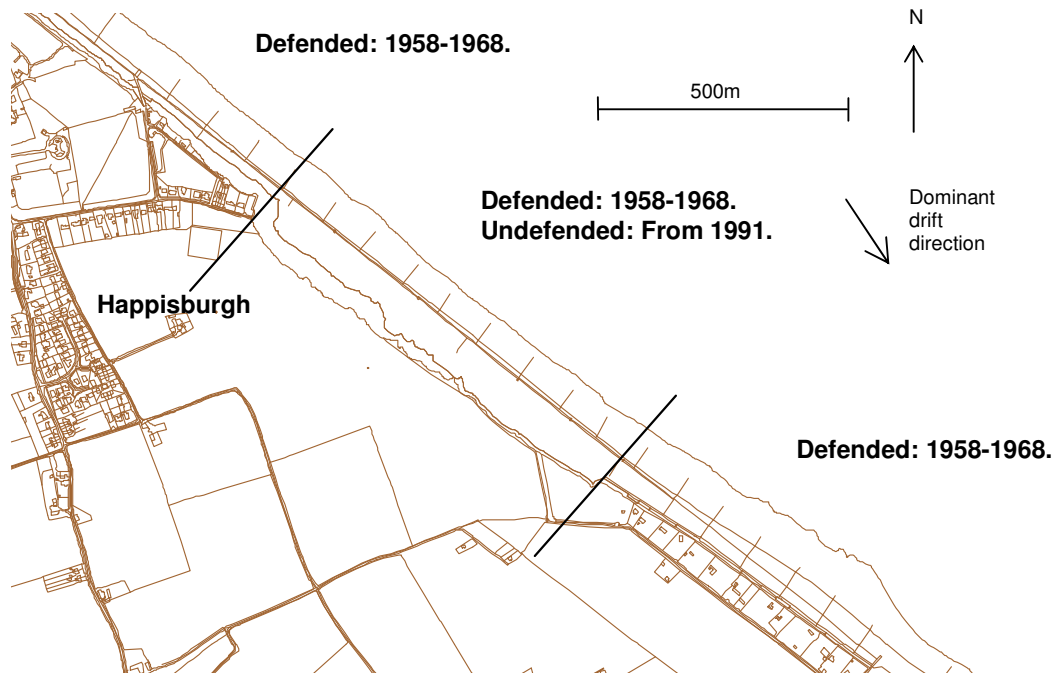


Figure 6.8 – Defence construction and abandonment at Happisburgh.

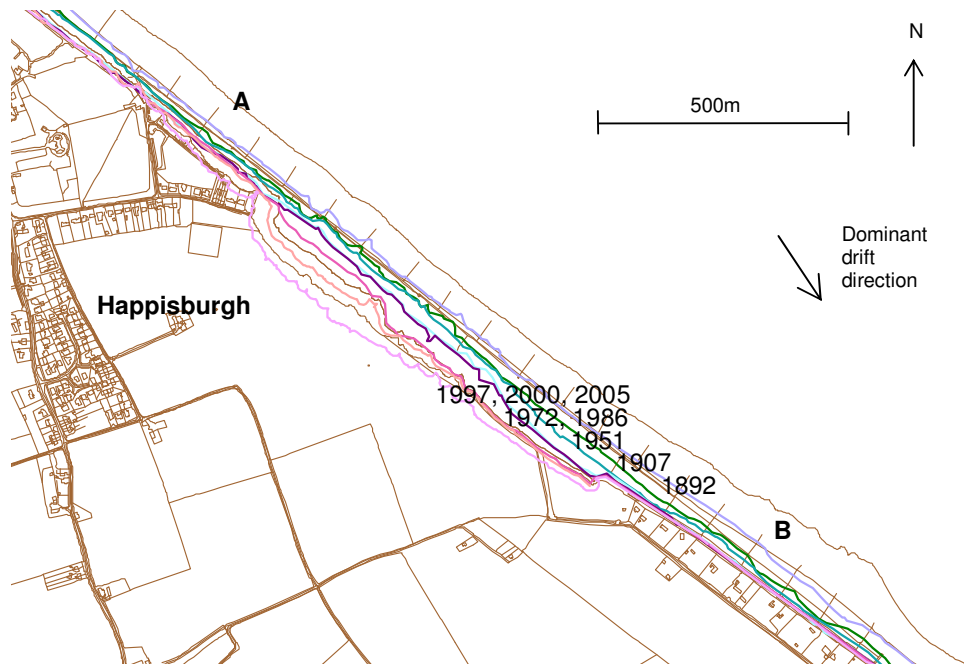


Figure 6.9 – Cliff top positions from 1892 to 2005 at Happisburgh. Cliff defences reduced retreat between 1951 and 1991. A and B refer to the coastal positions on Figure 6.10.

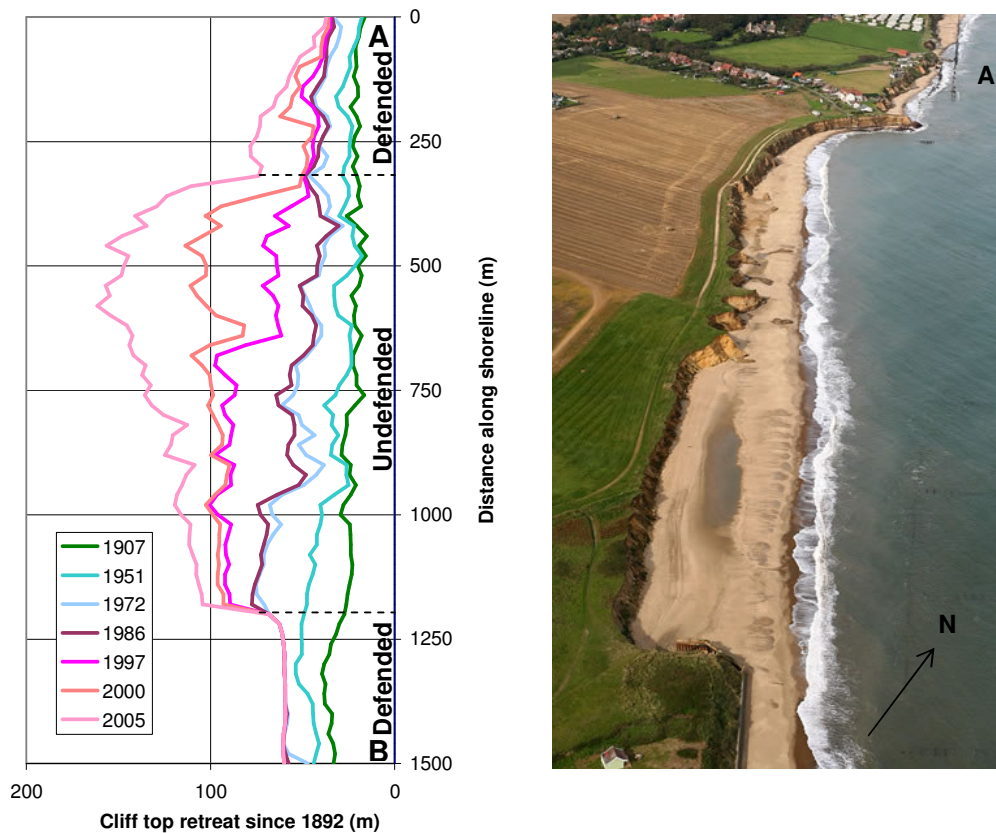


Figure 6.10 – Bay formation at Happisburgh, The cross-shore scale is stretched 3.7 times horizontally compared to the longshore scale. For reference points see Figure 6.9. A bay was created after 1986. Set-back appears less at the down-drift end on the graph due to initial cliff top position. Photograph taken by Mike Page on 12th October 2006.

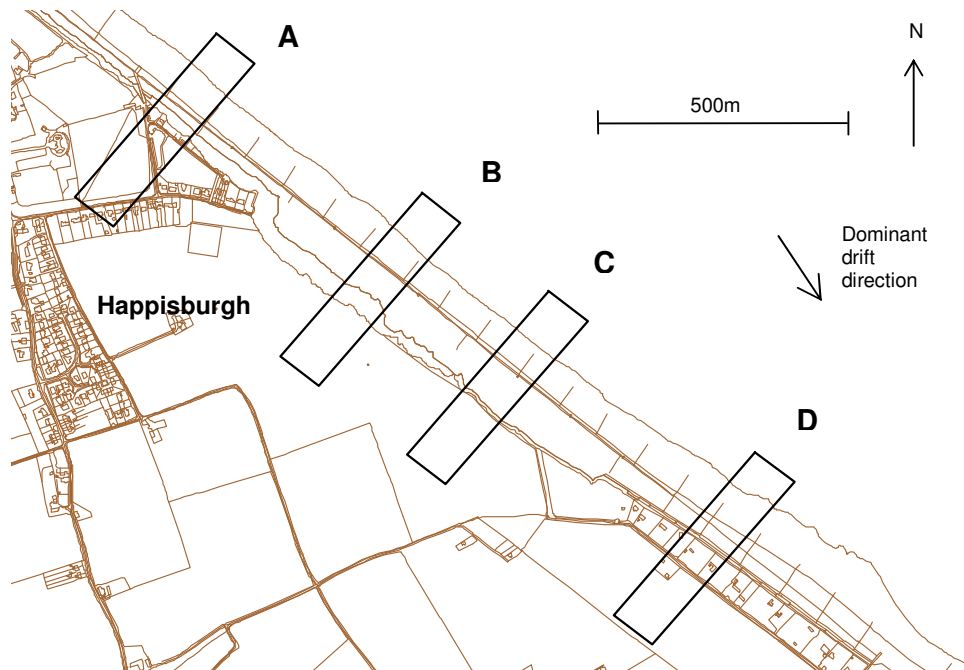


Figure 6.11a – Position of average retreat profiles at Happisburgh. Profiles are 100m wide and located 200m up and down-drift of the undefended shoreline, and in the middle of the undefended shoreline.

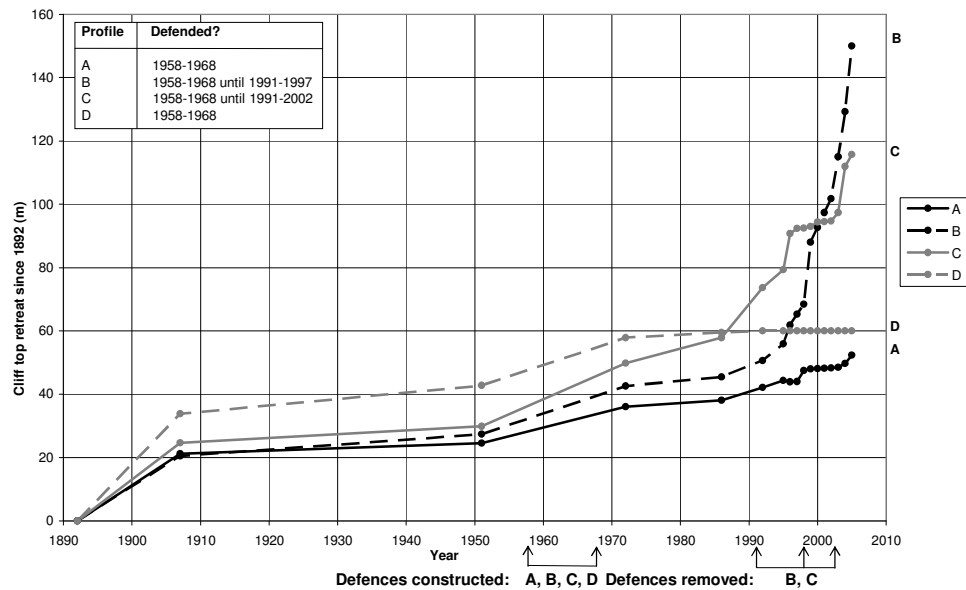


Figure 6.11b – Retreat profiles at Happisburgh from 1892. Retreat rapidly increased due to defence degradation after 1991. For profile location, see Figure 6.11a.

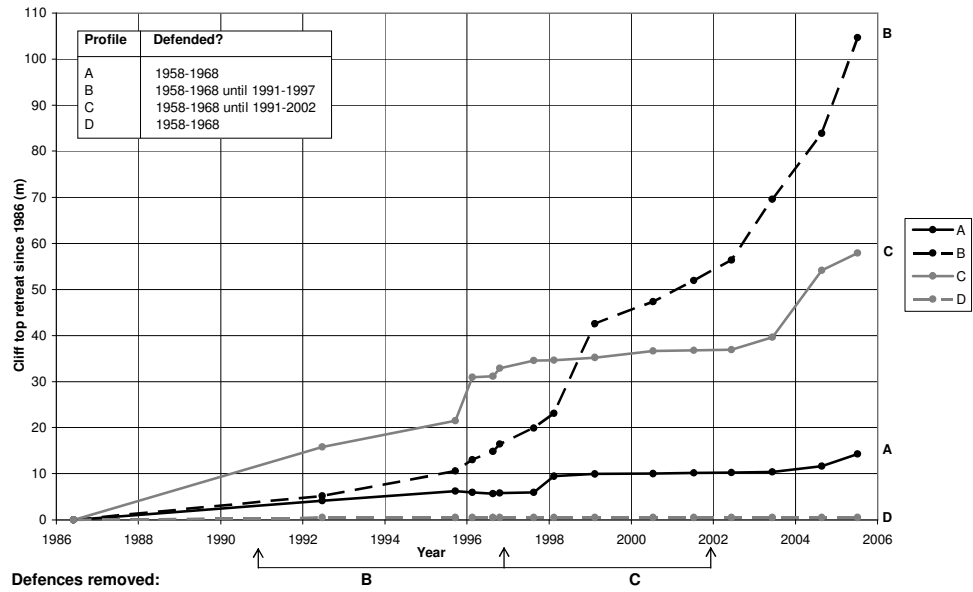


Figure 6.11c – Retreat profiles at Happisburgh from 1986 (the nearest year prior to defence removal). For profile location, see Figure 6.11a.



Figure 6.12 - Up-drift defence outflanking at Happisburgh. This defence is situated at the down-drift end of the set-back, thereby creating an 'initial groyne effect'. Drift direction is from left to right of the figure. Photograph taken 16th August 2006.



Figure 6.13 – Abandoned groynes and revetments at Happisburgh. Some of these defences are not visible when it is high tide, so pose a danger. Other abandoned defences are much more subtle, and protrude out of the beach by only a few centimetres. Photograph taken 16th August 2006.



Figure 6.14 – Abandoned World War 2 scaffolding at Milford-on-Sea, Christchurch Bay. Now located in water between the beach and the offshore bar, it raises the issue of safety of abandoned defences. Photograph taken 10th March 2005 by Ian West (West, 2008).

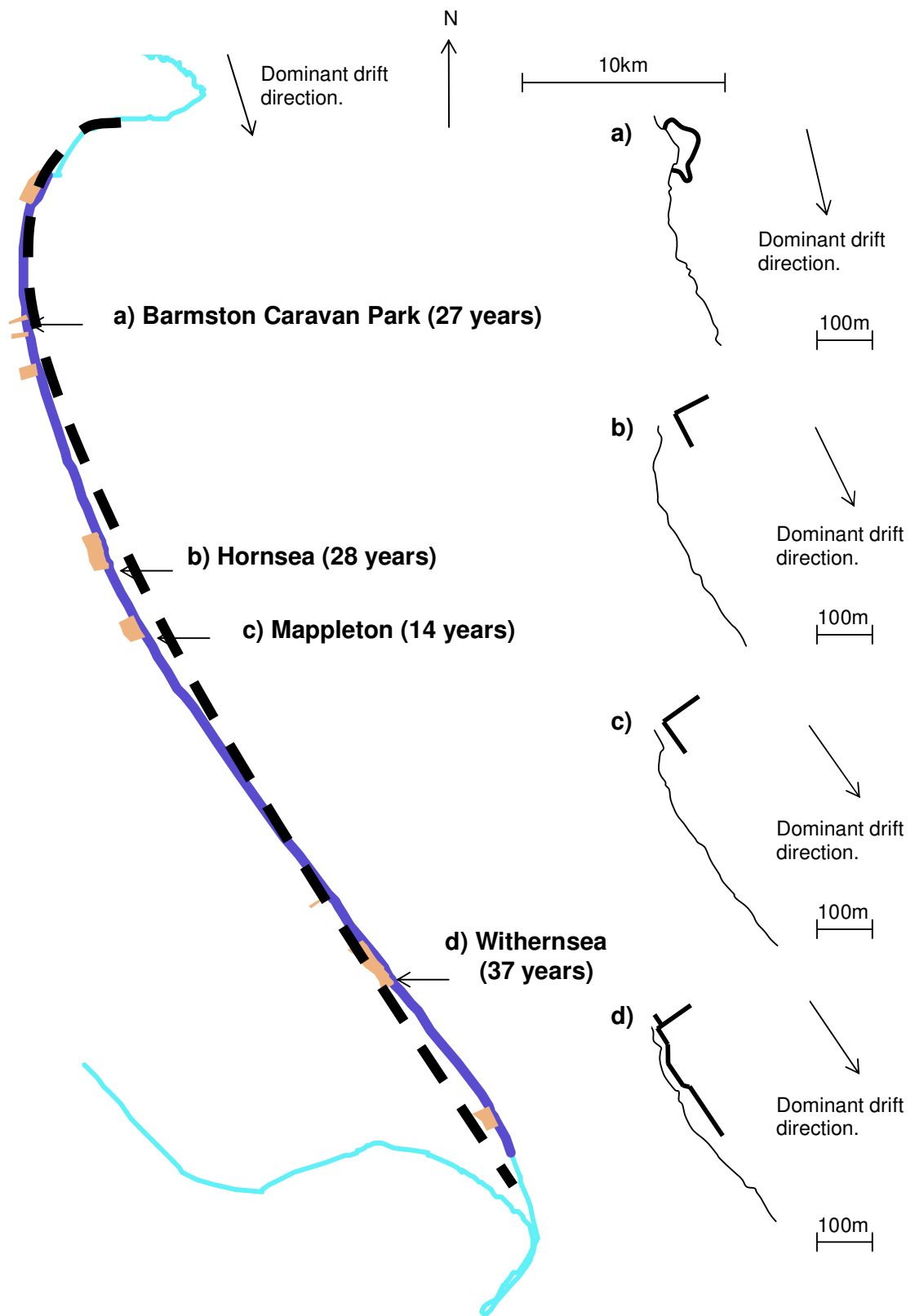


Figure 6.15 – Planform of the Holderness coast in 2005 compared to a parabola, a typical shape of a one headland bay. The artificially created bays (showing time since formation) of Barmston Caravan Park, Hornsea, Mappleton and Withernsea on the right of the figure also form parabolas. The thin line represents the cliff top and the solid line the defences.

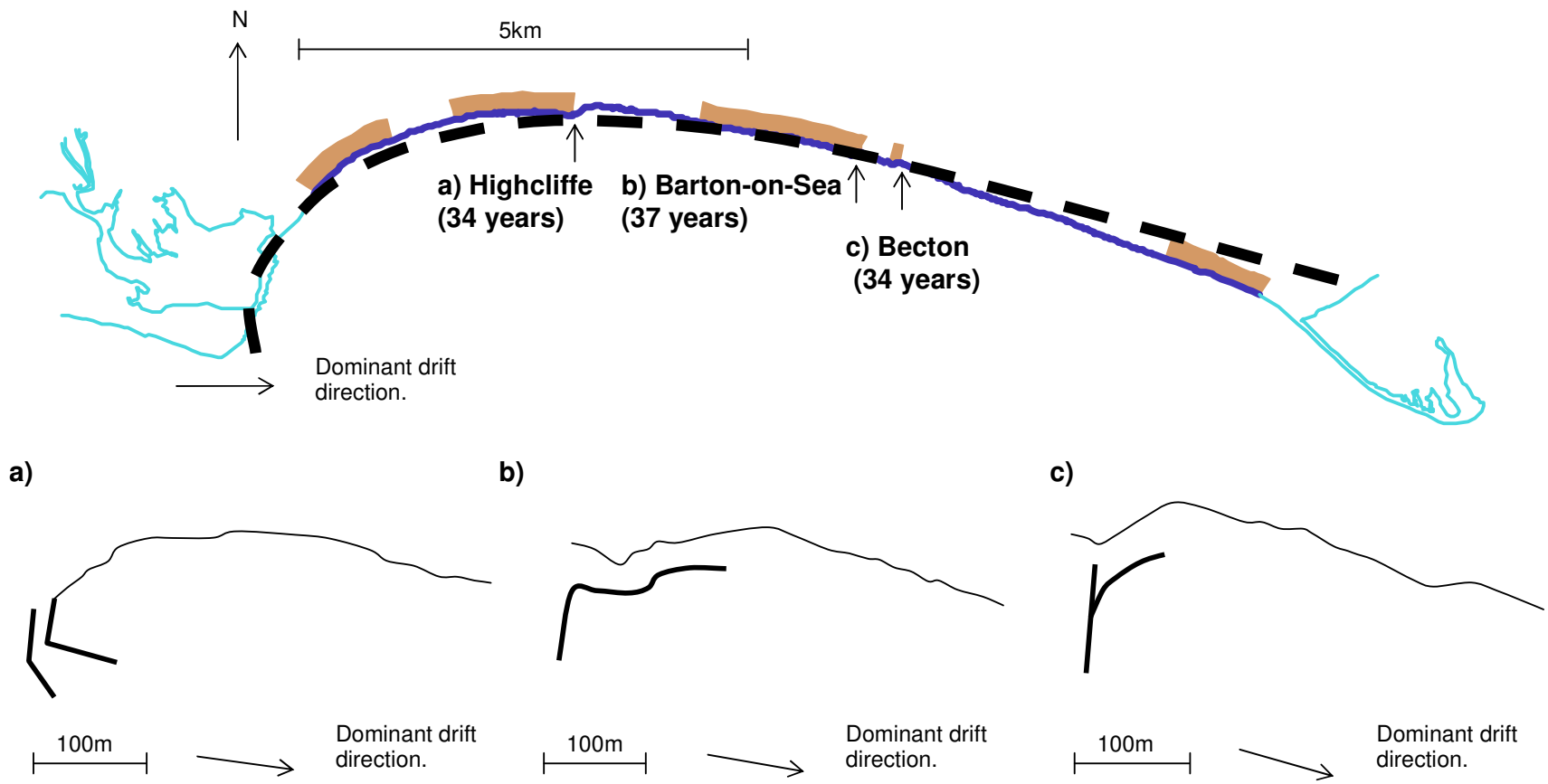
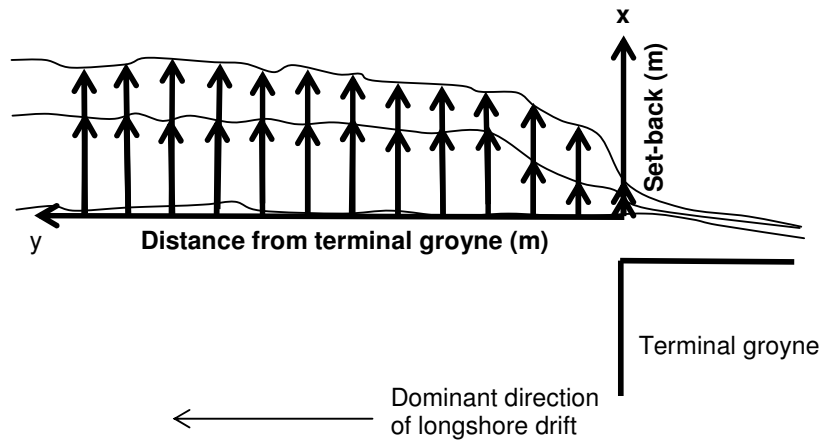
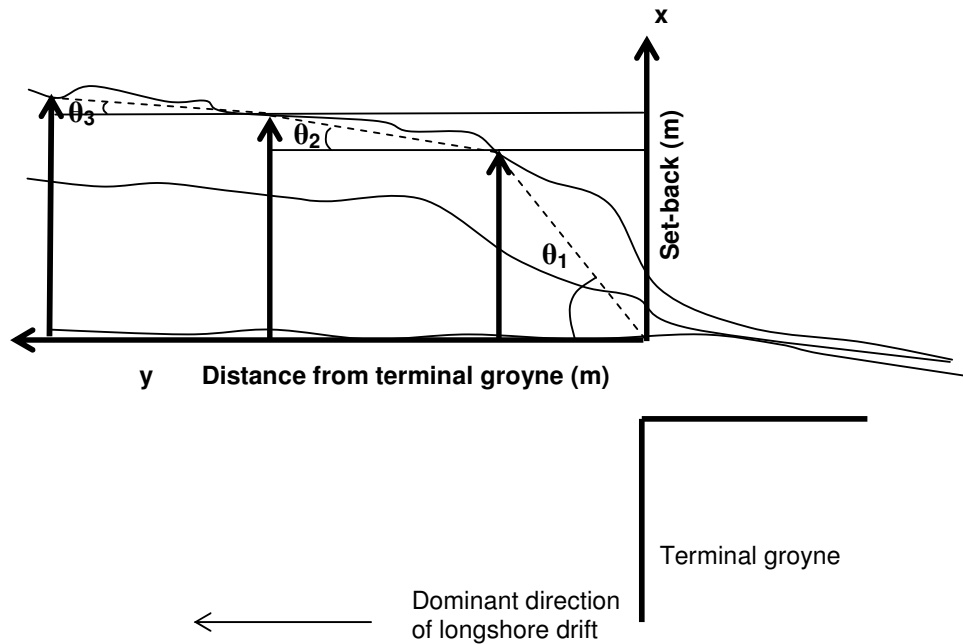


Figure 6.16 – Planform of Christchurch Bay in 2005 compared to a parabola, a typical shape of a one headland bay. The artificially created bays (showing time since formation) of Highcliffe, Barton-on-Sea and Becton also form parabolas. The thin line represents the cliff top and the solid line the defences.

a) Stage 1: Measure longshore and cross-shore set-back.



b) Stage 2: Calculate angle of planform between each transect.



- 1) Measure set-back distance (x axis) at 10m intervals down-drift (y axis) for each smoothed cliff top position.
- 2) Calculate angle from with respect to previous transect.
- 3) When $d\theta/dy = \text{constant or zero}$, this indicates the end of the shadow zone.

Figure 6.17 – Shadow zone measurements for typical cliff set-back and bay formation. Calculation of longshore and cross-shore extent of shadow zone.

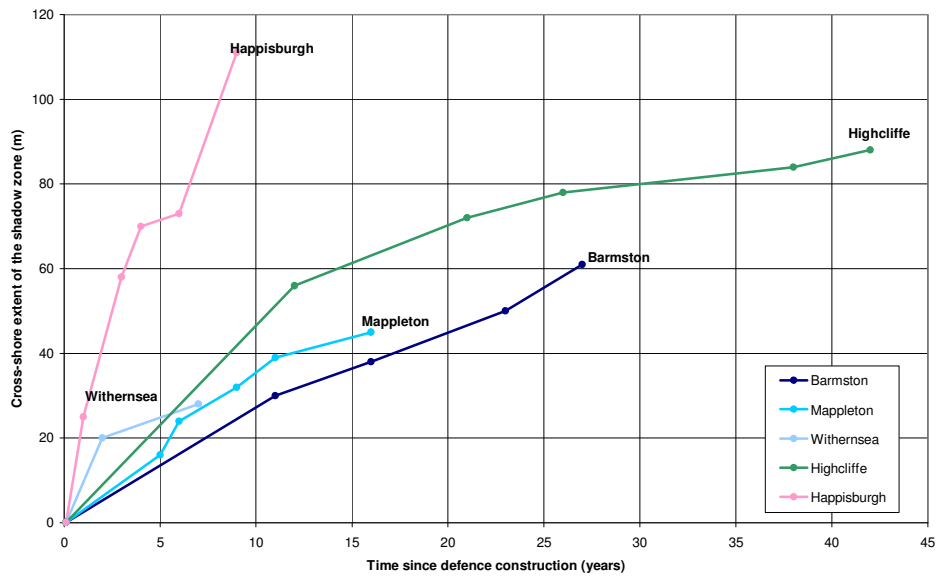


Figure 6.18 - Cross-shore extent of shadow zone. The results tend towards a linear trend, as shown in Chapters 4 and 5.

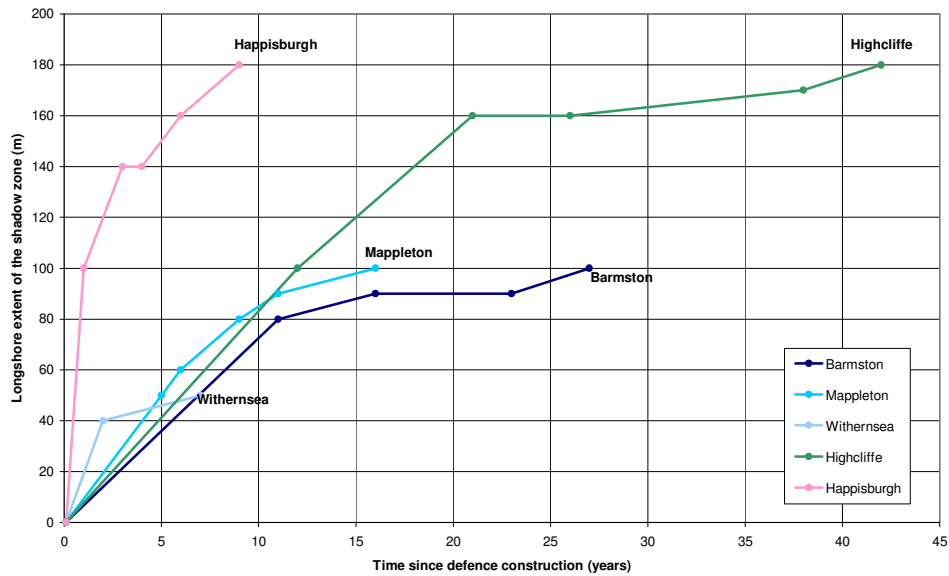


Figure 6.19 - Longshore extent of shadow zone. The longshore growth of the shadow zone tends to follow a natural logarithmic relationship with time.

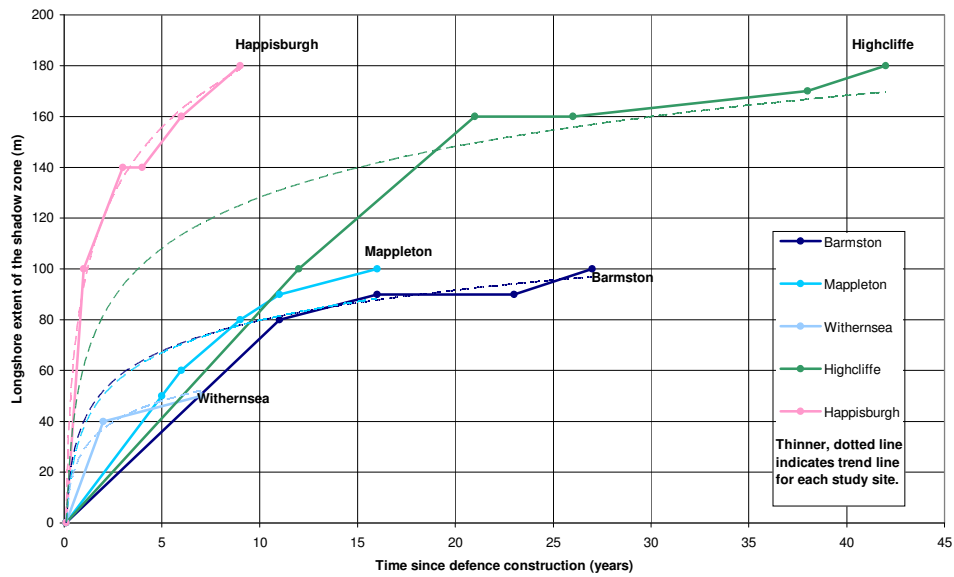


Figure 6.20 - Longshore extent of shadow zone and regression lines. Regression lines fit well over long time spans.

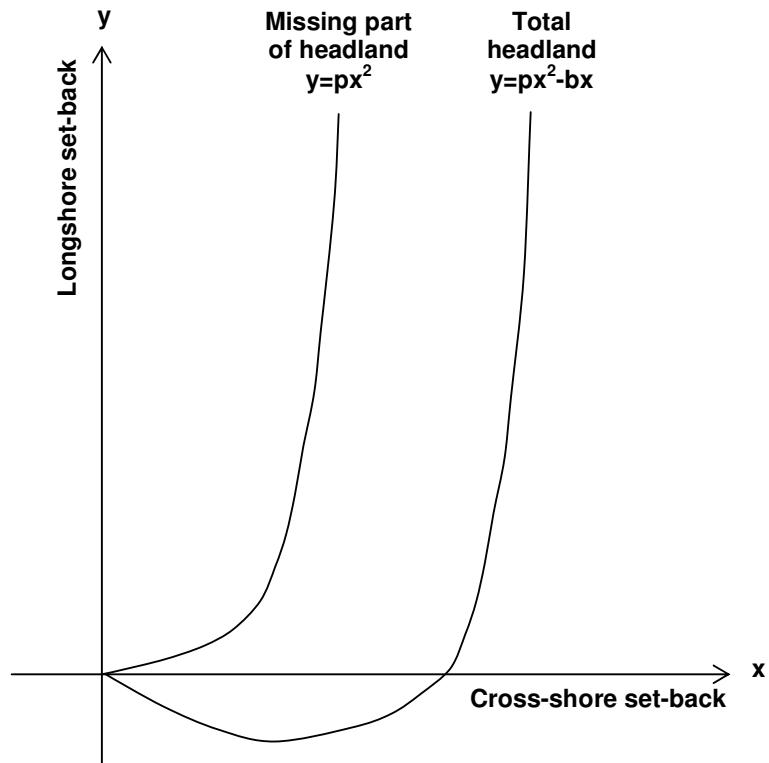


Figure 6.21 – Parabolic equations and bay planforms. $y=px^2$ (Equation 6.2) misses part of the headland and does not take account of outflanking. $y=px^2-bx$ (Equation 6.3) provides a better fit for natural and artificial bays.

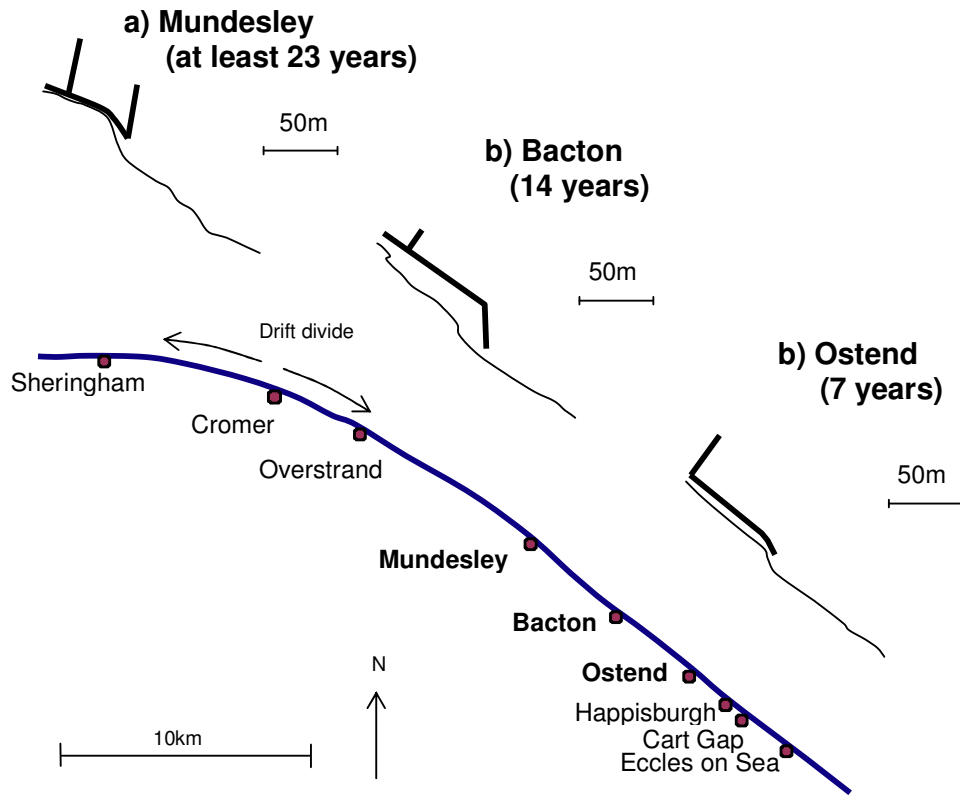


Figure 6.22 - Artificial bays forming in Norfolk. a) Mundesley, b) Bacton, c) Ostend. Bold lines indicate groynes, seawalls and revetments. Thinner lines indicate the cliff top. The defences on each coast were later extended, so the bays are now limited in growth. The bays form a parabolic shape despite forming on a headland. Dates of defence ascertained from North Norfolk District Council (1979, 1989).

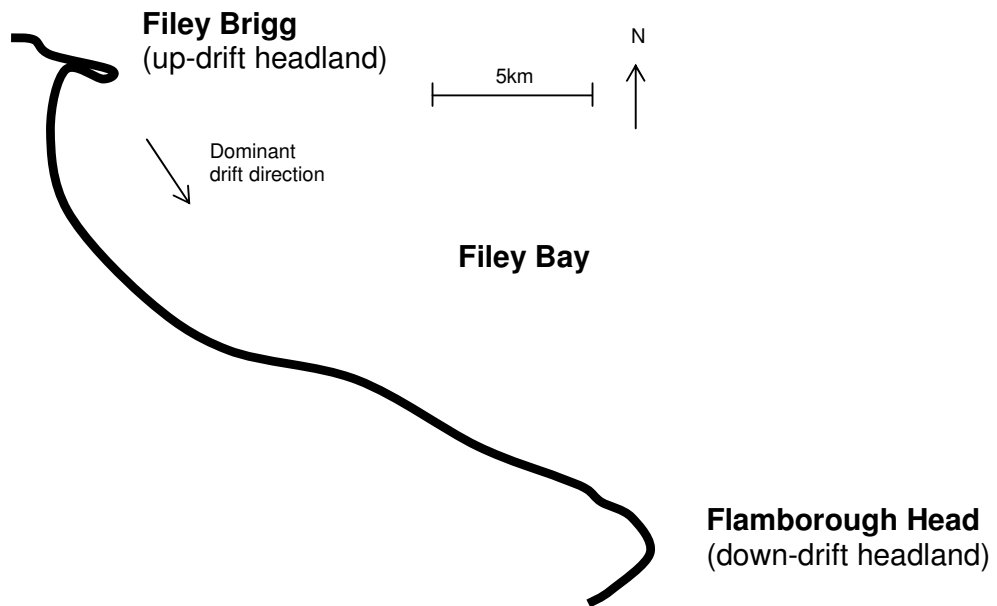


Figure 6.23 – Filey Bay has an up-drift headland and a down-drift headland, both of which act as boundaries to sediment transport.

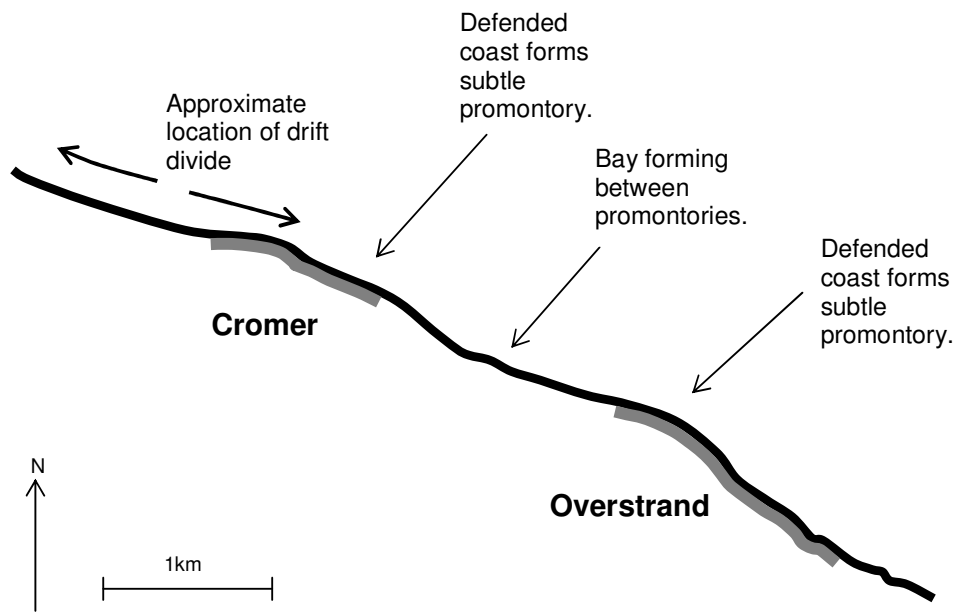


Figure 6.24 – Promontories forming at Cromer and Overstrand. Cromer and Overstrand have been defended for over 100 years causing the adjacent cliff to become set-back forming a shallow bay. The thick grey line indicates the limit of seawall or revetment frontage in 2005.

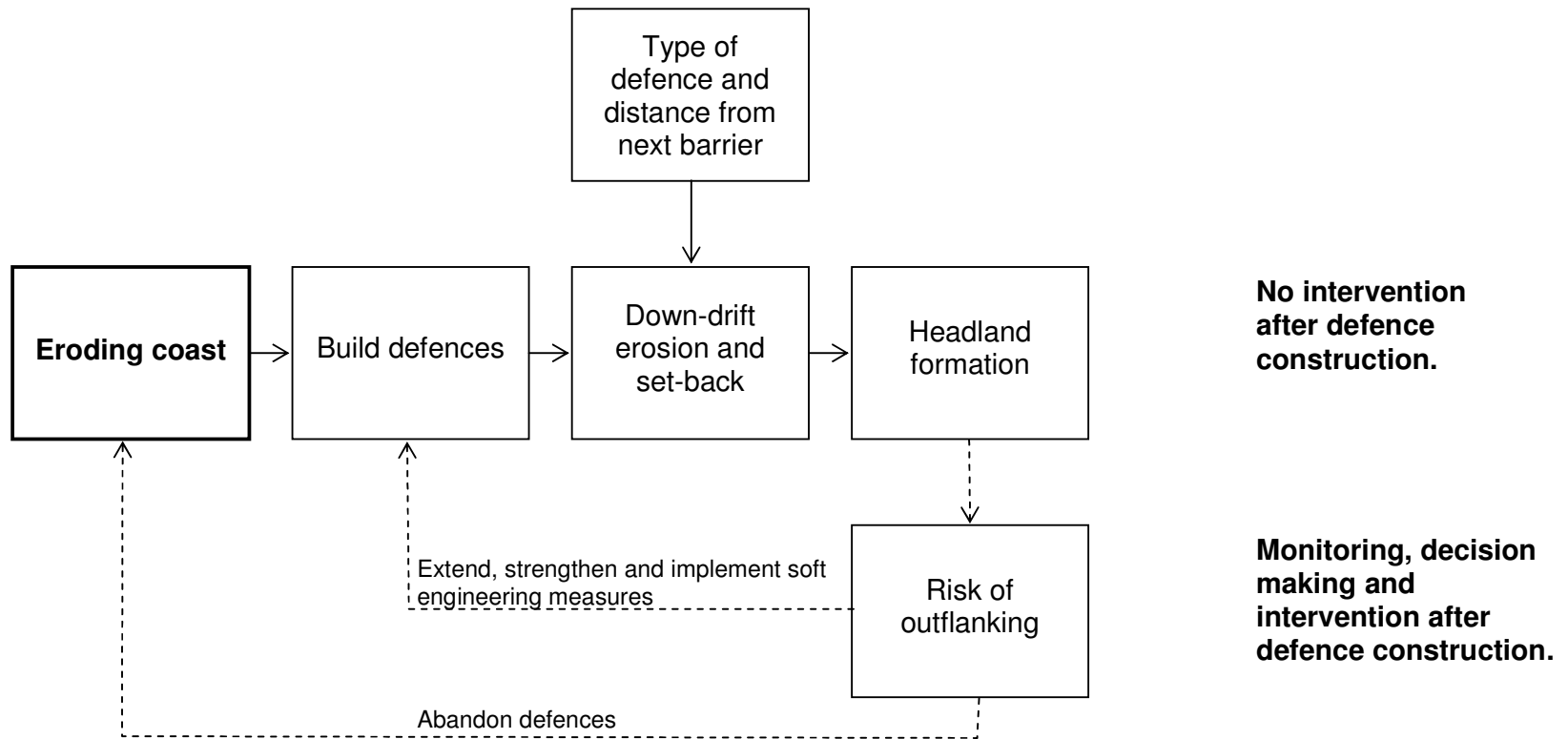


Figure 6.25 – The development of outflanking, abandonment and bay growth. On an eroding coast (starting point), defences are built and the down-drift coastline becomes set-back. The set-back is partially controlled by the type of defence and its distance from the next barrier.

Table 6.1 – Summary of the results for Happisburgh.

	Studied coastline	
Average retreat rate from 1892 to 1951 (m/yr)	0.5±0.4	
Average predicted retreat in 2005 with respect to 1892 (m)	60±38	
	Profile B	Profile C
Observed retreat in 2005 with respect to 1892 (m)	105±12	58±12
Excess retreat in 2005 (m)	45±50	-2±50

Table 6.2 - Outflanking solutions for the study sites at Holderness and Christchurch Bay.

Study site	Outflanking solution
Barmston Caravan Park	No outflanking problems.
Hornsea	Three additional groynes constructed at end of defences. Ineffective and later removed. Outflanking structure constructed, consisting of a groyne and shore parallel defence and not connected to the main defences. Although strengthening and maintenance was required, the structure has been successful in inhibiting outflanking of the main defences.
Mappleton	Designed for outflanking to occur around terminal groyne and revetment.
Withernsea	Rock armouring extended down-drift parallel to the cliff on four occasions. The seawall is now protected, but cliff erosion and outflanking of the armouring continues down-drift. A beach breakwater was also added down-drift of the terminal groyne, but this was under designed and later removed.
Highcliffe	Bastion constructed around Chewton Bunny. To date, successful as no major changes to defence required. Major beach replenishment to create beach between rock groynes to protect timber revetment.
Barton-on-Sea	Rock armouring extended down-drift parallel to cliff on two occasions.
Becton	Rock armouring moved inland on one occasion.

Table 6.3 – Outflanking solutions in other localities.

Location	Defence type	Problem and initial defence	Solution	Outcome	Reference
Sylt, Germany.	Seawall.	70m long seawall constructed in 1907 to prevent erosion.	Seawall extended.	Continued erosion and beach lowering led to toe protection and armouring and 3km long seawall by 1987.	Dette and Gärtner (1987).
Norderney, Germany.	Seawall.	Seawall built between 1857 and 1858 to prevent erosion.	Seawall extended.	Helped hold the existing beach, but nourishment also required.	Kunz (1987).
Ofir-Apúlia, northern Portugal.	Revetment and rock groynes.	Revetment built in front of hotel to prevent erosion.	Extended revetment and construction of groyne down-drift.	Revetment extended again to cover whole of hotel frontage and further groynes constructed, shifting the terminal groyne effect down-drift.	Granja and Carvalho (1991, 1995).
Sandringham, Melbourne, Australia.	Rock groynes.	Groyne constructed in 1990 to inhibit erosion of beach.	Second groyne constructed in 2006.	Previously stable adjacent cliff started to erode, and led to the building of a second groyne in 2006, with a third being proposed.	Stephenson (2007).
Smith Point, Virginia.	Groynes.	Terminal groyne becoming outflanked.	Spur constructed at 90° to terminal groyne pointing down-drift.	Created a lower energy environment and trapped sand, thus protecting the terminal groyne.	Anderson <i>et al.</i> (1983).
Edisto Beach, South Carolina.	Wooden groynes.	Access road to beach threatened leading to groyne construction between 1948 and 1949.	Additional groynes built in 1954 commencing up-drift to down-drift with no nourishment.	Severe erosion. Groyne field extended on eight occasions since 1954, including nourishment within the groyne field. Over longer timescales, the down-drift coast relies on a supply of sediment from up-drift, so replenishment constantly required.	Kana <i>et al.</i> (2004).

Table 6.4 – Regression lines for the growth of the longshore extent of the shadow zone.

Study site	Equation of trend line	R ²
Barmston	$y_s = 17.3 \ln(t) + 39.8$	0.96
Mapleton	$y_s = 18.4 \ln(t) + 37.4$	0.91
Withernsea	$y_s = 12.0 \ln(t) + 28.3$	0.99
Highcliffe	$y_s = 29.0 \ln(t) + 61.5$	0.94
Average	$y_s = 19.2 \ln(t) + 41.8$ $y_s = a \ln(t) + 2a$	0.95
Happisburgh	$y_s = 39.0 \ln(t) + 92.9$ $y_s = a \ln(t) + 2.4a$	0.99

7. DISCUSSION

7.1 Introduction

As a world-wide phenomenon coastal erosion has increased and accelerated along cliffed coasts, with human intervention being one of the major causes (see Section 4.2.2 and 5.2.2). The aim of this thesis was to investigate the impact of the terminal groyne effect and shoreline evolution with particular reference to the down-drift coast (see Section 1.7). The terminal groyne effect was investigated with respect to down-drift erosion rates and the evolution of the terminal groyne effect examined. Following the three objectives, set-back sites were identified (Figure 3.2). The purpose of this chapter is to further examine the terminal groyne effect and down-drift erosion including its measurement, factors affecting set-back, cross-shore and longshore extent of the phenomena, and significance of the factors for future coastline evolution and management.

7.2 The terminal groyne effect and down-drift erosion

The analysis of soft cliff retreat adjacent to coastal defences, in particular the terminal groyne effect, has been achieved through the measurement of retreat rates, planform shape, coastline evolution and consideration of the implications for future coastal engineering.

7.2.1 Measurement and factors influencing the terminal groyne effect

7.2.1.1 Measuring the terminal groyne effect

The terminal groyne effect is associated with a set-back and increased erosion down-drift, measured in cross-shore and longshore dimensions (see definition in Section 1.6 and Glossary). It is difficult to define the position of maximum cross-shore set-back down-drift, as many factors other than the influence of the defences affect cliff top retreat (see Chapter 2). Four parameters, defined in Section 3.9.1, measured the terminal groyne effect, and each metric determines a different aspect of down-drift erosion:

- a) Cross-shore retreat and set-back after defence construction;
- b) Cross-shore and longshore excess retreat;
- c) Percentage increase in retreat rates;
- d) Comparison of retreat rates before and after defence construction.

Table 7.1 documents the advantages and disadvantages of these methods. The most useful measure of the terminal groyne effect within a study site is cross-shore set-back. This provides a clear measure of change that can be expressed in cross-shore and longshore dimensions. A comparison of retreat rates can work well, but only over intervals of at least 15-20 years so short noise of the data set is reduced (see Section 2.2.4). When comparing study sites, excess retreat is a useful parameter as similarities and differences can be drawn between sites. The percentage increase is not a useful measure, as large percentage differences do not always indicate real coastal change and can be associated with large uncertainties. Common problems from measuring set-back and the terminal groyne effect are discussed in Table 7.2. To overcome problems a set procedure was followed, errors calculated and if necessary, data omitted.

7.2.1.2 Other factors affecting the terminal groyne effect

Set-back and the terminal groyne effect are affected by many natural and artificial factors. The studies in this thesis agree with Jezard (2004) as each study site has a distinct down-drift response to engineering and management practices and other influencing factors as listed in Table 7.3. Distinguishing between these factors and the effect of defences in causing coastal erosion is critical for a thorough and accurate measure of the terminal groyne effect. This thesis has not attempted to undertake a detailed investigation into other factors that affect set-back, but these are of utmost importance for any future studies.

The terminal groyne effect is based on differences between the 'natural' retreat rate before and the induced retreat rate after defence construction over long time periods (>20 years). Whilst other studies take account of retreat rates after defence construction, some fail to acknowledge the factors which influence retreat rate before defence construction. For example, cliff, beach and nearshore mining from at least the 19th century dramatically increased retreat rates, but this is frequently ignored and/or underestimated (for example,

Valentin, 1954; Clayton, 1989; Maddrell *et al.*, 2001, 2003). In Christchurch Bay, 19th century mining and dredging also created high retreat rates, but it also led to sediment release in the early 20th century artificially lowering retreat rates before defence construction. In this thesis, many examples of beach mining finished by the 20th century. However at Sandgate, Kent, beach mining continued into World War 2 (Palmer, 1991). Past disturbances make future shoreline positions highly uncertain. Numerical modelling, given reliable parametric inputs could be a better methodology to predict shoreline position, but results may be difficult to verify given the level of uncertainty in map measurements. Uncertainty could be reduced, but not eliminated. Hence a thorough investigation of the coastal history must be undertaken to explain the causes of past retreat rates.

A high frequency of coastal storms increases erosion rates. Storms create short term noise within a long term record. Unless retreat rates are analysed over long periods of time it can lead to data mis-interpretation and erroneous conclusions (Galgano, 1998; Galgano *et al.*, 1998). An increase in wave energy was one possible reason given at the 1999 Mappleton land tribunal (Lands Tribunal, 1999), but further investigation is required into exactly how erosion was affected (Section 4.3.3).

At Warden Point, Isle of Sheppey erosion of the London Clay cliffs is cyclic with periods of large failures, followed by small slides and topples. When retreat is plotted against time on a graph, it creates a stepped appearance as shown in Dixon and Bromhead (2002). Regular records and measurements (10 in 140 years) indicate a 30-40 year cliff erosion cycle at Sheppey (Bromhead, 1979; Hutchinson, 1986). Measurements from OS maps (6 in 140 years) provide a snap-shot of cliff position. This can affect how the terminal groyne effect is calculated, and its possible mis-interpretation. A hypothetical example of the impact of cliff cycles in clay is shown in Figure 7.1. In this example, erosion cycles occur every 20 years. Map measurements of the retreat are made every 30 years. After 30 years a groyne was constructed on the coast. Although beach levels reduced down-drift, it did not affect the cliff set-back. The figure illustrates that for cliffs where large slumps occur the map measurement interval can potentially induce a false increase of retreat rates where one had not occurred. Hence regular measurements are essential.

Jeizard (2004) concluded the ability of the shoreline to respond to defences was the most important factor in controlling down-drift erosion. Secondary factors included sediment availability (controlled by the permeability and efficiency of the barrier) and coastal alignment. If an artificial headland is situated down-drift, this limits the freedom of shoreline response. In 9 out of 17 case studies, down-drift erosion is limited longshore by a hard headland (see Table 7.4 and Section 7.2.2). Down-drift headlands retain sediment up-drift reducing cross-shore retreat. Excess retreat and accelerated retreat rates decrease. Set-back originally forming a parabolic bay evolves to form a log-spiral bay. Therefore bay formation between two headlands is due to set-back down-drift of the up-drift headland, and through sediment accumulation slowing erosion up-drift of the down-drift headland. Decreased retreat rates may occur between the headlands of Cromer and Overstrand in Norfolk, but it is not clear within the uncertainty range of the data. With process based modelling, Dickson *et al.* (2007) suggest retreat rates will reduce here within 100 years as sediment is retained between headlands. In future decades, if the Becton outfall in Christchurch Bay is maintained, retreat rates could be reduced between the Becton outfall and the end of the Barton defences. This would be beneficial as outflanking to the Barton defences would be reduced (see Section 6.2.3). However, if the Becton defence becomes ineffective, a single large embayment will emerge down-drift of Barton. Retreat rates will increase between Barton and Becton Bunny. Furthermore, Galgano (1998) found on a barrier beach down-drift erosion continued through, and outflanked a groyne field 2km down-drift of Cape Spring Inlet, New Jersey. Hence, with a relatively large terminal groyne effect down-drift erosion can penetrate hard defences.

Natural features can also limit bay growth. At Becton, Christchurch Bay, the terminal groyne effect is reduced longshore due to a large beach down-drift. Sand is transported offshore, but it is probable this has minimal effect on cliff retreat (see Chapter 5). Conversely, a reduction in up-drift sediment supply (for example by up-drift defences) increases the terminal groyne effect. This is seen at Mappleton in Holderness, Barton and Becton in Christchurch Bay (Chapters 4 and 5 respectively). At Pawleys Island, South Carolina, a shoal limits the terminal groyne effect (Kana *et al.*, 2004).

Sediment availability and the direction of longshore drift are important factors controlling the cross-shore and longshore extent of the terminal groyne effect.

With localities where there is a mixed drift direction (for example, East Devon and West Dorset, see Figure 6.1), the terminal groyne effect may be less severe, and occur at both ends of the defence. However, Komar (1976) found at Tillamook Bay, Oregon, increased erosion could still occur at long distances down-drift (see Sections 2.3 and 6.2.3). With a variable wave climate, Stephenson (2007) suggests groynes may not be the preferred form of defence.

There are two theories indicating how the defence's position in the sediment cell influences the terminal groyne effect. Both theories assume sediment levels increased down-drift (see Figure 2.7). Bray (1992) indicates sediment levels increase throughout a littoral cell (Figure 2.7). If an efficient barrier was constructed at the down-drift end of the cell, it would have maximum impact on increasing retreat rates as it inhibits a greater volume of sediment than if placed at the up-drift end. This theory relates to Holderness, where there is 22km of undefended coast between Hornsea and Withernsea (Figure 4.7). Sediment builds up-drift of Withernsea. During a site visit in August 2006, beach levels down-drift were low and the shore platform was visible (Figure 4.38).

Conversely, Jezard (2004) proposed that a barrier placed at the up-drift end of a cell would have greater impact than at the down-drift end as sediment volume is already low. Retaining any more sediment would have a maximum impact on increasing erosion down-drift. Jezard's (2004) theory is more appropriate for Christchurch Bay, as the longshore extent of the terminal groyne effect is reduced down-drift as sediment volumes increase. However, it is complicated by defences located up-drift. Therefore beach levels are critical in determining the severity of down-drift erosion. Ideally beach profiles or beach volumes are a preferred data resource to analyse the terminal groyne effect, but with lack of data, cliff top positions remain the favoured approach. Therefore, there is no overall agreement as to whether the theory stemming from Bray's (1992) observations or Jezard's (2004) theory is correct, as each is location dependent.

7.2.2 Set-back and retreat rates

7.2.2.1 Set-back

When shore parallel and perpendicular defences are constructed on an eroding cliffed coast the adjacent shorelines become set-back. A higher magnitude of cross-shore set-back occurs on the down-drift coast than the up-drift coast. The

set-back of the down-drift coast frequently forms a crenulate shaped bay. Depending on the time interval measured, set-back can range from a few metres (measured over a decade) to hundreds of metres (measured over a century). Nearly all defended sites examined in Holderness, Christchurch Bay and Norfolk were set-back. Exceptions were found at the shore parallel rock armouring at Easington (constructed in 1999) and Tunstall (constructed in the early 1980s; Atkin, pers. comm., 2008) in Holderness. This is because they are not littoral drift barriers so do not retain sediment and not enough time has passed since defence construction to accurately measure set-back within the range of data uncertainty.

The terminal groyne effect is an old, ongoing problem (see Chapter 1). Almost 200 localities, half on cliffed coasts in England and Wales have a set-back adjacent to defences (see Section 3.2 and Figure 3.2). Approximately 100 sites out of the 200 are situated in the east and south-east regions of the UK. At some sites, cycles of set-back have been observed, causing defence outflanking, prompting defence extensions for over a century. Multiple set-backs lead to multiple extensions, creating an evolving terminal groyne effect. They are often fossilised and no longer erode. Multiple extensions are reported, but their implications are barely acknowledged in the academic literature, yet they are important to maintain coastal position and form the hard headland of down-drift embayments (see Section 7.2.3). Extensions are more frequent on the down-drift coastline than the up-drift coast. For example, Hornsea had one up-drift extension compared to five down-drift extensions over a 99 year period (see Figure 4.18 and Table 4.6). This occurred because a sediment deficit caused the continued or accelerated retreat down-drift, whereas sediment retained up-drift caused continued or decreased cliff retreat (see Section 7.2.3). Multiple set-backs are found elsewhere on the UK coast (a selection of prominent examples are shown in Figure 7.2), including, but not limited to, Bridlington, Cromer, Overstrand (see Figure 6.24), Mundesley, Lowestoft (Pakefield), Walton-on-the-Naze (Frinton-on-Sea), Hastings, Brighton, Bournemouth (see Figure 2.5), Lyme Regis (see Figure 2.4) and Blackpool. They can cause operational and management problems on the coast as they are more difficult to defend than the adjacent coast. At Happisburgh, Norfolk, emergency works in March 2007 extended the remaining intact defences by approximately 100m down-drift. This will create a multiple set-back and further outflanking. Set-back can be measured at different points on the headland in time and space relative

to the initial or secondary shoreline position. For example, at Hornsea, Holderness, extending the defences led to greater sediment retention increasing down-drift erosion rates between Hornsea and Withernsea from $0.9\pm 0.4\text{m/yr}$ (1854-1905), to $1.1\pm 0.4\text{m/yr}$ (1905-1952) to $1.8\pm 0.2\text{m/yr}$ (1952-2005). The rate of set-back can increase due to defence extensions and defence maintenance, as seen for example, at Withernsea after 1945 (see Figure 4.34b, Profile G).

7.2.2.2 Cross-shore retreat rates

Over a defined longshore distance, the retreat rate after defence construction can increase, remain constant or decrease with respect to the initial or natural retreat rate (see Chapters 4 and 5). A synthesis of results is shown in Figure 7.3 and Table 7.4. With large uncertainties in relative cliff top positions it can be difficult to determine which study site falls into which category (see Chapters 4 and 5). Excess retreat may occur at a site, even if the error range is greater than the recorded excess. Only 8 out of 17 case studies experienced excess retreat where the retreat exceeded the retreat data error. A further five cases probably had excess retreat (when the error range was compared to the excess), or a measured excess over a short distance. Most of these sites were constrained down-drift by a hard headland, which reduces excess retreat due to the containment of sediment between the defences. Figure 7.3a shows a 'real' and/or measurable terminal groyne effect as the cliff set-back and retreat rates accelerate causing excess retreat. In Figure 7.3b,c set-back is caused by holding the defended shoreline position and allowing erosion down-drift to continue at the same or at a decreased rate. This is an erroneous 'perceived terminal groyne effect'. 4 out of 17 case studies in Table 7.4 fall into one of these two categories.

Regardless of the relative rate of retreat, the set-back takes the form of an embayment. Where no down-drift headland is present, the bay forms a parabola. When a down-drift headland is present the set-back forms a log-spiral bay. Set-back and the terminal groyne effect are not static features, but evolve throughout time. In the first decade after defence construction retreat rates may be rapid and then decrease (Figure 6.18). The terminal groyne effect becomes more apparent with time as excess retreat increases and measurement uncertainties reduce (see Table 7.4).

Excess retreat is most likely to occur on previously undefended sites, rather than on those sites with multiple defence extensions. This is because it is the first time sediment has been retained up-drift, thus having a maximum impact down-drift. For example, retreat rates on the previous undefended site at Mappleton (see Section 4.3.3) increased from $1.7\pm 0.6\text{m/yr}$ (1952-1989) to $3.3\pm 0.8\text{m/yr}$ (1989-2005) after defence construction. In contrast, retreat rates at Hornsea were maintained at $2.6\pm 0.3\text{m/yr}$ after the fifth defence extension in 1977 (see Section 4.3.2). Similar to Hornsea, on the extensively defended and sediment starved eroding shore of Lake Michigan, building additional defences did not increase the down-drift retreat rate (Shabica *et al.*, 2004). Hence on sections of a sediment starved, heavily engineered coast, high retreat rates remain after additional defences are constructed.

In the short term (<20 years), it is unclear whether the terminal groyne effect causes excess retreat due to data uncertainties and other factors influencing retreat such as those listed in Table 7.3 (see Section 7.2.1) and those raised during the 1999 Mappleton land tribunal (see Section 4.3.3). However, over longer time periods, it is more probable that a measurable terminal groyne effect will emerge and that excess retreat will become more severe. With further research and better predictions of future cliff top retreat through process based models such as the SCAPE (Soft Cliff and Platform Erosion) process based model (Walkden and Hall, 2005), there will be an enhanced understanding via better observations and model outputs of whether excess retreat and a terminal groyne effect will occur. The result of the 1999 Mappleton land tribunal decided that retreat rates down-drift had not increased measurably during the building of, or due to the newly constructed defences (Lands Tribunal, 1999; Maddrell and Gowan, 2001). However, from a technical viewpoint, it must be recognised that defences nearly always cause excess retreat down-drift if enough time has passed. This is important as it could prompt claims for compensation when defences have been built, and for future defences where it is known defences interfere with erosional processes.

7.2.2.3 Longshore extent of the terminal groyne effect

Defences may affect erosion of the down-drift coast for tens to thousands of metres as shown in Table 7.4 and plotted on Figure 7.4. Generally, the longer a site has been defended, the greater the longshore coast is affected within its

regional setting, provided the growth is not limited by a hard or soft headland down-drift. Results are not shown for Bridlington or Withernsea on Figure 7.4. Bridlington's first defences were constructed over 900 years ago (East Riding of Yorkshire Council, 2004). As the region of influence expanded with time, it is probable it has affected retreat along most of Holderness. At Withernsea, 19th century mining prevents a full understanding of the longshore extent of down-drift erosion. Similarly at Pawleys Island, South Carolina, the terminal groyne effect was undetectable down-drift of a shoal (Kana *et al.*, 2004). Therefore, the extent of the terminal groyne effect is undeterminable where other processes dwarf the effect of sediment retention. Longshore drift rates (see Table 2.2) also affect the down-drift extent of excess retreat, providing an additional explanation into why Christchurch Bay's sites (in particularly Becton) have a lower down-drift extent than at Holderness. Galgano (1998) also found that arcs of erosion due to breakwaters at barrier beach inlets can be long and fillet like or short and intense. At first, bays grow rapidly longshore, then decrease (see Section 6.3.2 and Figure 6.19).

The terminal groyne effect expands unless natural or artificial barriers are present down-drift, inhibiting longshore growth. For example, at Becton, Christchurch Bay, a large beach slows longshore growth. At Hornsea, Holderness, where defences were constructed 1905, there was no down-drift disturbance until Withernsea (see Section 4.3.2), allowing the terminal groyne effect to influence erosion rate up to 22km down-drift (apart from Mappleton's groynes constructed in 1991 and Tunstall's rock armour protection constructed in the early 1980s). Galgano (1998) also found that on barrier beaches the arc of erosion continuously expands. Simultaneously, erosion rates decrease on the up-drift coast. Future research on the up-drift effects would provide additional information about the effect of defences (see Sections 4.4 and 5.4). A detailed comparison of the up and down-drift effects of defences on the rate of retreat would provide great insight into defence efficiency and shoreline response.

7.2.3 Coastal evolution and management

7.2.3.1 Defence problems

On an eroding coast there is a cycle of defence construction, set-back of the adjacent coastline and defence outflanking prompting defence extensions, thus creating further set-back and headland formation (Figure 6.25). Each step in this process will be examined.

Historically, man's answer to erosion has been to build hard defences. Constructing groyne does not increase the overall sediment volume, but contains it in one location. This can be detrimental to adjacent areas. Initially beach levels increase within a groyne system, but over decades beach levels can decrease due to a lack of sediment supply and availability if sediment supply continues to be constrained up-drift. Groynes cannot trap sediment, if there is none to be trapped (Craig-Smith, 1973). This leads to foreshore steepening (Leafe *et al.*, 1998; Taylor *et al.*, 2004), exposing foundations, creating scour (Pearce, 2008) and making the defences more vulnerable to wave attack. Thus defences initially benefit the coast, but can cause long term protection difficulties (Craig-Smith, 1973).

After defence construction (whether groynes or seawalls), set-back continues to occur on the adjacent coastlines causing outflanking making the extremities of the defence ineffective and promoting emergency works. The terminal groyne effect is frequently not reported on the up-drift coast, yet a perceived terminal groyne effect does occur. This is illustrated at Withernsea, Holderness (Figure 7.5). The figure shows up-drift outflanking in 1912 (Figure 7.5a) compared to the coast in 2006 (Figure 7.5b), and is perhaps best named the 'initial groyne effect'. In Withernsea, this was caused by seawalls maintaining the cliff position, but the up-drift coast continuing to erode. It is seen at all study sites, and becomes increasingly apparent with time (for example, for Hornsea, Holderness, see Figure 4.18 and Table 4.6). Numerous outflanking solutions have been designed (see Tables 6.2 and 6.3). The terminal groyne effect and associated outflanking are frequently and incorrectly viewed as problems with simple solutions. For example, Russell (1960) and Poff *et al.* (2004) suggest semi-permeable groynes as a solution to reduce or eliminate outflanking, but on an eroding coast, set-back will continue regardless of what sediment can penetrate

the groyne field. Each solution is site specific and depends on environmental and defence conditions.

7.2.3.2 Headlands

Headlands will only form if shoreline positions are retained and defences are not outflanked to a state that they become ineffective. This is important as over tens to thousands of years a series of headlands and stable bays develop, given availability of sufficient beach material. (for example, Barrett and Andrews, 1991 described this process at Holderness). To overcome outflanking, defences are extended, creating multiple set-backs (see Section 7.2.2 and Figure 6.25) leading to headland formation. A typical headland is composed of a long shallow down-drift flank with multiple extensions, and a short sharp up-drift flank, relative to the initial defence position. Headland formation is also controlled by relative retreat rates. For example, although of a similar age, the headlands of Cromer and Overstrand (Figure 6.24) are more pronounced than at Hornsea and Withernsea (Figure 7.6). This is because high levels of retreat occurs both sides of Cromer and Overstrand due to their proximity to each other (that is, Cromer's terminal groyne effect increases erosion down-drift as does Overstrand's defences), whereas erosion is reduced up-drift of Hornsea and Withernsea due to sediment retention. Therefore headlands form by holding cliff top position and allowing the retreat rate on the adjacent coast to increase, remain constant, or decrease. Retreat rates within the defences are reduced or stopped (when seawalls are built into the cliff). It is the relative relationship between the retreat rate on the adjacent undefended coasts that create a symmetrical (Cromer or Overstrand) or asymmetrical (Hornsea or Withernsea) headland. The key aspect of whether a headland is symmetrical or asymmetrical is determined by the relative rate of up-drift erosion. A summary of headland formation and retreat rates is shown in Table 7.5.

7.2.3.3 Future coastal management

Ward (1922) and Valentin (1954) were two of the first scientists to recognise that the building of defences would lead to sediment starvation and headland formation making coastal protection increasingly difficult and costly (Townend and Burgess, 2004). Today, defence extensions are not such a desirable option to overcome the terminal groyne effect due to costs, a shift from hard to soft

coastal engineering and the desire to work with nature (Leafe *et al.*, 1998). The need to follow nature's steps in coastal engineering is not a new idea in order to create a sustainable shoreline (Charlier *et al.*, 2005). New defence schemes and improvements to existing ones can complement nature by natural headlands being used or augmented with artificial headlands or other defence works. For example, at Castle Cove, Isle of Wight, breakwaters were constructed at either end of the bay to create a contained bay system (Clark and Fort, 2000). A balance is required between protecting essential land such as residential and business areas and allowing less valuable land to erode. This provides beneficial sediment to protect the coast, reducing erosion and flood risk. With climate change and sea level rise this is particularly important (Dawson *et al.*, 2007). Indeed, Dickson *et al.* (2005, 2007) found that there was increased sediment availability in Norfolk when the coast was less heavily managed than today. Furthermore, where a high rate of sea level rise is predicted, some sectors of the coast will have decreased erosion rates as they benefit from additional sediment provision up-drift.

One way to work with nature is to reproduce its processes and outcomes. Silvester (1960) deduced that bays tend to a stable position and shape between two fixed headlands. For bays in formation, headlands also evolve and migrate (Wright, 1981). Subsequent work by Silvester, Hsu and others (see Sections 2.5 and 2.6 and Appendix 1) indicated that log-spiral and parabolic bay theories need a down-drift headland to form a stable bay. However, poor understanding and lack of data availability limits our total understanding of how headland-bay systems form (Craig-Smith, 1973; Saito *et al.*, 1996; Evans *et al.*, 2004). For bays still in formation, the down-drift headland frequently does not constrain retreat rates. Until this point is reached, the longshore length of the shadow zone can be predicted as the natural log of the time since defences were constructed (see Section 6.3.2 and Equation 6.1). However once the terminal groyne effect is constrained by the down-drift headland, the theory fails and the shadow zone is limited in growth. Subsequently retreat rates decrease adjacent to the down-drift headland. With time sediment builds between headlands, but for artificial bays, replenishment may also be required to reduce erosion. Other problems in creating artificial stable bays include the continual maintenance of headlands and knowledge of how bays respond to potential changes in wave direction, and hence drift direction (Reeve *et al.*, 2003).

With greater instability down drift due to coastal structures and climate change, there will be increased landsliding (Brown and Barton, 2007). Older landslide systems will be reactivated, such as those at Scarborough in north Yorkshire, Overstrand in Norfolk and Castle Cove on the Isle of Wight (Clements, 1994; Clark *et al.*, 1996; Clark and Fort, 2000). At Blackgang, Isle of Wight, the exposure of cliffs over several centuries has led to recurrent problems of instability, with less frequent major landslides occurring during extreme wet winters (Clark *et al.*, 1996). With climate change and continuous erosion, systems require monitoring and cause and effect relationships identified and managed effectively. For example, Townend and Burgess (2004) reported a link between changing climatic conditions and the effectiveness of defence stability and performance to withstand wave action. Landslides, particularly those vulnerable down-drift of defences, need to be monitored and localities identified that are prone to movement (see Section 2.2.4). This is especially important where there is a significant human impact and concern for the local community or a planned development (Clark *et al.*, 1994).

Strategic Shoreline Management Plans have integrated shoreline planning, reducing local and *ad hoc* defences (Leafe *et al.*, 1998). Therefore, in the UK new occurrences of the terminal groyne effect will be less common than in the past. However, as defence abandonment becomes more frequent there will be stages of defence fragmentation. This will create a new form of the terminal groyne effect as some defences are maintained whilst others are removed, such as at Happisburgh, Norfolk. How defences are abandoned will influence if, when, where, the frequency, and severity of the terminal groyne effect. The North Norfolk Shoreline Management Plan (Kelling to Lowestoft Ness Shoreline Management Plan, 2006) fails to provide insight into which defences will fail first and how this will create a terminal groyne effect. Future defence outflanking is not taken into account. For example, when constructing defences, Galgano (2004) stated groynes should be built from down-drift to up-drift to minimise the excess retreat on the down-drift coast. Hence it can be argued that defences should be abandoned from the up-drift to the down-drift direction. This may be beneficial in the long term, but Dickson *et al.* (2007) propose that defences should first be abandoned in areas of low land value. Ideally, in north Norfolk a mix of these approaches is required, creating a balance between loss of valuable land, sediment availability and time for engineers and scientists to gain experience and understanding to improve predictions of coastal response and

defence removal. By removing defences, there will be areas of intense increased erosion, potentially for several decades. Already there is controversy over the loss of land, and this will be of increasing concern to residents. Even when retreat rates reduce, erosion and outflanking will continue and appropriate designs at the end of structures will be required (see Hornsea's outflanking structure, Section 4.3.2 and Figure 4.20), even as an intermediate stage between stages of abandonment.

The general public frequently regard defences as permanent solutions to erosion (Carter, 1988). With a dynamic coastline defences only provide temporary solutions to reducing erosion. Defence abandonment is not a new process (see Section 6.2.3) and is part of the life cycle of coastal defence (Figure 6.25). Appropriate response is required for those communities affected by abandonment. For some communities, the present level of response is not enough. Current funding arrangements are based on long term strategic plans (identifying future problems, possible risks, solutions and impacts), economic factors (the gains and losses of national resources), approaches to risk (risk assessments and management plus the mitigation, control and acceptance of risks), environmental factors (environmental and heritage assets and habitat replacement and enhancement) and the overall performance and success of a proposed scheme (MAFF, 2001). Areas which are presently defended may not score high enough on future coastal defence project appraisals, so would not qualify for funding. Therefore the building and maintenance of existing or private defences could become more common, creating a series of small set-backs. For example, at Skipsea and Ulrome (Figures 2.20 and 7.7), Holderness, Easton Bavents, Suffolk and Happisburgh, Norfolk.

7.3 Synthesis

In Section 1.6 the terminal groyne effect was defined. The results of this thesis indicate that this definition is not sufficient. Firstly, set-back is caused by all defences – by both groynes and seawalls and not just by the terminal groyne. Secondly, the retreat rate does not need to increase down-drift to create a set-back. Finally, a set-back also occurs up-drift, despite sediment accumulation. Improved, more rigid definitions are as follows:

Down-drift set-backs occur due to the:

- **terminal groyne effect**, where defences stop or dramatically reduce erosion, induce a sediment deficit *down-drift* and cause an increase in retreat rate;

or

- **perceived terminal groyne effect**, where defences stop or dramatically reduce erosion, and *down-drift* retreat rates remain the same or decrease.

Up-drift set-backs occur due to the:

- **initial groyne effect**, where defences stop or dramatically reduce erosion, induce sediment accumulation *up-drift* and cause a decrease in retreat rate.

The term set-back (defined in Chapter 1 and Glossary) encompasses all of these definitions and is illustrated in Figure 7.8. Set-backs are continuously evolving and must be referenced with respect to space and time. It is not a permanent feature as defence configurations change. The terminal groyne effect can be measured and perceived in different ways. For example, it can vary depending on when and where it is measured, how long retreat rates are measured for, the extent of longshore coast measurement and what component of the retreat is measured. The terminal groyne effect is not a simple process to measure. It is essential to have accurate dates with *a priori* knowledge of factors affecting coastal retreat, including defence history and maintenance. Set-back, and subsequent bay formation is dependent on many other factors, and both these and their interaction with the terminal groyne effect must be better understood in a holistic and integrated manner.

Today, a holistic approach and soft engineering is increasingly favoured as a method of protection, working with nature rather than against it. With increasing difficulties in protecting the coast, greater costs of hard defences and the impact of climate change, the old English phrase of 'time and tide wait for no man' is becoming quite literal!

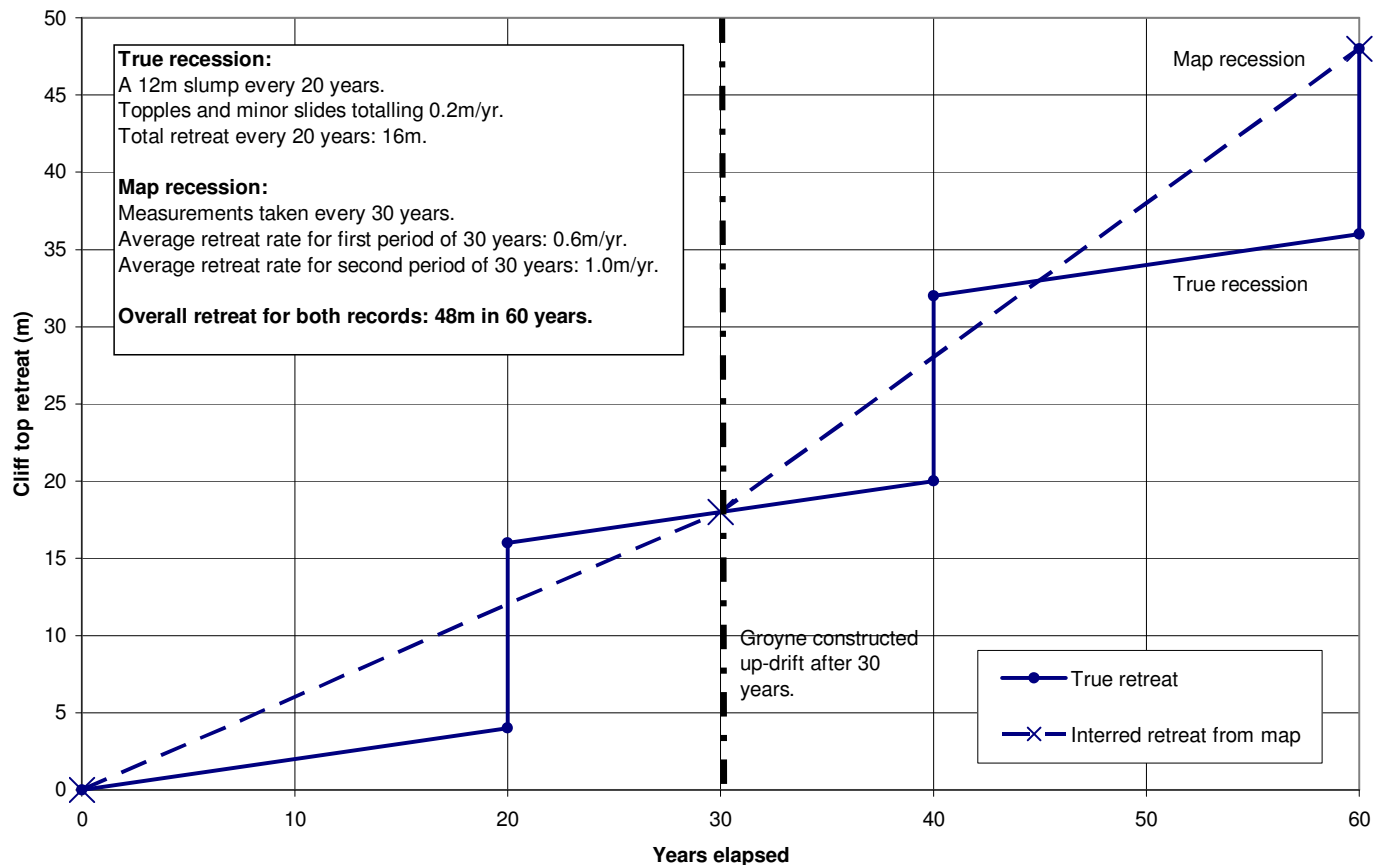


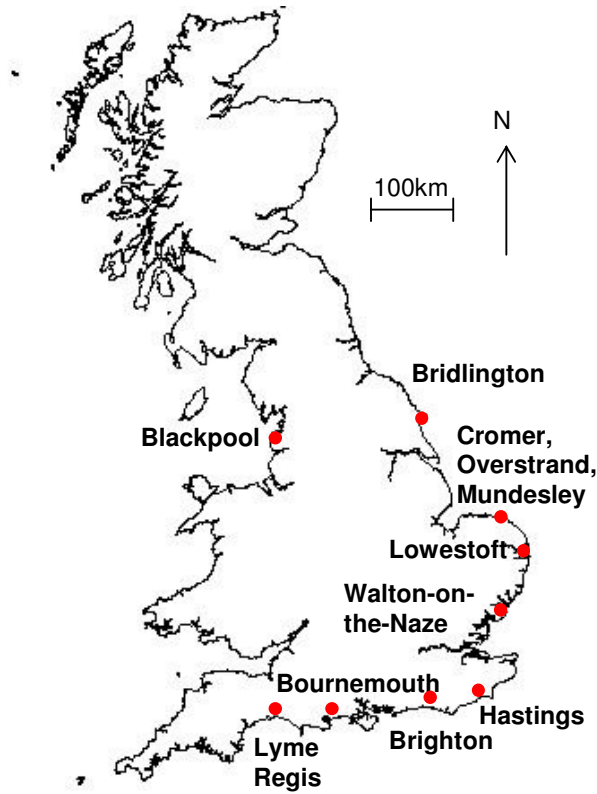
Figure 7.1 – A hypothetical erosion cycle. Map measurement intervals can obscure the impact of the terminal groyne effect. In this example, despite a groyne being constructed, retreat rates (for example, due to cliff cycles on a London Clay site) have not increased down-drift, but map measurements taken every 30 years suggest that retreat rates have increased.



Blackpool



Hastings



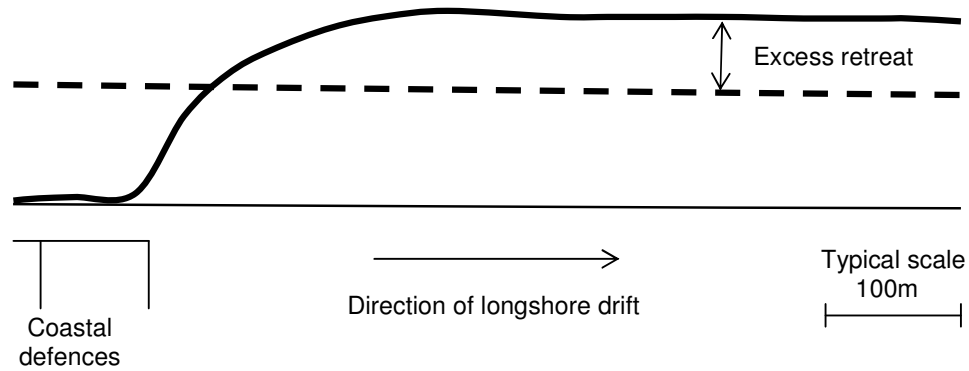
Bridlington



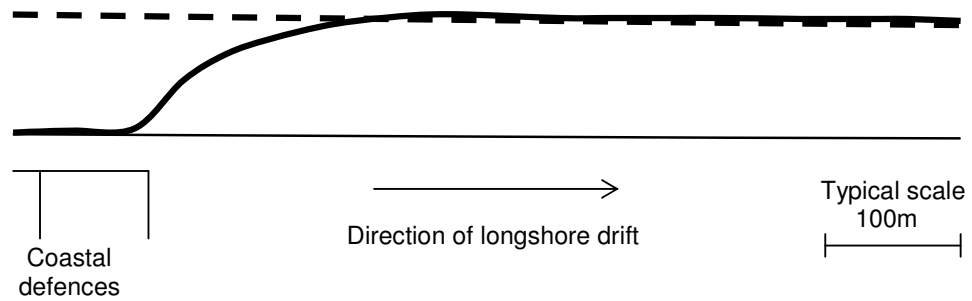
Walton-on-the Naze

Figure 7.2 – Multiple set-backs at selected localities around the UK. The earlier set-backs are fossilised as they no longer erode.

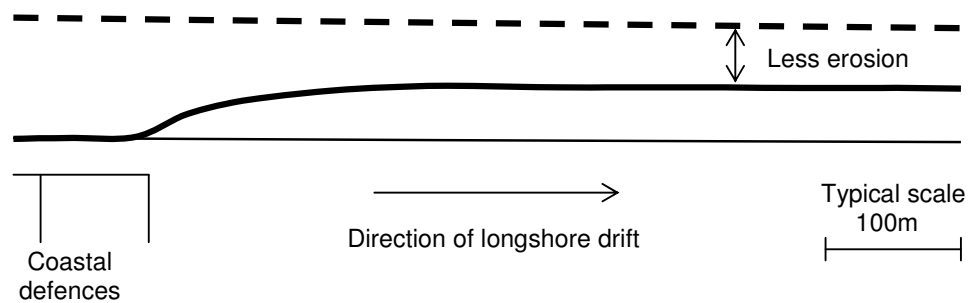
a) Increased retreat rate – a real, measurable terminal groyne effect.



b) Constant retreat rate – an erroneously perceived terminal groyne effect.



c) Decreased retreat - an erroneously perceived terminal groyne effect.



Cliff top position at time of defence construction.

Predicted cliff top position if defences not constructed.

Cliff top position after defence construction.

Figure 7.3 – Cross-shore set-back after defence construction. Retreat rates increase, remain constant or decrease after defence construction. See case study sites in Table 7.4.

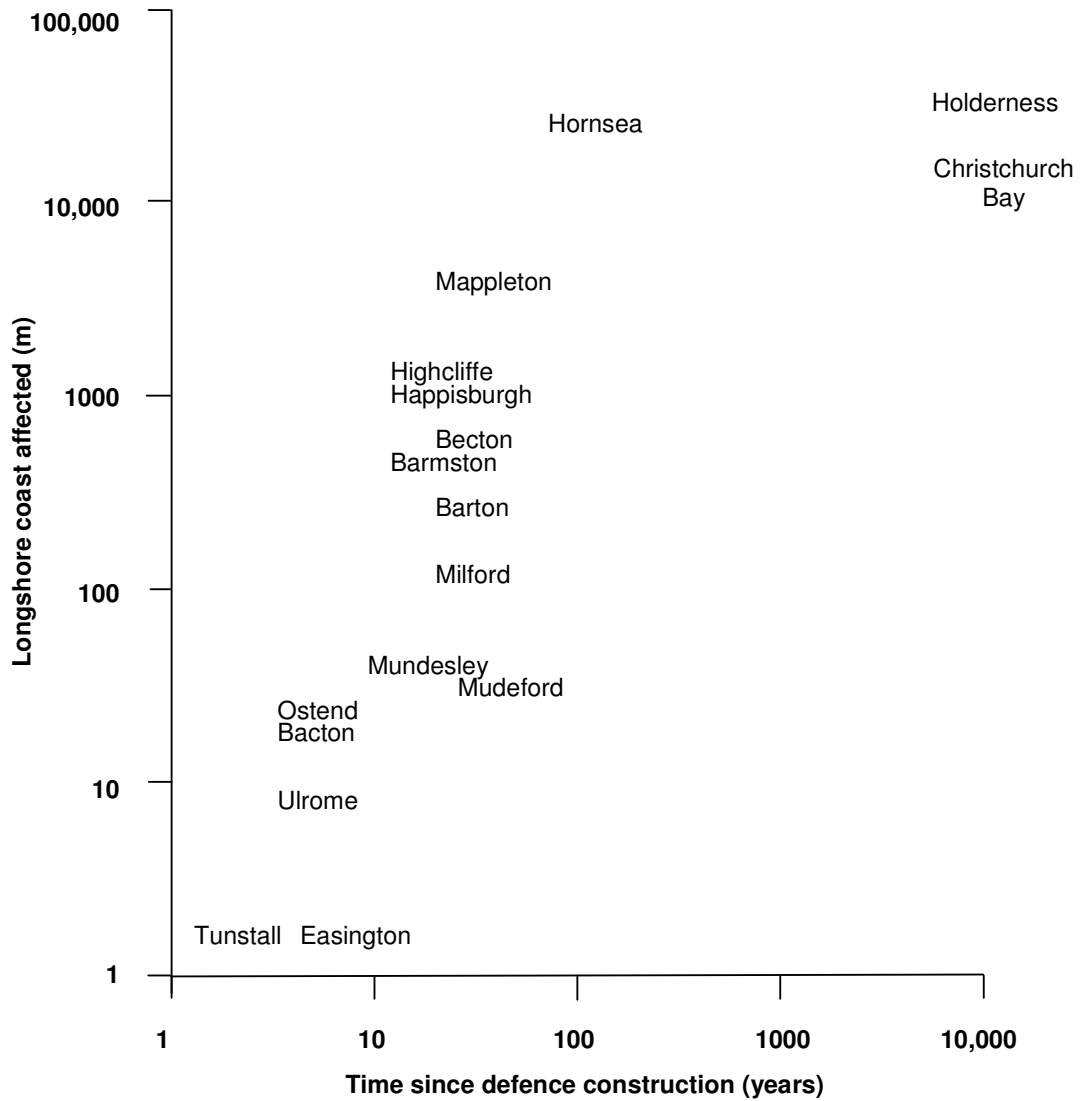


Figure 7.4 – Longshore extent of down-drift erosion since time of original defence construction. Holderness and Christchurch Bay are assigned a nominal 10,000 year date (although actual geological evolution of the bays took place over a considerable time span). Bridlington and Withernsea are omitted as the length of coast is undeterminable.

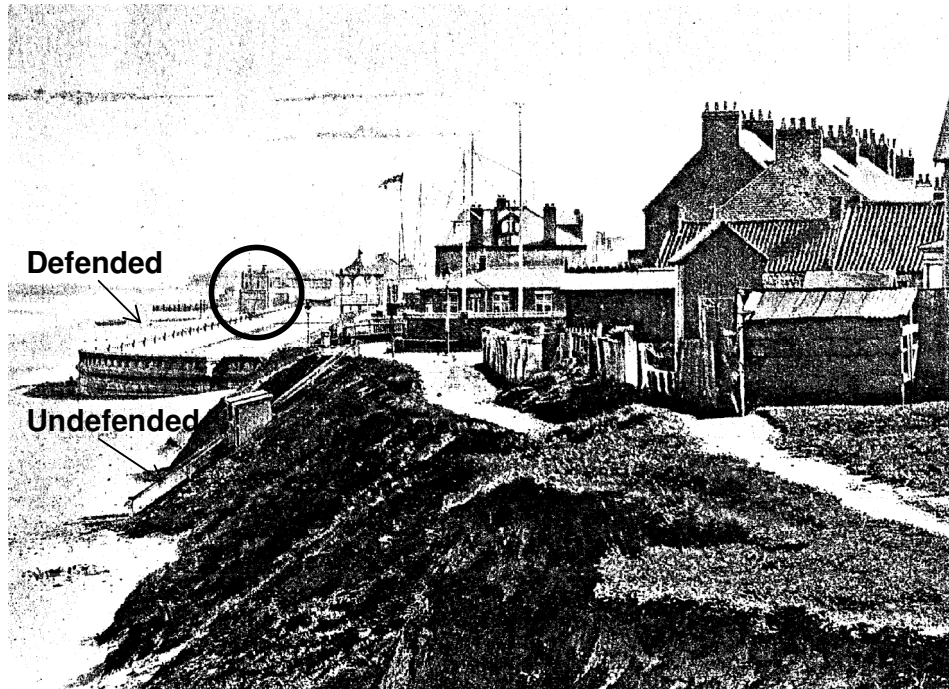


Figure 7.5a – Withernsea North Promenade defences in 1912 prior to the up-drift seawall extension in 1912 (Whittaker, 1990). For reference, the circle illustrates the same building on Figure 7.5b.



Figure 7.5b – Withernsea North Promenade defences and rock armouring in 2006. For reference, the circle illustrates the same building on Figure 7.5a. Photograph taken 10th August 2006.

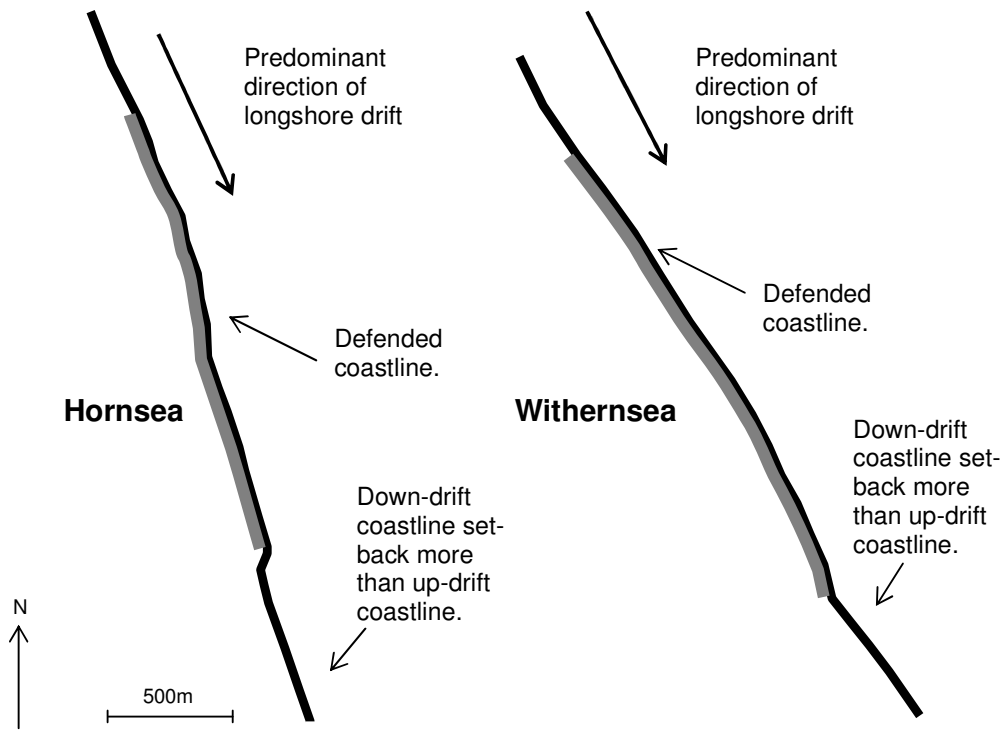


Figure 7.6 – Headlands forming at Hornsea and Withernsea. The up-drift retreat rate is low relative to the down-drift retreat rate, causing an asymmetrical headland. The thick grey line indicates the limit of seawall or revetment frontage in 2005.



Figure 7.7 - Private defences at Ulrome, Holderness. A seawall does not retain a beach. The up-drift coastline is set-back, creating an 'initial groyne effect' and allowing the defences to form a small headland. Photograph taken 10th August 2006.

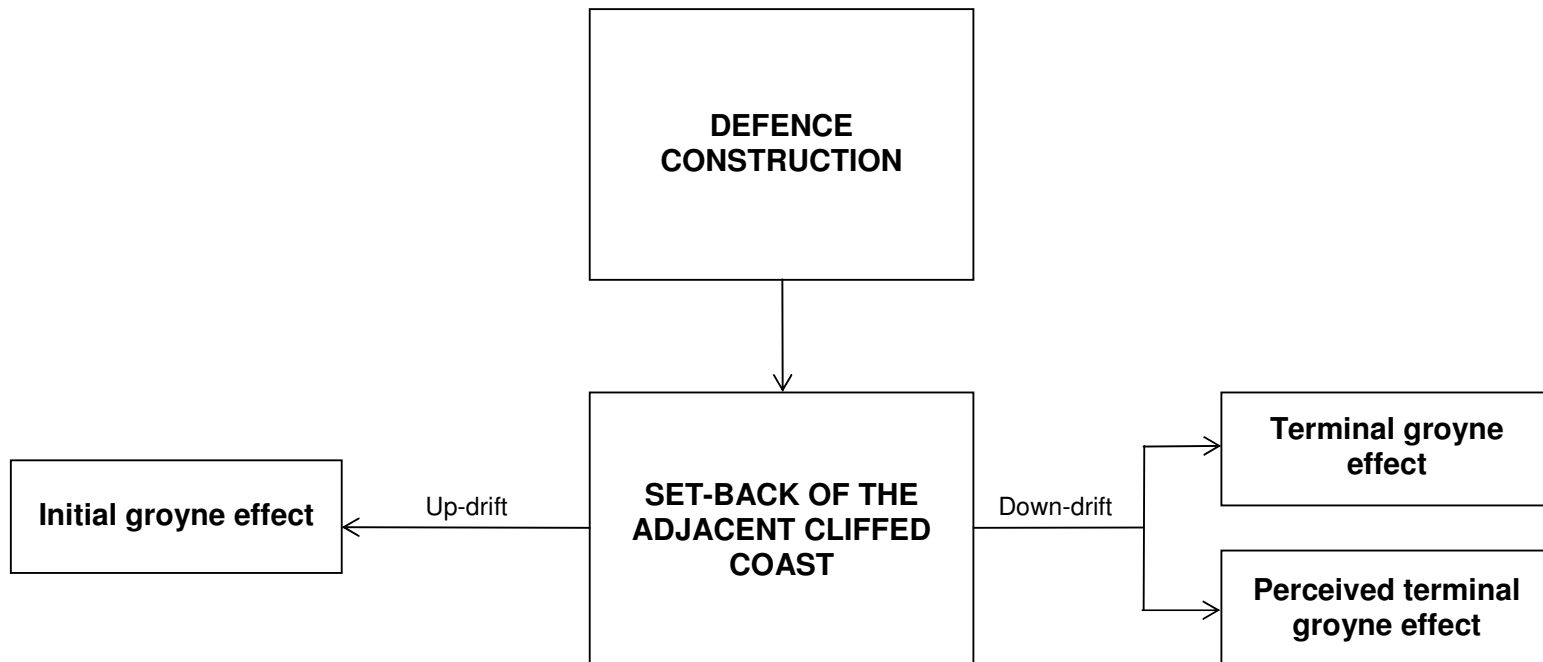


Figure 7.8 – Set-back adjacent to defences. The term set-back is an ‘umbrella’ term linking the three types of groyne effect. Down-drift, a set-back creating a terminal groyne effect or a perceived terminal groyne effect is dependant on whether retreat rates have increased after defence construction relative to their initial rate.

Table 7.1 - Advantages and disadvantages of the measurement methods of the terminal groyne effect (described in Section 3.9.1).

Method	Brief description	Advantages	Disadvantages
Cross-shore set-back after defence construction (m).	Average cross-shore retreat over a defined longshore distance.	<ol style="list-style-type: none"> 1) Simple to calculate. 2) Average value omits anomalies such as cliff gullies. 3) Bay growth can be seen. 4) Works well when calculated down-drift of the shadow zone in parabolic bays. 5) Excellent comparative measure over time within one site. 	<ol style="list-style-type: none"> 1) Comparison can lose meaning when retreat rates differ and measurement occurs over different time periods. 2) Does not work well with a down-drift headland as the log-spiral bay creates a variable cross-shore set-back longshore. 3) Measured cliff top position may not be the same as date of defence construction.
Excess retreat (m).	Predicted set-back (based on rate of retreat prior to defence construction) subtracted from observed set-back.	<ol style="list-style-type: none"> 1) Determines if retreat rates have accelerated after defence construction (a real or perceived terminal groyne effect) and its longshore extent. 2) Good measure for comparing sites before and after defence construction and between sites. 3) Valuable measure of the amount of land saved from erosion. 	<ol style="list-style-type: none"> 1) Retreat rates vary longshore. Therefore only valid for a limited distance. 2) Does not account for other factors influencing retreat rate. Assumes past environmental conditions will continue. 3) Up-drift defences affect erosion rate down-drift. 4) Does not work well if insufficient time passed or lack of data to account for frequency of storm activity. 5) Data uncertainties can obscure actual change in retreat rates.
Percentage increase in retreat rates (%).	Difference between retreat rate before and after defence construction, divided by the initial retreat rate.	<ol style="list-style-type: none"> 1) Can be used as a comparative measure before and after defence construction and between sites. 	<ol style="list-style-type: none"> 1) Using differing initial retreat rates can make comparison difficult. 2) Comparisons are misleading. 3) Calculation involves several stages deviating from initial data. 4) Large data uncertainties obscure results and become meaningless.
Retreat rates before and after defence construction (m/yr).	Cross-shore set-back divided by time elapsed between successive cliff top positions.	<ol style="list-style-type: none"> 1) Excellent measure for comparing sites before and after defence construction and between sites. 2) Corrects for cliff top position and date of defence construction. 3) Works well when calculated down-drift of the shadow zone in parabolic bays. 	<ol style="list-style-type: none"> 1) Does not work well with a down-drift headland as the log-spiral bay creates a variable cross-shore set-back along the coast. 2) Does not work well if insufficient time passed or lack of data to account for frequency of storm activity. 3) Data uncertainties can obscure actual change in retreat rates.

Table 7.2 - Problems associated with measuring set-back and the terminal groyne effect.

Procedure	Problem	Solution
Locating cliff top position when defences were constructed	1) Do not know the exact position of the cliff top as defences not constructed in the same year as map survey	1) Use the nearest cliff top position available. 2) Take distance and time differences into account, during analysis.
Calculating future cliff top position	1) Do not know future cliff top position if no defences were constructed. 2) Dependant on initial rate of retreat, assuming environmental conditions will remain constant.	1) Use long (>20 years) or appropriate time periods to average retreat rates. 2) Understand what controls coastal erosion during the time period to explain why that retreat occurred, for example, due to cliff, beach and nearshore mining, sediment availability, storm frequency and erosion cycles. 3) Include uncertainties in projections. 4) Average retreat rates over a longshore distance.
Date of defence construction unknown.	1) Unknown from maps.	1) Review literature and other resources. 2) List date of construction within a range of years.
Lack of cliff top positions.	1) Defences pre-date earliest map or constructed by second map addition. 2) A retreat rate without human influence cannot be calculated. 3) Defences built too recently to establish retreat rate after defence construction. 4) Do not know date of defence construction.	1) Analyse maps and literature to ascertain age and extent of defences. 2) If minor defences constructed, use rate averaged over a longshore length of the coast. Proceed with caution. If major defence constructed do not use data. 3) Review literature and other resources. 4) Cannot use site for detailed analysis.
Other factors influencing erosion rate.	1) Up-drift defences increase erosion rate. 2) Beach, cliff and nearshore mining. 3) Wave climate. 4) Cliff geology and hydrogeology.	1) Establish cause of change. 2) Indicate significant changes when the cause is not known. 3) Do not use unreliable data. 4) Check frequency of map measurements. 5) Use wave and precipitation data.
Map errors.	1) Measurements and uncertainties.	1) Produce uncertainty range. 2) Omit or use other data if available. 3) Proceed with caution, use generalisations. 4) Compare with literature.
Spatial and temporal scales of set-back.	1) Cross-shore measurement of the terminal groyne effect is variable in time and longshore direction.	1) Avoid shadow zone. 2) Follow procedures outlined in Chapter 3. 3) If the procedure cannot be followed, understand data limitations, adapt and apply a new method.



Table 7.3 - Additional factors other than defences affecting set-back (Hutchinson et al., 1980; Clayton, 1989; Robertson, 1990; Terpstra and Chrzastowski, 1992; Galgano, 1998; Jezard, 2004)

Factor	How	Comments
Cliff, beach and nearshore mining.	Creates artificially high retreat rates.	1) Essential to find when, where and how much mining occurred. 2) Requires a thorough understanding of how it affects the erosion rate. Can compare adjacent stretches of coast.
Defence type, age and efficiency.	Defences retain different volumes of sediment.	1) Age and efficiency affects volume of sediment retained. 2) Shore perpendicular defences retain more sediment than shore parallel defences.
Variation in cliff composition.	Lateral variations in geology. Variations in cliff height. Time for cliff top to respond. Stage and length of erosion cycles.	1) Variations in geology (for example sand lenses) make the cliff more susceptible to erosion. 2) Frequency and size of landslide activity. 3) At least one erosion cycle must occur when calculating retreat rates.
Beach, sediment supply and longshore drift volumes.	Variation in sediment volume and stores. Sediment composition. Variations in longshore drift throughout time and space. Defence interaction.	1) Sediment supply reduced due to littoral drift barrier and cliff input. 2) Larger longshore drift rates have a greater impact down-drift. 3) Sediment boundaries and offshore losses. 4) Reduction in beach sediment affects volume required to protect shore platform and cliff toe.
Exposure and composition of shore platform, including foreshore geology.	Controls overall set-back.	1) When beach volume is low the shore platform sediment is exposed down-drift and within groyne compartments, leading to foreshore steepening. 2) Foreshore geology affects platform lowering and retreat rates.
Variability of waves.	Short term wave conditions and long term wave climate. The frequency of storms affects the erosion of the cliff toe.	1) Variable wave climate can alter wave strength, fetch and longshore drift direction. 2) Stormy conditions can remove beach material and increase erosion. Need to measure over long periods of time (>15-20 years).
Differing positions and locality.	Position in coastal cell affects sediment volume and length of coast. Orientation of coast with respect to wave direction and longshore drift direction. Headland sheltering.	1) Affects sediment availability. 2) Affects magnitude and direction of longshore drift. 3) Influenced by wave refraction and diffraction around natural bay headland. 4) Defences have greatest impact on drift aligned coasts.
Other defences and freedom of coast to respond.	Limits cross-shore and longshore growth.	1) Up-drift defences can increase erosion rates down-drift. 2) Down-drift defences can constrain growth and reduce cross-shore retreat.

Table 7.4 – Synthesis of results from case studies (see Chapters 4, 5 and 6). The results indicate if excess retreat has occurred, the longshore length of coast affected, and whether there are constraints on longshore growth. The sites are ordered from greatest to least excess retreat for each category.

Rate of down drift erosion after defence construction relative to initial rate	Study site	Measurement period	Time defended	Excess retreat	Down-drift longshore extent	Longshore growth constrained by hard headland?
			years	m	m	
Increased erosion and excess retreat (A real, measureable terminal groyne effect - Figure 7.3a).	Hornsea	1905-2005	99	88±42	Up to 22,000m	Yes
	Withernsea	1870-2005	130	88±49	Not distinguishable.	No
	Barton	1963-2005	38	42±29	Greater than 300m	Yes
	Becton	1963-2005	34	33±29	Up to 650m.	No
	Mappleton	1989-2005	14	25±12	3,900m – 4,400m.	No
	Mappleton	1989-1998	7	23±8	At least 1,700m.	No.
	Withernsea	1978-2005	37	20±13	Up to 700m.	No
	Barmston	1978-2005	At least 27	15±13	Up to 650m.	Yes
No increased erosion and excess retreat within confidence of data, or occurred for a limited distance, or potentially occurred (A real terminal groyne - Figure 7.3a).	Happisburgh	1989-2005	14 (defence removal)	22±50	900m.	Yes
	Barton	1963-1989	22	21±27	Up to 300m.	Yes
	Highcliffe	1963-1989	22	18±27	Up to 1,250m.	Yes
	Becton	1963-1989	18	18±27	Up to 500m	No
	Highcliffe	1963-2005	38	17±29	Up to 1,250m.	Yes
Retreat rates were maintained or decreased (A perceived terminal groyne effect - Figure 7.3a or 7.3b).	Barmston	1978-1989	At least 11	11±15	Up to 650m.	No
	Hornsea	1968-2005	28	10±21	Not distinguishable.	Yes
	Hornsea	1968-1989	12	4±21	Not distinguishable.	Yes
	Withernsea	1978-1989	21	-6±15	Not distinguishable.	No

Table 7.5 – Relative retreat rates and headland planform. The black line indicates the cliff top and the bold grey line indicates the defences.

Headland planform	Relative retreat rates after defence construction		
	Up-drift	Defended: Headland or proto-headland	Down-drift
 <p>Symmetrical headland</p>	Mimics down-drift response. Caused by an up-drift headland's terminal groyne effect increasing or maintaining retreat.	Reduced or stopped.	Increased or maintained retreat.
 <p>Asymmetrical headland</p>	Reduced or maintained retreat - retreat up-drift less than down-drift.	Reduced or stopped.	Increased or maintained retreat - retreat down-drift greater than up-drift.

8. CONCLUSIONS AND FURTHER RESEARCH

8.1 Conclusions

The thesis has analysed the evolution of set-backs due to defences on cliffed coasts, with particular reference to the relative retreat rates on the down-drift shoreline, before and after defence construction. Set-backs were found to be one of three types:

Down-drift set-backs that occur due to the:

- **terminal groyne effect**, where defences stop or dramatically reduce erosion, induce a sediment deficit *down-drift* and cause an increase in retreat rate;

or

- **perceived terminal groyne effect**, where defences stop or dramatically reduce erosion, and *down-drift* retreat rates remain the same or decrease.

Up-drift set-backs that occur due to the:

- **initial groyne effect**, where defences stop or dramatically reduce erosion, induce sediment accumulation *up-drift* and cause a decrease in retreat rate.

It is important to distinguish between the terminal groyne effect and the perceived terminal groyne effect as although the same planform shape results, set-back is caused in different ways. The type of set-back adjacent to defences, described by the above three definitions is depicted in Figure 7.8.

The aim of this thesis has been achieved by identifying set-backs nationally, regionally and at specific case study sites. 17 case study sites on soft cliffs were investigated in three study regions (Holderness, Christchurch Bay and north-east Norfolk). At each study site, it was determined whether a terminal groyne effect had or had not occurred. The coastal planform, evolution and

engineering implications were investigated on national, regional and local scales (see Figure 1.6).

8.1.1 Measurement and factors influencing the terminal groyne effect

Based on a desk study of set-backs adjacent to defences, an examination of the impact of littoral drift barriers on the adjacent coast, and by determining a methodology to measure set-back and the terminal groyne effect (Objective 1), the study found:

- The terminal groyne effect is reported on eroding defended coastlines world-wide, as shown in Table 2.3. Set-back and the terminal groyne effect involves the combined influences of all up-drift defences, not just the terminal groyne. In Chapter 3, approximately 200 set-back sites were identified in England and Wales using the Futurecoast data set (see Halcrow, 2002). Many of these sites had multiple or fossilised set-backs and a selection are shown in Figure 7.2. Regions where many set-backs were reported include the east and south-east of England, with half of all localities having one or more set-backs situated in a cliffed setting (Figure 3.2).
- An understanding of set-back and the terminal groyne effect is limited by data availability, uncertainty and measurement, as discussed in Chapter 3 and Tables 7.1 and 7.2. This includes whether retreat rates can be resolved unequivocally, and what causes and controls erosion (Table 7.3).

These findings show that set-backs are a common feature along the defended English and Welsh coasts. All of the 200 sites where set-back was identified fall into one of three types identified in Figure 7.8. For sites where defences have been present for very long periods of time (for example, >100 years), appropriate data is not always available, or may not be of good enough quality for analysis. Therefore, it is not always feasible to determine whether a terminal groyne effect has occurred. These sites must simply be referred to as set-back.

8.1.2 Set-back and retreat rates

Objective 2 was to ascertain if retreat rates have accelerated down-drift after defence construction, causing a terminal groyne effect for the selected 17 case studies, and if so, the longshore extent of the accelerated retreat. The

methodology compared the predicted retreat with the actual set-back after defence construction. Where set-back increased beyond the value which allowed for the maximum range of possible errors, this was named excess retreat, and was deemed to show the unequivocal influence of the defences. Owing to the variability in short term retreat rates, the method was more reliable for long term observations, as discussed in Sections 4.3.3 and 4.4.4. Therefore the terminal groyne effect became increasingly apparent with time. The following conclusions were drawn from 17 case studies:

- For 8 out of 17 case studies investigated in Chapters 4, 5 and 6, the terminal groyne effect could be resolved unequivocally. For a further five of the case studies, the terminal groyne effect was believed to have occurred, or occurred for a short distance, although with less certainty.
- For the four remaining cases there was a perceived terminal groyne effect when set-back occurred, but retreat rates did not increase down-drift. Therefore based on this research, the terminal groyne effect cannot be considered to be universal, as it has been shown that a perceived terminal groyne effect exists.
- When retreat rates increase, accelerated retreat occurs down-drift over variable length scales from tens to thousands of metres (Figure 7.4), depending on, amongst other factors, the type, age and efficiency of defences.
- As defences are extended and modified, set-back evolves (as demonstrated at Becton, Christchurch Bay). Therefore set-back and terminal groyne effect evolution leads to measurement from multiple baselines for each stage of the up-graded defences, as illustrated at Hornsea and Withernsea, Holderness.
- A set-back in longshore and cross-shore coastal position is most noticeable when an efficient defence (that is, one that maintains shoreline position or retains a significant portion of sediment up-drift) is first constructed on a coastline that was previously undefended (or protected by inefficient defences, as noted at Hornsea, Holderness). Extending defences on a highly defended, sediment starved coast does not always increase retreat rates down-drift. However, set-back still occurs, creating a perceived terminal groyne effect (seen after the last defence extension at Hornsea and Withernsea, Holderness).

- Following defence construction, sediment builds up-drift (such as at Hornsea, Holderness shown on Figure 4.24). Retreat rates decrease, but a set-back is still created up-drift as retreat continues. This creates an ‘initial groyne effect’. This occurred on all sites, but was predominant on those sites where defences had been present the longest.

Therefore, the terminal groyne effect is a common phenomenon when the coastline is set-back adjacent to defences, but there are exceptions, as shown in Table 7.4. It takes time for a set-back to be identified as a terminal groyne effect rather than a perceived terminal groyne effect (for example, Mappleton, Holderness Section 4.3.3). Data uncertainties are associated with this, partly because the prediction of future shoreline positions is based on past environmental conditions. Coastal defences create an imbalance in the sediment budget both up and down-drift, meaning that more of the coast than was previously acknowledged is influenced by defence construction (see Section 8.2). Cross-shore and longshore retreat and the terminal groyne effect is influenced by factors other than defences, such as those listed in Table 7.3, including lateral variations in geology, the longshore drift rate and frequency of coastal storms. Due to time constraints, it was not possible to investigate these in detail, and they remain a topic for further research (Section 8.2).

8.1.3 Coastal evolution and management

In achieving Objective 3, knowledge has been integrated from the three study regions and 17 case studies, and the common features from each site extracted. The practical implications of defences on an eroding coast were studied, the evolution of set-backs and the planform shape was analysed, and future engineering and shoreline management was considered (as discussed in Chapters 6 and 7). Observations and analysis concluded that:

- The set-back down-drift of seawalls and groynes forms in the shape of a parabola (Figures 6.15, 6.16 and 6.22). This embayment continues to grow down-drift providing there is no natural or artificial down-drift headland retaining sediment. Artificial bays have a similar shape to the bay in which they reside (for example, Highcliffe, Barton and Becton within Christchurch Bay), but individual shapes are a product of many factors, including defence

history, efficiency and age. Artificial bays situated on protruding coasts or subtle headlands (such as Norfolk) also have similar parabolic forms.

- When an embayment forms down-drift of defences, the retreat rate is often rapid in the initial years after defence construction, thereafter decreasing to a lower and steadier rate. The shadow zone, comprising the curved part of the bay migrates down-drift at a rate corresponding to the natural log of time since defence construction (Figure 6.19). Where there is a down-drift headland, this model breaks down as sediment movement is restrained, forming a double headland system.
- Selective defence removal or abandonment at Happisburgh, Norfolk (where the up-drift shoreline remained protected and the down-drift shoreline degraded) resulted in a temporary period of rapid cross-shore retreat creating a new form of set-back and/or terminal groyne effect. The bay's traditional planform parabolic shape was reproduced and migrated down-drift in a similar manner to the traditional form of the terminal groyne effect (see Chapter 6).
- As the coastline is set back, scour and outflanking of the defence occurs, progressively impairing its effectiveness at the extremities, leading to emergency works, for example, at Barton-on-Sea and Becton, Christchurch Bay (Section 6.2). Each site has an individual outflanking solution, with possible responses including additional groynes, beach recharge, breakwaters, defence extensions and outflanking structures.
- Artificial headlands form when set-back occurs up-drift and down-drift of coastal defences or when defences are partially removed. Set-back leads to outflanking, prompting defence extensions, creating multiple set-backs and headlands. Headlands are symmetrical (Cromer and Overstrand, Norfolk) or asymmetrical (Hornsea and Withernsea, Holderness) depending on the relative rate of retreat on the adjacent undefended coasts (shown in Section 7.2.3 and Table 7.5).

Broadly, the parabolic shape of an artificial embayment can be predicted on the down-drift coast regardless of coastal orientation (bay or headland), provided there is no down-drift headland limiting bay growth. By increasing awareness and integration of the down-drift response of seawalls and groynes, maintenance works due to defence outflanking could be planned in advance. New forms of the terminal groyne effect will be an important feature as shoreline

management shifts towards management realignment and softer engineering solutions (Section 6.2.2). After defences fail, sediment which accumulated on the up-drift shoreline will be subject to longshore drift. This will result in an increase in retreat rates on the up-drift coast.

8.2 Further research

Human intervention on the coast has influenced shoreline behaviour for hundreds of years and it will continue to impact upon engineering and management practices for centuries to come. A greater understanding of set-back, the terminal groyne effect and its impact on the regions studied will be beneficial, and arguably is essential to improve coastal planning and engineering, including the timing of defence removal during managed retreat. Suggestions for further research include the following:

1. A study of future defence removal.

- Managed realignment is to become more prevalent in the next century, yet there is a lack of practical experience and knowledge of coastal response. Analysing the long term impact of existing defences and selective defence removal (for example, as proposed in Norfolk), such as through process based models will help scientists better understand coastal behaviour. Suggested aspects of further research include how much stronger headland defence will need to be to withstand wave attack in the coming decades and centuries, possible rates of retreat due to realignment, and engineering solutions to overcome defence outflanking.

2. Development of crenulate bay theory for the formation of bays.

- There is increasing interest in the use of crenulate shaped bays to stabilise coasts, as they work with nature, create aesthetically pleasing defences, and potentially over the longer term, reduce costs. If bay formation down-drift of existing defences is to be exploited, greater knowledge is required of the rates and controlling factors of stable bay formation, particularly for bays within a cliffed setting and for those where no down-drift headland is present (Wang *et al.*, 2008). Existing models such as MEPBAY (see Klein *et al.*, 2003; Hsu *et al.*, 2008) could be used,

and supplemented by new modelling, overcoming problems in cliffed settings such as the additional input of cliff material during bay formation.

3. A study of the impact of defences on erosion rates and on the up-drift coast.

- Whilst down-drift set-backs are extensively recognised in the academic literature and amongst practicing engineers, the initial groyne effect is in comparison, under acknowledged and under studied. Its study would be beneficial, particularly as defences are abandoned, artificial headlands emerge and bays form between defences. If beach data was available, comparisons could be made between up and down-drift sediment volumes. Given data uncertainties ($\pm 10\text{m}$ as discussed in Section 3.5), further quantitative study through historical maps and aerial photographs may not be fruitful. However, in future decades, DGPS data would become of greater use due to smaller error bands ($\pm 2\text{m}$). Data uncertainties could be improved by evaluating historical maps, for example, through investigation of original map making methods.

4. An investigation of factors other than the defences, that influence the terminal groyne effect and bay formation.

- Factors such as shoreline orientation, wave climate, cliff morphology, processes of cliff degradation and retreat rate prior to defence construction influence the terminal groyne effect. A greater understanding of these factors, for example through field and laboratory observations, and how they influence and are influenced by defence construction, will better ascertain if a terminal groyne effect has occurred. Set-backs are influenced by sediment volumes and availability, and numerical modelling would help form relationships between these variables for single and double headland bays.

5. An extension of research to other study sites.

- With crenulate shaped bays forming down-drift of defences, there is little systemic knowledge of how bays form and the rates of set back, particularly on cliffed sites. Further study sites would provide practical insights for shoreline planning, management and engineering over the next century. Many terminal groyne effect studies have been undertaken

on barrier islands or beaches (particularly in the United States), and models developed based on their response. On cliffed sites these models may not be appropriate due to the differing freedom of shoreline response and additional sediment input from the cliff. Therefore, a link between the two geomorphic settings would be valuable. For coasts with no predominant littoral drift, there is no dominant set-back orientation. If stable crenulate bays are built on coasts of this kind, physical modelling would be required to ascertain the response of the adjacent coast. To help with the analysis of the above, the addition of field data, for example beach profiles, would help to provide a better understanding of coastal set-back and bay formation throughout time and space.

Of the above points, a study of future defence removal would be of particular importance as there is presently a limited understanding of how the coast will respond in the future, and what practical engineering steps are required to progress from a heavily engineered to a soft engineered coast. This may severely affect people residing in the coastal zone. Further investigation into bay stability down-drift of a single headland would be beneficial as hard and soft engineering approaches are mixed. In the coming decades, these protection methods and engineering decisions will remain important issues for shoreline management.

9. APPENDICES

A1 ADDITIONAL INFORMATION

A1.1 Crenulate bay types and stability

There are three types of crenulate shaped bay theory - logarithmic-spiral bay theory, parabolic bay theory and hyperbolic-tangent bay theory. These are shown in Table A1.1. Each theory is related to a different bay shape, environmental conditions and stability. Moreno and Kraus (1999) found from their studies of 23 Spanish and 23 North American beaches that one headland bays do not fit a logarithmic spiral planform as there is ambiguity in where to terminate the spiral. Rather, they found that the parabolic shape fits better. The results from this thesis agree.

Short and Masselink (1999) report on three types of stability: bays in static equilibrium (where the dominant waves are perpendicular to the bay, so there is no littoral drift within the bay), dynamic equilibrium (where there is active movement of sediment in the bay, but no net change in the sediment volume) and disequilibrium (where bays are eroding, adjusting to changing conditions). Recently, Hsu *et al.* (2008) added a fourth type, termed beach reshaping which occurs when the coast adjusts itself to newly installed structures. This coastal adjustment has been the subject of this thesis.

Stability plays an important role in the behaviour and creation of crenulate shaped bays. Creating a stable (whether through static or dynamic equilibrium), healthy beach environment is the ultimate goal of coastal engineers if they wish to minimise erosion. Silvester's (1960) laboratory investigations found if waves were directed at 45° to a flat coastline with two hard headland control points, a half-heart bay would eventually be produced. Although not a perfect curve, he explained that due to a lack of real influences such as storms, such a bay would remain stable under prevailing wave conditions, even allowing for short term reversals in drift. Hence once stabilised, no long term erosion would be anticipated provided that the beach is large enough. In this research, it is acknowledged that crenulate bays can become stable, but in this thesis the aim

is not to investigate the stability of crenulate shaped bays, rather the occurrence and planform of developing bays (frequently in the shape of the parabola) as a result of down-drift erosion. However the benefits of stable bays in future coastal planning is acknowledged; they can generate lower costs as their on-going maintenance is less than more traditional defences (Silvester, 1978; Silvester and Hsu, 1997), particularly if natural features, such as rock outcrops of the coastline are used as headlands (Herrington, 2005). Further research is required into creating stable bays down-drift of artificial headlands as a method of coastal protection (Hsu *et al.*, 2008).

A1.2 Trapezium Rule

The Trapezium Rule is used to calculate the area under a curve using Equation A1.1. This method was compared to GIS measurements and it was found that there was an average of 7% difference in area between the two methods (Figure A1.1).

$$\text{Area} = \frac{d}{2} \{(y_0 + y_n) + 2(y_1 + \dots + y_{n-1})\} \quad (\text{Equation A1.1})$$

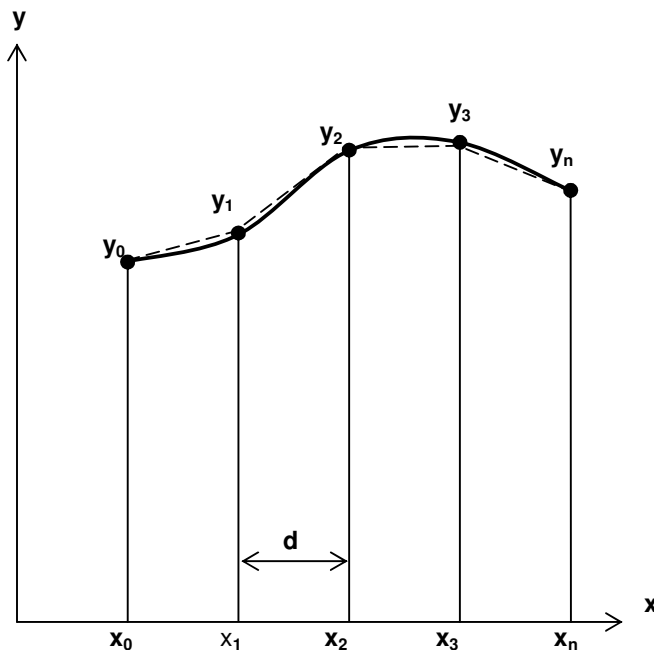

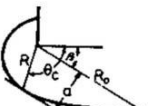



Figure A1.1 – The Trapezium Rule used in the methodology (see Section 3.8 for calculating cliff top retreat).

Table A1.1 – Crenulate shaped bay theories.

	Log-Spiral	Parabolic	Hyperbolic-tangent
Diagram (Silvester and Hsu, 1997)			
Equation (Silvester and Hsu, 1997; Moreno and Krauss, 1999)	$\frac{R_2}{R_1} = e^{\theta \cot \alpha}$	$\frac{R}{R_0} = C_0 + C_1 \left(\frac{\beta}{\theta}\right) + C_2 \left(\frac{\beta}{\theta}\right)^2$	$y = \pm a \tanh^m(bx)$ For small values of x $y = \pm (bx)^m$
Variables (Silvester and Hsu, 1997; Moreno and Krauss, 1999)	R ₁ , R ₂ : Radii from log-spiral centre where R ₂ >R ₁ . θ: Angle between R ₁ and R ₂ . α: Constant angle between radius and tangent.	R: Radius from the point of diffraction. R ₀ : Control line. θ: Angle between wave crest line and R. β: Wave obliquity, the angle between wave crest line and the control line. C ₀ , C ₁ , C ₂ : Coefficients that vary uniformly with β. May be read off a table (for example, Silvester and Hsu, 1997 p222).	y: Distance across-shore. x: Distance along shore. a: Distance between the relative origin and the straight shoreline (m). b: Scaling factor of a (m ⁻¹). m: Coefficient controlling the curvature (dimensionless).
Development of theory (Krumbein, 1944; Silvester, 1960; Mashima, 1961; Yasso, 1965; Silvester, 1970; Hsu and Evans, 1989; Hsu <i>et al.</i> , 1989a,b,c; Moreno and Krauss, 1999)	Originated from Krumbein's (1944) observations of Half-Moon Bay, California and Yasso (1965). Developed by Silvester (wave tank models and investigation of bay shape) and other scientists.	Mashima (1961) first mentioned bays conforming to a parabola, described by y=px ² -b. Hsu and others have developed the theory relating it to headland control and bay stability.	Moreno and Kraus (1999) developed the theory to reduce ambiguity in arriving at an equilibrium shoreline. It provides a good fit for beaches where only the up-drift headland is present.
Advantages (Silvester and Hsu, 1997; Short and Masselink, 1999; González and Medina, 2001; Klein <i>et al.</i> , 2003; Benedet <i>et al.</i> , 2004)	Simple, well known theory and easily seen in the field. The log-spiral centre may be refitted as the bay evolves. Any part of the log-spiral may be used and related to the real bay.	Control points, and origin based on physical properties of the bay and wave orientations. Better fit than the log-spiral theory for the proposed and actual equilibrium shape of the bay. It is widely used for checking the stability of crenulate shaped bays.	Model was introduced to simplify the process and reduce ambiguity. This is a relatively good fit for bays especially when only one up-drift headland is present.
Disadvantages (Yasso, 1965; Hsu <i>et al.</i> , 1989a,b; Tan and Chiew, 1994; Short and Masselink, 1999; González and Medina, 2001; Benedet <i>et al.</i> , 2004)	The log-spiral centre does not match the diffraction point. The log-spiral is based on the curved section of the beach that may become stable before the bay is in equilibrium. The effective wave direction is not used.	Theory has more coefficients to determine and therefore is more complex and time consuming. Difficulty locating where the bay ends, i.e. the down-drift control point.	Excludes the effective wave direction and fixed up-drift headland. Therefore the effect of a changing headland or control point cannot be predicted.

A2 DATA FOR FIGURES

A2.1 List of set-back sites

Table A2.1 – Set-backs sites. For Figure 3.2 (continued over 5 pages).

Region	Low-lying	Grid reference	Cliffs	Grid reference	Total
North-east	Berwick-upon-Tweed	398609 653340	Marske-by-the-Sea Brotton	464427 521692	
	North Sunderland Seahouses	421125 631857		470802 520023	
	Amble	426711 604305			
	Blyth	431366 580884			
	Tynemouth	436465 568820			
	Sunderland	439783 557828			
	Hendor, Sunderland	440092 555815			
	Seaham	442329 548998			
TOTAL:	8		2		10
Yorkshire	Spurn	541712 412884	North of Whitby	488808 511356	
			Whitby	490821 510931	
			Scarborough	503185 489475	
			South of Scarborough	504537 486919	
			Filey	511558 480821	
			Bridlington	517133 466219	
			Barmston Caravan Park	516763 458808	
			Barmston Main Drain	517188 458731	
			Ulrome	517072 456989	
			Skipsea	517769 454589	
			Hornsea	520206 447792	
			Mappleton	522528 443843	
			Tunstall	531266 431642	
Withernsea	533915 427983				

Region	Low-lying	Grid reference	Cliffs	Grid reference	Total
Yorkshire (continued)			Easington Kilnsea	540357 418613 541441 415594	
TOTAL:	1		17		18
East Midlands	Theddlethorpe St Helen Trusthorpe, Mapplethorpe South of Sandilands Authorpe Chapel St Leonards North of Ingoldmells South of Ingoldmells Skegness Black Buoy Sands	548002 388556 551369 383678 553227 379305 555509 373857 555702 371922 556734 369409 556928 366932 556378 363393 538404 338797			
TOTAL:	9		0		9
Eastern	Heacham East of Old Hunstanton West of Old Hunstanton Titchwell Gorleston-on-Sea Lowestoft South of Kessingland / Benacre Walberswick Aldeburgh Felixstowe Harwich / Little Oakley Mersea Flats West Mersea Southend-on-Sea	567130 338051 568272 341920 568737 342307 575879 344390 652748 303453 654112 292615 653613 284661 649140 274427 645953 256205 629096 233367 623251 228606 60450 4214195 601664 212607 587271 185985	Hunstanton Sheringham West Runton East Runton Cromer Overstrand Trimingham Mundesley Bacton Ostend Happisburgh Whimpwell Green Hopton-on-Sea South of Hopton-on-Sea North of Pakefield South of Pakefield	568020 341573 615008 343029 618221 343107 620195 342681 622904 341946 624235 341021 628338 338699 630816 336647 634532 333473 636699 331848 638402 330802 638751 330183 652942 299930 653445 298846 653532 290718 653106 289557	

Region	Low-lying	Grid reference	Cliffs	Grid reference	Total
Eastern (continued)			Southwold Bawdsey Walton-on-the-Naze Frinton-on-Sea	650572 275975 635115 240559 624631 222112 623199 219132	
TOTAL:	14		20		34
South-east	Whitstable South of Whitstable South West of Herne Bay Ramsgate / Cliffs End South of Deal Kingsdown Hythe St Mary's Bay Rye Rye / Winchelsea Winchelsea / Cliff End Langney Point Westdean Newhaven Brighton Goring-by-Sea Littlehampton West of Littlehampton Bognor Church Norton / Pagham Selsey Selsey East Wittering West Wittering	610834 166584 613505 166430 618615 167746 634205 164493 637402 151859 637440 147911 615903 134833 608239 127905 594035 119335 591077 116760 588925 114806 564228 103099 547270 099582 544012 100707 533715 104036 512545 102791 501474 101746 502978 101908 494343 099856 483985 094013 486142 092762 485175 093149 480104 097407 477669 098107	Warden Point, Sheppey Leysdown-on-Sea, Sheppey South of Leydown-on-Sea, Sheppey Swalecliffe East of Herne Bay Hillborough West of Maragate East of Margate Long Nose Spit North of Ramsgate South of Ramsgate East of Dover West of Dover Far west of Dover Fairlight Hastings Bexhill Bexhill Eastbourne Seaford East of Peacehaven West of Peacehaven Rottingdean Hill Head	600844 172108 603249 170059 603831 169095 613776 167088 620976 167978 622574 168437 633993 170179 636703 170915 638948 170876 638579 166080 636256 164803 634482 143072 631308 141678 629567 140014 586796 112329 582453 110252 576083 108609 573954 107913 561170 099809 547689 100552 540257 101597 538709 101946 536773 102720 454869 102618	

Region	Low-lying	Grid reference	Cliffs	Grid reference	Total
South-east (continued)	South Hayling Eastney Southsea	474234 098570 466841 099190 464131 098996	Stubington Titchfield Lepe Gurnard Bembridge East Ventnor West Ventnor Milford-on-Sea Becton Barton-on-Sea Highcliffe / Naish Farm	452788 103916 451162 104419 445371 099049 448710 095873 465312 087968 458047 079229 456112 078106 428715 092136 425463 093065 424341 093142 422018 093800	
TOTAL:	27		35		62
South-west	Weymouth Widemouth Bay / Bude Minehead Hinkley Point Power Station	368050 079999 218796 102916 297405 145860 321242 145572	Steamer Point Hengistbury Head Bournemouth West Bay Lyme Regis Sidmouth South of Dawlish Watchet	419310 093070 417650 090784 413586 091829 346345 091133 333902 092623 312507 087827 295466 075967 308731 142595	
TOTAL:	4		8		12
Wales	Aberaeron Aberystwyth Borth / Ynyslas Tywyn Barmouth Tal-y-bont Penthos Penmon	245640 262145 259183 281372 262084 291532 259428 300934 262006 316943 258846 321034 232967 333765 262288 380948	Pendine Saundersfoot New Quay Cei Bach Porthmadog Carreg Ddu Trefor	223677 208725 213506 203640 238241 259542 241808 259126 254523 338211 227591 340350 236812 346428	

Region	Low-lying	Grid reference	Cliffs	Grid reference	Total
Wales (continued)	Beamaris Llandegfan Vaynol Hall Bangor Llandudno Towyn West of Kinmel Bay East of Kinmel Bay Prestatyn	259876 377288 256589 374184 253528 369409 259648 372210 278354 382069 300791 380009 297764 379897 299777 380671 306086 382993			
TOTAL:	17		7		24
North-west	Wallasey Hightown St Anne's Fleetwood Heysham Power Station Heysham Piel Island Tummer Hill Scar Seascale Whitehaven South of Workington North of Workington Maryport Dubmill Point Lees Scar Lighthouse	327052 391529 330729 403899 332167 429796 333878 448191 342116 461376 341910 461611 322517 462199 318163 467593 304540 501415 297596 518149 298990 528637 299919 530688 303511 536480 307924 545654 310704 552945	Lytham St Anne's Blackpool Sheep Island / South End St Bees Harrington Skinburness	334064 428247 329414 436324 320137 463800 297431 511606 300035 525463 312601 555616	
TOTAL	15		6		21
GRAND TOTAL:	95		95		190

A2.2 Holderness

A2.2.1 Reference profiles

Table A2.2 – Cliff retreat data. For Figure 4.11.

Profile	Distance down-drift	Cliff top position (year)							
	km	1854	1888	1905	1929	1952	1978	1989	2005
1	6.3	0	25.5	32.8	45.2	45.5	87.5	131.2	153.6
2	13.6	0	19.0	35.2	67.8	113.4	144.3	146.5	168.4
3	27.7	0	31.3	48.6	71.6	112.6	161.0	178.3	228.0
4	34.9	0	24.5	47.4	64.7	76.0	103.4	134.0	160.2
5	48.7	0	76.2	105.6	127.7	144.8	169.1	198.2	214.7

A2.2.2 Barmston

Table A2.3 – Cliff retreat data. For Figure 4.14b.

		Year												
		1854	1888	1905	1929	1952	1978	1989	1996	2001	2002	2003	2004	2005
Profile	A	0.0	41.5	67.2	83.0	89.7	151.6	168.3	173.9	-	181.0	181.6	182.1	183.7
	B	0.0	50.6	66.5	91.1	93.7	154.7	157.8	167.7	175.8	176.5	177.2	180.0	182.6
	C	0.0	50.9	71.0	92.5	100.4	170.5	197.4	207.1	229.3	231.0	232.0	234.9	235.4

Table A2.4 – For observed and predicted set-back. For Figures 4.16 and 4.17, with averages calculated down-drift of the shadow zone.

Distance	Retreat rate			Retreat		Excess retreat	
	1929-1978	1978-1989	1989-2005	1978-1989	1978-2005	1978-1989	1978-2005
m	m/yr	m/yr	m/yr	m	m	m	m
50	1.8	2.2	2.0	24.4	53.6	5.9	8.0
100	1.7	3.0	2.3	32.5	63.3	13.9	17.7
150	1.8	2.1	2.0	22.8	53.0	4.2	7.4
200	1.6	2.5	2.3	27.6	61.4	9.0	15.8
250	1.6	2.8	2.4	31.1	63.5	12.5	18.0
300	1.6	2.1	2.5	22.6	66.2	4.0	20.7
350	1.7	2.1	2.1	22.6	57.8	4.0	12.2
400	1.7	2.7	2.4	29.8	65.3	11.2	19.7
450	1.5	3.2	2.6	35.7	70.6	17.1	25.0
500	1.6	2.9	2.3	32.0	62.9	13.4	17.3
550	1.6	3.1	2.0	34.0	52.7	15.5	7.1
600	1.8	2.7	2.0	29.6	55.0	11.1	9.4
650	2.0	2.4	1.7	26.4	46.0	7.8	0.5
Average	1.7	2.7	2.2	29.3	60.0	10.7	14.4

A2.2.3 Hornsea

Table A2.5 - Cliff retreat data. For Figure 4.21b.

		Year							
		1854	1888	1905	1929	1952	1968	1989	2005
Profile	A	0	53.7	75.2	81.6	86.6	88.5	90.4	92.1
	B	0	28.1	28.1	28.1	28.1	28.1	28.1	28.1
	C	0	30.5	38.6	38.6	38.6	38.6	38.6	38.6
	D	0	39.3	51.6	104.6	104.6	104.6	104.6	104.6
	E	0	32.9	52.5	107.1	161.0	167.0	175.2	187.4
	F	0	48.8	67.6	105.0	173.5	202.3	254.1	288.3

Table A2.6 – For observed and predicted set-back. For Figures 4.22 and 4.23, with averages calculated down-drift of the shadow zone.

Distance	Retreat rate			Retreat		Excess retreat	
	1929-1968	1968-1989	1968-2005	1968-1989	1968-2005	1968-1989	1968-2005
m	m/yr	m/yr	m/yr	m	m	m	m
100	1.9	2.3	2.1	48.9	75.9	0.5	-9.4
200	2.2	2.5	2.3	52.4	84.3	4.0	-0.9
300	2.4	2.6	2.3	54.2	86.0	5.8	0.7
400	2.6	2.4	2.3	49.4	86.1	1.0	0.8
500	2.5	2.4	2.6	51.4	94.9	3.0	9.7
600	2.5	2.6	2.8	55.5	103.3	7.1	18.1
700	2.3	2.8	3.0	57.9	111.2	9.5	26.0
800	2.0	3.3	3.1	69.0	115.3	20.6	30.0
900	2.2	3.0	2.7	63.4	100.2	15.0	14.9
1000	2.0	2.7	2.6	57.6	95.0	9.2	9.7
1100	2.5	2.3	2.5	47.4	91.9	-1.0	6.6
1200	2.4	2.3	2.2	47.6	82.0	-0.8	-3.3
1300	2.2	2.5	2.7	52.3	99.0	3.9	13.7
1400	2.2	2.3	2.7	49.2	100.7	0.8	15.4
1500	2.9	1.7	2.3	36.0	84.6	-12.4	-0.7
1600	2.1	2.7	2.8	57.3	104.2	8.9	19.0
1700	2.2	2.5	2.7	53.5	98.6	5.1	13.4
1800	2.3	2.5	2.6	52.8	95.7	4.4	10.4
1900	2.2	2.2	2.7	45.4	98.6	-3.0	13.4
2000	2.4	1.8	2.3	38.2	83.5	-10.2	-1.8
2100	2.2	2.1	2.2	49.0	80.7	0.6	-4.6
2200	2.1	2.6	2.4	56.9	87.3	8.5	2.0
Average	2.3	2.5	2.6	52.2	94.9	3.8	9.7

A2.2.4 Mappleton

Table A2.7 - Cliff retreat data. For Figure 4.28b.

		Year										
		1989	1992	1994	1995	1998	2000	2001	2002	2003	2004	2005
Profile	A	0	4.3	5.5	9.2	15.7	16.2	17.2	17.3	17.3	17.3	17.4
	B	0	2.1	5.4	-	-	13.7	-	-	-	14.4	14.6
	C	0	12.7	20.5	24.0	33.2	43.3	44.3	44.3	44.5	45.1	48.0

Table A2.8 – For observed and predicted set-back. For Figures 4.29, 4.30 and 4.31, with averages calculated down-drift of the shadow zone.

Distance	Retreat rate				Retreat		Excess retreat	
	1952-1989	1978-1989	1989-1998	1989-2005	1989-1998	1989-2005	1989-1998	1989-2005
m	m/yr	m/yr	m/yr	m/yr	m	m	m	m
100	2.0	2.5	2.5	2.3	22.4	36.6	6.7	8.7
200	2.0	2.1	3.7	3.0	33.1	47.3	17.4	19.4
300	1.9	2.1	3.7	3.0	33.4	48.0	17.7	20.1
400	2.1	2.2	3.6	3.1	32.3	49.8	16.6	21.9
500	2.1	2.0	4.3	3.2	38.4	50.6	22.7	22.7
600	2.0	1.9	4.7	3.5	42.4	55.3	26.7	27.4
700	2.0	1.8	4.7	3.6	42.3	58.0	26.6	30.1
800	2.0	1.8	4.8	3.6	42.8	57.7	27.1	29.9
900	2.0	1.9	3.8	3.3	34.1	52.6	18.4	24.8
1000	1.9	1.5	4.2	3.6	37.4	57.5	21.7	29.6
1100	2.0	1.2	4.5	3.6	40.2	58.0	24.5	30.1
1200	1.9	1.4	3.9	3.6	35.2	58.0	19.5	30.1
1300	2.0	0.9	4.4	4.4	39.3	69.6	23.6	41.7
1400	2.1	1.1	4.1	4.6	37.2	73.1	21.5	45.2
1500	1.9	1.3	4.2	4.6	37.6	74.2	21.9	46.4
1600	1.7	1.1	4.4	4.8	40.0	76.1	24.3	48.2
1700	1.8	0.9	4.8	4.5	43.4	71.5	27.7	43.6
1800	2.0	0.5	-	3.9	-	62.5	-	34.6
1900	1.8	0.8	-	3.3	-	53.3	-	25.4
2000	1.6	1.0	-	3.7	-	59.7	-	31.8
2100	1.5	0.7	-	4.0	-	64.2	-	36.3
2200	1.7	1.2	-	4.1	-	65.6	-	37.7
2300	1.9	1.4	-	3.7	-	59.5	-	31.6
2400	1.7	1.8	-	3.4	-	54.2	-	26.3
2500	1.7	1.2	-	3.6	-	57.6	-	29.7
2600	1.7	1.3	-	3.3	-	53.5	-	25.7
2700	1.8	1.3	-	3.0	-	48.6	-	20.7
2800	1.7	1.6	-	3.1	-	50.4	-	22.5
2900	1.5	1.8	-	3.1	-	49.2	-	21.4
3000	1.7	1.7	-	3.5	-	55.6	-	27.7
3100	1.8	1.5	-	3.7	-	59.9	-	32.0
3200	1.7	1.3	-	3.5	-	56.4	-	28.5
3300	1.6	1.0	-	3.2	-	51.8	-	24.0
3400	1.7	1.1	-	3.7	-	60.0	-	32.1
3500	1.3	1.0	-	3.4	-	54.4	-	26.5
3600	1.4	0.5	-	4.0	-	63.8	-	35.9
3700	1.7	0.7	-	3.6	-	57.6	-	29.7
3800	1.6	0.9	-	3.8	-	60.5	-	32.6
3900	1.7	1.3	-	2.8	-	45.1	-	17.2
4000	1.7	1.4	-	3.2	-	51.5	-	23.6

Continued on next page....

Distance	Retreat rate				Retreat		Excess retreat	
	1952-1989	1978-1989	1989-1998	1989-2005	1989-1998	1989-2005	1989-1998	1989-2005
m	m/yr	m/yr	m/yr	m/yr	m	m	m	m
4100	1.5	1.5	-	3.0	-	47.9	-	20.1
4200	1.6	0.8	-	2.9	-	45.7	-	17.8
4300	1.5	0.9	-	3.0	-	47.8	-	19.9
4400	1.5	1.2	-	3.1	-	49.8	-	21.9
4500	1.7	0.8	-	3.3	-	52.3	-	24.4
4600	1.3	1.2	-	2.7	-	43.8	-	16.0
4700	1.3	2.6	-	3.1	-	49.0	-	21.1
4800	1.4	2.7	-	2.8	-	44.7	-	16.9
4900	1.4	2.4	-	3.4	-	54.2	-	26.3
5000	1.6	2.5	-	3.4	-	55.0	-	27.1
5100	1.6	3.0	-	2.9	-	46.2	-	18.3
5200	1.5	2.9	-	2.8	-	44.4	-	16.5
5300	1.7	2.0	-	2.9	-	46.3	-	18.4
5400	1.9	2.5	-	2.5	-	40.2	-	12.3
5500	1.8	2.9	-	2.2	-	35.8	-	7.9
5600	1.7	2.8	-	2.1	-	33.9	-	6.1
5700	1.7	2.0	-	2.5	-	39.9	-	12.0
5800	1.9	1.8	-	2.9	-	46.0	-	18.1
5900	2.2	2.2	-	2.5	-	40.1	-	12.2
6000	2.3	2.4	-	2.3	-	37.2	-	9.3
6100	1.9	1.8	-	2.4	-	37.6	-	9.7
6200	1.8	1.8	-	2.2	-	35.3	-	7.4
Average	1.7	1.6	4.3	3.3	38.4	53.0	21.5	25.1

A2.2.5 Withernsea

Table A2.9 - Cliff retreat data. For Figure 4.34b.

		Year							
		1854	1888	1905	1929	1952	1978	1989	2005
Profile	A	0	54.8	56.2	73.3	-	-	82.6	88.7
	B	0	52.0	52.0	52.0	52.0	52.0	52.0	52.0
	C	0	59.3	63.3	51.0	51.0	51.0	51.0	51.0
	D	0	62.6	75.9	45.5	45.5	45.5	45.5	45.5
	E	0	98.3	105.6	140.5	140.5	140.5	140.5	140.5
	F	0	120.3	140.5	151.9	190.8	198.4	198.4	198.4
	G	0	121.8	137.8	167.1	219.7	277.5	290.7	338.6

Table A2.10 - For observed and predicted set-back. For Figures 4.35 and 4.36, with averages calculated down-drift of the shadow zone.

Distance	Retreat rates			Retreat		Excess retreat	
	1929-1978	1978-1989	1989-2005	1978-1989	1989-2005	1978-1989	1978-2005
m	m/yr	m/yr	m/yr	m	m	m	m
100	2.5	0.4	1.4	4.6	38.2	-13.1	-5.3
200	2.4	2.8	2.0	30.9	52.7	13.2	9.3
300	2.2	1.4	2.4	15.7	65.6	-2.1	22.1
400	2.3	1.4	2.4	15.0	63.8	-2.7	20.3
500	2.0	0.9	2.4	10.0	64.2	-7.7	20.8
600	2.0	1.7	2.0	18.5	54.1	0.7	10.6
700	2.0	1.2	2.4	13.1	63.9	-4.6	20.5
800	2.0	0.5	2.0	5.9	54.7	-11.8	11.2
900	1.8	0.6	1.9	6.9	51.1	-10.8	7.7
1000	1.7	1.0	2.0	10.6	52.9	-7.1	9.4
1100	1.7	1.0	1.8	10.6	49.8	-7.1	6.4
1200	1.8	0.0	1.7	0.0	45.3	-17.7	1.9
1300	1.7	0.0	1.9	0.0	50.0	-17.7	6.5
1400	1.5	0.0	1.9	0.0	51.2	-17.7	7.7
1500	1.5	0.0	2.2	0.0	59.1	-17.7	15.7
1600	1.3	0.5	2.2	5.2	60.1	-12.5	16.7
1700	1.1	1.3	2.5	14.3	67.6	-3.4	24.1
1800	1.4	0.9	2.6	10.4	69.5	-7.3	26.0
1900	1.1	1.8	2.7	19.9	72.7	2.2	29.2
2000	1.0	1.6	2.8	17.7	76.2	0.0	32.7
2100	1.0	3.2	3.6	35.5	98.0	17.7	54.5
2200	1.0	3.2	3.5	35.1	94.4	17.4	50.9
Average	1.6	1.1	2.3	12.2	63.2	-5.5	19.7

A2.3 Christchurch Bay

A2.3.1 Highcliffe

Table A2.11 - Cliff retreat data. For Figure 5.16b.

Profile		Year								
		1872	1898	1909	1932	1963	1975	1989	2001	2005
A	A	0.0	3.1	6.1	10.1	13.3	18.4	23.3	25.8	25.8
	B	0.0	17.2	19.3	27.2	37.3	41.1	42.0	43.5	45.1
	C	0.0	20.9	22.4	24.4	31.6	33.1	34.0	34.9	36.4
	D	0.0	19.3	24.3	28.8	49.1	79.5	101.3	105.2	110.9

Table A2.12 - For observed and predicted set-back. For Figures 5.17 and 5.18, with averages calculated down-drift of the shadow zone.

Distance	Retreat rate			Retreat		Excess retreat	
	1932-1963	1963-1989	1963-2005	1963-1989	1963-2005	1963-1989	1963-2005
m	m/yr	m/yr	m/yr	m	m	m	m
50	0.2	2.8	2.1	73.8	87.4	59.2	63.8
100	0.3	3.1	2.2	81.1	91.4	66.5	67.7
150	0.3	2.5	2.0	63.9	82.0	49.3	58.3
200	0.7	1.7	1.6	44.0	68.9	29.3	45.3
250	0.6	1.8	1.4	46.2	58.7	31.5	35.0
300	0.7	1.9	1.3	49.2	56.4	34.6	32.7
350	0.7	2.0	1.4	52.4	60.8	37.8	37.1
400	0.6	2.3	1.7	61.1	71.3	46.5	47.7
450	0.7	1.6	1.4	41.4	58.2	26.7	34.5
500	0.8	1.4	1.0	36.4	43.1	21.8	19.5
550	0.7	1.6	1.2	42.7	49.2	28.1	25.6
600	0.5	1.4	1.1	37.4	45.4	22.8	21.7
650	0.5	1.3	1.1	35.0	44.8	20.4	21.1
700	0.3	1.2	1.0	32.2	44.1	17.5	20.4
750	0.4	1.3	1.1	32.8	44.6	18.2	21.0
800	0.5	1.5	1.0	37.8	43.9	23.2	20.3
850	0.8	0.8	0.6	21.6	27.3	7.0	3.6
900	0.5	0.9	0.8	23.4	34.7	8.8	11.1
950	0.4	1.2	0.9	30.9	37.3	16.3	13.7
1000	0.4	1.4	0.9	35.1	39.4	20.5	15.8
1050	0.5	0.6	0.4	15.7	17.3	1.1	-6.3
1100	0.8	0.5	0.3	11.7	14.3	-2.9	-9.3
1150	0.5	0.8	0.5	20.4	22.9	5.8	-0.7
1200	0.6	0.4	0.4	11.3	15.4	-3.3	-8.2
1250	0.5	0.5	0.4	12.6	16.6	-2.0	-7.0
Average	0.6	1.3	1.0	32.7	40.3	18.1	16.6

A2.3.2 Barton

Table A2.13 - Cliff retreat data. For Figure 5.22b.

Profile		Year								
		1872	1898	1909	1932	1963	1975	1989	2001	2005
Profile	A	0	24.5	42.3	58.7	82.6	91.3	94.3	94.9	96.9
	B	0	32.3	38.7	58.3	69.1	77.9	79.3	80.8	82.0
	C	0	49.4	53.6	89.6	109.7	117.5	119.8	120.8	123.6
	D	0	37.1	44.5	62.3	77.1	97.1	116.6	133.1	149.0

Table A2.14 - For observed and predicted set-back. For Figures 5.23 and 5.24, with averages calculated down-drift of the shadow zone.

Distance	Retreat rate			Retreat		Excess retreat	
	1932-1963	1963-1989	1963-2005	1963-1989	1963-2005	1963-1989	1963-2005
m	m/yr	m/yr	m/yr	m	m	m	m
50	0.4	1.6	1.8	41.0	28.3	30.4	10.1
100	0.5	1.5	1.7	38.0	53.0	27.5	34.8
150	0.5	1.5	1.6	39.0	73.5	28.4	55.3
200	0.5	1.5	1.4	37.8	70.2	27.2	52.0
250	0.5	1.0	1.4	26.2	65.4	15.7	47.1
300	0.4	1.0	1.3	25.4	60.6	14.9	42.4
Average	0.5	1.3	1.5	33.3	61.4	20.8	41.2

A2.3.3 Becton

Table A2.15 - Cliff retreat data. For Figure 5.29b.

Profile		Year								
		1872	1898	1909	1932	1963	1975	1989	2001	2005
A	A	0.0	36.8	41.2	52.7	66.1	77.3	91.5	105.5	119.0
	B	0.0	46.7	54.9	64.9	73.1	80.3	126.4	138.6	151.8
	C	0.0	38.5	48.7	63.6	65.8	71.0	112.3	123.0	125.1

Table A2.16 - For observed and predicted set-back. For Figures 5.30 and 5.31, with averages calculated down-drift of the shadow zone.

Distance	Retreat rate			Retreat		Excess retreat	
	1932-1963	1963-1989	1963-2005	1963-1989	1963-2005	1963-1989	1963-2005
m	m/yr	m/yr	m/yr	m	m	m	m
50	0.1	2.1	1.8	54.8	77.6	50.7	70.4
100	0.0	1.6	1.5	41.1	63.3	36.9	56.1
150	0.1	1.8	1.4	46.5	59.3	42.4	52.1
200	0.2	1.4	1.4	36.2	58.7	32.0	51.4
250	0.3	1.2	1.4	32.0	59.1	27.8	51.9
300	0.0	1.4	1.4	37.0	60.8	32.8	53.6
350	0.1	1.2	1.2	32.3	48.8	28.1	41.6
400	0.1	0.8	1.0	22.1	43.6	17.9	36.4
450	0.3	0.6	0.9	15.5	38.1	11.4	30.9
500	0.3	0.5	0.9	12.7	37.7	8.5	30.4
550	0.2	0.2	0.3	4.1	14.5	-0.1	7.3
600	0.3	0.3	0.4	7.5	18.2	3.3	11.0
650	0.3	0.3	0.4	7.0	15.0	2.8	7.8
Average	0.2	0.9	1.0	23.3	41.3	18.0	33.3

A2.4 Norfolk

A2.4.1 Happisburgh

Table A2.17 - Cliff retreat data. For Figures 6.11b and 6.11c.

		Year																		
		1892	1907	1951	1972	June 1986	July 1992	Oct 1995	Mar 1996	Sept 1996	Nov 1996	Sept 1997	Mar 1998	Mar 1999	Aug 2000	Aug 2001	July 2002	July 2003	Sept 2004	2005
Profiles	A	0	21.2	24.6	36.0	38.1	42.2	44.3	44.3	44.0	43.8	43.9	47.5	48.0	48.1	48.2	48.3	48.4	49.7	52.3
	B	0	20.5	27.4	42.6	45.4	50.6	56.0	56.0	58.4	60.2	61.8	68.5	87.9	92.7	97.3	101.7	115.0	129.3	150.0
	C	0	24.6	29.8	49.8	57.8	73.6	79.3	79.3	88.8	89.0	90.7	92.5	93.0	94.5	94.6	94.7	97.4	112.0	115.7
	D	0	33.8	42.8	57.9	59.5	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0

A2.5 All localities – extent of shadow zone

Table A2.18 – Extent of shadow zone. For Figures 6.18, 6.19 and 6.20.

a) Barmston

	Time elapsed	Extent of shadow zone	
		Longshore	Cross-shore
	Years	m	m
1978	0	0	0
1989	11	80	30
1994	16	90	38
2001	23	90	50
2005	27	100	61

b) Mableton

	Time elapsed	Extent of shadow zone	
		Longshore	Cross-shore
	Years	m	m
1989	0	0	0
1994	5	50	16
1995	6	60	24
1998	9	80	32
2000	11	90	39
2005	16	100	45

c) Withernsea

	Time elapsed	Extent of shadow zone	
		Longshore	Cross-shore
	Years	m	m
1998	0	0	0
2000	2	40	20
2005	7	50	28

d) Highcliffe

	Time elapsed	Extent of shadow zone	
		Longshore	Cross-shore
	Years	m	m
1963	0	0	0
1975	12	100	56
1984	21	160	72
1989	26	160	78
2001	38	170	84
2005	42	180	88

e) Happisburgh

	Time elapsed	Extent of shadow zone	
		Longshore	Cross-shore
	Years	m	m
1996	0	0	0
1997	1	100	25
1999	3	140	58
2000	4	140	70
2002	6	160	73
2005	9	180	111

A3 OTHER RESOURCES

A3.1 Maps

All UK historical and modern maps or outlines were downloaded from Digimap or Ordnance Survey. They were accessed via their respective web pages: <http://edina.ac.uk/digimap/> or <http://www.ordnancesurvey.co.uk>.

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A3.2 Study sites

See list of resources used in Tables 3.4 (Holderness), 3.5 (Christchurch Bay) and 3.6 (north-east Norfolk).

A3.2.1 Holderness

A3.2.1.1 Beach profiles

Figure 4.3: Beach profiles PO39, PO42, PO47 measured in September 2005 were obtained from East Riding of Yorkshire Council.

A3.2.2 Christchurch Bay

A3.2.2.1 Beach Profiles

Sections 5.3.2, 5.3.3 and 5.4.3: Analysis undertaken on beach profiles BT8, BT9, MF6, MF7, MF8, MF9, MF10, MF11 and MF12 (Barton to Milford) and discussed in text. Profiles available from the Channel Coastal Observatory, Southampton.

Figure 3.4: Data taken from beach profile MF12 measured between 1989 and 2004 was obtained from the Channel Coastal Observatory, Southampton.

Figure 5.6: Beach profiles 5f00202, 5f00176, 5f001150 measured on 8th September 2005, 12th July 2005 and 24th March 2005 respectively were obtained from the Channel Coastal Observatory, Southampton.

A3.2.2.2 Photographs

Figure 6.14: Photograph of Milford-on-Sea World War 2 scaffolding taken on 10th March 2005. © Ian West. Accessed on 9th February 2008. Available at: <http://www.soton.ac.uk/~imw/hordle.htm>

A3.2.3 North-east Norfolk

A3.2.3.1 Photographs

Figure 6.10: Photograph of Happisburgh taken on 12th October 2006. © Mike Page. Accessed on 15th February 2008. Available at: http://www.happisburgh.org.uk/gallery/mikepage/121006_1.jpg/vi
ew

10. GLOSSARY

Artificial barrier.	See littoral drift barrier.
Artificial bay.	A man-made embayment or crenulate shaped bay created down-drift of defences.
Artificial headland.	Defences which protrude seaward of the adjacent undefended coast.
Barrier.	See littoral drift barrier.
Barrier beach.	An elongated island composed of unconsolidated sand-sized sediment running parallel to the main coastline.
Breakwater.	Shore perpendicular and parallel littoral drift barrier(s) which protect the entrance to harbours and provide shelter from the waves. They can be placed at differing orientations to reduce the amount of sediment by-passing.
Coastal defences.	Hard man-made coastal engineering works, including breakwaters, jetties, groynes and seawalls.
Crenulate shaped bay.	A bay in the shape of a half-heart, down-drift of a hard headland represented by a tightly curved section that straightens out into a relatively straight coastline parallel to the wave crests.
Defence works.	See coastal defences.
Down-drift.	Location down-stream of the coastal defences with respect to the predominant longshore drift direction.
Down-drift erosion.	The process of erosion or retreat that occurs on the undefended down-drift shoreline, due to up-drift protection works. Erosion down-drift may increase relative to the initial retreat rate.
End effects.	Occurs down-drift of a seawall where wave reflection and diffraction leads to scour, reducing beach levels down-drift, initiating set-back.
Engineered barrier.	See littoral drift barrier.

Erosion rate.	See retreat rate.
Excess retreat.	The difference between the expected and actual cross-shore retreat (assuming past environmental conditions continue).
Groyne.	A shore perpendicular hard defence constructed of wood or rock armouring designed to inhibit longshore drift.
Groyne field.	A series of groynes.
Headland.	See artificial headland.
Headland thinning.	When a natural headland stands increasingly seaward from the softer hinterland, erosion causes the headland to thin, the equivalent to outflanking in an artificial system. It can lead to arch, stack and island formation.
Initial groyne effect.	Where defences stop or dramatically reduce erosion, induce sediment accumulation up-drift and cause a decrease in retreat rate, leading to set-back.
Jetty.	Shore perpendicular littoral drift barrier(s) often located in pairs at the mouth of a river, tidal inlet, lagoon or estuary to stabilise the channel and to prevent shoaling. Jetties often extend into the breaker zone and can be up to 1km long, interrupting the supply of longshore drift to the down-drift coastline
Littoral drift.	See longshore drift.
Littoral drift barrier.	Any defence that blocks or hinders the movement of longshore drift.
Longshore drift.	The predominant direction of sediment transport – the sum of the sediment transport from all individual wave trains from each wave direction.
Outflanking.	When the continued set-back of the undefended coast adjacent to defences creates a set-back that makes the extremities of the defence ineffective, possibly leading to defence failure.

Perceived terminal groyne effect	Where defences stop or dramatically reduce erosion, and down-drift retreat rates remain the same or decrease, leading to set-back.
Promontory.	See artificial headland.
Retreat.	The cross-shore difference in two shoreline positions.
Retreat rate.	The cross-shore retreat of the coastline divided by the time elapsed between successive coastline positions.
Revetment or rip-rap.	Shore parallel rock armouring that waves can penetrate. Seawalls can be vertical or sloping.
Set-back.	The cross-shore retreat between a shoreline position at the time of defence construction, and subsequent shoreline positions. Subsequent shorelines may be defended or undefended shoreline.
Soft cliffs.	Cliffs predominantly formed of clays, shales, sandstones or unconsolidated sands.
Terminal groyne effect.	Where defences stop or dramatically reduce erosion, induce a sediment deficit down-drift and cause an increase in retreat rate, leading to set-back.
Up-drift.	Location up-stream of the coastal defences with respect to the predominant longshore drift direction.

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12. PERSONAL COMMUNICATIONS

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