Coastal Processes Baseline

Sidmouth & East Beach Management Plan

Prepared for

East Devon District Council

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CH2MHILL®

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Executive Summary

Background

This report has been prepared for East Devon District Council (EDDC) as part of the Sidmouth and East Beach Management Plan (BMP), which covers the coastline between Jacob's Ladder Beach, to the west of Sidmouth, and East Beach, to the east.

This report is one of a series of reports that accompany the BMP and provides a review of coastal processes and cliff behaviour, based upon the latest beach survey data, aerial imagery, historical maps and anecdotal evidence that has been provided by local residents.

In addition to developing a conceptual understanding of cliff-beach-foreshore behaviour and shoreline response for this coastline, key objectives for this study to consider have been:

- **To research the rates of historical and contemporary shoreline recession along the BMP frontage and adjacent shorelines, utilising data provided by local residents (see point 2 of this executive summary).**
- **Specifically investigate the potential impact of the 1990s Sidmouth Sea Defence Scheme on the beach behaviour and cliff response at East Beach through looking and historical and contemporary rates of change, to quantify any change and determine the possible cause (see point 3 of this executive summary).**
- **To review and update the SMP2 predicted erosion zones, taking account of the significant erosion which has taken place since those erosion zones were predicted (see point 4 of this executive summary).**

1. <u>Conceptual understanding of beach behaviour and shoreline response</u>

Coastal setting

The seaside resort of Sidmouth lies within the low-lying valley of the River Sid, bounded by cliff headlands cut into soft mudstones and sandstones.

It is a meso-tidal shoreline, with a spring tidal range (for Lyme Regis) of 3.7m. Offshore tidal flows tend to be quite slow and are unlikely to be capable of transporting shingle. Alignment of the coastline means that waves approach the shoreline from the southern quadrant, with waves most commonly arriving from the south-west and south, which drives alongshore transport in an eastwards direction. However, large and long period waves frequently arrive from the south-east, which results in drift reversals and a movement of sediment in a westwards direction. The dominance of a particular wave direction in any one year can therefore significantly affect the net drift direction over that period.

The shingle-sand beaches of much of the south coast of England were formed many thousands of years ago during post-glacial sea-level rise. The sediment was derived from re-working of river gravels on the bed of the English Channel as sea levels rose, and erosion and transgression of the coastal cliffs.

Under modern day conditions there is, however, a much reduced natural supply of sediment to the coast. Cliff erosion locally only provides silt and fine sand, which tends to be drawn offshore. The natural headland formations limit the supply of beach-building material (i.e. gravel and coarse sand) from further east or west, and weirs on the River Sid mean the supply of sediment from the upper catchment no longer reaches the coast. The available sediment within the beach system has also been progressively reduced over time as a result of: (a) construction of Sidmouth town along the former gravel spit of the River Sid, thereby removing this sediment from the beach system; (b) removal of gravel from the beach for building purposes; and (c) natural abrasion and draw down of the beach material.

Currently, there is limited new material entering the Sidmouth frontage. Some sediment leakage in and out of the frontage may occur during storms, however the defended headland at Chit Rocks and the training wall and outfall pipe on the western side of the River Sid tend to inhibit sediment movement in and out of the frontage. As a result, at this local scale there appears to be a finite amount of sediment held within a closed system at Sidmouth.

Consequently, coastal management at Sidmouth has been undertaken against a legacy of finite shingle reserves and a long-term decline in beach sediment.

Management history

The earliest formal defences along this coast are believed to date back to the 1820s, when records indicate that timber groynes and breastwork were constructed along the Sidmouth frontage. This coincides with the development of Sidmouth as a popular tourist destination, with the esplanade and associated seawall dating from around the 1830s. Around this time, a catastrophic storm event reportedly resulted in severe erosion of Chit Rocks, exposing the Sidmouth frontage to waves from the south-west and fundamentally changing the behaviour of this shoreline. Records indicate that in the subsequent decades there were continued problems of beach erosion and damage to defences, due to the volatile nature of the beaches; although beaches were found to recover this could take several years.

Following extremely low beach levels in the late 1980s/early 1990s, a coast protection scheme was constructed in the mid-1990s comprising a rock revetment, seawall, rock groynes, detached rock breakwater structures and beach replenishment. The aim of this scheme was to provide a more substantial beach along the Sidmouth town seafront through re-nourishing the frontage with new beach material, whilst effectively ‘locking down’ this sediment through reducing the amount of sediment transport along the frontage and reducing the volatility of the beaches. This was achieved through the construction of (a) three rock groynes, which reduce the longshore transport of material by blocking the drift, and (b) two breakwaters which reduce the wave energy at the shoreline and thereby also reduces longshore transport along the beach.

Beach profile data has indicated that up to 2014, material became trapped behind the breakwaters to form tombolo or salient beaches. This is due to waves from the south-south-west being reduced by the breakwaters and therefore preventing material from behind the breakwaters being moved eastwards, whilst storms from the east-south-east continued to move material westwards (i.e. to behind the breakwaters). Pre-scheme modelling predicted that this accretion would occur, but not to the detriment of adjacent beaches, and it was recognised that the redistribution of the nourished beaches might be necessary (i.e. beach recycling would be needed along the Sidmouth town frontage). During the 2014 storms, it appears that shingle behind the breakwaters was eroded and redistributed to the eastern end of the groyne bay, between the eastern breakwater and Bedford Steps groyne.

To the east of Sidmouth the beach remains unmanaged. However, there are natural controls on the movement of sediment into and out of East Beach as a result of large cliff failures and landslide debris lobes further to the east, which act in a similar way to groynes and block the longshore movement of material until the toe of the landslide becomes sufficiently eroded to allow sediment to bypass.

Shoreline change

Historical data, including maps, aerial images and photographs provided by the public, have been used to assess the evolution of this coastline, both pre- and post-scheme.

<u>Sidmouth frontage</u>

Since construction of the defence scheme at Sidmouth and nourishment of the beach, the beach monitoring data shows that sediment appears to be redistributed within the frontage, with shingle from the groyned section tending to be moved and retained behind the rock reefs. The 1st Five Year Monitoring Programme (2000 to 2005) found there to be gains in the order of 4,000 to 5,000m^3 in the lee of the detached rock breakwaters and losses in the region of 5,000 to 6,000m^3 between the three rock groynes. This suggests that, when considered as a whole frontage, there had been no net loss or gain, with a net east to west movement of material. A similar pattern of net shingle redistribution had been indicated by the more recent data (between 2002 and 2012), prior to the 2014 storm (Plymouth Coastal Observatory, 2010). Crude estimates of volume change using this data also indicated that as a whole the frontage has experienced limited net change, although volumes fluctuate from survey to survey.

Up to the 2014 storm, the available data suggested that once sediment ended up in the lee of the breakwaters it became trapped and was not returned eastwards under usual south-westerly conditions. However, the 2014 storm resulted in the erosion and redistribution of some of the material held behind the breakwaters. Future monitoring data will reveal the subsequent redistribution of the beach material, but it is suspected that material will start to build behind the breakwaters over the next few years.

Historically, the Sidmouth frontage and adjoining frontages have been susceptible to storms, with shingle becoming stripped from the beaches, leading to exposure and damage to defence structures. Storm analysis of beach behaviour since the scheme indicates that the beaches remain vulnerable to storms, with material becoming redistributed within the groyne bays, depending upon the prevailing wave directions during this storm. This tends to result in material becoming stripped from one end of the bay and being moved alongshore. Analysis of post-storm profiles show that the beaches within the BMP extent do recover after storms.

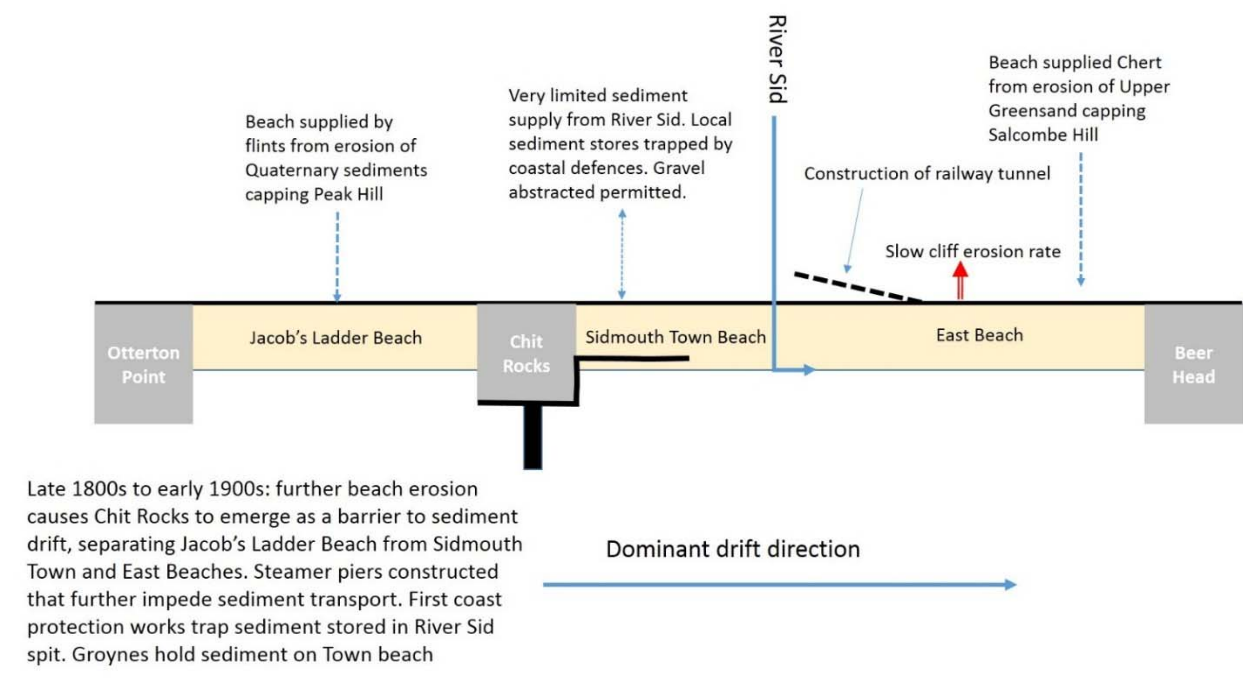
Particularly severe storms were experienced in February 2014; the largest since the scheme was constructed. Data collected by the Plymouth Coastal Observatory (PCO) shows that during these storms there was significant redistribution of sediment across the frontage, with erosion of the beach behind the breakwaters; an area which previous monitoring indicated as a net store of sediment. The data also suggests that sediment bypassing of the groynes may have occurred, indicated by beach accretion along the length of the groynes (although it is not possible to define whether this is sand or shingle). Through this mechanism material may be able to pass between groyne bays.

<u>East Beach</u>

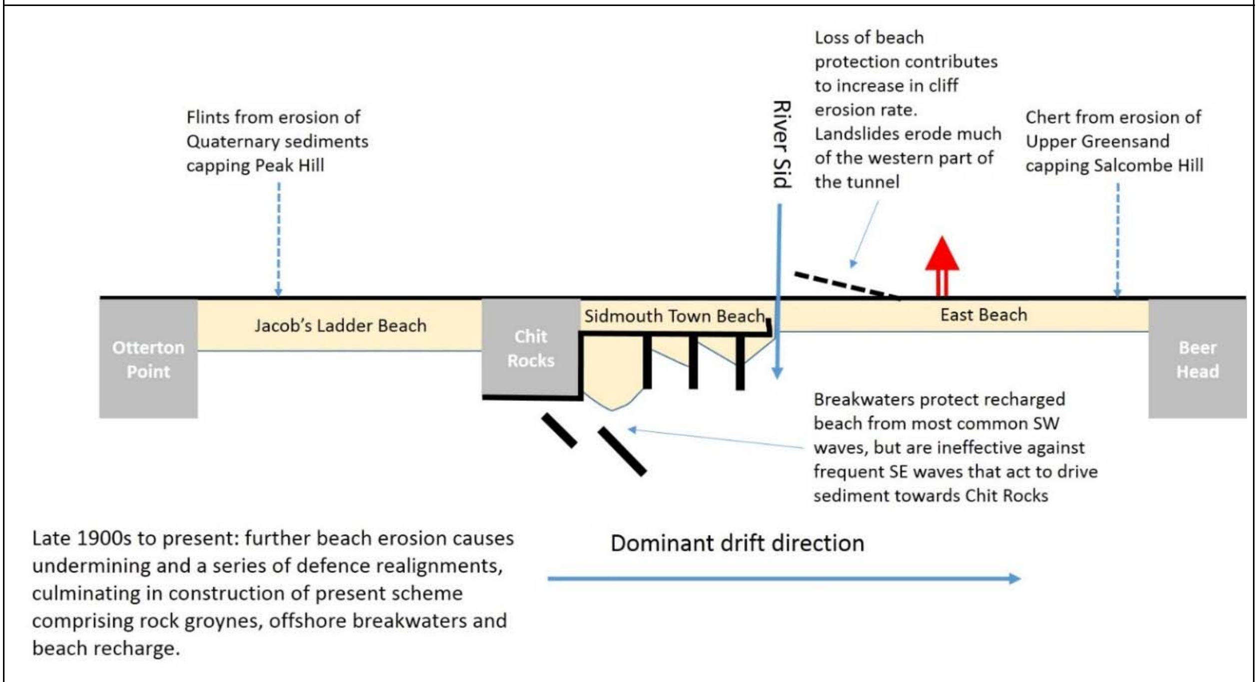
Cliff failure along the undefended cliffs which back East Beach is due to both changes in (a) groundwater conditions (and therefore rainfall), and (b) the beach level, which affects exposure of the cliff toe to wave action. Evidence suggests failures have been particularly common at Pennington Point, which is probably due to its exposed position and the weaker materials present here. Pennington Point forms a cross section through the eastern valley side slope of the River Sid and consequently the materials exposed comprise a greater thickness of colluvium and a greater depth of weathering than seen elsewhere along the coast. Anecdotal evidence and information derived from aerial photographs and historical maps shows that cliff failures at Pennington Point and East Cliff have been a common occurrence over the last 100 or so years, but there is evidence to suggest that erosion of the cliffs has accelerated in recent years. A number of possible causes have been considered and these are discussed below (see point 3 below).

Conceptual model of shoreline behaviour and response

Conceptual models of the coast pre- and post-scheme have been developed based on a synopsis of the various data sources and are presented in the figure below:



Initiation of first defences in response to declining sediment budget, around 100 years ago.



Additional defences in response to recent storms and on-going declining sediment budget

2. <u>Rates of historical and contemporary shoreline recession along the BMP frontage and adjacent shorelines, utilising data provided by local residents.</u>

Beach profile data, anecdotal information and previous monitoring reports have been analysed, together with a new study of long term cliff recession rates, which has utilised both historical Ordnance Survey maps dating from late 19th Century and historical aerial photography, dating from the 1940s to 2015. The cliff recession analysis has been based on cliff behaviour units defined on the basis of the local cliff lithology.

Results of this new analysis show that for the cliffs to the west of Sidmouth (eastern part of Jacob's Ladder Beach) an average long-term rate of change for the cliff top is 0.20m/year and for the cliff toe is 0.42m/year, based on the map data. The aerial photography data show a long-term average recession rate of 0.15m/year at the cliff top and 0.05m/year at the cliff toe. However, the short-term data indicate periods of localised, more rapid cliff top erosion between 1946 and 1950, 2006 to 2009 and 2009 to 2012. In each time period, the average cliff top recession rates are around 1.0m/year. The data from the cliff toe are in good agreement and show very slow long-term erosion of 0.05m/year. Widespread advances in the cliff toe since 2006 indicate debris lobes deposited on the beach by cliff failures. This corroborates the record of cliff top retreat also recorded at this time.

To the east of Sidmouth, along East Cliff, the long-term average rate of cliff recession shown on historical maps is 0.19m/year at the cliff top and 0.15m/year at the cliff toe. The data indicate a phase of rapid cliff recession from the 1890s to 1940s/50s, with less change from that point to 1991. The aerial photo data show a long-term average recession rate at the cliff top of 0.19 to 0.27m/year and 0.25m/year at the cliff toe. The short-term data for the cliff top suggests periods of widespread and rapid recession between 1946 and 1950 and since 2006. This is reflected by rapid erosion of the cliff toe over the same time periods. Taken as a whole, the historical data for East Cliff suggests the cliff experienced a phase of more rapid erosion and recession from 1890s to 1950, limited change from 1950 to 2006, and more rapid recession thereafter. The data also shows that the western 250m part of the cliff behaviour unit covering East Cliff has retreated markedly more rapidly than the eastern section.

3. Beach behaviour and cliff response at East Beach

A key concern of residents has been the perceived acceleration in cliff recession at the western end of East Beach since construction of the defence scheme. This has been particularly evident due to a number of cliff falls in recent years. Previous estimates of cliff recession along this frontage have varied widely, from 0.03m/year (Gallois, 2011) to 2.3m/year. These variations can be attributed to use of different epochs of historical data that often cover short time periods, different locations of measurement or classification of cliff behaviour units, and errors in the primary data. The landslide potential of these cliffs also means that spot measurements are not necessarily indicative of the behaviour of the whole cliff frontage.

As discussed above (see point 2), the new analysis of cliff recession for East Cliff indicates that when the entire frontage is considered the cliff experienced a phase of more rapid recession from 1890s to 1950, limited change from 1950 to 2006, and more rapid recession thereafter, with more rapid recession experienced at the western end of East Beach within 250m of the River Sid.

The process of cliff recession at this location is dominated by discrete landslide events that combine to produce a long-term cliff recession rate. Landslide behaviour is determined by a combination of top-down effects (principally rainfall saturating the weak materials of the upper cliff leading to failure) and bottom-up effects (caused by cliff toe erosion and undercutting by direct wave attack, particularly at times of low beach level). The frequency of landsliding is likely to increase in the future in response to predicted increases in rainfall and sea-level rise.

There are several possible explanations for the recent increase in cliff recession that appears to be occurring at the western end of East Beach:

- Downdrift erosion as a direct consequence of the defences at Sidmouth. This could be the result of the defences cutting off supply of sediment to East Beach and/or the diffraction of waves around the end of the defended frontage. Both these impacts could result in beach loss and cliff erosion.
- Impact of the former railway tunnel which was excavated parallel to the cliff toe in the 19th century. The tunnel has been progressively eroded since the mid-20th Century to present acting as a focus for wave erosion and causing localised collapses.
- The location of natural geological fault lines in the cliff.
- Natural changes, such as changes in rainfall or reduction of sediment supply from the east.

Cliff behaviour at East Cliff appears to be very strongly controlled by faults and the progressive erosion of the tunnel, which act as lines of weakness and focus of groundwater flow, rainfall and beach levels. Much of the tunnel was lost in the 20th Century, but its eastern part is still present and have been shown to have an influence on cliff retreat. The faults and tunnel features control localised groundwater flows that promote cliff top failures associated with peak rainfall events. These also act as zones for preferential cliff toe erosion due to wave action if the beach level is sufficiently low.

Intense rainfall events have been clustered in the last c.20 years. Beach levels have fluctuated over the last c.150 years, though have been persistently low for the last c.10 years. Together, these factors have provided the necessary conditions for accelerated erosion.

Fluctuating beach levels that allow direct erosion of the cliff toe when they are low also have a key role. Reconstruction of the past behaviour of beaches and cliffs from anecdotal evidence suggests that cliff failures are particularly common when beach levels are low. It is clear that the beach at Sidmouth and East Beach is subject to a cycle of stability, depletion and recovery which takes place over a cycle of 20 to 40 years. Superimposed on this are seasonal effects, which are determined by the direction and intensity of storm activity.

Based on the available data, it is not possible to definitively state that beach depletion and accelerated cliff recession are the result of a depleted sediment supply yet it is evident that construction of coastal defences along this frontage (dating back to the 1700s) have fundamentally changed the response and evolution of this shoreline over centuries. The evidence suggests that prior to the construction of the present Sidmouth scheme in the 1990s, linkages between East Beach and Sidmouth were already diminished by a combination of the existing defences, in particular the River Sid training wall, and low-beach levels along the frontage that occurred following the 1989 storms (pre-1989 there is evidence of a continuous beach linkage when beach levels are elevated). Post-scheme beach profile data for Sidmouth do not suggest that the Sidmouth frontage is retaining any sediment additional to that placed as part of the 1990s scheme (see point 1 above), further supporting the view of an absence of beach linkages and sediment supply to the frontage. In addition, this coastline is characterised by two dominant wave directions, meaning that sediment transport is not uni-directional, so East Beach (even without defences in place at Sidmouth) relies on sediment feed from both east and west.

Aerial photograph evidence showing the pattern of cliff recession at East Cliff indicates retreat of a linear cliff top rather than progressive development of an embayment. The recent failures of the cliff top are therefore likely to have been triggered by periods of extreme weather that have been coincident with the period of low beach levels at the western extent of East Beach. Intense rainfall causes saturation of the weak and unconsolidated upper cliff materials causing them to collapse, sometimes triggering joint-controlled failure of the basal mudstone. This has led to particularly rapid erosion at Pennington Point, which is for the most part characterised by particularly weak valley fill sediments that are particularly susceptible to failure through saturation. Storms, occurring at a time of low beach levels, have caused rapid toe erosion, promoting block failure.

4. Review and update the SMP2 predicted erosion

Estimates of potential erosion have been produced by this study for the cliffed coastline to the west and east of Sidmouth. The estimates account for past and present cliff behaviour. The projections are based on accurate measurements of cliff recession from historical vertical aerial photographs covering the period 1946 to 2015 and historical Ordnance Survey maps covering the period 1890 to 1991. The episodic nature of cliff failure and uncertainties over the precise relationships between increased rainfall, rising sea-level and cliff recession rate mean that making erosion projections over short periods of time is likely to involve high levels of uncertainty. Consequently high and low estimate projections for the next 100 years have been made. Annual cliff losses are not provided, but it is likely that the high rates of erosion experienced recently will continue for several years, before a lower rate is established. The table below shows a comparison of predictions of total shoreline change for a No Active Intervention scenario from the SMP2 and cliff recession rates estimated for the present study (in bold text):

Location	Short Term (to 2025)	Medium Term (to 2055)	Long Term (to 2105)
Beer Head to Salcombe Hill (West)	Total erosion in this area is predicted to be 5-6m by 2025.	Total erosion in this area is predicted to be14-18m by 2055.	Total erosion in this area is predicted to be29-53m by 2105.
CBU 8 (cliffs of Salcombe Hill)	-	-	**Total recession 100 years: 16.5 to 26.5m**
CBU 7 (cliffs immediately east of the River Sid)	-	-	**Total recession 100 years: 20.9 to 30.9m**
Sidmouth	No rates provided.	No rates provided.	No rates provided.
CBU6 and 5 (Chit Rocks and Sidmouth)	**n/a** **This coastline has been defended over the period covered by historical data.**	**n/a** **This coastline has been defended over the period covered by historical data.**	**n/a** **This coastline has been defended over the period covered by historical data.**
Chit Rocks to Big Picket Rock	Total erosion of 3-5m predicted by 2025 (SCOPAC, 2004).	Total erosion of 9-11m predicted by 2055 (SCOPAC, 2004).	Total erosion of 19-29m predicted by 2105 (SCOPAC, 2004).
CBU4 (eastern part of Jacob's Ladder Beach)	-	-	**Total recession 100 years: 16.5 to 21.5m**

5. Key uncertainties and limitations

The key uncertainties and limitations to our understanding of the behaviour of the coastline at Sidmouth comprise the following:

- The current monitoring of beach levels does not provide a good basis by which to assess volume changes, due to the distribution of profiles and the response of the beach, which is not very well replicated by interpolation of adjacent profile lines.
- Work completed by PCO for EDDC shows the design volume to MLWS (-2mOD) to be 182,062m^3, however this is based on a relatively crude volume calculation, which does not account for the recorded difference in placed beaches compared to the design beaches. This means it is very difficult to assess the long term success of the scheme.
- The sediment pathway between the nearshore and offshore remains uncertain, particularly how much and where sediment may be being stored in the nearshore/offshore zone. More detailed and regular bathymetry surveys supported by sediment sampling would help to clarify this matter.
- Based on previous analysis, assumptions have been made regarding the transport of shingle across the River Sid, which are assumed to be small, in terms of shingle. A better understanding of this potential linkage would add confidence to the arguments presented in this report.
- The nature of sediment transported between East Beach and Beer Head and potential interruption of sediment supply by periodic landslides. It would be useful to have beach monitoring data along this whole length of coast to improve understanding of the links between beach behaviour and response at East Beach and beaches further east.

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1 Introduction

1.1 The Study Area

This report has been prepared for East Devon District Council (EDDC) as part of the Sidmouth and East Beach Management Plan (BMP), which covers the coastline from Jacob's Ladder Beach, in the west, to East Beach, in the east, as well as the western bank of the River Sid up to the weir (Figure 1-1), and which feeds into the long-term coastal flood and erosion risk management for Sidmouth.

The coastal town of Sidmouth is located in the centre of the area covered by the BMP. Sidmouth is home to approximately 21,100 people (ONS census, 2011) and is predicted to increase by 3.8% (647 people) by 2021 (Devon County Council, 2007). It also supports an important tourist industry, providing holiday accommodation and visitor attractions and facilities, including the esplanade, which has been a prominent feature since the early 19th Century. The coastline is also designated for its environmental interests, including: Sidmouth to West Bay Special Area of Conservation (SAC); Lyme Bay to Torbay SAC; Sidmouth to Beer Coast Site of Special Scientific Interest (SSSI); Ladram Bay to Sidmouth SSSI; and the Dorset and East Devon United Nations Educational, Scientific and Cultural Organisation (UNESCO) World Heritage Site (the 'Jurassic Coast'). These and all other environmental interests are described in more detail in the Environmental Baseline report (CH2M HILL, 2015a) produced as part of developing the BMP.

The coastline is defined by high coastal cliffs to the west and east, between which lies lower-lying land through which the River Sid flows to meet the sea. A sand and shingle beach extends the length of the BMP coastline.

Between Jacob's Ladder Beach and the mouth of the River Sid (Figure 1-1), the lower-lying coastline, where the main centre of Sidmouth is located, has a long history of coastal management dating back to the early 19th Century . Today this coastline is protected from coastal flooding and erosion by a seawall with a rock revetment at its toe, three rock groynes, two detached rock breakwater structures and a replenished beach. The River Sid discharges across the beach to the east of the town centre. Works to control the outflow of the River Sid have been undertaken since the 18th Century , and today a training wall, which is believed to date from the 1920s, is located along the west bank of the River Sid. A South West Water outfall also runs alongside the training wall and across the sea bed to approximately 200m offshore.

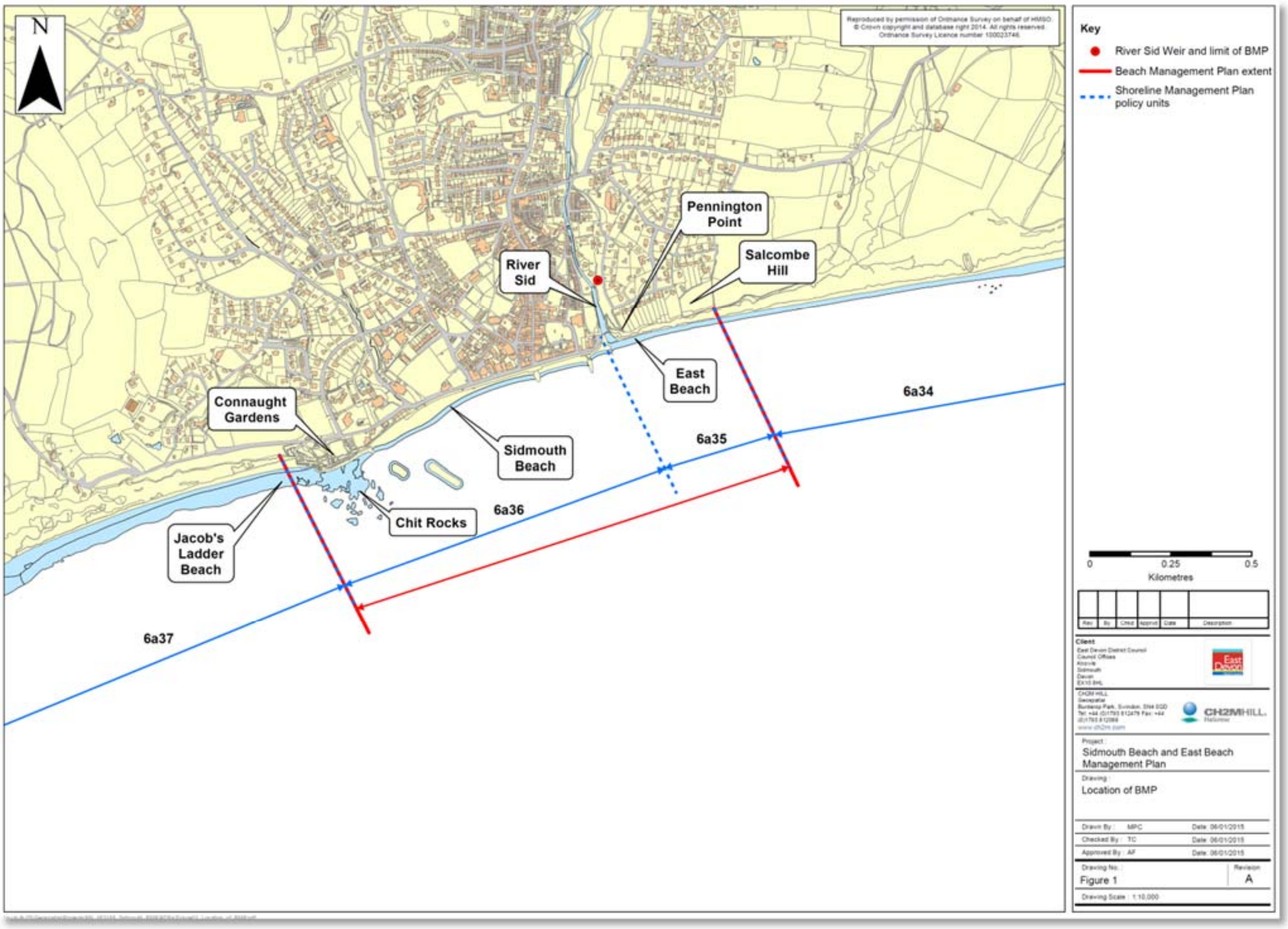


Figure 1-1 Map showing the Sidmouth and East BMP extent.

1.2 Basis of this report

This report will form an integral part of the BMP, the aim of which is to provide a detailed plan to manage and monitor the existing coastal defence structures and beach form in an integrated, justifiable and sustainable way; along with potential measures to reduce the rate of cliff erosion along East Beach.

This report will be the third revision of the BMP first produced in 1993. The first BMP accompanied the design and construction of a coast protection scheme comprising a rock revetment, seawall, rock groynes, detached rock breakwater structures and beach replenishment. The aim of this scheme was to improve and stabilise the active coastal cliffs around Chit Rocks and mobile beach between Chit Rocks and the mouth of the River Sid. A second revision was produced in 1998, following a review of the scheme performance.

The boundaries of this third revision of the BMP have been extended from previous versions to incorporate changes to coastal management policy defined by the South Devon & Dorset Shoreline Management Plan Review (SMP2) in 2011 (Halcrow, 2011), and to address ongoing concerns of beach and cliff erosion to the east of the River Sid at East Beach. The current BMP therefore covers the coast from Jacob's Ladder Beach, in the west, and to the end of East Beach, in the east (SMP2 Policy Units 6a35 and 6a36). Note that East Beach actually extends to Beer Head and the boundary used here corresponds to the Cliff Road frontage (Figure 1-1).

To ensure that future management decisions are sustainable, the options development process must be underpinned by a robust knowledge of coastal processes and responses, defence condition and performance, socio-environmental setting, and economic justification for future management, as well as any uncertainties around the level of understanding. A series of supporting studies to the BMP have therefore been produced:

- Coastal processes baseline (this report);
- Defence assessment report;
- Economics baseline; and
- Environmental baseline.

This coastal processes baseline provides an overview of coastal processes and shoreline change, and conclusions from this study will:

- Provide a point of reference when completing the other supporting studies;
- Be used to assess the existing management regime; and
- Be used to inform the development of future management options for the coastline.

In response to concerns regarding possible impact of the existing defences along the Sidmouth frontage on the adjacent undefended coast to the east (i.e. East Beach), EDDC specifically requested that this revision of the BMP address the following:

1) To review and update the SMP2 predicted erosion zones in the light of the significant erosion which has taken place since those erosion zones were predicted.

2) To research and quantify historical erosion rates for East Beach and recommended what it should be for Aim 2.

3) To research historical beach and cliff erosion rates in unit 6a35 as far back in time as possible with an appropriate degree of confidence. To review the SMP2 report of a recent increase in cliff erosion there, in light of this research. To compare beach and cliff erosion rates at East Beach before and after the construction of the Sidmouth Sea Defence Scheme in the 1990s. To quantify any changes and determine their cause.

In addressing the above, the following work has been undertaken and is reported in the following sections:

- **Description of the coastline (Section 2**) – this provides a baseline characterisation of the beach and cliffs.
- **Review of coastal management works undertaken along the coastline (Section 3)** – defences have existed along the Sidmouth frontage since the 1880s, which have fundamentally altered the behaviour of this coastline. Understanding why and when these defences were built feeds into the understanding of how the coastline has evolved and the influences on this evolution.
- **Physical setting (Section 4)** – this provides a description of the natural controls on the coastline, in terms of the geological setting, waves, tides and resultant sediment transport, and investigates how these may have been altered by mean-made defences
- **Shoreline change (Section 5)** – this section considers past change (i.e. over the last 130 years) and beach condition and shoreline behaviour since implementation on the Sidmouth coastal protection scheme. This review is based on a range of information, including anecdotal information provided by members of the public.
- **Conceptual understanding of shoreline behaviour (Section 6)** – this section brings together the information presented in the previous sections and presents our understanding of how the coastline is currently operating.
- **Projections of future change (Section 7)** – a key objective of this report is to review the projected erosion rates previously presented, based on the new assessments of historical and contemporary change.
- **Uncertainties and recommendations (Section 8)** – based upon the improved understanding upon controls (both natural and man-made), linkages and beach-cliff response, recommendations have been made relating to both future management and monitoring, which will feed into the main BMP.

2 Description of the coastline

2.1 Introduction

Although the BMP specifically considers management of the frontage between Jacob’s Ladder Beach in the west, to East Beach in the east, controls on the shoreline behaviour potentially extend beyond these boundaries. Therefore this section and the later sections covering conceptual understanding of shoreline behaviour consider the wider coastline between Big Picket Rock to Beer Head (see Figure 2-1).

The coastline between Otterton Ledge and Beer Head is defined by high, active cliffs interspersed with embayments or low-lying land and fronted by shore platforms and a beach of shingle and coarse sand. The geology and geomorphology of the cliffs and beach vary considerably along this length of coastline in response to the eastwards dip of the bedrock.

A brief description of the key characteristics of the shoreline is provided in the sections below, based on observations made during a site visit in December 2013 and information derived from other sources. A more detailed description of the cliffs follows and on the basis of their lithology and geological structure, a number of Cliff Behaviour Units (CBUs) have been defined. These CBUs have then been used in the quantification of historical cliff recession rates and predictions of future recession rates.

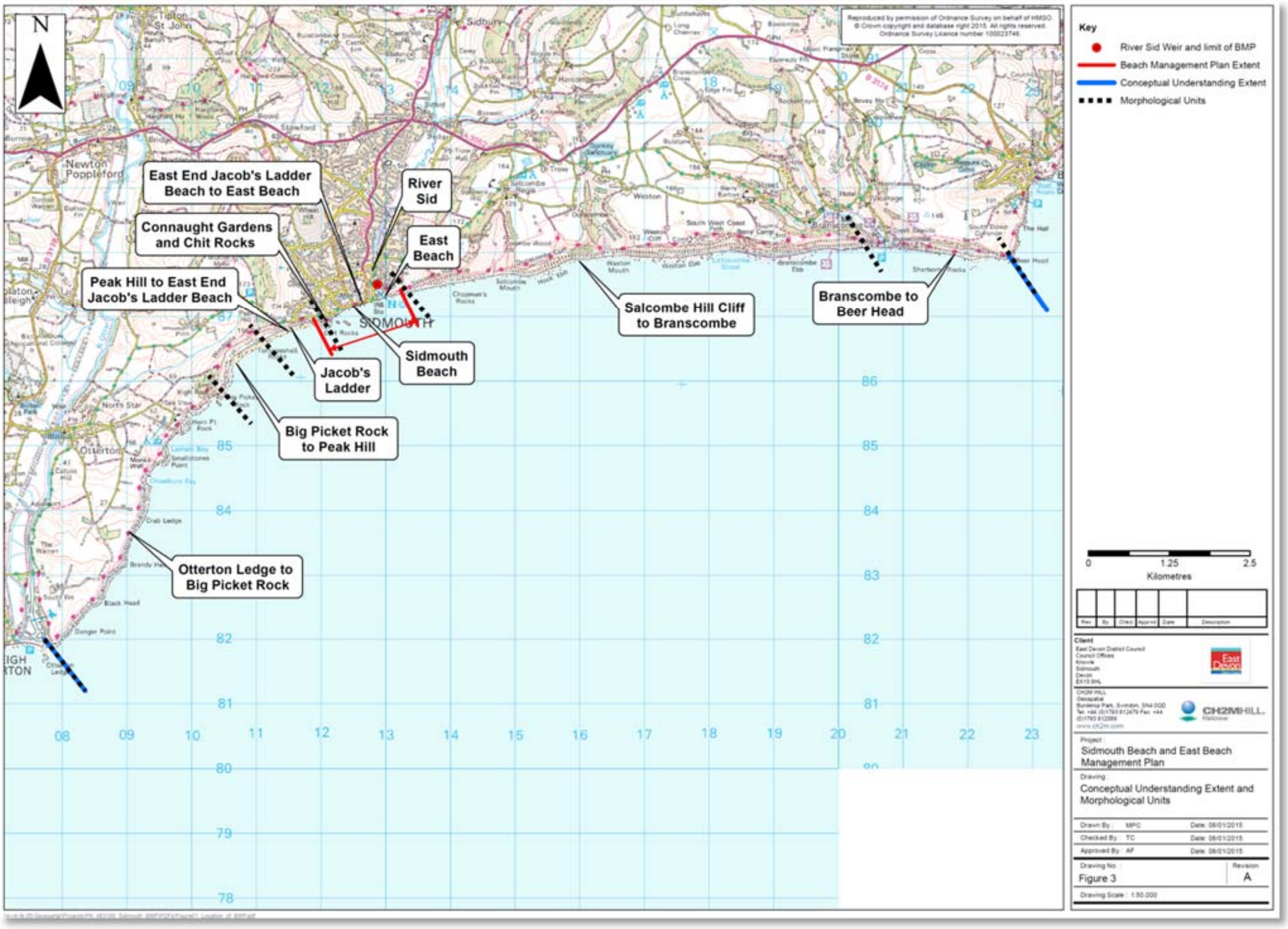


Figure 2-1 Map showing the BMP frontage, within the context of the wider coastal setting.

2.2 Description of the shoreline

2.2.1 Otterton Ledge to Big Picket Rock

The cliffs are primarily comprised of Otter Sandstone and reach up to 160m in height (Halcrow, 2011). The Otter Sandstone is underlain by the Budleigh Salterton Pebble Bed Formation, which has a small outcrop to the east of the mouth of the River Otter at Otterton Ledge. The coastline is characterised by rocky headlands and shore platforms enclosing discrete shingle pocket beaches (SCOPAC, 2003).

2.2.2 Big Picket Rock to Peak Hill

The cliffs comprise a basal part of relatively strong Otter Sandstone, which is overlain by an upper part of weaker Mercia Mudstone (see Figure 2-2). High Peak Hill and Peak Hill have a cap of Upper Greensand and Clay-with-Flints. The general easterly dip of the rocks means the rocks that crop out at sea-level changes along the coastline, which has an influence on coastal morphology. Towards the west, the basal unit is the stronger (more erosion resistant) Otter Sandstone, which tends to form headlands, while towards the east, the sandstone dips below beach level and the shoreline is formed in weaker mudstone that tends to form bays. The Mercia Mudstone is particularly susceptible to erosion and SCOPAC (2003) report that the main processes are a combination of basal wave erosion/seepage, periodic cliff failures, and gullying by overland flow. The beach is comprised of an upper berm of coarse clastic material and a low gradient sandy foreshore (SCOPAC, 2003).

Figure 2-2 Photograph showing view to High Peak Hill/Big Picket Rock, looking west. Photograph taken during site visit 9th December 2013. Note near-vertical basal cliff formed in Otter Sandstone (left of image) and shallower angled, heavily incised upper cliff formed in Mercia Mudstone. The hills are capped with Upper Greensand and Clay-with-Flints. The cliffs are fronted by a substantial gravel beach

2.2.3 Peak Hill to East End Jacob's Ladder Beach

The cliffs are comprised primarily of Mercia Mudstone (see Figure 2-3), as the Otter Sandstone dips below beach level, and reduce in height towards Sidmouth. A geological fault at the eastern end of Jacob's Ladder Beach once again brings the more resistant Otter Sandstone to beach-level, where it forms the Chit Rocks promontory and rock platform (Figure 2-4 and shown diagrammatically on Figure 4-1). The Otter Sandstone continues beneath Sidmouth town and dips below beach level at Pennington Point.

Figure 2-3 Photograph showing view from Peak Hill to the eastern end of Jacob's Ladder Beach, looking west – the cliffs are cut into Mercia Mudstone. Note extensive gravel beach and vegetated talus at the base of the cliffs. Photograph taken during site visit 9th December 2013.

2.2.4 East End Jacob's Ladder Beach to East Beach (the BMP frontage)

2.2.4.1 East End Jacob's Ladder Beach and Chit Rocks

The western limit of the BMP starts at Jacob's Ladder Beach, where geological faulting brings the Otter Sandstone above beach level to form the steep cliffs and shore platform of Chit Rocks (Figure 2-4). The upper beach is comprised of well-sorted, rounded shingle and exhibits a number of berms, whilst the lower intertidal beach is comprised of sand.

The Otter Sandstone outcrop at Chit Rocks is protected from erosion by a seawall, which extends east from the east end of Jacob's Ladder Beach, and a rock revetment which extends eastwards from Jacob's Ladder around the outcrop (see Figure 2-5).

Figure 2-4 Photographs of eastern end of Jacob's Ladder Beach showing: left, Mercia Sandstone cliffs and western extent of seawall (looking north-west), and right; Otter Sandstone outcrop at Chit Rocks with seawall and Jacob's Ladder (looking east). The cliff face crossed by the Jacob's Ladder is the scarp formed by a N-S aligned fault that brings the Otter Sandstone above sea-level to form Chit Rocks. Photographs taken during site visit 9th December 2013, when the beach was steep and narrow and the seawall was buried by shingle, indicative of a recent storm.

Figure 2-5 Photographs showing Otter Sandstone outcrop at Chit Rocks with seawall and revetment, looking east. Photographs taken during site visit 9th December 2013.

2.2.4.2 East Chit Rocks to the River Sid

Between Chit Rocks and Pennington Point, lies the low lying River Sid valley, which has incised into the Otter Sandstone. Here defences, including seawalls, detached breakwater structures and rock groynes, have been constructed to protect the town of Sidmouth from erosion and flooding and the seawall effectively fixed the backshore position between Chit Rocks to the mouth of the River Sid. A training wall channels the River Sid out to sea and a number of outfalls exist along the frontage, namely:

- Central Beach - ponding of the outfall in the upper shingle beach that drains the area of rising ground behind the western end of the Sidmouth Beach.
- South West Water Outfall – from the terminal manhole located at the western end of Sidmouth, the outfall is buried beneath the pavement (SWW, 2013). The outfall continues under the slipway where it meets with the beach. The outfall is only buried under the beach for part of its length. The outfall is encased by sheet piling and concrete and runs along the seabed about 200m offshore to the outfall discharge position, which is marked by a beacon.

At Sidmouth, the upper beach is comprised of poorly sorted shingle (imported to the site from an inland quarry as part of the 1990's Sidmouth Coastal Protection Scheme Phase 2), exhibiting a sequence of parallel storm ridges. The lower intertidal beach has a low gradient and is composed of coarse sand. The beach is widest and highest to the west of Sidmouth, in the lee of the breakwaters, and two tombolos have formed between the beach and detached breakwater structures. Within the two groyne bays to the east, the upper shingle beach is narrow, but the lower intertidal beach is wider. To the east of the training wall and eastern outfall, an accumulation of shingle is sometimes observed.

A sequence of photographs showing the coastline from west to east are presented in Figure 2-6.

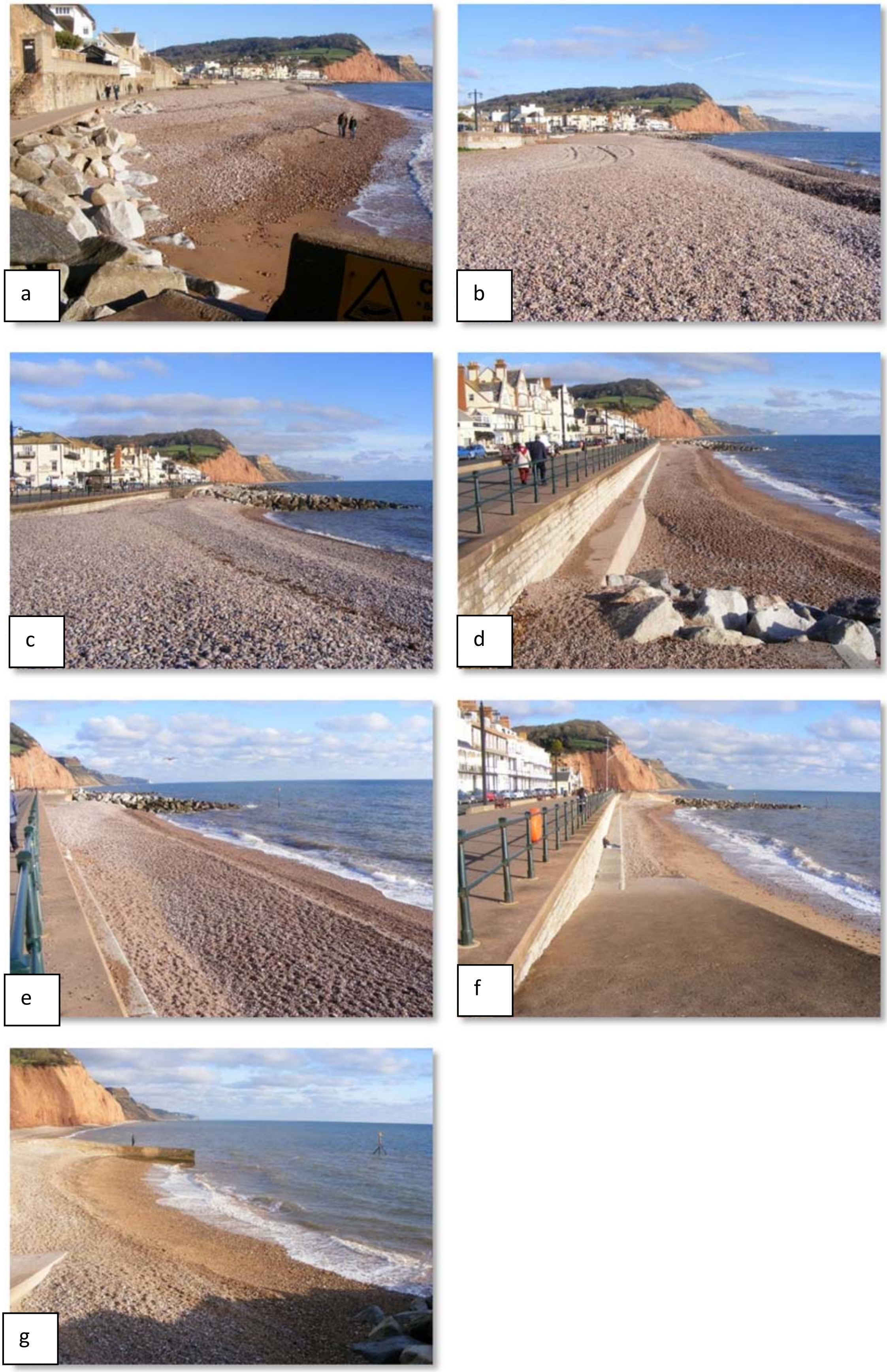


Figure 2-6 Sequence of photographs from west to east (a-g) showing coastline between Chit Rocks and the training wall on the west bank of the River Sid, all looking east. Photographs taken during site visit 9th December 2013.

2.2.4.3 The River Sid

The River Sid flows to the sea to the east of Sidmouth and marks the boundary of low-lying land and the higher and steeper Salcombe Hill Cliffs. It has a compact catchment with steeply sloping valley sides and tributary streams. It is tidal up to the weir and is regulated and is confined to a channel in its lower course through Sidmouth town (SCOPAC, 2003). It was first diverted to run in an artificial channel at the eastern margin of its valley in the mid-1700s (Gallois, 2011); the former course of the River Sid is shown in Figure 4-2.

The west bank of the River Sid, which for the purpose of this study includes the length of the bank from 'East Town' Weir to Alma Bridge and across the beach, is constrained by defences. The east bank, which is bounded by a cliff in the Otter Sandstone, remains undefended and the BMP only considers the stretch up to Alma Bridge. The length of the River Sid from the mouth at Alma Bridge to the 'East Town' Weir is shown in Figure 2-7.

Figure 2-7 Photographs show the mouth of the River Sid looking upstream: left, downstream of Alma Bridge, and right; upstream of Alma Bridge to the 'East Town' Weir. Photographs taken during site visit 12th January 2014.

At the mouth of the River Sid, a bank of shingle material extends from East Beach in an upstream direction. During a site visit in January 2014, the shingle bank was observed to deflect the main channel flow to the west against the training wall (refer to Figure 2-8); this is beach material that has been driven into the channel and is not sediment derived from the river catchment.

Figure 2-8 The mouth of the River Sid: left, looking downstream with the shingle bank on the left, and right; the main channel discharging to the sea along the flanks of the river flood defence and training wall. Photographs taken during site visit 12th January 2014.

2.2.4.4 East Beach

The BMP extent along East Beach includes the east bank of the River Sid, Pennington Point and Salcombe Hill Cliffs as far as Alma Lane. Immediately to the east of the River Sid, at Pennington Point, the Otter Sandstone is exposed at the base of the cliffs and overlying this is Mercia Mudstone (see Figure 2-9).

At the mouth of the River Sid, a bank of shingle material extends around Pennington Point from East Beach in an upstream direction. Superficially, the composition of the beach has been observed to change in an eastwards direction, from one primarily of shingle, to an upper beach of coarse sand overlain by a veneer of poorly sorted shingle and a lower beach of coarse sand. With the exception of a collection of imported boulders at the toe of the cliffs at Pennington Point, this coastline is undefended.

Figure 2-9 Photographs showing the coastline to the east of the River Sid, looking north east: left, the shingle bank at Alma Bridge and Pennington Point, and right; Pennington Point and Salcombe Hill Cliffs. Here the boundary between the Otter Sandstone and overlying Mercia Mudstone is shown by the dashed line and the base of the weathered mudstone and valley fill sediments of the Rover Sid is shown by the dotted line. Photographs taken during site visit 9th December 2013.

The cliffs at Pennington Point and Salcombe Hill Cliffs are eroding and the shingle beach at the mouth of the River Sid and beach at Pennington Point/East Beach is particularly dynamic, changing in form and volume through the seasons. Anecdotal data suggests that historically the shingle beach at Pennington Point was much larger in size and depth (e.g. Newsome, *pers. comms,* 2013) and it extended across the mouth of the River Sid to and around the training wall for longer periods of time; this has been investigated further as part of this study – *refer to the review of anecdotal evidence in Section 5.6 and Appendix A*. It is also noted that in the past, gravel from Upper Greensand chert and Clay-with-Flints in the headwaters of the River Sid are likely to have provided a small source of sediment for the beach, however, any remaining gravel is now captured by a large number of weirs on the River Sid (refer to Section 4.3.2) and periodically removed by the Environment Agency (Burch*, pers. comms, 2014*); the quantities removed are uncertain but it is understood that material is not re-distributed to the beach.

2.2.5 Salcombe Hill Cliff to Branscombe

The cliffs are cut into gently dipping Mercia Mudstone, overlain by Upper Greensand and Clay-with-Flints (see Figure 2-10). Deeply incised stream valleys punctuate the coast at Salcombe Mouth, Weston Mouth and Branscombe Mouth. The cliffs are subject to large scale and complex slope failure (SCOPAC, 2003). They are covered by World Heritage and Special Area Conservation (SAC) designations for geology and ecology respectively (SCOPAC, 2003). The beach is higher and wider than it is to the west, but is still comprised of an upper berm of coarse clastic material and a low gradient sandy foreshore (SCOPAC, 2003).

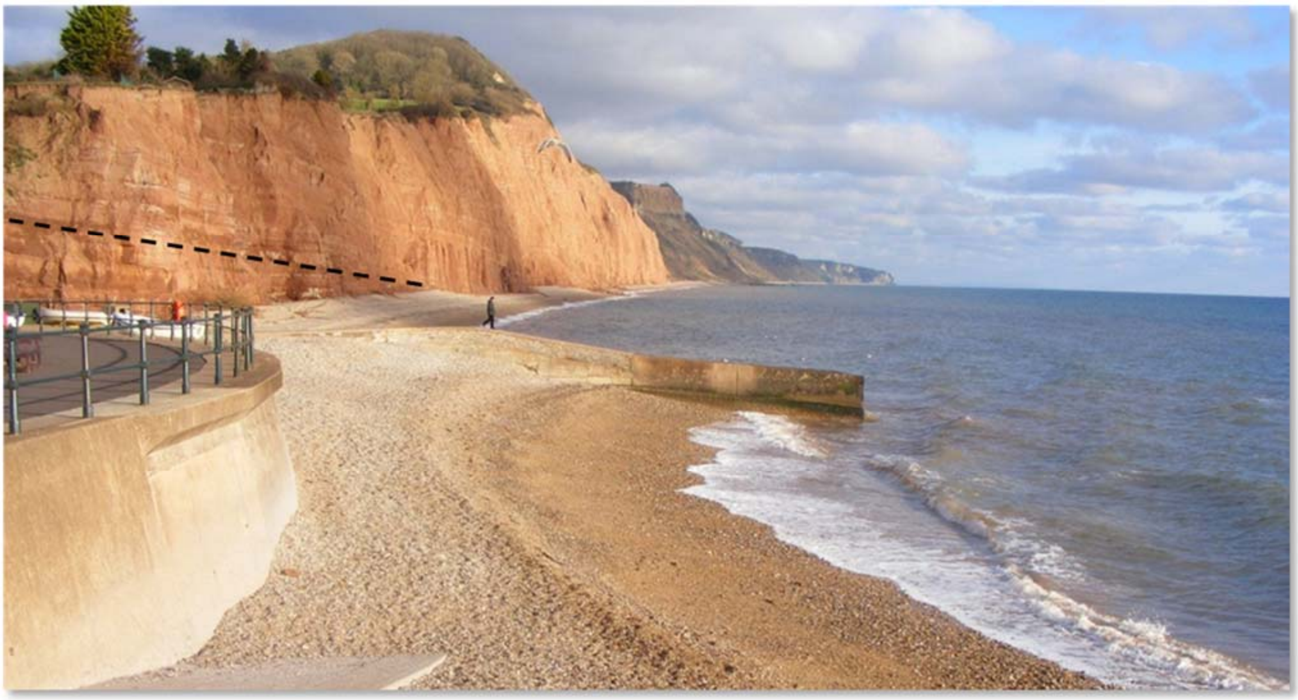


Figure 2-10 Photograph showing view from the Salcombe Hill Cliff to Branscombe, looking east. Pennington Point, which is underlain by Otter Sandstone, is in the foreground. Dashed line shows approximate boundary between basal Otter Sandstone and overlying Mercia Mudstone. Photograph taken during site visit 9th December 2013.

2.2.6 Branscombe to Beer Head

The cliffs are comprised of Greensand and Chalk (SCOPAC, 2003) and are defined by complex landslides, occurring due to basal erosion and sub-aerial weathering processes. The beach is comprised of an upper berm of coarse clastic material and a low gradient sandy foreshore (SCOPAC, 2003).

2.3 Characteristics of the cliffs

2.3.1 Introduction

Key to assessing cliff behaviour and recession potential is the understanding and definition of the mechanisms and causes of cliff instability and erosion. The extent to which these mechanisms induce cliff failure are themselves determined by the cliff geomorphology and structure. The process of cliff recession is complex and includes a range of forcing processes and feedback mechanisms:

- Forcing mechanisms can be classified as those external to the cliffs, such as incoming wave energy and rainfall; and those which are internal to the cliff, such as variations in material properties due to stratigraphy or weathering, cliff elevation, morphology and alignment.
- The primary driver of cliff recession is ‘bottom-up’ toe erosion. This causes undermining of the cliff toe, removing support, and triggers collapses of the cliff. The toe erosion process is effectively continuous, but cliff failures only occur when a threshold amount of erosion has been reached, and the stresses exceed the incipient strength of the rock mass. This cycle of erosion means that ‘bottom-up’ cliff recession events through rock fall and landslide processes are episodic through time. Adjacent sections of cliff operate independently of each other, consequently toe erosion in each section of cliff are at different points in the cycle, which means cliff failures are episodic in space and time.
- A secondary cliff recession process is ‘top down’ failure caused by rainfall and excess groundwater. Rainfall causes surface water run-off and groundwater levels to rise, which saturates the weak upper cliff materials (weathered Mercia Mudstone and slope wash materials known as ‘Head’) causing cliff failure. Over time, cliff failures will tend to bring a slope or cliff to an angle at which it is stable. Therefore, while failures are triggered by a period of sustained rainfall, a given rainfall event does not cause failure of the entire length of cliff top because the cliff geology and morphology varies

along the coast. This variation is brought about by episodic failures of the upper cliff being triggered by 'bottom-up' toe erosion, and variation in upper cliff material properties and thicknesses.

- The elevation of the beach acts as an important control of the 'bottom-up' cliff recession process. When the beach is high it absorbs wave energy and protects the cliff toe from erosion; when the beach is low, waves can break at the cliff toe and cause erosion. The beach has no control over the 'top-down' failure mechanism and therefore cliff top failures that are triggered by rainfall will occur even if the beach level is high.
- A principal feedback mechanism involves sediment being transferred to the beach following a cliff failure, where it temporarily acts to protect the cliff toe from further erosion before being reworked into the shoreline and offshore sediment systems. This process is strongly dependent on the rate of littoral transport rate, which determines how long 'protective' cliff fall material is present at the cliff toe. The evidence from aerial photographs suggests that along much of the Sidmouth frontage, cliff fall materials (i.e. landslide debris lobes) are reworked within a period of around 5 years. In contrast, further east at Dunscombe Cliff and Weston Cliff, landslide debris formed of more resistant Greensand have persisted for over 20 years to significantly reduce cliff toe erosion at these locations.

These processes and feedbacks give rise to a complex cliff recession process that is episodic over space and time. When investigating historical rates of recession, it must be remembered that average recession rates can be misleading if based on short-periods of data.

For the purpose of this study the cliffs have been assessed against a classification framework developed by Lee and Clarke (2002), which considers the characteristic of the cliff and the mechanisms by which they retreat. Lee and Clarke classify cliffs that have similar characteristics and retreats by similar mechanisms into Cliff Behaviour Units (CBU's). There are four main CBU types within the framework, although the cliffs in the study area fall into two of those types, simple cliffs and composite cliffs, as shown in Figure 2-11 and described below. The CBU's have been used to underpin the assessment of cliff recession rates.

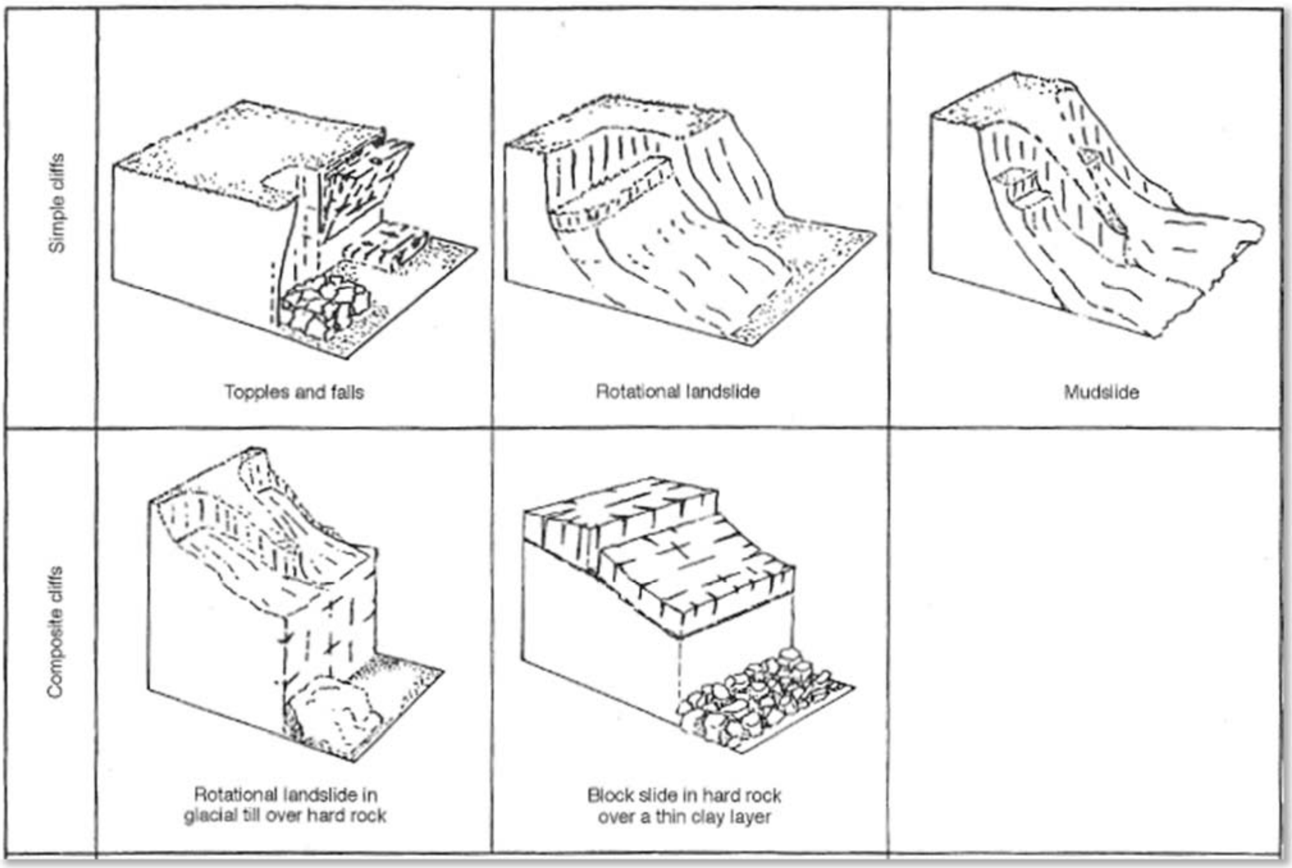


Figure 2-11 Cliff behaviour units: simple cliffs and simple landslides (Lee and Clark, 2002).

- Simple cliffs have sediment inputs from rock falls that lead directly to foreshore deposition. Cliff recession occurs as a result of toe erosion and undercutting that can be described by an average recession rate. Along this shoreline, these CBUs occur where the cliffs are formed solely in the Otter Sandstone or the Mercia Mudstone, where failure is typically through topples and falls. Small failures tend to occur in the massive (i.e. weakly-bedded) sections of the Otter Sandstone that crops out to the west of Sidmouth. Gallois (2011) notes the Mercia Mudstone is characterised by joints that run sub-parallel with the cliff face which promotes failures.
- Composite cliffs comprise partly coupled sequences of contrasting sub-systems, typically bedded hard and soft rocks. The primary failures are driven by a combination of toe erosion of the lower strata and elevated groundwater levels that weaken the upper strata. The partly-coupled nature of these two systems means that while the upper unit will fail episodically in response to recession of the lower unit, it can also fail independently of the low unit, in response to other factors such as elevated ground water levels. These CBUs occur where the Mercia Mudstone overlies the Otter Sandstone, and where there is a thick capping of Clay-with-flints. East of Salcombe Hill larger failures are recorded where a competent cap of strong Upper Greensand overlies the less competent Mercia Mudstone. Gallois (2011) notes failures in the upper cliff often trigger secondary events in the lower cliff that are controlled by the pattern of joints, and therefore failures can occur irrespective of beach size and toe erosion.

2.3.2 Cliff Behaviour Units

Eight CBUs have been recognised between High Peak Headland and Salcombe Hill/Dunscombe Cliff, as shown in Figure 2-12 and described in Table 2-1 below:

- CBU 1 marks the western boundary of the study area at High Peak.
- CBUs 2, 3 and 4 comprise the bay of Jacob's Ladder Beach.
- CBUs 5 and 6 cover the defended headland of Chit Rocks and Sidmouth town frontage.
- CBU 7 covers the cliffs immediately east of the River Sid, and
- CBU 8 covers the cliffs and landslides of Salcombe Hill.

The rocks exposed in the cliffs are largely determined by the eastward dip, meaning younger mudstone rocks form the cliffs to the east.

Faults cause a repeat of some layers, allowing the Otter Sandstone to reappear at Chit Rocks and Pennington Point. A capping of Upper Greensand is seen only in the higher cliffs at Peak Hill, Salcombe Hill and Dunscombe Hill.

The CBU's have been used to underpin the assessment of cliff recession rates and to determine any changes in cliff past cliff behaviour.

Figure 2-12 Map showing extents of CBUs.

Table 2-1 Cliff Behaviour Units recognised between High Peak and Salcombe Hill.

CBU	Description
1	Composite cliff. High Peak headland. Approx. 160m high cliffs in Otter Sandstone, Mercia Mudstone and Upper Greensand with a cap of clay-with-flints. Failure through landslides and limited toe erosion. Fronted by a rocky shore platform.
2	Composite cliff. Peak Hill Cliffs. Approx. 100m high cliffs in Otter Sandstone, Mercia Mudstone and Upper Greensand with a cap of clay-with-flints. Failure through landslides and limited toe erosion. Fronted by a beach.
3	Composite cliff. Peak Hill Cliffs. Approx. 100m high cliff in Otter Sandstone, Mercia Mudstone and Upper Greensand with a cap of clay-with-flints. Failure through landslides and limited toe erosion. Fronted by a beach.
4	Simple cliff. Jacob's Ladder Beach Cliffs. Approx. 25m high cliffs in Mercia Mudstone with a cap of clay-with-flints. Cliff failure through toe erosion and landslides. Fronted by a beach.
5	Simple cliff. Chit Rocks and Jacob's Ladder. Approx. 25m high cliffs of Otter Sandstone, but fronted by defences, forming a defended headland and rocky shore platform.
6	Sidmouth frontage and exit of the River Sid. Low frontage less than 10m OD in height, which is defended by a seawall. The beach is held in place by three rock groynes and protected by two offshore breakwaters. The River Sid outflows via a channel cut in the Otter Sandstone – the river mouth is periodically blocked by beach gravel.
7	Composite Cliff. Salcombe Hill Cliff and Cliff Road, Sidmouth. Undefended Otter Sandstone and Mercia Mudstone cliffs up to 50m high that are fronted by a beach. The base of these cliffs include the remains of a 19th Century tunnel that runs parallel to the beach. Cliff failure through toe erosion and landslides up to 50m wide
8	Composite cliff. Salcombe Hill and Higher Dunscombe cliffs. Up to 160m high undefended Mercia Mudstone and Upper Greensand cliffs with a capping of Clay-with-flints. Fronted by a beach. Cliff failure through toe erosion and landslides, with particularly large failures up to 175m wide in the Upper Greensand.

3 Coast Protection Works and Management

This section provides a summary of the coastal protection works constructed and implemented within the BMP extent (full details of the coastal management history is presented in the Defence Assessment report (CH2M HILL, 2015b)). A map showing the coastal works at Sidmouth is presented in Figure 3-1, and a summary of the coastal protections works up to the present date are presented in Table 3-1 and Section 3.1.1.

3.1 History of management along this coast

The earliest formal defences along this coast are believed to date back to the 1820s, when records indicate that timber groynes and breastwork were constructed along the Sidmouth frontage. This coincides with the development of Sidmouth as popular tourist destination, with the esplanade and associated seawall dating from around 1830s. There were also plans to develop a harbour or marina around this time, and associated works to construct a railway. Prior to this Sidmouth was simply a fishing village, with little need for any defences, apart from works to control the flow of the River Sid. SCOPAC (2003) reports that at this time there was also a significant change in coastal behaviour due to erosion of Chit Rocks during a catastrophic storm event in 1824. These rocks had formerly provided significant protection from south-westerly waves as well as forming a natural hard point which helped stabilise the Sidmouth frontage.

Resultant rapid loss of beach volume necessitated the building of a seawall founded on the backshore gravel beach berm to protect the town/village in 1830. Records indicate that from the time defences were constructed, issues of erosion and damage continued; for example during construction of the railway line in the 1830s, there is evidence to suggest that works had to cease in the winter of 1837, when storms damaged the railway (Messenger, 1974). The record of defence works, in Table 3.1 below, also makes mention of numerous repairs and damage to structures. This is indicative of the ongoing and long term problems of erosion and flooding along this shoreline, which predate the current defences. The original seawall was subsequently replaced by successively more substantial structures, with foundations in the Otter Sandstone bedrock, in response to overwashing, breaching and progressive beach drawdown and a major groyne along the bank of the River Sid was also inserted in 1918 to stabilise the river mouth and promote updrift beach accretion (SCOPAC, 2004).

Despite these beach works problems of beach loss continued and records suggest that the beach at Sidmouth was very dynamic experiencing significant drawdown during winter and subsequent summer accretion, although evidence reported in SCOPAC (2004) suggests that beach recovery could take several years to occur.

Beach levels and volumes fell during the 1980s and there was a concern that Sidmouth Beach had reached a critical state and was becoming diminished over time, partly due to the defences affecting the longshore drift along the frontage and causing wave focussing at the shoreline. This concern prompted the design of the most recent works, which specifically aim to reduce wave energy at the Sidmouth town shoreline, reduce reflective scour from the seawall and thereby stabilise the nourished beach.

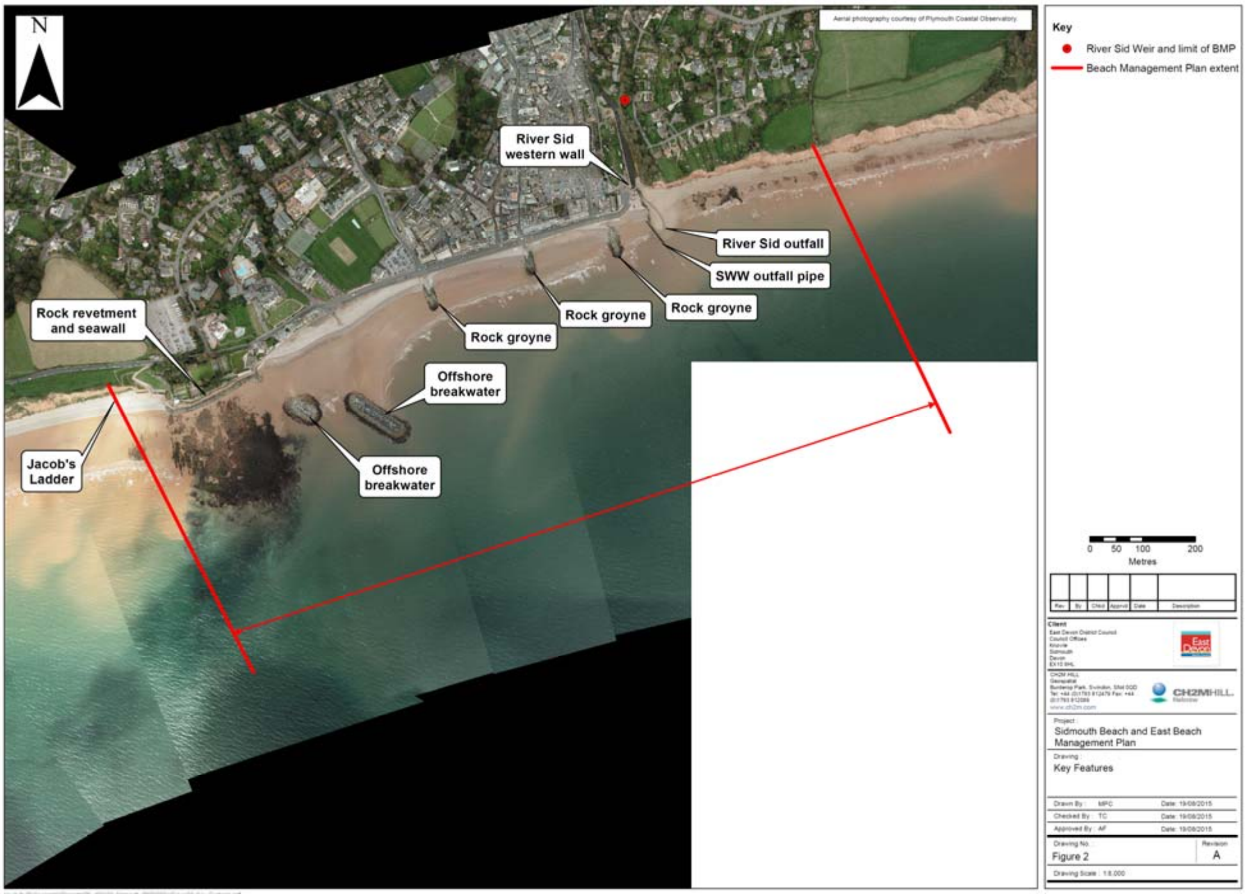


Figure 3-1 Map showing the location of coastal works located within the Sidmouth and East BMP extent.

Table 3-1 History of coast protection works at Sidmouth.

Date of Construction	Description of Defence
1700s	The River Sid was diverted to run in an artificial channel in the mid-1700s.
1825 to 1826	Timber groynes and breastwork constructed along the length of the Sidmouth frontage in response to ‘great storm’ of 1824.
1835	New seawall (420m) constructed between Bedford Steps and the River Sid. The seawall was founded on the gravel bank and not on the bedrock.
1875	Dunnings Pier constructed at the eastern end of Sidmouth Esplanade.
1917 to 1919	Seawall between Bedford Steps and the River Sid repaired.
1918 (approx.)	Promenade seawall and land reclamation at eastern end of Sidmouth (original date of construction unknown).
1920 to 1921	New low level seawall constructed between West Pier (no longer exists) and Bedford Steps.
1921	Works undertaken on West Pier.
-	Dunnings Pier damaged.
-	West Pier damaged.
1924	New low level seawall extended from Bedford Steps to Dunnings Pier.
1925	Seawall damaged.
1926	Dunnings Pier replaced by Port Royal groyne, later known as East Pier groyne.
1920s (approx.)	River Sid training wall and outfall constructed (original date of construction unknown).

Date of Construction	Description of Defence
1953 to 1957	Seawall between Bedford Steps and River Sid, timber groynes repaired.
1957	New seawall and promenade (190m) constructed from Jacob's Ladder to Clifton Beach.
1990	Emergency works to seawall at Bedford Steps.
1990 to 1991	**Phase I Sidmouth Coast Protection Scheme** Remaining exposed sections of the original masonry seawall encased. Old wall (beach concrete) immediately west of the East Pier encased. New low-level rock apron to the sea wall constructed between timber groynes 1 and 3. Existing timber groynes 1 and 5-12 removed. East Pier secured at its present length. Seaward end of the West Pier encased.
1993	Emergency works, including construction of low level rock revetment at the foot of the seawall for approximately 400m from West Pier to York Steps and repairs to the seawall.
1994	**Connaught Gardens Coast Protection Scheme** New rock revetment extended 155m from Jacob's Ladder Beach east to Clifton Beach. Concrete apron constructed at Jacob's Ladder Beach east.
1995	**Phase II Sidmouth Coast Protection Scheme** New rock revetment constructed at Clifton Beach extending from Connaught Gardens to West Pier. Promenade re-surfaced and installation of handrail along the esplanade. Flood gates installed to span the gaps between the concrete toe wall along the promenade. Reinforced concrete encasement of the seawall between East Pier and the river training wall. Removal of Glen Road timber groyne situated between West Pier and Belmont Steps. Construction of two large offshore breakwaters. Construction of two rock groynes, York Steps groyne and East Pier groyne (constructed at location of East Pier). Beach recharge of 185,000 tonnes (assuming 1 tonne is equal to 1.76m^3, this equates to around 105,000m^3) between West Pier and East Pier groyne, burying the 1993 low level rock revetment. It is understood that the design profile varies along the length of the frontage. The quantity of beach material imported onto the Phase 2 scheme frontage during the course of the works was, in the event, less than the design requirement as determined by the physical model. This situation arose, at least in part, because of the need to terminate the importation of beach material at the onset of the 1995 holiday season. The deficit was largely contained within the York Groyne to Bedford steps frontage. This did not give too much cause for concern in itself as the beach material imported was significantly coarser than that which was tested in the physical model, therefore a smaller volume of material was required to achieve the same standard of protection. **Physical modelling undertaken by HR Wallingford (1992) concluded that the beach under the preferred scheme (Test 34*) would behave as below under the Phase II Scheme:** **Test 34 comprised two offshore breakwaters, two groynes, replenished beach with a 10m berm at +4.6m OD along the entire beach with a 1:7 slope to the seabed.* 1) Under storm conditions between ESE and SSW, beach levels remained acceptable along the frontage for all wave events. Long period storms from the SSE tended to flatten the beach slope. 2 Under ESE wave attack, there was a tendency for the beach to broaden at the western end, although some material was able to pass west beyond the limit of the offshore breakwaters. 3) Under SSE wave attack, beach draw-down was predicted. 4) SSW no longer cause material from the western frontage to migrate eastward and ESE wave continue to cause westward migration of material in central portion of the beach. The result is an overall a tendency for a net increase in the amount of shingle in the lee of the breakwaters (i.e. accretion behind the breakwaters), with beach levels expected to remain acceptable along a large section of the frontage. 5) Net drift from west to east reduction from 6,353m^3/year to 2,120m^3/year expected.

Date of Construction	Description of Defence
	6) Crest levels of the beach need to be maintained to a height of +3.0mOD for the scheme to perform acceptably. 7) Routine beach management required, including regular monitoring of beach levels, redistribution of shingle following periods of severe storms or once an imbalance in the beach size at either end of the frontage has developed. 8) An area of reduced tidal current speeds during the eastward tide predicted (HR Wallingford, 1993).
1999	**Clifton Walkway** Construction of a walkway, on top of the rock revetment.
Late 1990's/2000's	Training wall extended with addition of new concrete blocks (Bailey, *pers. comms.*, 2015).
2000	**Phase III Sidmouth Coast Protection Scheme** Details are provided in Section 3.1.1 below.
2015	**Beach Recycling** Movement of material from the western to eastern end of the beach in line with recommended Sidmouth Coast Protection Scheme design/1998 BMP/2005 PAR (see Section 3.1.1).

3.1.1 Phase III 2000

Following completion of Phase I and II works, the beach showed signs of cut back at the York Steps groyne. The 1998 BMP (first revision) (Posford Duvivier, 1998a) identified that the distance between the offshore rock breakwaters and York Steps groyne was too great, causing the beach to gradually reduce in profile in an easterly direction (something that was also predicted by physical modelling as part of the original scheme design (HR Wallingford, 1992). With a narrow beach, the integrity of the groyne and seawall could be threatened. There were also concerns that the beach was losing around 4,000m^3 of sediment annually (based on surveys in 2000 and 2001).

The BMP examined a series of beach management options for the frontage, and selected Option 2 as the preferred option, which included:

- Construction of a new groyne at Bedford Steps.
- Small amount of recycling every 5 years (10,000m^3 of material every 5 years at a cost of £40,000 per event).
- Reduced beach recharge at intervals as for Option 1 (i.e. recharge in years 15 and 35 at a cost of £50,000 per event).
- Monitoring as far as Option 1 (i.e. monitoring at £10,000 annually).

Reconstruction of the Bedford Steps rock groyne involved the redistribution of 18,000m^3 of nourished material from its western to its eastern side, and an additional 6,000m^3 was placed to the east of York Steps groyne.

Despite the recommendations in the 1998 BMP, no further recycling or recharge was undertaken until 2015, as monitoring from 2006 to 2011 (Royal Haskoning, 2005b) indicated that although there had been redistribution of sediment along the frontage (gains in the lee of the detached rock breakwaters and losses between the three groynes) there had been no net loss to the frontage. Recycling was undertaken in 2015 to address significant changes in beach levels along the Sidmouth town frontage following a series of large storm events in February 2014.

3.2 Coastal management and monitoring post scheme

To support the latest coastal protection scheme at Sidmouth, a BMP was prepared to accompany the scheme. The first version was issued in 1993, followed by a revised version issued in 1998. Between the two versions, and as described below, beach monitoring was undertaken and conclusions from this are reported in the 1998 BMP (Posford Duvivier, 1998a).

Beach monitoring at Sidmouth commenced in 1995, during the construction of Phase II of the Sidmouth Coast Protection Scheme. Monitoring and analysis was undertaken by Posford Duvivier. The beach was surveyed before placement of the beach recharge material, after placement of the recharge and at the end of the contract. After the end of the contract, beach surveys were undertaken by EDDC, up to May 1998, although the data was passed to Posford Duvivier for analysis. Only the findings of the beach monitoring from the end of the contract survey on the 25th October 1995 until the last survey on 28th May 1998 are presented within the 1998 BMP (first revision). The surveyed area extends from Clifton Beach to the River Sid training wall. For the ease of surveying and later monitoring, the beach was divided into four zones (A to D) subdivided into a further 16 zones (A1-A3; B1-B7; C1-C3 and D1-D3) on the basis of physical barriers or distinct changes in the seawall plan profile (refer to Figure 3-2). The surveys were undertaken to coincide with spring tides to obtain maximum coverage of the beach. In addition, during the monitoring process, offshore hydrographic data obtained during October 1995 was added to each of the survey lines to extend their limits seaward to a minimum of -3.0m ODN. Details of the key findings of the first monitoring programme is presented in Section 5.5.1.1.

Following the 1998 BMP, a further five year monitoring programme was implemented; the baseline survey was undertaken in April 2000, with subsequent surveys undertaken bi-annually in 2001, 2002, 2003, 2004 and 2005. A number of beach monitoring reports and nine bi-annual summary reports were produced between 2001 and 2005, and included review and assessment of the monitoring data. The most recent beach monitoring and summary reports were produced in August 2005 (extract provided in Royal Haskoning, 2005b) and January 2005 (Summary Report 8) (Royal Haskoning, 2005a) following completion of the October 2004 survey. The key findings of the first five year monitoring programme are presented in Section 5.5.1.2.

An application was made for a second five year beach monitoring programme between 2006 and 2011 (Royal Haksoning, 2005b). Following award of funding, this was incorporated into the overarching Southwest Regional Coastal Monitoring Programme (SWRCMP). The baseline survey for the SWRCMP was undertaken in August 2007, therefore no data is available for 2006. The SWRCMP is ongoing, so beach monitoring data is available from August 2007 to the present day. For the purpose of the present BMP, this previous analysis of the data has been reviewed (see Section 5.5.1.3) and newly analysed (see Section 5.5.2).

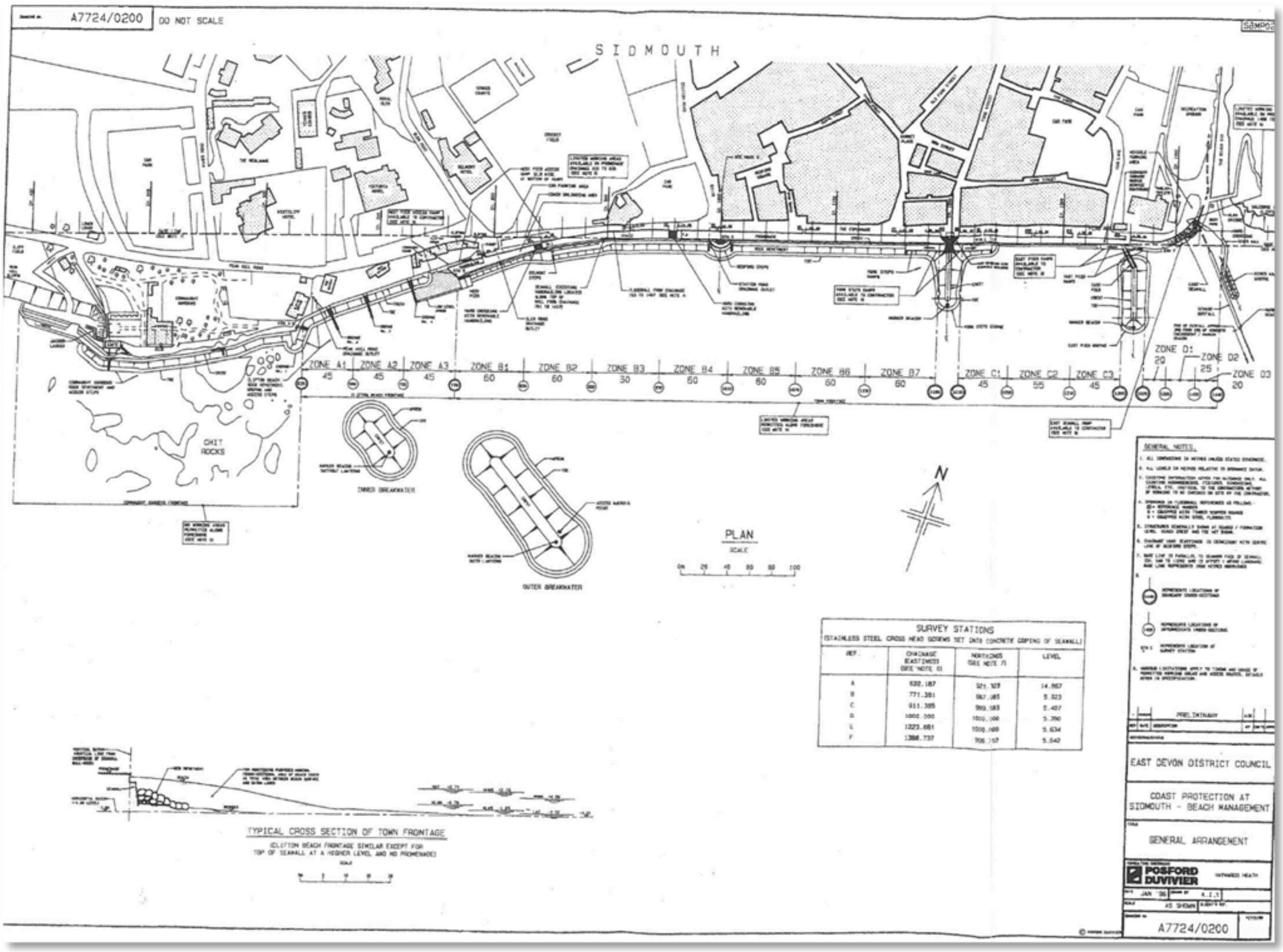


Figure 3-2 1995 to 1998 beach monitoring survey zones.

4 Physical setting

This section considers the controls on the coastal behaviour and shoreline evolution. It discusses the origins of the coastline that is present today, which remains a major influence of how the shoreline currently responds, the waves, tides and precipitation that affect the coastline, and the sediment transport patterns that result. No new modelling has been undertaken for this revision of the BMP, and the information presented here draws from existing literature, using a selection of key references, notably:

1. Plymouth Coastal Observatory (PCO) Annual Survey Report (PCO, 2013).
2. South Devon and Dorset Shoreline Management Plan (SMP2) (Halcrow, 2011);
3. SCOPAC Sediment Transport Study (SCOPAC, 2003; SCOPAC, 2004);
4. Futurecoast (Halcrow, 2002); and
5. Sidmouth Phase 2 Coast Protection Scheme. Revised Beach Management Plan (Posford Duvivier, 1998a).

4.1 How the coastline formed

Formation of the current coastline between Otterton Ledge and Beer Head began when sandstones and mudstones were laid down during the Triassic Period, some 203 to 250 million years ago. Subsequent tectonic activity led to the uplift and faulting of the bedrock, creating the complex exposures evident in today’s cliff line. Over the past 2.5 million years (the Quaternary Period), there has been erosion of these deposits, in response to changes in climate and sea-level, which has led to the development of the coastline and cliffs that are exposed today.

A diagrammatic geological cliff section of the coastline between Otterton Ledge and Salcombe Mouth (located just to the east of Sidmouth) is shown in Figure 4-1, whilst Figure 4-2 shows the geology of the coastline between Big Picket Rock and Salcombe Hill (located just to the east of Sidmouth).

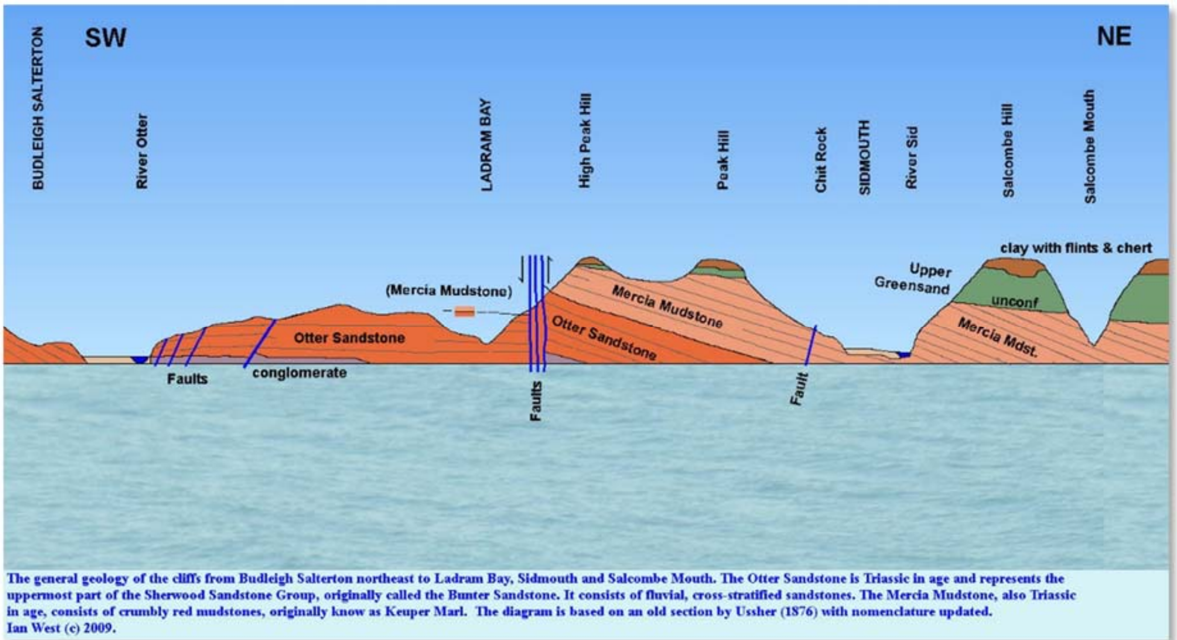


Figure 4-1 Diagrammatic geological cliff section of the coastline between Otterton Ledge and Salcombe Mouth (east of Sidmouth), looking inland from the sea (West, 2013). The Otter Sandstone outcrop at Chit Rocks and at the base of Pennington Point (NE of the River Sid), and faults in cliff east of River Sid have been omitted for clarity.

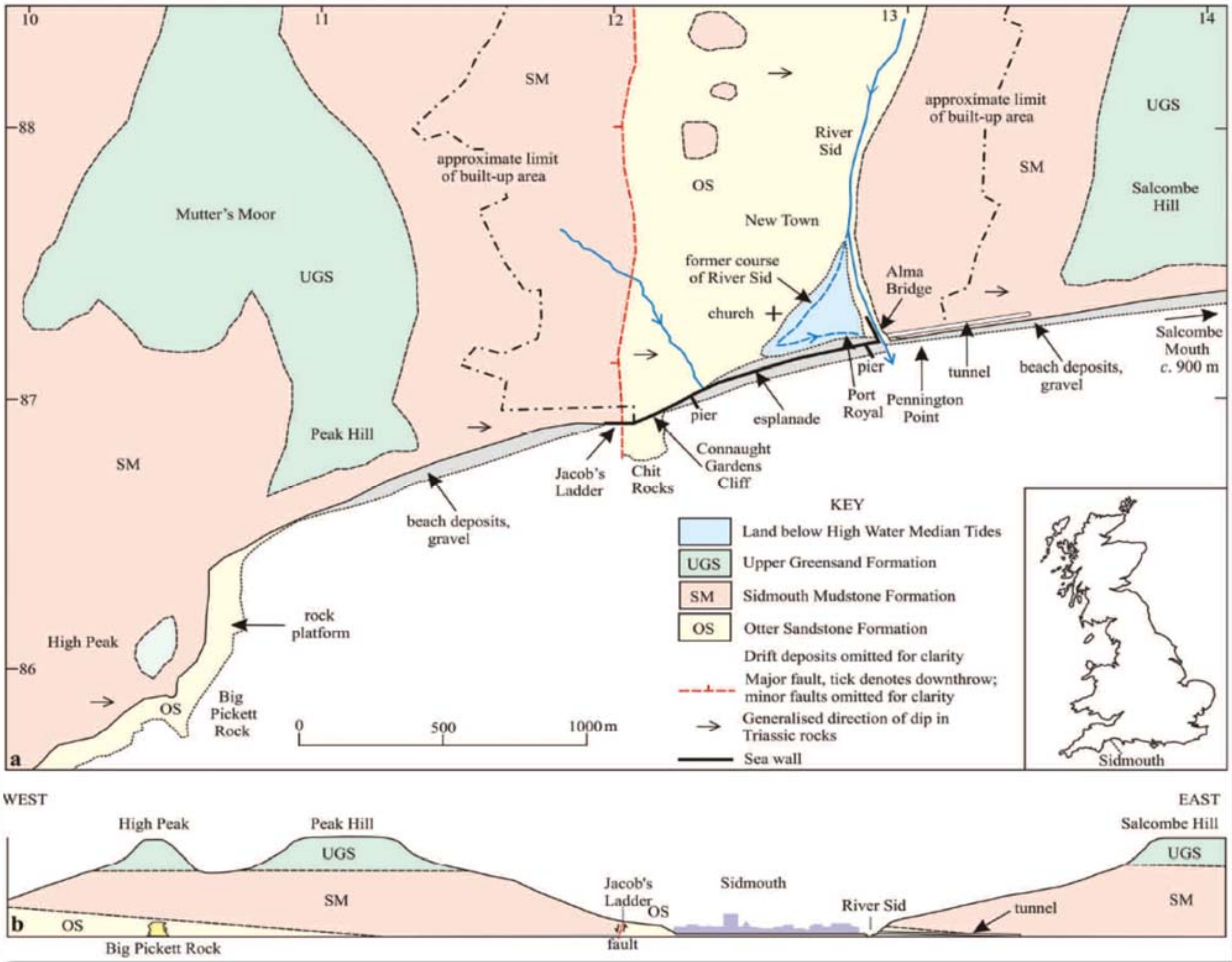


Figure 4-2 Above (a) Geological sketch map of Sidmouth and the adjacent area showing key locations. Geological data based on BGS 1:50,000 solid geology mapping. Below (b) Geological sketch section of the coast (Gallois, 2011).

During the most recent cold climate phase, between c.26,000 and 13,000 years ago, glaciers advanced as far south as the midlands and sea-level was up to 100m lower than present. At this time, the English Channel was a river valley draining southern England and northern continental Europe. Periglacial processes deeply weathered the cliffs to form a debris apron that extended offshore from the current coastline and the rivers deposited extensive spreads of gravel into the English Channel during high discharge summer melts. Glaciers advanced further south during earlier glaciations, reaching Bristol and London, but the south Devon coast has never been glaciated.

As temperatures warmed during the Holocene (c.10, 000 years ago), the glaciers melted and sea levels rose. The period between 10,000 and 5,000 years before present was characterised by rapidly rising sea-levels from c. -25m to -5m OD at a mean rate of 5mm/year (Shennan and Horton 2002). During this time the sea re-occupied the English Channel. This resulted in the following processes:

a) Coastal erosion processes were initiated, first with the removal of the periglacial debris apron (as described below) and then erosion of the bedrock. Differential erosion of different bedrock materials has resulted in the formation of the present configuration of the shoreline, consisting of a series of headlands and embayments (for example, Otterton Edge, Big Picket Rock and Beer Head).

b) The periglacial debris apron and spreads of river gravels were reworked by rising sea levels, from what is now the sea bed, landwards and alongshore to form a long barrier gravel beach that extended from Otterton Ledge as far as Chesil Beach (Portland) (SCOPAC, 2004). Pebbles only present in cliffs at Budleigh Salterton, are today found in beaches as far east as Chesil Beach and the Isle of Portland, demonstrating the continuity of this former beach system.

Large volumes of gravel that have been mapped offshore indicate that some beaches/barriers could not respond to rising sea-levels and were drowned, resulting in moribund deposits that are too deep to be transported by waves or currents under present day sea-level.

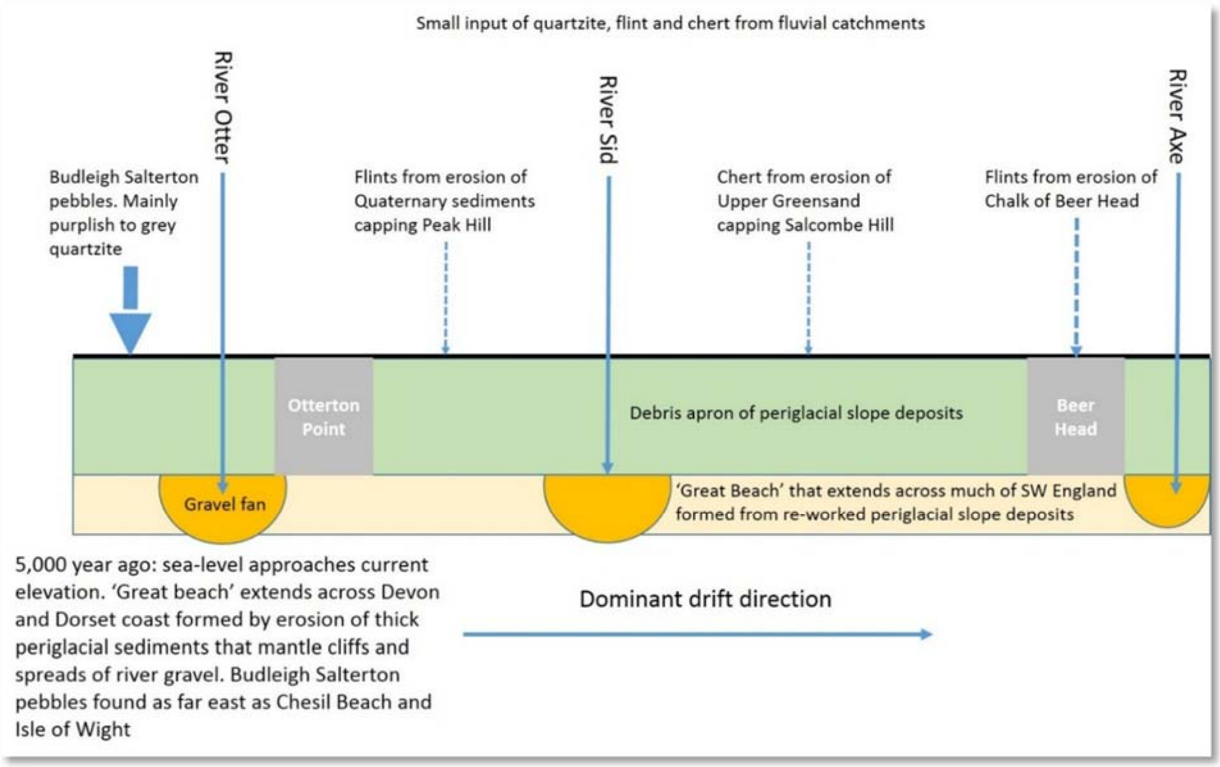
By c. 5,000 years ago sea-level was approaching current elevation and the rate of rise reduced to 1mm/year. The periglacial sediments had been reworked (or become overstepped by rising sea levels), and erosion of bedrock cliffs was initiated. In the last 2,000 years on-going cliff erosion has resulted in the development of headlands and bays. As the barrier continued to migrate onshore and meet with a coastline that varied in orientation and geological resistance, it became segmented and today exists at only a few locations between Otterton Ledge and Beer Head, for example Sidmouth and Branscombe (Halcrow, 2011). The supply of periglacial sediment is now exhausted and sediment is primarily supplied by erosion of cliffs and shore platforms and, as in the case of Sidmouth, beach replenishment. There is also no contemporary sediment supply from the River Sid due to human modification of the river channel upstream from the mouth which prevents sediment reaching the shoreline. Overall, this means the rate of sediment supply today is significantly lower than it was earlier in the Holocene, and this has been the situation for several centuries.

Documentary evidence from Domesday records of the 11th Century indicate that the rivers Otter, Sid and Axe were once fronted by gravel spits and the sheltered river mouths were used as harbours. However, intense storms, believed to be associated with a period of climate cooling known as the Little Ice Age (between the 14th and 19th Centuries) blocked the river mouths with gravel and forced abandonment of the harbours by the 15th Century. This period of storminess is also likely to have also caused increased cliff recession and a pulse in sediment supply, accentuating the problems at the harbour mouths.

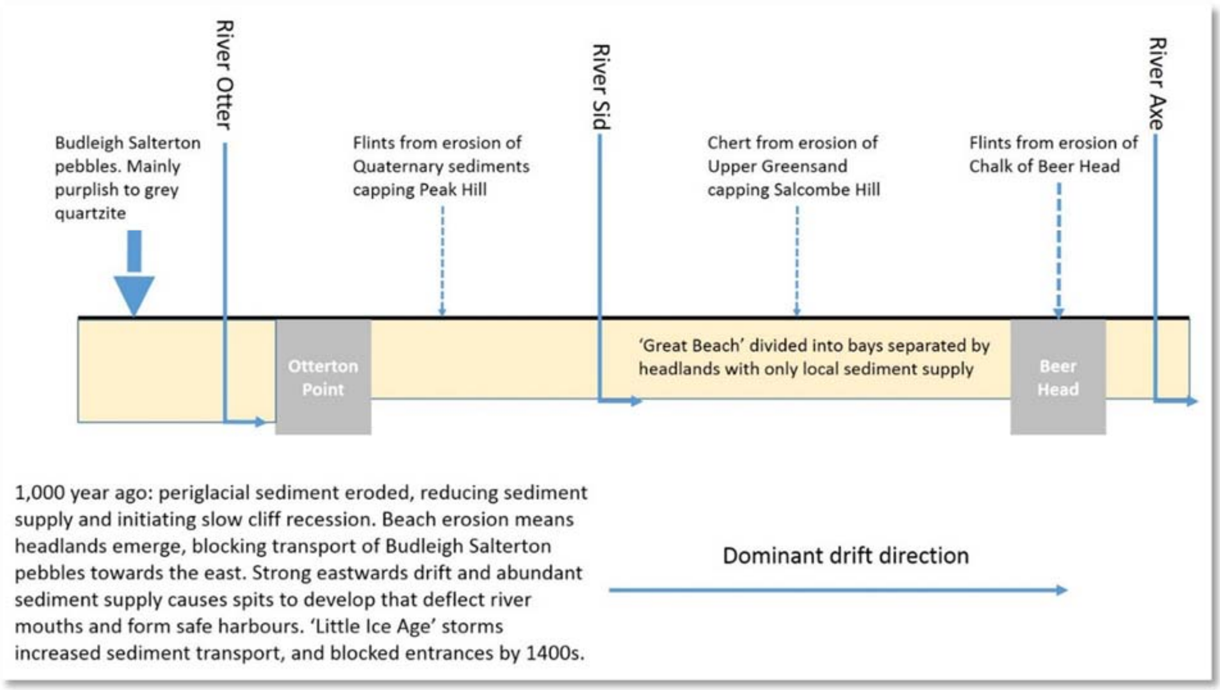
Cliff recession and sediment supply at Sidmouth over the last 10,000 years is therefore a result of:

- A step change from the continuous barrier beach system, formed at a time of very high sediment supply, to the current pattern of headlands and bays with poor long-shore drift linkages and negligible sediment supply from cliffs that are dominated by fine-grained materials, and small rivers with limited coarse sediment bedload.
- Reduction in the amount of sediment stored within the beaches, as gravel is worn down, drawn offshore or submerged by rising sea-levels.

A conceptual evolutionary model for the coastline between Otter Ledge and Beer Head is presented in Figure 4-3.



Sea-level rising to near current elevation around 5,000 years ago.



Establishment of headlands and bays around 1,000 years ago.

Figure 4-3 Conceptual evolutionary model for the coastline between Otter Ledge and Beer Head.

4.2 Waves, tides and rain

4.2.1 Typical waves

The coastline between the Jacob's Ladder Beach and East Beach is orientated in a north-east to south-west direction. Various wave data sets are available relevant to this frontage (see Figure 4-4 and Table 4.1); these all indicate that waves predominately approach this coastline from the south-west and south-east.

The Met Office hindcast wave data for location '407' is closest to the BMP area and provides the longest record of data. This data set indicates that a predominant south-westerly wave regime along this coastline, but that south-easterly storm conditions occur throughout the year for days at a time.

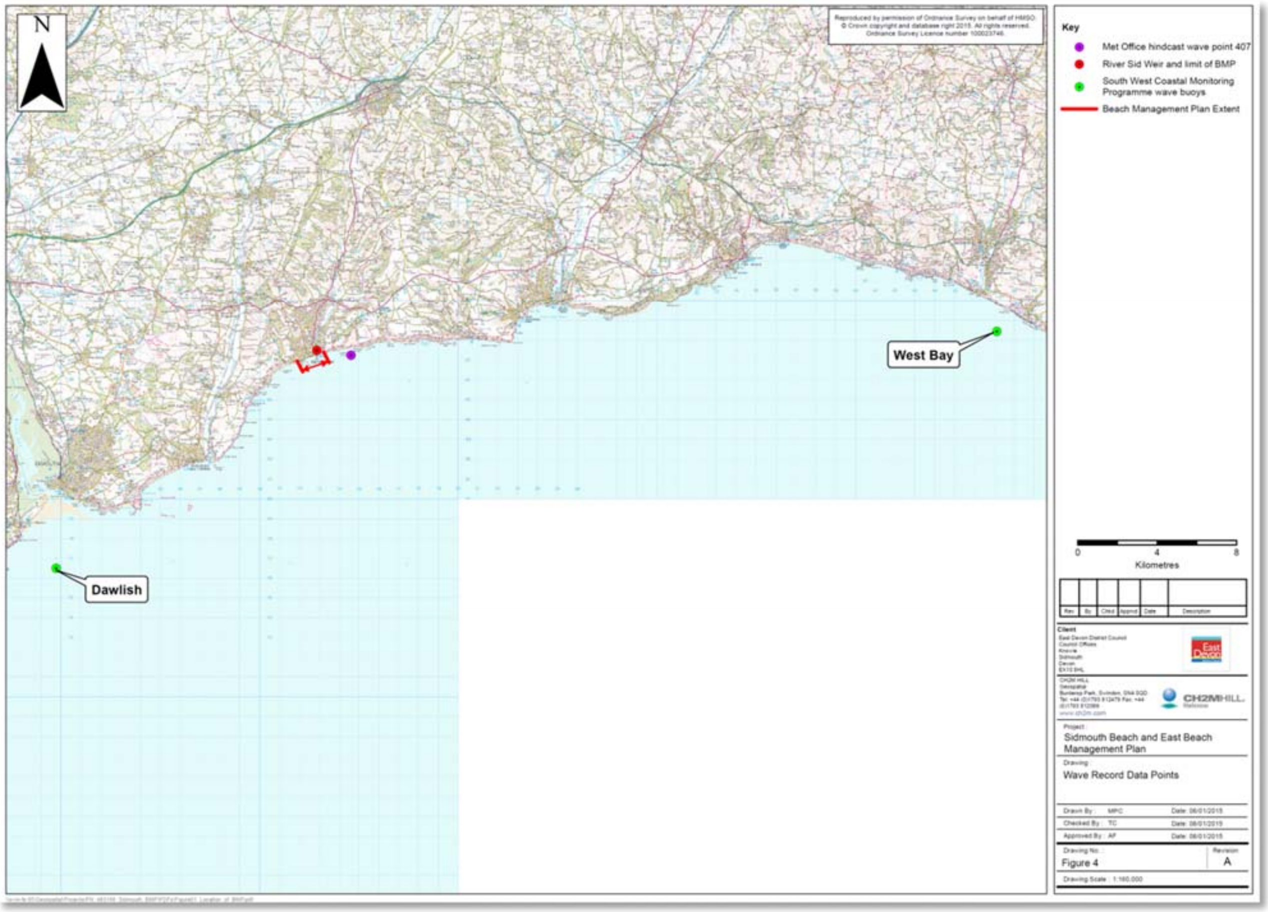


Figure 4-4 Map showing the locations of the wave data collection points.

Table 4-1 Wave data sets relevant to this study.

Name	Location	Record length	Details
Location 407, Sidmouth (Figure 4.7)	Sidmouth	Hindcast data for 33 year period between Jan 1980 and Dec 2013	Met Office hindcast wave data which used the WaveWatch III hindcast model.
Dawlish Directional Waverider Buoy (Figure 4-5)	9 miles south-west of Sidmouth	Measured data: 2 years - Dec 2010 to Dec 2012	Operated as part of the SWRCMP
Seaton nearshore wave data point (Figure 4-6)	East of Beer Head	Modelled data: 1991 - 2000	Transformed inshore wave data from Futurecoast (Halcrow, 2002). Derived from offshore Met Office Wave Model 1991 - 2000
West Bay Directional Waverider Buoy (Figure 4-8)	East of Sidmouth, near Bridport	7 year period Nov 2006 to June 2013.	Operated as part of the SWRCMP

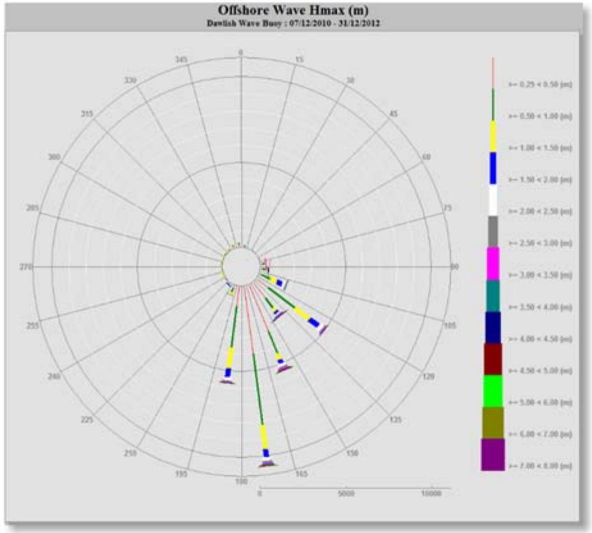


Figure 4-5 Offshore wave height recorded by the Dawlish Directional Wave Buoy between 7/12/2010 and 31/12/2012 (PCO, 2013).

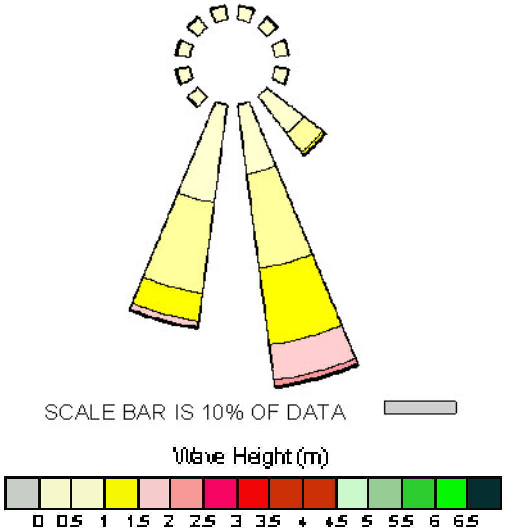


Figure 4-6 Results of wave modelling for Seaton (Halcrow, 2002).

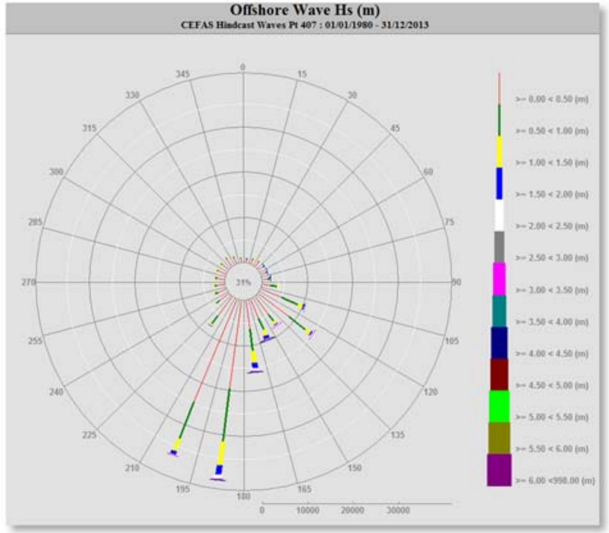


Figure 4-7 Met Office WaveWatch III hindcast wave record for location '407' between 1/1/1980 and 31/12/2013.

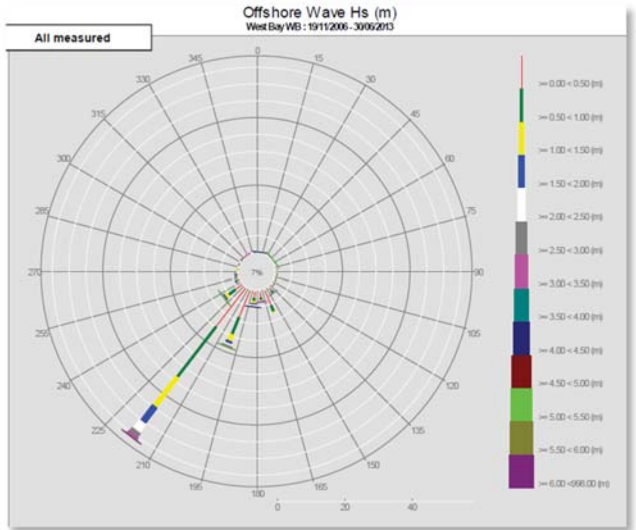


Figure 4-8 Offshore wave height recorded by the West Bay Directional Buoy between 19/11/2006 and 30/06/2013 (PCO, 2013).

4.2.2 Tides

This is a meso-tidal coastline with a spring tidal range (for Lyme Regis) of 3.7m (see Table 4-2).

Within the wider Lyme Bay, flood-tide currents flow in a north-eastward direction and ebb-tide currents flow in a south-westward direction (SCOPAC, 2003). Float track data collected for the Sidmouth Coastal Defence Scheme Modelling (HR Wallingford, 1992), found tidal flows offshore to be quite slow and did not exceed 0.25m/s during the spring tidal cycle. Tidal measurements collected inshore, on the 18th April 1992 near the Sidmouth Outfall for the Sidmouth Coastal Defence Scheme Modelling (HR Wallingford, 1993), varied between 0.05m/s and 0.17m/s relative to high water. The modelling predicted (HR Wallingford, 1993) that the breakwaters would reduce current flow during the eastward flood tide.

There is no data available on post-scheme conditions.

Table 4-2 Tide levels (in mOD) for Lyme Regis, the nearest tide data point to Sidmouth (UKHO, 2013).

Tidal Condition	Tide Level (mOD) (UKHO, 2013)
Highest Astronomical Tide (HAT)	2.45
Mean High Water Spring (MHWS)	1.95
Mean High Water Neap (MHWN)	0.75
Mean Sea Level (MSL)	-
Mean Low Water Neap (MLWN)	-0.65
Mean Low Water Spring (MLWS)	-1.75

4.2.3 Extreme waves and water levels

The Environment Agency’s R&D project ‘Coastal Flood Boundary Conditions for UK Mainland and Islands’ (Environment Agency, 2011a) provides the most recent assessments of: Extreme water levels and Extreme swell waves. This data set provides estimates of both contemporary (2013) and projected future extreme water levels for a range of return periods (this data is presented in Appendix E, Table E.1).

The current (2013) 1 in 1 year water level is calculated to be 2.72m, but this increases to 3.18m for a 1 in 100 year event; this compares to a HAT (Highest Astronomical Tide) level of 2.45m.

The extreme swell wave data (Appendix E, Table E.2) indicates that of the three predominant onshore wave directions; southeast, south and southwest; the largest waves, with the longest period, tend to come from the south, with an average wave height of 3.7m and period of 12s for a 1 in 1 year condition, and wave height of 5.25m and period of 12s for a 1 in 100 year condition.

The most recent estimate of extreme resultant waves for this area, which reflect the combined influence of wind-waves and swell waves, is provided by the Environment Agency commissioned project ‘Parameters for Tidal Flood Risk Assessment – Wave Parameters’ (Royal Haskoning, 2012) (see Appendix E, Table E.1). This dataset also shows that the largest and longest waves tend to come from the south.

A joint probability analysis assessing the combinations of extreme water levels and extreme wave heights that provide a range of extreme return period conditions has also been completed as part of this project, with the results presented in Appendix E.

4.2.4 Rainfall

Rainfall is an important factor in cliff instability and landslides because it causes groundwater levels to rise, which increases porewater pressures that in turn weakens slope materials. The relationship between high rainfall and cliff instability are well-established around the UK coast at sites such as Ventnor, Lyme Regis and Scarborough (Lee and Clark, 2002) and is very likely to have a role at Sidmouth where the cliffs are formed in weak mudstones.

Regional annual rainfall summaries are available from the Met Office and the record for South West England and Wales are presented in Figure 4-9. The ten wettest years on record are highlighted and numbered in order of severity (the wettest year first) on the chart and are: 2012 (1), 1960 (2), 1882 (3), 2000 (4), 1903 (5), 1926 (6), 1877 (7), 1994 (8), 2014 (9), 2002 (10). The data highlights that five of the wettest years in the 141 year record have occurred since 1994.

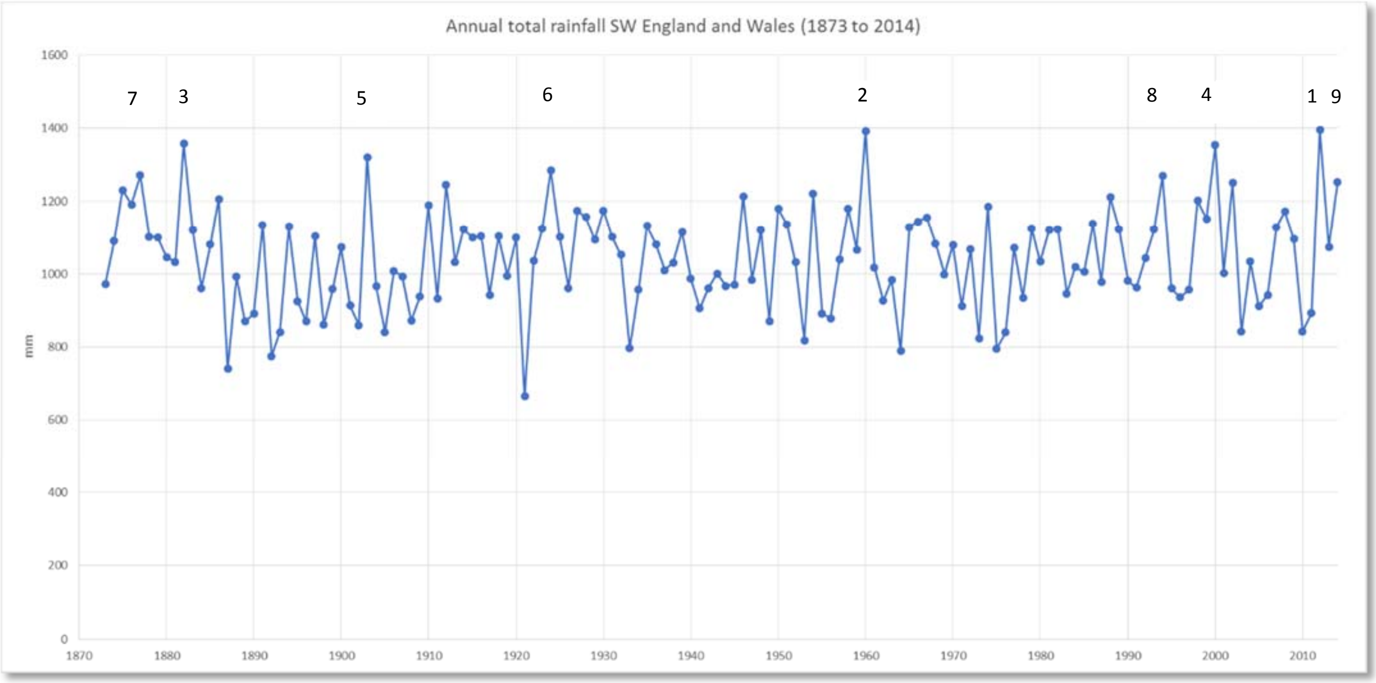


Figure 4-9 Regional annual rainfall record for SW England and Wales (source data: MetOffice). 10 wettest years labelled, note clustering of wet years since 1994.

4.3 Sediment dynamics

4.3.1 Sediment pathways

Although there is a not a great deal of information available on tidal currents, it is believed that these are low and not capable of moving gravel-sized sediment along the beach (Posford Duvivier, 1991; HR Wallingford, 1992; HR Wallingford, 1993). Therefore movement of beach material (i.e. gravel / shingle) alongshore and cross-shore is determined by wave strength and direction.

The predominant wave influence (see Section 4.2.1) along the coastline between Otterton Ledge and Beer Head is from the south-west, with less frequent but sometimes large waves from the south-east.

SCOPAC (2004) produced a map of the sediment transport mechanisms, for various sediment types, for the area between Otterton Ledge and Beer Head (see Figure 4-10). For the Sidmouth frontage this indicated that there is potential for gravel and sand to be transported in both directions. SCOPAC (2003) also reported a predominant weak west to east sediment transport pathway along the coast from Otterton Ledge to Beer Head, and at Sidmouth there is indirect evidence for east and south-east waves to create a short-term littoral drift reversal. The map also suggests a potential fluvial input to the frontage; however, this is believed to be low due to trapping by weirs within the River Sid upstream of the mouth.

Based on observations and available data, sediment transport along the BMP extent can be summarised as follows:

1. Otterton Ledge to Chit Rocks: transport is confined to individual pocket beaches with negligible by-passing of headlands (SCOPAC, 2003).
2. The Chit Rocks headland and shore platform, to the west of Sidmouth, acts as a natural barrier to the eastward transport of material from Jacob's Ladder Beach to Sidmouth Beach, with little or no drift

into Sidmouth frontage from the west bypassing Chit Rocks and the adjacent nearshore detached breakwaters (SCOPAC, 2003).

3. Similarly, at the eastern end of Sidmouth frontage, the River Sid training wall, combined with the eastern-most groyne (Pier Groyne), inhibit littoral transport in both west-east and east-west directions. There is, however, disagreement within the literature regarding the effectiveness of this barrier. Posford Duvivier (2001) report that there is very little, if any, linkage between Sidmouth Town Beach and East Beach. However, SCOPAC (2003) reports that some “outflanking seaward” by both sand and gravel in an eastwards direction may occur at the (easternmost) terminal rock groyne and the mouth of the Sid; it is assumed that this statement means that material is able to bypass the end of these structures from west to east. The SCOPAC (2003) report suggests that the sediment pathway is via a nearshore sediment store which is reported to exist south and east of the mouth of the River Sid and that any movement of sediment eastwards across the Sid occurs as pulses. SCOPAC (2003) goes on to suggest that further evidence for this pathway is the composition of natural clasts on Sidmouth Beach, most are either flint or chert and thus must ultimately derive from cliff erosion between Salcombe Hill and Beer Head to the east. However this conclusion appears to be based on visual observations of beach composition as the report also states that no quantitative analysis of the beach lithology has been undertaken.

4. Certainly there is evidence that material can be transported across the river mouth from east to west, but this appears to become trapped on the western (Sidmouth Town) side of the training wall and outfall structure (though historical photographs show this has not always been the case when a large beach was present along the Sidmouth frontage; refer to Section 5.6). Without further analysis it is not possible to determine whether this material is then able to bypass the end of the structure to feed Sidmouth frontage. The westward movement of shingle in this way can temporarily block the river mouth forcing the river to discharge to the sea by seeping through the shingle (SCOPAC, 2003). Observations made over a 30 year period between the early 1930s and late 1960s (Laver, 1981) found that the average length of time during which the river mouth was blocked by shingle was 16 days, but that it could be up to 3 to 4 months.

5. Along the Sidmouth frontage itself, the rate of longshore transport is controlled by the two detached breakwater structures and three rock groynes. The alignment of the coast relative to the predominant wave directions means that drift can commonly occur in both directions. Before the construction of the most recent scheme, Hydraulics Research (1992) calculated a net west to east residual transport flux of around 6,350m^3/year, based on modelling of inshore waves, but that over a year the gross potential rate averages over 52,000m^3. This means that there is potential for large volumes of shingle to be transported in a westwards direction, driven by easterly and south-easterly storms, which although low in frequency can be of high magnitude (large wave heights/periods) and capable of moving large volumes of beach material in a short period of time (Posford Duvivier, 2001). When the scheme was reviewed in 1998, it was found that the plan shape of the beach had changed significantly since 1996, with a net accretion of sediment in the lee of the breakwaters, to the detriment of the frontage between York Groyne and Bedford Steps. Although the original design had anticipated sediment accumulation behind the breakwaters, this change had taken place much quicker than anticipated and this was attributed to a period of easterly conditions in winter 1995/6 which resulted in material effectively becoming trapped behind the breakwaters. This emphasised the importance of the less frequent easterly conditions, compared to the more normal westerly conditions.

6. East of the BMP frontage, between East Beach and Beer Head, longshore transport takes place relatively freely, but localised and temporary interruptions can be caused by eroded cliff debris on the beach.

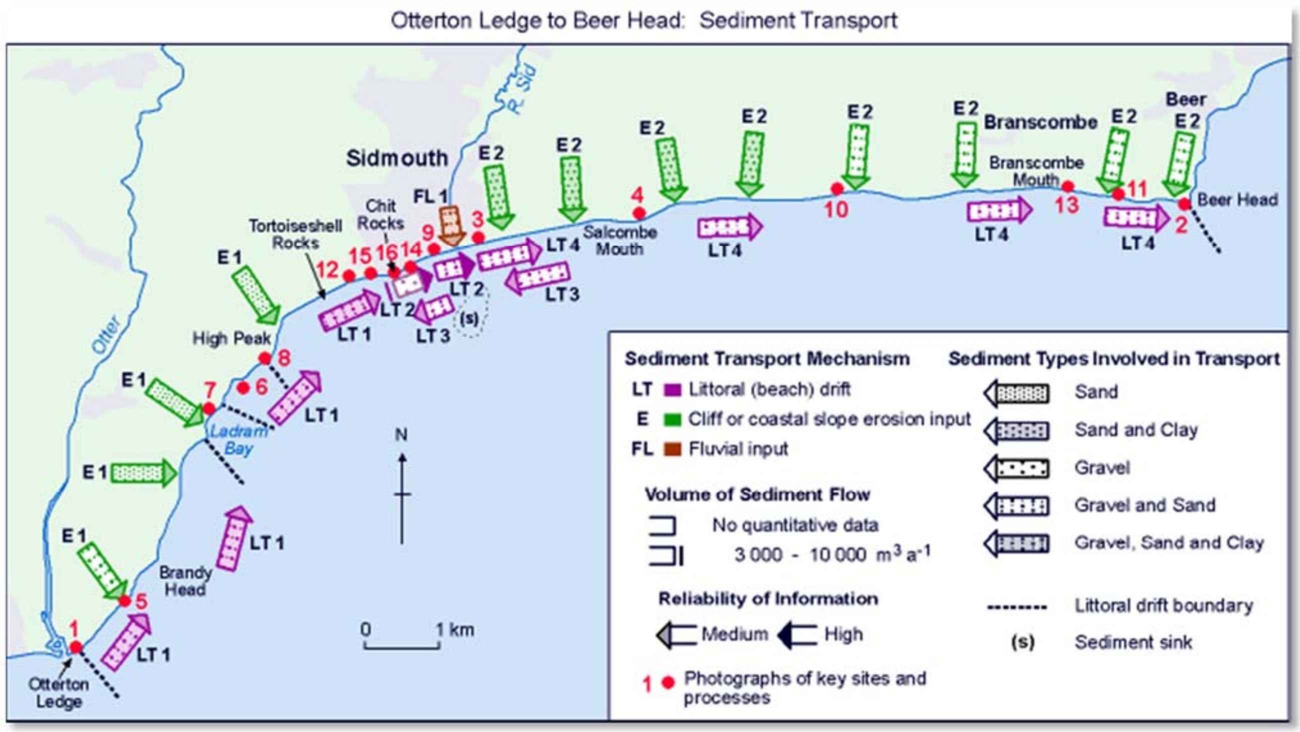


Figure 4-10 Sediment Transport for Sidmouth and the surrounding area (SCOPAC 2004).

The beaches along this frontage are known to have been very volatile in the past and subject to large drawdown of sediment during storm periods. Tindall (1929) undertook analysis of beach profile data from 1922 to 1926 and found that beach levels were lower in winter as the beaches were drawn down and higher in summer as they recovered and aggraded. He reported that beach behaviour was strongly affected by individual storms and thereby the direction and continuity of longshore drift, itself determined by incident wave direction. Laver (1981) concluded that beach levels were actually lower in the 1920s than in the 1970s.

Posford Duvivier (2001) reported that storms from the south west result in draw down and depletion of Sidmouth Beach, whilst recovery of the beach is dependent on storms from the south east, which are reported to occur less frequently. SCOPAC (2004) reports that the same processes occur along East Beach and that under these conditions, the drop in beach level often at East Beach due to draw down has a knock-on effect of exposing the cliff toe to greater weathering.

Figure 4-11 Aerial photograph showing the mouth of the River Sid and the accumulation of beach gravel against the training wall and outfall resulting from a south-easterly storm (circled in red) (Halcrow, 2002).

4.3.2 Potential sources of beach sediment

As described in Section 4.1, there are very limited contemporary inputs of shingle to this frontage and the sediment that forms these beaches was originally sourced from periglacial deposits which are now exhausted or lie in deep waters offshore, beyond the influence of waves and currents. The key supply of new sediment to this system is therefore through artificial nourishment. As part of the Sidmouth Coastal Defence Scheme, 185,000 tonnes (approximately 105,000m^3) of flint gravel was placed on the Sidmouth beach between West Pier and East Pier Groyne (SCOPAC, 2003). Later, in 2000, a further 6,000m^3 was placed between the existing York Steps Groyne and East Pier Groyne. The nourishment material was sourced from a local inland quarry and reported to be similar in size to the indigenous beach sediment (SCOPAC, 2003).

Erosion of the shore platforms between Otterton Ledge and Beer Head supply significant quantities of fine sediment, but this is likely to be removed seawards in suspension (SCOPAC, 2003) and may be lost from the sediment system between Otterton Ledge and Beer Head permanently.

Historically the River Sid may have supplied some shingle to the beaches, but under current conditions the total sediment supply from the Sid catchment is low. Erosion of the valley upstream provides some Upper Greensand cherts and Clay-with-Flints and the river is estimated to potentially deliver a small annual load of approximately 400m^3 fine sediment and 100m^3 coarse material with much of this is likely to occur during high discharge events (Rendel Geotechnics and University of Plymouth, 1996; Posford Duviver 1999; SCOPAC, 2003). This limited input is currently diminished further as the shingle becomes trapped by the large number of weirs present along the river and is periodically removed by the Environment Agency (Burch, *pers.comms*, 2013); although the quantities removed are uncertain. Therefore for this assessment, the River Sid is assumed to supply no coarse sediment to the beach.

The cliffs, both at Sidmouth and along adjacent shorelines, are a potential source of shingle, albeit it relatively small. The cliffs at Sidmouth are formed in Triassic sandstones (Otter Sandstone Formation) and mudstone (Mercia Mudstone Formation), with a cap of Cretaceous Upper Greensand with chert that thickens towards the east. All the cliffs are capped by a veneer of superficial sediments comprising 'Clay-with-Flints' (the weathered remnants of the former Chalk bedrock cover) that is rarely thicker than a few metres, and slopewash materials derived from underlying bedrock. Erosion of the Triassic rocks supply sand and silt-sized material that is drawn offshore or stored on the intertidal beach, but there is no appreciable supply of gravel to the upper beach. The Greensand cherts are very hard and do form beach-building gravel, but they only account for a small volume of the material supplied by erosion of the Greensand.

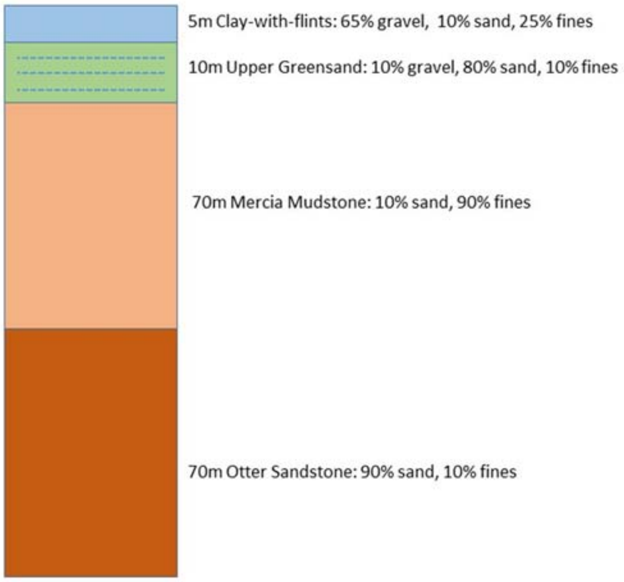
There are potential sediment sources to the east and west of the BMP frontage, but, as discussed above, longshore inputs are inhibited at either end of Sidmouth Beach. Even if this were not the case the total supply of gravel from cliff erosion along the adjacent frontage would be very low. Peak Hill cliffs backing Jacob's Ladder Beach have an intermittent and thin cap of Greensand that supplies a small volume of gravel, while east of Sidmouth, from Salcombe Hill to Beer Head the cliffs include a greater thickness of Upper Greensand that will supply slightly more gravel, but still amounting to a negligible total.

Using a simple model that accounts for the cliff height and rock types along the coast, the potential sediment supply from the cliffs (assuming no defences) has been estimated to determine the spatial distribution and relative volumes of gravel supply per linear metre retreat of the cliffs for each cliff behaviour unit (CBU - see Section 6.2 for further explanation). Figure 4-12 shows an example of the model, showing the assumptions.

From this, the following conclusions have been made:

- While total sediment supply per linear metre retreat would be around 500,000m^3, the bulk of this is from erosion of Peak Hill cliffs which supply sediment to Jacob's Ladder Beach (CBUs 1, 2, 3 and 4). or from Salcombe Hill cliffs which supply East Beach eastwards (CBUs 7 and 8). Very little material is supplied to Sidmouth town frontage (CBU 6). CBUs 5 and 6 are defended along their entire length, so the actual sediment supply is zero. Although the net drift is to the east, there are periodic reversals associated with south easterly storms, meaning it could be possible for sediment from CBUs 7 and 8 to be driven west towards the Sidmouth frontage (CBU 6), but material would need to bypass the River Sid training wall and Pier Groyne.
- While theoretical gross sediment supply is high, only around 5% of the total is gravel, meaning very little material is available to build upper beaches. Approximately 60% of all sediment supplied is fines that are likely to be transported offshore. The remainder sand-sized sediment may form or contribute to intertidal beaches.
- The model can be tested using the historical cliff recession data. Assuming the long-term average cliff recession rate for the whole frontage is approximately 0.15m/year, the annual supply of sediment from all CBUs is estimated to be around 75,000m^3, with only around 3,500m^3 being gravel. Of this, around half is derived from Peak Hill cliffs to the west of Chit Rocks, which is believed to be a barrier to littoral transport, leaving less than 2,000m^3 annual gravel supply to beaches of CBUs 7 and 8 that could conceivably nourish the town frontage during drift reversals, assuming it is able to bypass the River Sid training wall.

Peak Hill (155m OD): schematic section and sediment supply model



Material	Volume supplied by 1m recession of 100m of cliff (m^3)	Gravel (m^3)	Sand (m^3)	Fines (m^3)
Clay-with-flints	500	325	50	125
Upper Greensand	1,000	100	800	100
Mercia Mudstone	7,000	0	700	6,300
Otter Sandstone	7,000	0	6,300	700
TOTAL	15,500	425 (3%)	7,850 (51%)	7,225 (46%)

Figure 4-12 Example sediment supply model using data from Peak Hill.

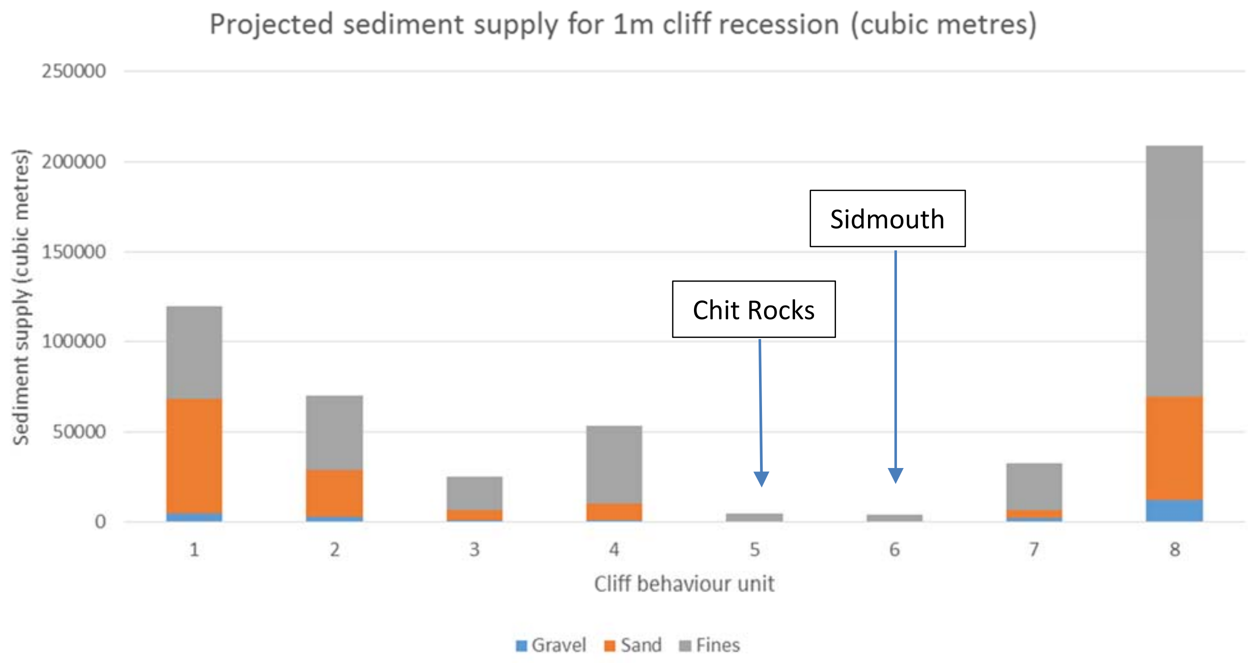


Figure 4-13 Relative sediment supply from CBUs, by particle size.

5 Shoreline change

5.1 Introduction

The following section provides a summary of shoreline change between Otterton Ledge and Beer Head over the last 130 years. This analysis has drawn upon:

- Analysis of historical aerial photographs to determine changes in beach and cliff position (Section 5.2);
- New cliff recession analysis using both historical maps and photographs to derive rates of change (Section 5.3);
- A review of cliff recession data specifically relating to erosion at East Cliff (Section 5.4);
- Beach profile analysis, based on post-scheme monitoring data (Section 5.5); and
- Appraisal of anecdotal evidence provided by members of the public (Section 5.6).

5.2 Analysis of aerial photography

Aerial photography dating back to 1946 was obtained from the National Monument Record Centre and used to assess how the shoreline and beach characteristics have changed over the last 69 years; reported in Table 5-1.

The same aerial photography has also been assessed to observe changes to cliffs and to identify periods of cliff activity, for each CBU (Table 5-2) (see Figure 2-12 for location map). This has been supplemented by observations made during a site visit in 2014. CBUs 5 and 6 (highlighted) cover the defended headland of Chit Rocks and Sidmouth town frontage, whilst CBU 7 (highlighted) covers the cliffs immediately east of the River Sid, at East Beach.

Unfortunately there are only three images available pre-scheme and these are widely spaced: 1946, 1950 and 1988 and it should also be noted that, as for the historical photographs discussed later, the aerial images only represent a snapshot in time and should be used with caution to identify trends.

From the images assessed the following key observations can be made:

- Sidmouth frontage - Nourishment of the beach, together with the construction of the rock groynes and detached breakwaters, has significantly changed the beach morphology along the Sidmouth frontage from that pre-scheme. Pre-scheme, the beach, when full, was more continuous with no build up evident either side of the timber groynes.
- East of the frontage, along East Beach, the photographs indicate varying periods of cliff activity and stability and also varying beach width (although this is difficult to determine due to photographs potentially being taken at different states of the tide). The most recent aerials from 2015 indicate that compared to 2012, there has been significant cliffs failures along this section, with widespread activity also evident further east along the cliffs of Salcombe Hill.
- Along the Sidmouth frontage, in the lee of the breakwaters, the upper shingle beach is wider than the adjacent beaches. With the exception of the photograph from 2006, the beach within the groyne bays is wider at the western end and narrower at the eastern end. The 2010 and 2012 photographs also show an accumulation of material in the lee of the River Sid training wall and SWW outfall.
- In the 2001/2002 and 2010 photographs, the beach within the groyne bays is wider at the western ends as is the beach in the lee of the breakwaters in the 2006 photographs. This indicates that at the time, the drift direction was to the west, which is the opposite to the predominant net drift direction which is to the east. It is noted that these photographs were taken in Spring and late Summer, when the beach is likely to be recovering from winter storms (i.e. easterly and south-easterly wave (storm) conditions).

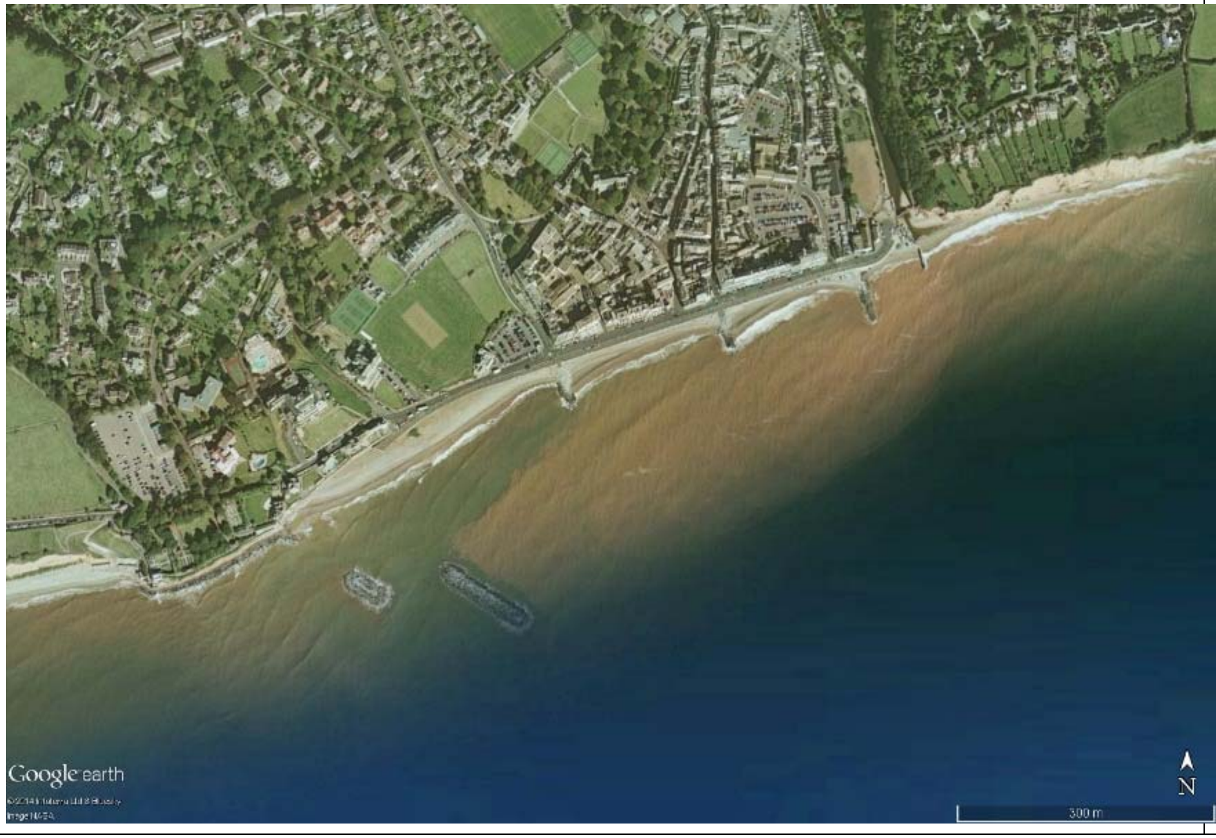
- The 2006 photograph was taken in June and reflects summer conditions, when the beach is evenly spread between the groyne bays and the beach around the mouth of the River Sid is wider, with no significant accumulation in the lee of the River Sid training wall and the outfall.
- The 2012 photograph shows the beach in the most depleted state, with very narrow beaches at the western end of the groyne bays, but simultaneously accumulation of shingle in the lee of the River Sid training wall and SWW outfall. This photograph was taken in September and could reflect post-storm conditions or overall low beach levels.
- The SWW outfall appears to be buried across a longer portion of its length in earlier photographs but in later photographs, it appears to be more exposed. The exception to this is in 2006, when it and the training wall are buried.

Table 5-1 Review of aerial photography for shoreline and beach characteristics and change.

Date	Photo	Interpretation
1946		• Sediment passing over Chit Rocks. • Beach on east side of West Pier wider than on east side and therefore acting as a barrier to the westwards movement of material. • Narrow beach (although photograph likely to be taken at high tide). The beach between West Pier and East Pier is narrower than to the east. • Beach on east side of East Pier is wider than on the west indicating some east to west transport. • Groynes visible, but appear buried. • River Sid training wall (before lengthened) is acting to train the wall, but sediment is bypassing around the end to the east and west. • Beach encloses River Sid, although river appears to be draining through the shingle bank. • Cliffs at Pennington Point are eroding. • Wide and continuous East Beach

Date	Photo	Interpretation
1950		• Groynes constructed at Jacob's Ladder Beach east and around Chit Rocks headland. • Possibly more groynes constructed along frontage. • Beach between Chit Rocks and West Pier significantly narrowed since 1946. • Upper beach between West Pier and East Pier narrower than in 1946. • Upper beach east of East Pier narrower to the west. • The River Sid is flowing through the shingle bank. • Cliffs on Pennington Point have eroded further. • Wide continuous East Beach

Date	Photo	Interpretation
1988		• Construction at Jacob's Ladder Beach east completed. • No notable change around Chit Rocks. • Beach appears to have widened between Chit Rocks and West Pier. • Beach between West Pier and East Pier wider, similar to 1946. • Beach width across the mouth of the River Sid has increased, similar to width in 1946. • The River Sid is pooling behind the shingle bank, possibly draining through the bank. It has moved eastwards away from the training wall up against the cliff at Pennington point. It could have pushed in this direction by westerly waves. • Wide continuous East Beach

Date	Photo	Interpretation
2001 / 2002 (Google Earth)		• Evidence from the photograph including the colour of the trees, status of the cricket pitch and number of people on the beach suggest that the photo was taken during spring time. • Beach appears to be wide at the eastern end of Jacob's Ladder Beach. • Beach in lee of the breakwaters is wide. • Upper and lower beach within groyne bays wide at western end, indicating drift from east to west, which is counter to the net drift direction. • River Sid training wall extension very clear in the photographs. • Shingle bank extends across the mouth of the River Sid, appears to be narrower than in previous aerials. • Narrow and fragmented East Beach

Date	Photo	Interpretation
30th June 2006 (Google Earth)		• The upper beach appears to be wide at the eastern end of Jacob's Ladder Beach. • Upper beach in lee of the breakwaters is wider than in 2002, and the beach itself here is wider at the western end. • Upper beach within groyne bays wider at both western and eastern ends and narrower between, indicating drift occurring in both directions. • Shingle bank extends across the mouth of the River Sid and the width of beach is wider than previous photograph. However, this may be due to the tidal state at the time of the photo. • Continuous East Beach re-established within recessed cliff frontage

Date	Photo	Interpretation
Late summer 2010 (Google Earth)		• Evidence from the photograph including the colour of the trees status of the cricket pitch, number of people on the beach and in the water suggests that this photograph was taken during the late summer. • The upper beach appears to be wide at the eastern end of Jacob's Ladder Beach. • The lower sand foreshore at the eastern end of Jacob's Ladder Beach is exposed as the photo was taken at low tide. The sand foreshore appears to extend around Chit Rocks to the detached breakwaters, suggesting it is linked and possible transport could be taking place along it. • The upper beach in the lee of the breakwaters is similar to 2006. The lower sandy beach extends to the detached breakwaters to form a tombolo with the western breakwater. • Beach within groyne bays wide at western end, indicating drift from east to west, which is counter to the net drift direction. • River Sid training wall extension very clear in the photographs. • Shingle bank extends across the mouth of the River Sid, with accumulation of material in the lee of the extended River Sid training wall. • Extended training wall and outfall appear to be blocking westward movement of shingle across the mouth of the River Sid. • East Beach set-back within recessed cliff frontage; foreshore feature apparent

Date	Photo	Interpretation
17th Sept 2012		• Jacob's Ladder east beach appears healthy. • The upper shingle beach in the lee of the breakwaters is narrow, as is the beach between the groyne bays. • The beach in the groyne bays is widest at the eastern end. The beach is particularly narrow to the west, with what appears to be little shingle at the toe of the seawall. • River Sid training wall extension and SWW outfall very clear in the photographs. • Shingle bank extends across the mouth of the River Sid, with accumulation of material in the lee of the extended River Sid training wall. • River Sid has carved a channel through the shingle banks and a small delta exists where the River Sid meets the sea. • East Beach set-back within cliff embayment and continuous to east

Date	Photo	Interpretation
19th March 2015		• Jacob's Ladder east beach appears healthy. • Beach accreted in lee of breakwaters. • Beach within groynes appears to be a similar width though image taken around time that beach recycling occurred to increase beach size within groyne bays. • River Sid training wall extension and SWW outfall very clear in the photographs. • Shingle bank does not appear to extend across River Sid and East Beach is narrow and set-back compared to previous photos. • Widespread cliff failures on the East Cliff. • Waves breaking near the cliff toe along much of East Cliff due to low beach levels. • Healthy beaches in the east of the frontage towards Dunscombe Hill, suggesting net drift towards the east in previous months.

Table 5-2 Review of aerial photography for cliff characteristics and position (highlighted sections are those within the BMP frontage, also see Figure 2-12 for locations).

CBU	1946	1950	1988	2006	2009	2012	2014 site visit	2015
1	Not covered	Partial coverage. Cliffs show widespread activity.	Partial coverage. Cliffs show widespread activity.	Not covered.	Not covered.	Limited cliff activity with middle and upper parts well-vegetated. No upper beach present.	Not inspected.	Not covered.
2	Partial coverage. Widespread cliff activity at eastern end of frontage where headscarp shows recent failure. Upper beach at least 20m wide.	Widespread cliff activity at eastern end of frontage, where headscarp shows recent failure. Upper beach obscured by high tide.	Widespread cliff activity at eastern end of frontage, but headscarp area now vegetated. Upper beach at least 20m wide.	Widespread cliff activity at eastern end of frontage, but headscarp area now vegetated. Upper beach very thin veneer over sand and less than 10m wide.	Widespread cliff activity at eastern end of frontage, but headscarp area now vegetated. Upper beach remains a thin veneer over sand and less than 10m wide.	Widespread cliff activity at eastern end of frontage, but headscarp area now vegetated. Upper beach absent.	Not inspected.	Not covered.
3	Widespread cliff activity. Upper	Widespread cliff activity.	Activity widespread on lower cliff. Upper cliff well-vegetated.	Activity widespread on lower cliff. Upper cliff well-vegetated.	Activity widespread on lower cliff. Upper cliff well-vegetated.	Activity widespread on lower cliff. Upper cliff well-vegetated.	Activity widespread on lower cliff. Upper cliff well-vegetated.	Not covered.

CBU	1946	1950	1988	2006	2009	2012	2014 site visit	2015
	beach at least 20m wide		Upper beach at least 12m wide.	Upper beach at a thin veneer over sand and less than 10m wide.	Upper beach remains a thin veneer over sand but is 30m wide.	Upper beach a very thin veneer.	Upper beach very narrow.	
4	Widespread cliff activity. Upper beach at least 20m wide.	Widespread cliff activity. Addition of 2 wooden groynes in 100m immediately west of Chit Rocks Headland.	Widespread cliff activity. Upper beach at least 20m wide. There is no beach between the 2 wooden groynes west of Chit Rocks Headland.	Cliffs partially vegetated. Upper beach widens towards the east from 12 to 27m. Groynes west of Chit Rocks now removed.	Cliffs partially vegetated. Accumulation of upper beach that widens towards the east from 24 to 38m.	Cliffs partially vegetated. Loss of upper beach that is now a thin veneer at western end, but still 38m wide at eastern end.	Cliffs partially vegetated. Upper beach very wide at eastern end, with material accumulating against Jacob's Ladder.	Partial coverage at east of unit. No change detected since 2012.
5	Esplanade in place around Chit Rocks with evidence of outflanking on western side at Jacob's Ladder. Wooden groynes present but very little beach material present.	Wooden groynes present but no beach material present.	Wooden groynes present but no beach material present.	Chit Rocks protected by rock armour. No beach present in front.	Chit Rocks protected by rock armour. No beach present in front.	Chit Rocks protected by rock armour. No beach present in front.	Chit Rocks protected by rock armour. No beach present in front.	No change detected since 2012.
6	Series of wooden groynes present, with upper beach at least 25m wide at promontory c. 200m west of the River Sid and narrowing to 10m in a westward direction. Western-most beach, east of Glen Road, is at least 10m wide. Outfall structure west of River Sid training wall has accumulation of gravel on eastern side, suggesting recent drift towards	Wooden groynes still present and beginning to affect beach width. Beach promontory remains and is at least 20m wide. Western-most beach, east of Glen Road has disappeared. Accumulations behind groynes and outfall suggest drift towards the west. River Sid mouth is open.	Western-most beach, east of Glen Road reappeared and now at least 15m wide. Groynes on main beach not visible and beach has a uniform width of at least 24m across the outfall and river training wall. River Sid mouth is blocked by gravel.	Offshore breakwaters and rock groynes now present to create four beach pockets west of the River Sid. Pattern of gravel accumulation suggests drift to east. Western-most pocket beach is widest at 43m, others much narrower at 10 to 20m. River Sid mouth is blocked by gravel.	Four beach pockets west of the River Sid unchanged. Pattern of gravel accumulation suggests drift to east. Western-most pocket beach still widest at 43m, others much narrower at 10 to 20m. River Sid mouth is blocked by gravel.	Four beach pockets west of the River Sid show loss of sediment. Pattern of gravel accumulation suggests drift to east. Western-most pocket beach still widest but now no more than 30m wide, others much narrower with only a thin gravel veneer in their western parts. River Sid mouth is open, but a gravel delta has accumulated on the	Westernmost pocket shows most extensive gravel accumulation. Staining and sorting of pebbles at back of beach suggests this material may be the original recharge sediment that has yet to be affected by marine action. Other beaches are healthy.	When compared to 2012 photo, there is negligible change in westernmost pocket. The 2nd and 3rd pockets appear to have more sediment that is evenly distributed along the frontage. There is negligible change in the last pocket defined by the river training wall.

CBU	1946	1950	1988	2006	2009	2012	2014 site visit	2015
	west. Gravel beach extends across mouth of River Sid.					eastern side of the training wall.		
7	Open coast, with gravel beach at least 30m wide adjacent to River Sid and narrowing to at least 25m in east. Cliffs indented with fresh exposures, suggesting recent failure. Footpath present south of Cliff Road gardens.	Open coast, with gravel beach at least 20m wide. Cliffs indented with fresh exposures, suggesting recent failure. Footpath present south of Cliff Road gardens.	Open coast, with gravel beach at least 25m wide. Cliffs less indented, but recent erosion still evident. Footpath present south of Cliff Road gardens.	No recent failures, but cliffs show evidence for erosion. Footpath south of Cliff Road gardens now eroded. Upper beach is typically less than 10m wide, with gravel veneer over inter-tidal beach.	Recent failure at west of cliffs. Gravel upper beach now at least 20m wide.	No recent failures, but cliffs exposures suggest erosion. Gravel upper beach now at least 25m wide	No recent failures. Recent landslides noted to be limited to the upper cliff, formed of clay-with-flints. Gravel upper beach very narrow and typically less than 10m wide.	When compared to 2012 photo, there has been a significant failure at Pennington Point, two on East Cliff and widespread activity on the cliffs of Salcombe Hill. Boulder debris is commonly seen on the foreshore associated with these failures. The state of the tide means no comment can be made on the beach.
8	Partial coverage. Cliffs show widespread activity. Upper beach at least 30m wide.	Cliffs show widespread activity. Upper beach at least 30m wide.	Cliffs show widespread activity. Upper beach at least 25m wide.	Cliffs show widespread activity. Upper beach at least 25m wide. Significant failure on Dunscombe Cliff covers upper beach with debris apron.	Cliffs show widespread activity in their lower part. Upper beach at least 25m wide. Debris apron still present on beach fronting Dunscombe Cliff.	Cliffs show widespread activity in their lower part. Upper beach at least 35m wide. Debris apron still present on beach fronting Dunscombe Cliff.	Not observed in detail. Debris apron present on beach fronting Dunscombe Cliff.	Partial coverage. Widespread but localised activity with debris lobes on the beach.

5.3 New analysis of cliff recession rates

5.3.1 Data Used

Analysis of historical maps and photographs was undertaken using Geographical Information Systems (GIS) to quantify the amount of cliff recession that has occurred at Sidmouth and along the neighbouring coastline over time:

- **Historical Ordnance Survey maps dating from late 19th Century to present:** historical maps were available in a format where scanning and georeferencing (i.e. fitted to a coordinate system) had been undertaken already. This meant the data could be imported into GIS and directly compared to determine change in feature positions.
- **Historical aerial photography, dating from the 1940s to present:** available in a range of formats. The most recent data, from 2006, 2009, 2012 and 2015 were collected using high resolution digital cameras under the current coastal monitoring programme and are georeferenced using a digital elevation model derived from LiDAR data to generate very accurate orthorectified imagery. Older images were captured using traditional methods and are only available as paper prints. A review of the English Heritage archive of historical aerial photography data was undertaken and three epochs of data were identified that covered the whole study area, had an appropriate scale and were of sufficient quality for analysis. To allow comparison and analysis in GIS, these images were scanned and then georeferenced using features of known position and elevation identified in OS Mastermap and LiDAR data. The resolution and accuracy of the resultant orthorectified imagery is limited by the quality of the source image and rectification process. The datasets used in the cliff recession analysis are summarised in Table 5-3.

Table 5-3 Datasets used in cliff recession analysis.

Dataset	Date	Map scale/Photo resolution	Error of fit (RMSE)
OS map	1890	1:10,650	Unknown, assumed c. 2m
OS map	1906	1:10,650	Unknown, assumed c. 2m
OS map	1933-38	1:10,650	Unknown, assumed c. 2m
OS map	1963	1:10,650	Unknown, assumed c. 2m
OS map	1991	1:10,000	Unknown, assumed c. 1m
Aerial photograph	1946	35cm	1.05m
Aerial photograph	1950	50cm	2.02m
Aerial photograph	1988	20cm	1.15m
Aerial photograph	2006	10cm	0.15m
Aerial photograph	2009	10cm	0.13m
Aerial photograph	2012	10cm	0.13m
Aerial photography	2015	4cm	0.1m (assumed)

The 'error of fit' of georeferenced aerial imagery is described by the Root Mean Square Error (RMSE), which describes the difference between true position of a feature (defined by Ordnance Survey data) and the feature's position in the georeferenced image. Any features mapped from the image have an accuracy of ± the RMSE. When considering rates of coastal change, the RMSEs of each input image are summed and then divided by the time period in years between the two images to give an error in metres on the annual rate of change (Moore et al., 2003). Rates of change can therefore be quoted with an associated error statistic. The RMSEs for combined aerial image periods that are shown in **Error! Not a valid bookmark self-reference.**. The other principal source of error relates to mapping of the position of the cliff top and toe. This is minimised by careful interpretation of the data and use of several measured transects to derive statistically representative data for each cliff unit.

Table 5-4 Combined RMSEs for photos to be quoted for rates of change over the stated time periods (RMSEs of each input image have been summed and divided by the time period (in years) between the two images).

Photos		Maps	
Date range	**Combined error (±m/year)**	**Date range**	**Combined error (±m/year)**
1946 to 1950	0.77	1890 to 1906	0.25
1950 to 1988	0.08	1906 to 1938	0.13
1988 to 2006	0.07	1938 to 1963	0.16
2006 to 2009	0.09	1963 to 1991	0.11
2009 to 2012	0.09	1890 to 1991	0.03
2012 to 2015	0.05	n/a	n/a
1946 to 2012	0.02	n/a	n/a
1946 to 2015	0.02	n/a	n/a

5.3.2 Approach

The resulting GIS database of map and aerial photography data were analysed in two ways:

1. GIS-based analysis of all past editions of OS maps and historical aerial photographs.
2. Qualitative assessment of the impact of large landslide events on the rate of recession.

The GIS-based analysis of all past editions of OS maps and historical aerial photographs was undertaken by measuring the change in cliff top and cliff toe positions in the different data along a series of fixed transects. The advantage of this method is that feature position and change can be mapped and measured accurately at any location, and error in the resultant measurements can be quoted. The disadvantages are that recognition of feature positions is often difficult. In aerial photography this is due to vegetation, blurred imagery and shadow; and in mapping problems are derived from interpretation of symbology used in the earliest editions of mapping. However, when a large database of imagery and mapping are assembled a reasonable picture of the pattern and rate of historical change can be derived.

The cliff top and cliff toe in each set of imagery and map were first digitised at a consistent scale of 1:1,000. Next, a series of shore-normal transects were created, with at least three in each CBU. The distance between the landward end of each transect and its intersection with the digitised cliff top and/or cliff toe line in each year was subsequently measured. The difference between the two lengths represents the quantity of recession (or advance in the case of lobes of debris deposited at the cliff toe) at that point (Figure 5-1).

Once the distance by which the cliff top had retreated was established, the rate of recession was calculated by dividing the amount of recession (in metres) by the time between the two input sets of imagery or maps (in years) to give a recession rate (in metres/year). Because the error of the input data is known, or can be estimated, the accuracy of the calculated rate of change can be quoted. Analysis of the data, combined with an understanding of the behaviour of each cliff unit, gives information on the magnitude and frequency of episodic landslide events (i.e. how much cliff is lost in a single cliff recession event, and how often events occur), and how these combine over time to form a long-term average cliff recession rate.

The resulting data are presented in a range of formats:

- Short-term rates of change represent the change between two adjacent epochs of data, which is typically around 20 years. These data give an indication of the magnitude of individual cliff failures (i.e. rock falls or landslides) and their frequency. The RMS error of measurements, particularly for all data prior to the 1950s is relatively high, meaning that unless erosion is very significant it is unlikely to be greater than the error.

- Long-term rates of change represent the total change between the earliest and latest epoch of data (69 years for aerial photography, 101 years for OS mapping). This shows the impact of several individual landslide events over time. The RMS error on these measurements is relatively low.
- Averages for all transects in a cliff unit provide statistically robust information on historical change and capture variations in landslide magnitude and frequency along a section of cliff.
- Data for individual transects show variation along the cliff face to provide information on the magnitude of local episodic landslide events.

As these cliffs are subject to episodic failure, a qualitative assessment of the impact of large landslide events on the rate of recession was then undertaken and incorporated into the predictions of future cliff change.

The datasets were subjected to a purely qualitative visual assessment intended to document the location of recent landslides from the cliff that are identified by scars or debris in photography, or new headscarp embayments in mapping. This method provides information on the nature of cliff recession and is used to validate the results of more precise GIS-based analysis.

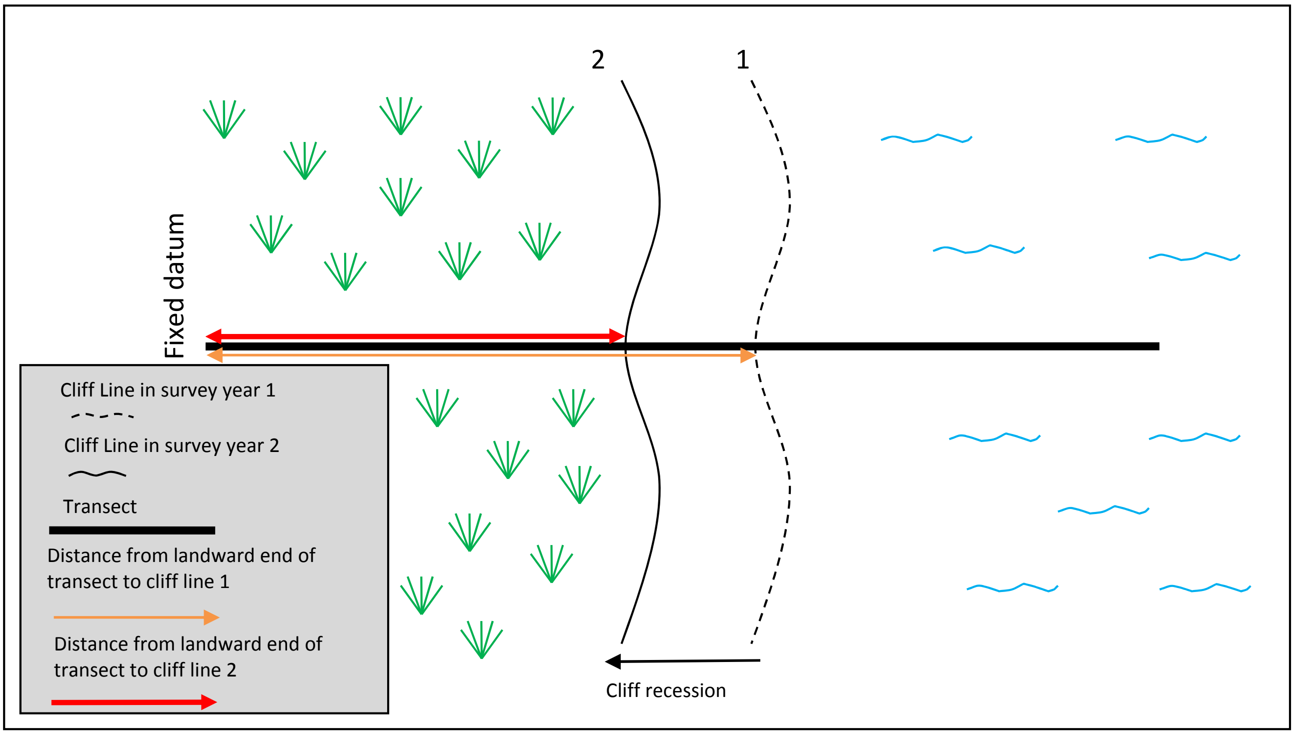


Figure 5-1 Cliff recession measurement. Cliff recession is difference is distance between a fixed datum at the landward end of profile and coastline in survey years 1 and 2. The average annual rate of change is calculated as this distance divided by the time in years between the two surveys.

5.3.3 Results of cliff analysis

5.3.3.1 GIS Based Analysis

Average cliff recession data over the short-term (i.e. between each record) and long-term (i.e. over the full length of the record) for each CBU derived from historical OS maps (1890, 1906, 1938, 1963 and 1991) and aerial photos (1946, 1950, 1988, 2009, 2012 and 2015) are provided in Table 5-5 and Table 5-6.

Cliff top position changes for each CBU determined from historical maps and aerial photographs are plotted in Figures B.1 to B.11 in Appendix B. Cliff toe positions derived from analysis of historical maps and aerial photographs (where advances of the toe position represent debris lobes) are provided in

Figures B.12 to B.21 in Appendix B. The full data set, including the location of transects, is provided in Appendix B.

Table 5-5 Cliff erosion rates calculated from historical Ordnance Survey maps (1890 to 1991); values in m/year.

CBU	Average Short Term Cliff Top				Average Long Term Cliff Top	Average Long Term Cliff Toe
	1890-1906	1906-1938	1938-1963	1963-1991	1890-1991	1890-1991
1	-0.23^	-0.06^	-0.24	-0.47	-0.20	-0.14
2	-0.19^	-0.16	-0.07^	-0.30	-0.16	-0.07
3	-0.55	-0.16	-0.24	-0.19	-0.17	-0.21
4	-0.39	-0.36	-0.66	-0.15	-0.20	-0.42
7	-0.38	-0.30	-0.68	-0.36	-0.19	-0.15
8	-0.19^	-0.20	-0.63	-0.17	-0.06	-0.07
MEAN	-0.32	-0.21	-0.42	-0.27	-0.16	-0.17

Note: 'short-term' defines change between adjacent records, 'long-term' defines the total change over the full record.

*No data, ^ Rate of change less than error and must be treated with caution.

Table 5-6 Cliff erosion rates calculated from historical aerial photos (1946 to 2015); values in m/year

CBU	Average Short Term Cliff Top						Average Long Term Cliff Top		Average Long Term Cliff Toe
	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	2012-2015	1946-2015	1950-2015	1946-2015
1	*	-0.13	*	*	*	*	*	-0.14	-0.23**
2	-1.39	-0.23	-0.24	-0.38	-0.28	*	-0.03	-0.05	-0.21
3	-2.40	-0.62	*	-1.58	*	*	-0.21	-0.38	-0.18
4	-1.41	-0.28	-0.05^	-1.17	-0.83	*	-0.15	-0.12	-0.05
7	-1.54	-0.08^	-0.31	-2.64	-1.18	-1.03	-0.27	-0.19	-0.25
8	-1.78	-0.09	-0.25	-1.14	-0.56	*	-0.15	-0.10	-0.12
MEAN	-1.70	-0.24	-0.21	-1.38	-0.72	*	-0.16	-0.16	-0.17

*No data ^ Rate of change less than error and must be treated with caution. **1950-2012

The cliff transect data indicates the following:

- **CBU 2 (western part of Jacob's Ladder Beach).** This cliff is covered by six transects, summarised in Tables 5.5 and 5.6. Cliff top change data from historical maps and historical photos are presented in Appendix B Figures B1 and B2. Cliff toe change data are shown in Appendix B Figures B12 and B13. The data from historical maps are in general agreement, showing a relatively uniform recession rate at the cliff top and a marginally lower rate at the toe. Several transects show advance of the cliff top between 1938 and 1963 and one shows advance between 1890 and 1906, indicating error in the mapping data. Overall, the historical maps indicate slow cliff top retreat between 1890 and 1991 with an average rate of 0.16m/year (Table 5.5). The short-term erosion rates suggest that the period 1963 to 1991 experienced the most rapid recession, at an average rate of 0.30m/year.

  The pattern from aerial photographs covering the period 1946 to 2012 shows very limited change overall, with an average cliff top recession rate of 0.03m/year (Table 5.6). However, the pattern of change over the short term is confused by apparent error in the position of the cliff top in the 1950 image that suggests advance between 1950 and 1988 (Appendix B Figure B2). Data from more recent years are more reliable and suggest a phase of more rapid loss of up to 0.38m/year from 2006 to 2009 and 0.28m/year from 2009 to 2012 that is likely to be associated with episodic cliff recession events. The data from the cliff toe suggests limited change between 1940 and 1988, but particularly rapid erosion thereafter (Appendix B Figure B13).

- **CBU3 (central part of the Jacob's Ladder Beach).** This cliff is covered by six transects, summarised in Tables 5.5 and 5.6. Cliff top change data from historical maps and historical photos are presented in Appendix B Figures B3 and B4. Cliff toe change data are shown in Appendix B Figures B14 and B15. The data from historical maps are in close agreement, showing near-continuous retreat of the cliff top and cliff toe between 1890 and 1991. Cliff top transect 18 shows a period of significant advance between 1938 and 1963, which is likely to mapping error. Overall, the data shows cliff top erosion at a rate of 0.17m/year, with the periods 1890 to 1906 and 1938 to 1963 recession above the long-term average (Table 5.5). Data from the cliff toe shows relatively uniform recession, but the period 1938 to 1963 shows accelerated erosion in half of the profiles.

  The data from aerial imagery is more ambiguous due to data gaps and local errors in the rectification process, suggesting periodic advances of the cliff top. However, taken as a whole, the cliff top data shows long-term erosion of the cliff top at 0.21m/year and of the cliff toe at 0.18m/year between 1946 and 2012 (Table 5.6).

- **CBU4 (eastern part of Jacob's Ladder Beach).** This cliff is covered by seven transects summarised in Tables 5.5 and 5.6. Cliff top change data from historical maps and historical photos are presented in Appendix B Figures B5 and B6. Cliff toe change data are shown in Appendix B Figures B16 and B17. Cliff top change data from historical maps and historical photos are presented in Appendix B Figures B5 and B6. Cliff toe change data are shown in Appendix B Figures B16 and B17. Historical maps show progressive erosion in most transects although two show advance between 1906 and 1938, suggesting mapping or georectification error in part of the 1938 map. The average long-term rate of change for the cliff top is 0.20m/year and for the cliff toe is 0.42m/year (Table 5.5). The average short-term rates of change for the cliff top must be treated with caution due to the apparent error in some of the data, but do suggest a period of more rapid recession in some transects between 1906 and 1938 and relatively slower change rates since that time. This pattern is also reflected in the cliff toe data.

  The aerial photography data shows a long-term average recession rate of 0.15m/year at the cliff top and 0.05m/year at the cliff toe (Table 5.6). However, the short-term data indicates periods of localised, more rapid cliff top erosion between 1946 and 1950, 2006 to 2009 and 2009 to 2012. In each time period, the average cliff top recession rates are around 1.0m/year. The data from the cliff toe are in good agreement and show very slow long-term erosion of 0.05m/year. Widespread advances in the cliff toe since 2006 suggesting debris lobes are in good agreement with the evidence for cliff top retreat at this time.

- **CBU5 and 6 cover Chit Rocks and Sidmouth frontage**, which have been defended over the period covered by historical data. Therefore no assessment has been undertaken.

- **CBU 7 (East Cliff, immediately east of the River Sid).** This cliff is covered by ten transects summarised in Table 5.5 and 5.6. Cliff top change data from historical maps and historical photos are presented in Appendix B Figures B7 and B8. Cliff toe change data are shown in Appendix B Figures B18 and B19. The long-term rate of headscarp recession from historical maps indicates an average recession rate of 0.19m/year at the cliff top and 0.15m/year at the cliff toe (Table 5.5). However, the transect data for the cliff top are ambiguous, and while there is a uniform pattern apparent, several locations indicate advance of the cliff between 1938 and 1963, suggesting localised error in the mapping (Appendix B Figure B7). Nevertheless, the data do suggest a phase of rapid cliff recession from the 1890s to 1940s/50s, with less change from that point to 1991. The data from the cliff toe also show a uniform pattern, but with widespread advance between 1938 and 1963, which is likely to relate to errors in the mapping.

  The aerial photo data show a long-term average recession rate at the cliff top of 0.27m/year and 0.25m/year at the cliff toe. The short-term data for the cliff top suggests periods of widespread and rapid recession between 1946 and 1950 and since 2006. This is reflected by rapid erosion of the cliff toe over the same time periods. Taken as a whole, the historical data for East Cliff suggests the cliff experienced a phase of relatively more rapid recession from 1890s to 1950, limited change from 1950 to 2006, and more rapid recession thereafter.

However, this CBU-wide average disguises a distinct spatial pattern that becomes particularly apparent from the 2006 image onwards from which point the western 250m part of the CBU has retreated markedly more rapidly than the eastern section. In the period 1946 to 2006, limited change is recorded in the whole CBU, with an average recession rate of 0.03m/year. However, from 2006 to 2015, the western 250m retreats at an average rate of 1.5m/year, while the eastern part retreats at 0.25m/year, which is equivalent to the long-term average.

- **CBU 8 (cliffs of Salcombe Hill).** This cliff is covered by nine transects summarised in Table 5.5 and 5.6. Cliff top change data from historical maps and historical photos are presented in Appendix B Figures B10 and B11. Cliff toe change data are shown in Appendix B Figures B20 and B21. Historical maps indicate a long-term erosion rate of 0.06m/year at the cliff top and 0.07m/year at the cliff toe (Table 5.5). Data from transects show a reasonable level of agreement, although there are apparently errors in the earliest maps, which suggest an advance of the cliff. Transect data from the cliff toe are less ambiguous and suggest a phase of more rapid erosion since 1963.

  The data from aerial photography shows a long-term average recession rate of 0.15m/year at the cliff top and 0.12m/year at the cliff toe (Table 5.6). Profile data indicate that the rate of change at the cliff top and the cliff toe have changed little through time.

Notwithstanding the localised errors revealed in the source data, which relate to inaccuracies in the Ordnance Survey mapping and georectification of the maps and aerial photography, the data indicate that the long-term cliff recession in all CBUs has been moderate. The average cliff top recession rate from aerial photography for all cliffs is 0.16±0.02 m/year between 1946 and 2012. The rate for the cliff toe is slightly higher at 0.17±0.02 m/year, which is likely to reflect rapid erosion of landslide debris lobes. CBU 3 (Western Jacob's Ladder Beach Cliffs) and CBU 7 (East Cliff) have cliff top recession rates slightly above this average at 0.21±0.02 and 0.27±0.02 m/year respectively.

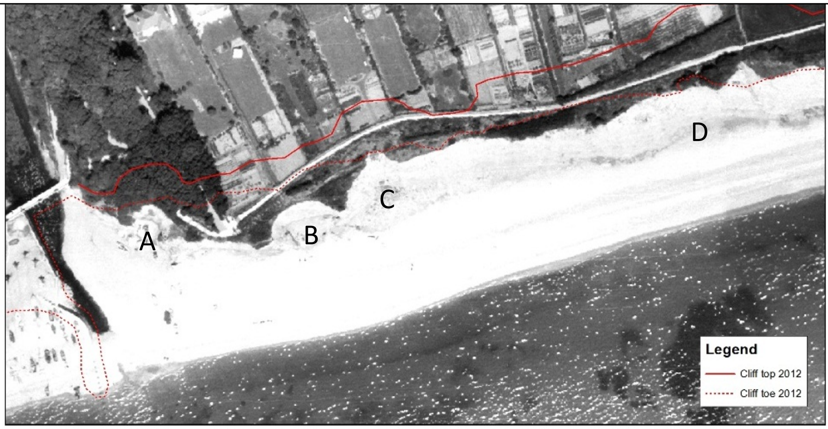
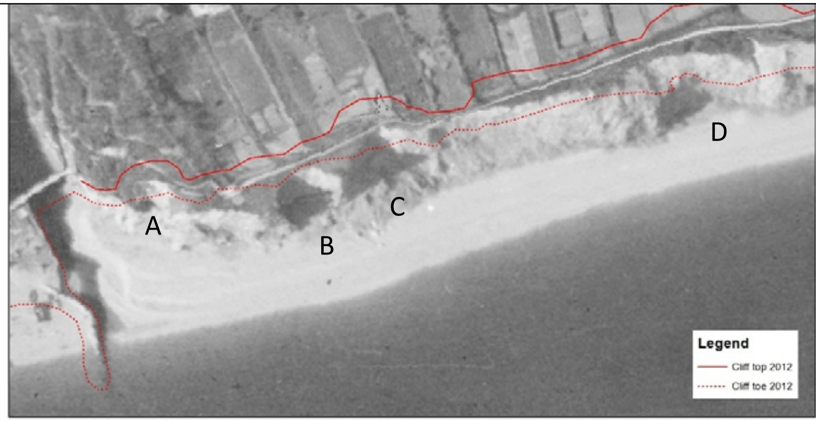
Simple spatial patterns in cliff recession rates are not clearly evident, with all CBUs showing phases of more rapid cliff recession since the late 19th Century. Furthermore, relationships are complicated by variations in recession rate through time due to the episodic nature of cliff failure and the errors inherent in the source data. However, the data do indicate two spatial-temporal relationships:

- In CBU 4, covering part of Jacob's Ladder Beach, the cliff recession rate derived from aerial photos shows a clear deceleration between 1946 and 2006, and then an acceleration from 2006 to 2012. The cliff top data from historical maps shows a similar pattern, with rapid change between 1890 and 1938, and more limited erosion since 1938. This CBU has not directly benefitted from coast protection over the assessment period and consequently the data represent a natural cliff response to changes in the environmental factors that drive cliff erosion in this area. This broad pattern does not appear to relate to beach volumes, which have remained constant in this CBU. However, the rapid change indicated by maps between 1890 and 1938 is associated with exceptionally wet years in 1882, 1903 and 1926, and the change indicated from 2006 onwards is associated with exceptionally wet years in 2002, 2012 and 2014 (see section 4.2.4).
- In CBU 7, covering East Cliff, to the east of the River Sid, shows a similar pattern to CBU 4. The data shows the cliff experienced a phase of more rapid recession from 1890s to 1950, limited change from 1950 to 2006, and more rapid recession from 2006 to 2015, particularly in the westernmost 250m of the CBU. The broad association of rapid cliff recession and exceptionally wet years is also valid in this CBU, but low beach levels also play an important role.

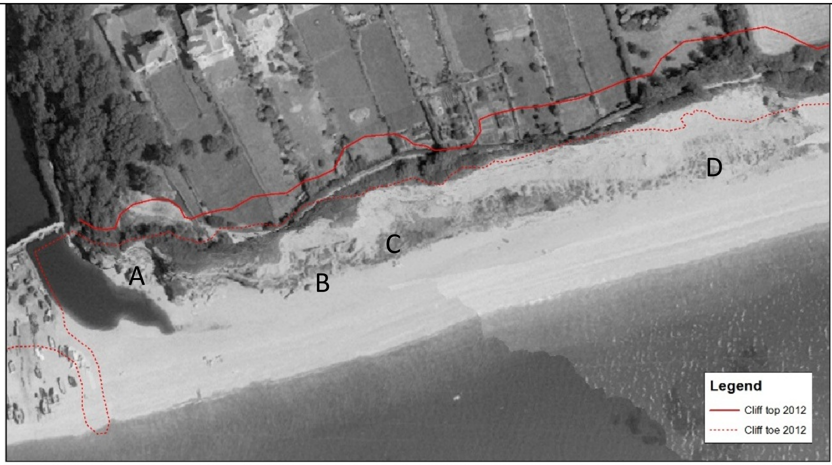
5.3.3.2 Qualitative Assessment of Landslide Frequency and Distribution

Long-term average recession rates include the contribution of localised episodic landslide events, where significant cliff recession can occur in a single event, but their precise contribution to the total amount of cliff recession is masked. Information on the significant amount of cliff recession that can occur in a short period time can be found in the short-term record of change. Such episodic events are suggested in all CBUs over the full monitoring period, but are particularly prevalent in CBUs 7 and 8. Due to the errors inherent in the source data and the method used to determine cliff recession rates, it is not clear precisely where landslides have occurred and at what time and therefore a visual assessment of the data has been undertaken to document the location of 'fresh' landslides in each of the photos.

Due to the particular concern about cliff recession at Pennington Point and East Cliff, available records of landsliding have been assembled for CBU 7. The historical records (Frederick Sherrell Ltd, 1995; Royal Haskoning, 2009; Gallois, 2011), aerial imagery and site inspections indicate that these cliffs have a history of episodic landsliding that occurs either as collapse of the upper cliff, in response to intense and/or sustained rainfall, or through failure of the lower cliff by undercutting from wave attack. In all cases, these data are limited by the data record and represent a minimum number of events that have occurred. Aerial photography indicating the evolution of this section of coast is shown in Figure 5-2.

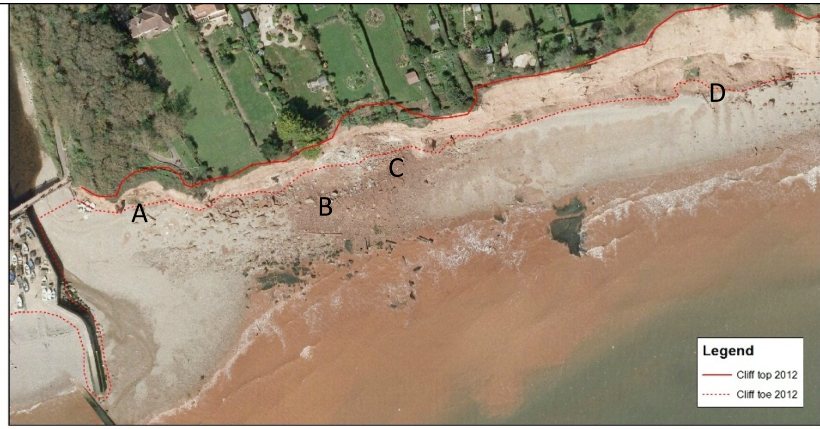
Failures in upper cliff (Clay-with-Flints and weathered mudstone) at A, B and C associated with faults and weathered material at Pennington Point. This section was also coincident with the route of a tunnel, lost by 1995 (Frederick Sherrell Ltd, 1995). Pennington Point cliff top well-vegetated. 	Failures at A, B and C have developed to affect lower part of cliff (mudstone). Embayment developing at D. Locations B, C and D are coincident with mapped faults and the western part of the railway tunnel that had been lost by 1995 (Frederick Sherrell Ltd, 1995). 
East Cliff – 1946. 2012 cliff top and toe shown in red.	*East Cliff – 1950. 2012 cliff top and toe shown in red.*

Rockfalls at A and retreat of the cliff top at Pennington Point. Cliffs appear inactive between B and D and a vegetated talus slope has developed at the toe. Sherrell (1995) shows the tunnel was present East of D in 1995 (it is still present here as of 2015).

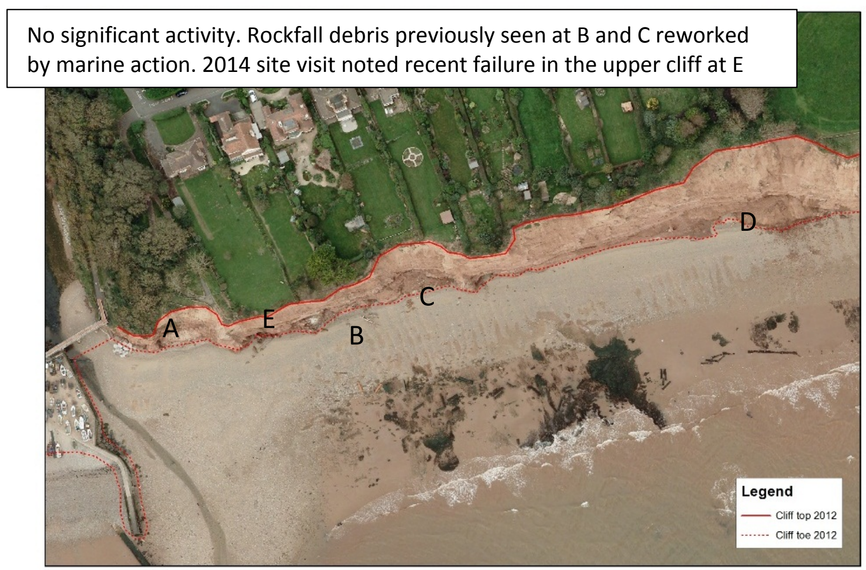


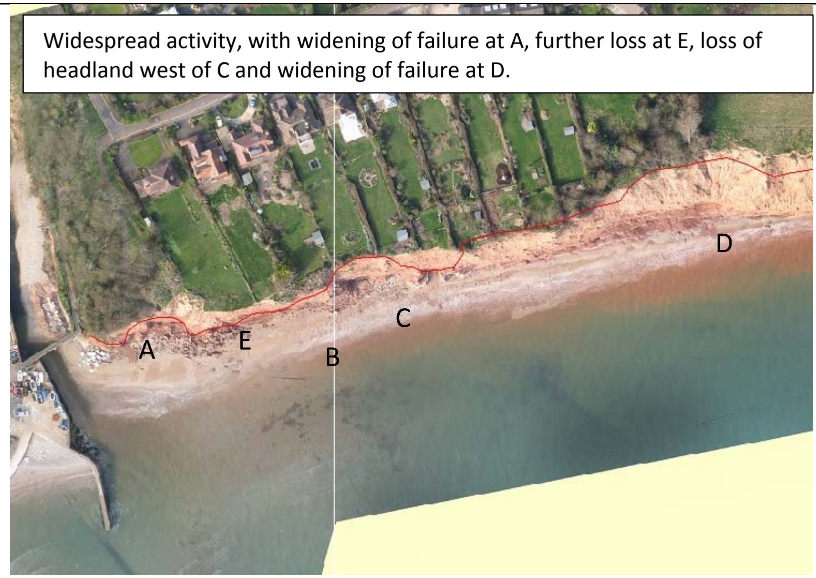
East Cliff – 1988. 2012 cliff top and toe shown in red.

Rockfall in upper cliff at A occurred in 2008 but debris removed by 2009. Large failures occurred at B in 2000, C in 1995 and 2000, and at D in 2000/01 (Haskoning 2009, Gallois 2011). Rockfalls in lower cliff at B and C in 2009. Events are all coincident with faults. Coast path has been lost. Talus slope seen in 1988 lost due to toe erosion.



East Cliff – 2009. 2012 cliff top and toe shown in red.





East Cliff – 2012	*East Cliff – 2015 (2012 cliff top highlighted in red)*

Figure 5-2 Aerial photography indicating the evolution of the western part of East Cliff and Pennington Point.

5.4 Review of cliff recession data for East Cliff

5.4.1 Introduction

A specific objective of this BMP is to assess the public's perception that erosion at East Cliff has increased over the last 20 years and if it has increased, then what has caused it. To address this, this section reviews available information relating to past assessments of cliff recession rates, the accuracy of these data and considers possible causes of change in cliff recession rate.

5.4.2 Previous assessments of recession rates

5.4.2.1 Summary

A range of assessments of cliff erosion over the historical period have been undertaken in the past on the Pennington Point/East Cliff section of coast and are listed below:

- Frederick Sherrell Ltd (1995) studied the cliffs of Pennington Point east of the River Sid and combined geological mapping with historical OS maps to show that cliff recession was episodic over time, and that most rapid recession was associated with both the steeply inclined faults, which lie approximately perpendicular to the coastline, and the remains of the former railway tunnel excavated in the cliff. Their analysis indicates recession rates of around 0.7m/year between 1928 and 1937 along most of the East Cliff frontage, and between 1.0 and 2.3m/year between 1937 and 1947, which was associated with preferential erosion at faults.
- Andrews and Davin (2009) used an analysis of maps and aerial photos to calculate cliff top retreat of 0.15m/year between 1888 and 1996, 0.41m/year between 1997 and 2008. The maximum recession rate measured was 0.98m/year between 1997 and 2008.
- Posford Duvivier (2001) also used analysis of maps and aerial photos to calculate an average rate of 1.5m/year between 1980 and 1995, and 1.7m/year between 1990 and 1996.
- Portsmouth University's (2004) analysis calculated recession rates of between 1.4 and 1.9m/year between 1980 and 2001.
- Posford Haskoning (2002) concluded a rate of between 1.6 and 2.0m/year since the 1980s.
- Gallois (2011) presents cliff lines traced from historical mapping dating back to 1802 and concludes that average erosion rates since this time have been significantly lower than other researchers have concluded, with rates of between 0.05 and 0.03m/year.
- Royal Haskoning (2009) undertook a cliff erosion review at Pennington Point and concluded that the high cliff recession rates calculated by Posford Haskoning (2002) were skewed by episodic landslide events and thus were not representative of long-term historical change and should not be used to underpin projections of future change. This study also plotted the location of the abandoned railway tunnel and concluded that by 1995, the tunnel had been eroded at the western end of Pennington Point and since 1995, there has been ongoing erosion along the Pennington Point cliff frontage which has resulted in further loss of the tunnel. This report did not consider the tunnel to present any increased risk of cliff recession to the coastal footpath.
- Halcrow (2011) projected cliff recession for these cliffs in the SMP and assumed a future recession rate over the next 100 years of 0.3m/year based on analysis presented in SCOPAC (2004) as the SMP2 disagreed with the higher rates presented in Posford Haskoning (2002) for similar reasons to those presented in Royal Haskoning (2009).

5.4.2.2 Uncertainties and Limitations Associated with Assessments of Cliff Recession at East Cliff

The variation in calculated rates of change reflects use of different epochs of historical data, different locations of measurement or classification of cliff behaviour units and errors in the primary data.

The precise details of the methodology and input data used to calculate the rates presented above are not known, and consequently caution is needed in their interpretation. Any analysis of historical mapping will be affected by mapping and interpretation error in the original survey. Pre-metric OS maps also include error in re-projection to the National Grid. Assessments of aerial imagery are constrained by the accuracy of rectification of the image associated with warping the flat image over the undulating topography and errors in interpretation of geomorphological features.

All analyses of historical data will typically result in average annual recession rates being calculated. Along this coastline, where coastal change is driven by low frequency but high impact episodic cliff failures, this can result in very different average annual rates being calculated, depending upon the length of the data set. This is demonstrated by the difference in average annual values presented by Posford Haskoning in 2002, compared to Royal Haskoning in 2009.

The results presented above also provide little or no information on the magnitude and frequency of cliff recession events that are typically episodic in time and localised in space.

5.5 Beach profile analysis

Data relating to beach levels and volumes is available since 1995 and therefore provide information on how the beaches have changed since the most recent scheme was introduced.

Key findings from previous monitoring reports have been summarised (Section 5.5.1), and new beach profile analysis has been undertaken to estimate the change in cross-sectional area and beach volume since 1995 (5.5.2). Response of the beach to storm conditions has also been considered.

5.5.1 Review of previous monitoring reports

5.5.1.1 1995 to 1998 Monitoring Programme (BMP rev 1, Posford Duvivier, 1998a)

Figure 5-3 shows the beach monitoring surveys zones set up by Posford Duvivier, whilst Table 5-7 shows the results of the volumes analysis. The key findings were as follows:

- In zones A1 to B3 (western beach, in the lee of the breakwater) inclusive accretion is the governing process, with the majority of the accretion taking place between January and April 1996.
- In zones B5 to B7 and C1 to C2 (Bedford Steps to York Steps Groyne), erosion is markedly predominant. In zone B5, immediately east of the Bedford Steps, erosion occurred continually from October 1995 until April 1996.
- Zones B4, C3 and D1 to D3 (York Steps Groyne to River Sid training wall) exhibit erosion and accretion of similar magnitudes, probably within the margins of error in surveys, with no particular pattern of erosion/accretion with respect to timescale.

It would be reasonable to infer that the sediment lost from zones B5 – B7 and C1 - C3 was simply redistributed to zones A1 - A3 and B1 - B4. When considering the volumes reported, it appears, however, that there was a net gain of sediment across the Sidmouth frontage, as a whole, of around 18,000m^3 over the period considered (1995 to 1998). It is not possible, however, to determine whether this was sand or shingle, nor identify the possible source of this additional sediment.

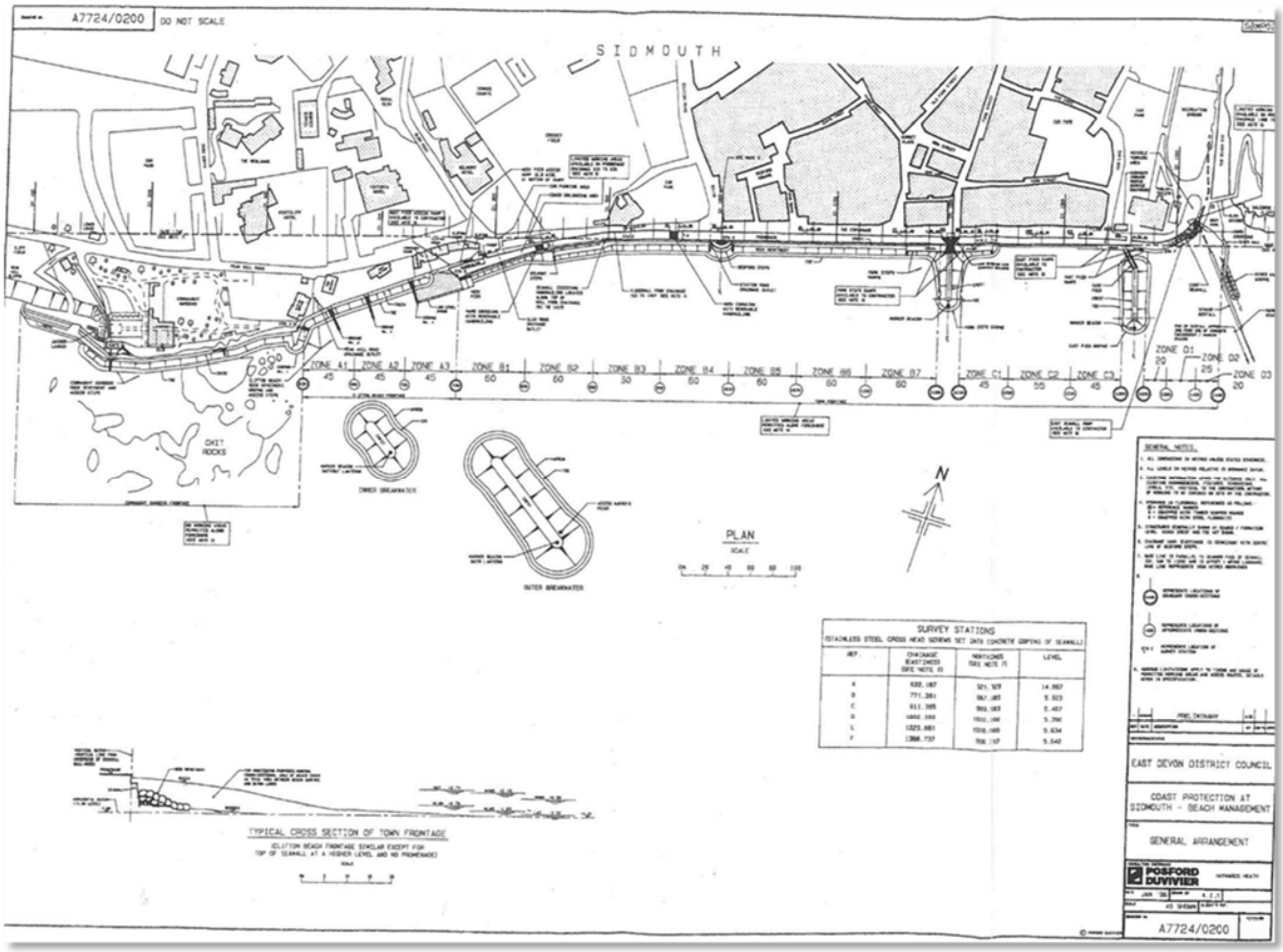


Figure 5-3 1995 to 1998 beach monitoring survey zones.

Table 5-7 Volumes analysis 1995 to 1998 beach monitoring (Posford Duvivier, 1998). Grey shading denotes net erosion taking place within the compartment and no shading denotes net accretion taking place within the compartment.

Period Between Surveys		**Beach Zone / Compartment Number**																			
From	**To**	**A1**	**A2**	**A3**	**West Pier**	**B1**	**B2**	**B3**	**B4**	**Bedford Steps**	**B5**	**B6**	**B7**	**York Steps Groyne**	**C1**	**C2**	**C3**	**East Pier Groyne**	**D1**	**D2**	**D3**
25-Oct-95	08-Dec-95																				
08-Dec-95	09-Jan-96																				
09-Jan-96	24-Jan-96																				
24-Jan-96	19-Feb-96																				
19-Feb-96	13-Mar-96																				
13-Mar-96	17-Apr-96																				
17-Apr-96	15-May-96																				
15-May-96	01-Aug-96																				
01-Aug-96	25-Sep-96																				
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13-Dec-96	07-Feb-97																				
07-Feb-97	09-Apr-97																				
09-Apr-97	17-Sep-97																				
17-Sep-97	13-Nov-97																				
13-Nov-97	14-Jan-98																				
14-Jan-98	26-Feb-98																				
26-Feb-98	28-Apr-98																				
28-Apr-98	28-May-98																				
Erosion (m^3)		-9112	-5032	-6794		-7997	-16586	-7488	-9121		-6971	-11330	-10595		-16437	-6823	-9826		-12734	-8547	-11127
Accretion (m^3)		13192	10745	11053		17078	23305	12321	8982		4928	7647	6950		12274	4496	8750		12644	8314	12014
Erosion/Accretion Factor		-0.69	-0.47	-0.61		-0.47	-0.71	-0.61	-1.02		-1.41	-1.48	-1.52		-1.34	-1.52	-1.12		-1.01	-1.03	-0.93
Net Volume (m^3)		**4080**	**5713**	**4259**		**9081**	**6719**	**4833**	**-139**		**-2043**	**-3683**	**-3645**		**-4163**	**-2327**	**-1076**		**-90**	**-233**	**887**

5.5.1.2 2000 to 2005 Monitoring Programme (Royal Haskoning, 2005b)

The first five years of beach monitoring at Sidmouth is reported in Beach Monitoring Report No. 9 August 2005, taken from Royal Haskoning (2005b). Using beach monitoring data from 2000 to 2001, volumes were calculated above datum planes of -3.0mODN and -2.0mODN. Allowing for an initial settling down period, a comparison of the surveys between 2001 and 2005 showed:

- Between zones A and B4 (in the lee of the breakwater, between Chit Rocks to Bedford Steps groyne), there was an increase in volume in the order of 4,000 to 4,500m^3.
- There was a net loss in volume within zones B5 to C3 (i.e. the beach between Bedford Steps Groyne and East Pier groyne) of c. 6,190m^3 above -2.0mODN and 5,130m^3 above -3.0mODN.

In addition, the report (Royal Haskoning, 2005b) noted that:

- The beach was performing better than predicted in previous reports.
- Along the frontage, the net losses were balanced out by the net gains, therefore it was concluded that there had been no net loss from the system compared to 2001.

The results may be inferred to mean that over the period considered there was a redistribution of sediment from the groynes area to behind the breakwaters, suggesting that sediment was moved from east to west along the frontage. This assumes that there is no new input of sediment from further west.

5.5.1.3 Ongoing Annual Monitoring Programme (2007 to present)

PCO have undertaken beach profile analysis along this frontage, as part of the Southwest Regional Coastal Monitoring Programme (SWRCMP), since the first baseline survey in 2007. The BMP extent (Jacob's Ladder Beach to East Beach) is located in PCO Unit 6aSU10. This review draws specifically from the Annual Report (PCO, 2013), and the Beach Management Plan Report (PCO, 2010). The findings from the most recent monitoring report (PCO, 2013) are shown in Figure 5-4 and Figure 5-5, and can be summarised as follows:

- Between Spring 2012 and Spring 2013, the profiles show the beach cross sectional area reduced, with the exception of profile 6a01456 (located in the lee of the breakwaters), and profile 6a01441 (located on East Beach), which showed a significant increase of 43m^2; an overall change of +105%.
- Over the longer term, between 2007 and Spring 2013, the profiles indicate that the beach reduced in cross-sectional area, with exception of profile 6a01456 (located in the lee of the breakwaters), which increased by 6% and profile 6a01441 (located on East Beach), which increased by 89%.

In addition to the annual monitoring reports, PCO also produce a series of Beach Management Plan Reports for the coastline at Sidmouth in support of the BMP. The most recent report (PCO, 2010) includes the historic beach monitoring data collected by Posford Haskoning during the first five year monitoring programme alongside the more recent data collected as part of the SWRCMP. Their key findings were:

- Topographic difference model - 2000 Baseline to July 2009 (shown in Figure 5-6): overall, the western section of the beach gained material behind the offshore breakwaters, whilst the eastern part of the management unit was dominated by erosion downdrift of the Bedford Steps groyne. Unfortunately the model does not include East Beach.
- Changes in MHW elevation 2001 to 2007 (shown in Figure 5-7): Mean high water (MHW) retreated landwards slightly in both the far west and eastern sections of the frontage between 2001 and 2007. There was also a trend of net retreat of MHW along East Beach.

In summary, the 2007 to 2013 beach profiles and the results of the topographic difference model both suggest a net movement of material from east to west. This could either infer a change in the predominant net transport direction, or be the result of material along the Sidmouth frontage being moved westwards under south-easterly conditions, becoming trapped behind the breakwaters and not being returned eastwards under the more usual eastwards transport.

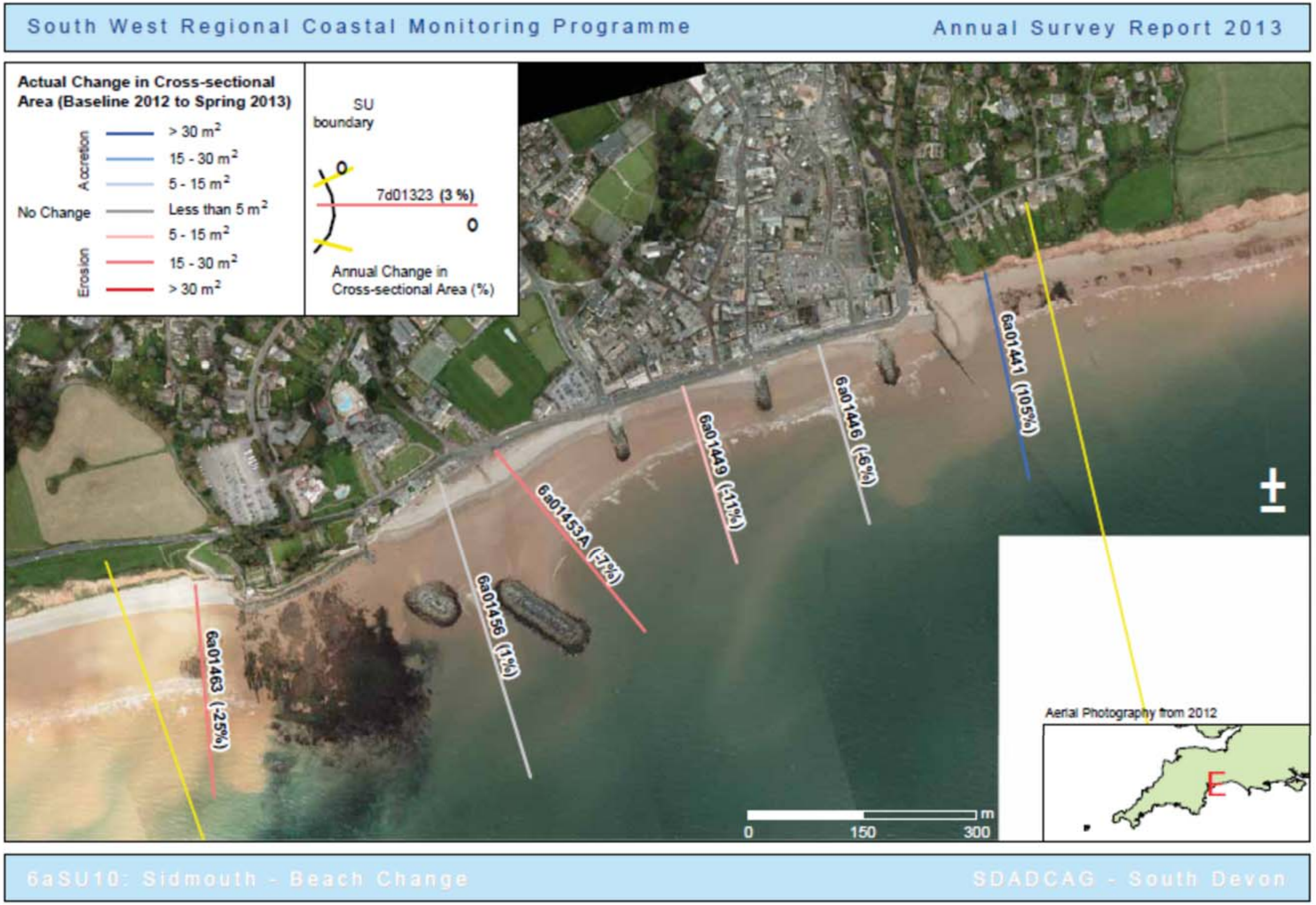


Figure 5-4 Beach profile analysis results for PCO Unit 6a showing short-term change in cross-sectional area for 2012 to 2013 (PCO, 2013).

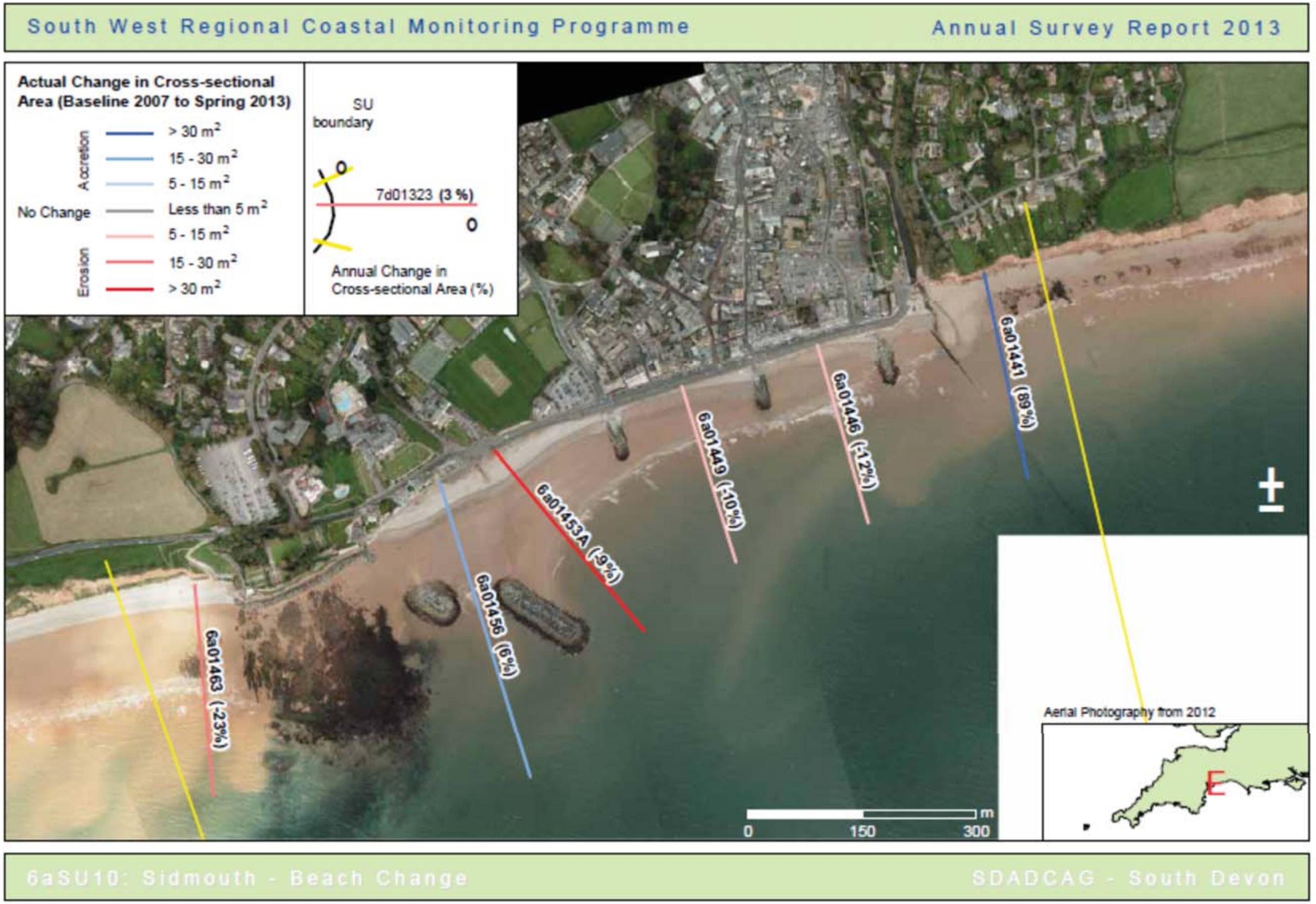


Figure 5-5 Beach profile analysis results for PCO Unit 6a showing longer-term change in cross-sectional area for 2007 to 2013 (PCO, 2013).

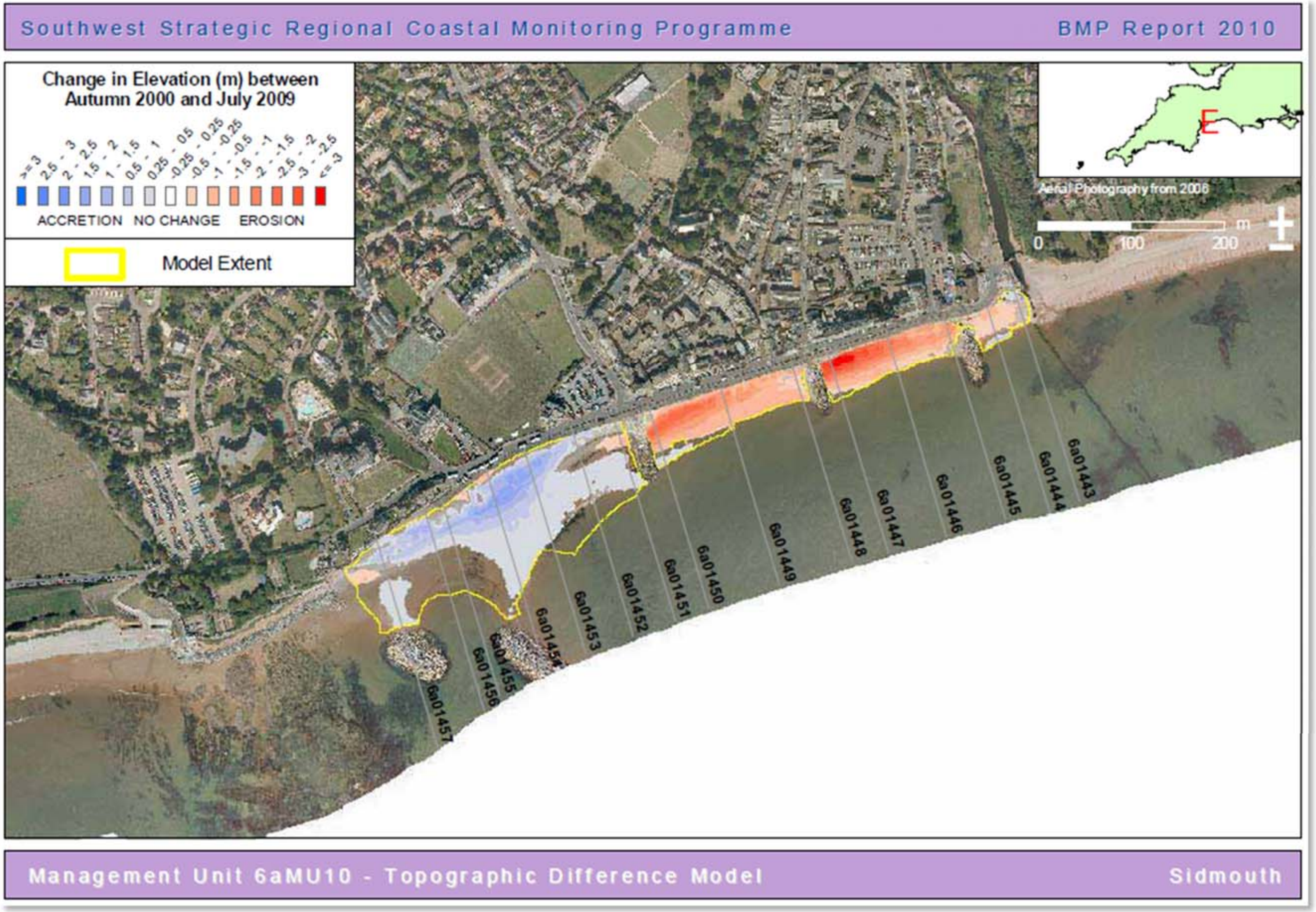


Figure 5-6 Beach elevation change at Sidmouth between 2000 and 2009 (PCO, 2010).

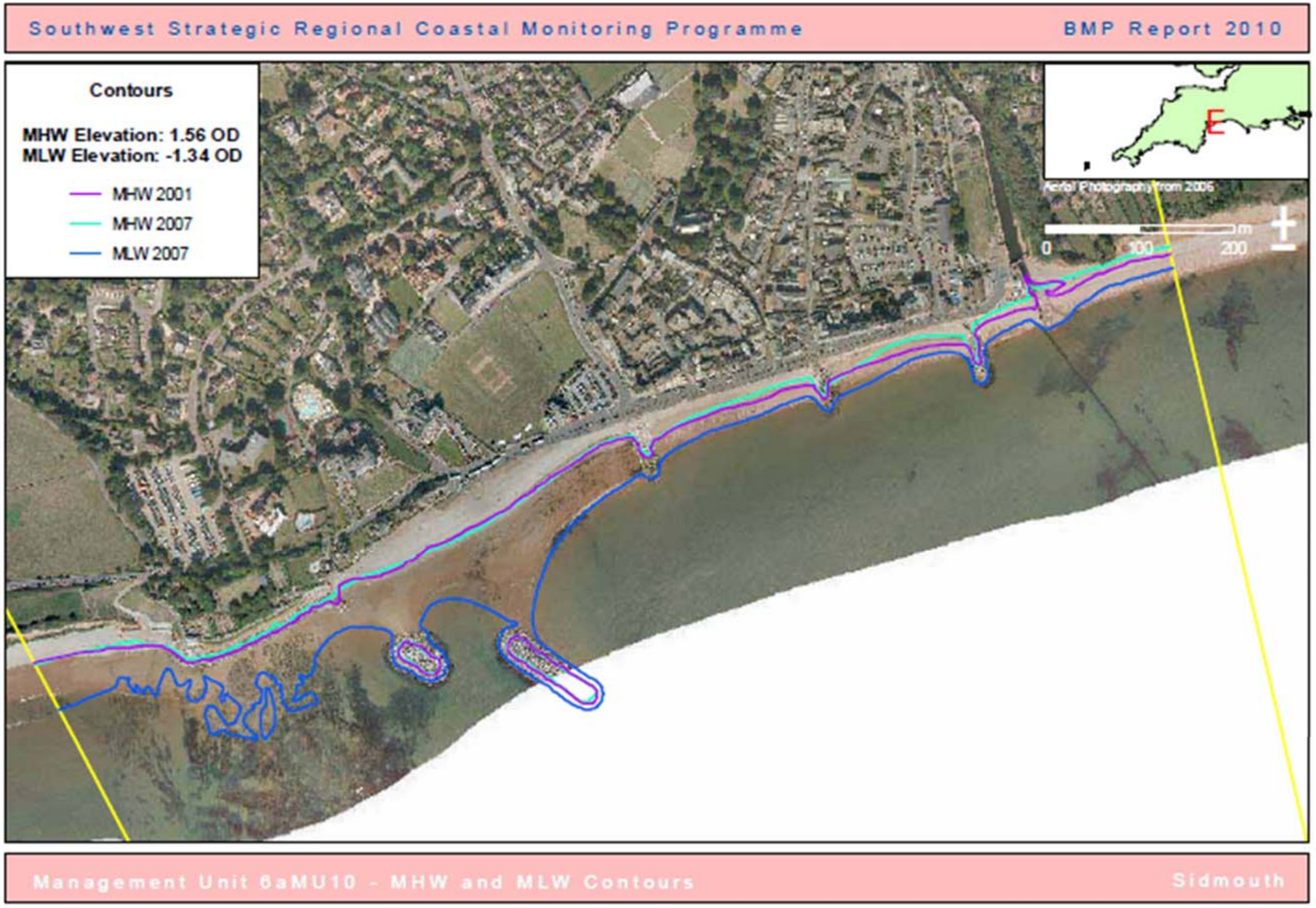


Figure 5-7 Change in position of Mean High Water at Sidmouth between 2000 and 2009 (PCO, 2010).

5.5.2 New analysis of beach profile data

5.5.2.1 Data

Additional analysis of the PCO beach profile data has been undertaken to incorporate data up to 2014. The locations of the beach profiles are shown in Figure 5-8 and plots of the beach profiles within the BMP extent are included in Appendix C, together with details of the timings and frequencies of each beach profile survey completed since 2007.

Within the BMP extent, PCO monitor all profiles from 6a01463 to 6a01441 annually during the summer, and six profiles (6a01463, 6a011456, 6a01453A, 6a01449, 6a01446, and 6a01441) twice a year during the spring and autumn. There are, unfortunately inconsistencies within the dataset, namely: changes in profile locations, missing surveys, different timing of surveys, and the lengths of profiles differing over time (further details are provided in Appendix C).

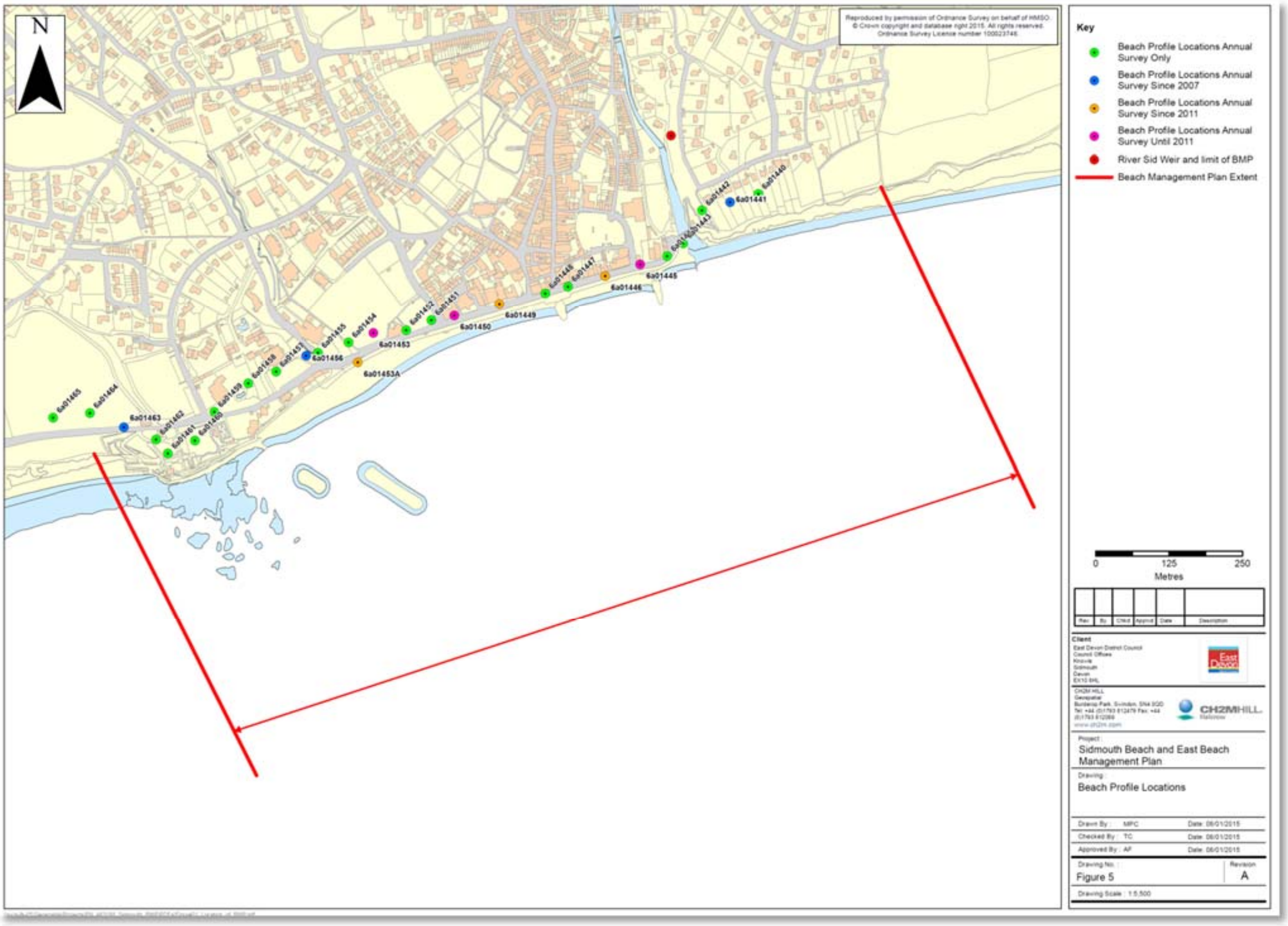


Figure 5-8 Map showing the location of all beach profile locations within the BMP extent.

5.5.2.2 Approach

To assess both volume and cross-section change, the frontage was considered in four stretches:

- Jacob's Ladder Beach east (profiles 6a01643 and 6a01642);
- Chit Rocks (profiles 6a01461 to 6a01459;
- Sidmouth (profiles 6a01458 to 6a01443); and
- East Beach (profiles 6a01442 to 6a01441).

For each profile location, the cross-sectional area, compared to a defined baseline (or Master Profile) was calculated using CH2M's in-house software SANDS, for each survey. The Master Profile was defined as -2.0m OD, which is just below mean low water springs; this enabled the maximum extent of data to be captured within the analysis. The outputs from the cross-sectional analysis is used within SANDS to determine the volume between adjacent survey locations.

5.5.2.3 Results of cross-section area (CSA) analysis

A summary of the CSA analysis are presented in Table 5-8 and a full table of results is presented in Appendix D. Table 5-8 also shows data for the period 2007 to 2012, to provide a consistent data set for the entire frontage. Additional data is available, up to 2014, for selected profiles.

Key findings are:

West of Sidmouth frontage, at Jacob's Ladder Beach

- There was a net trend of accretion between 2007 and 2014 shown by the two profile locations. The data indicates a fluctuating pattern of change, with generally loss of beach (above -2mOD) during winter periods and recovery by the summer survey. Data for the period 2012 to 2014 suggests a net loss, which predominately relates to a period of beach loss in 2013. The 2014 data does, however, indicate some recovery.

Chit Rocks

- At Chit Rock, the data indicates a net beach growth between 2007 and 2008 for all three profile locations. This predominately relates to the transient sand veneer beach which covers the rock platform of Chit Rocks.

Sidmouth Frontage

- Between 2007 and 2012 there was a general trend of accretion behind the two breakwaters, indicated by profiles 6a01458 to 6a01456. This concurs with the data collected as part of the scheme monitoring (see above). The profile data indicates that accretion has taken place over the whole profile, with little change in beach slope occurring. The more recent data for 6a01457 shows the impact of the 2014 storms, when the upper section of beach was eroded and the beach berm pushed landwards.
- Between the eastern end of the breakwaters and Bedford Steps Groyne, the profile data suggests that beach levels have tended to fluctuate, with build-up of a beach ridge at the toe of the seawall, but then its subsequent erosion.
- Between the Bedford Steps Groyne and York Steps Groyne, the data suggests a net eastwards movement of material, with sediment tending to erode from the centre of this bay and be built up against the York Steps Groyne. However, the full data set for 6a01448 at Bedford Steps Groyne indicates that, even over the short data set available (2007 to 2012), this has not been a consistent trend and is dependent upon the prevailing conditions.
- A similar trend is evident for the bay between York Steps Groyne and East Pier Groyne, again the data indicates that for the period 2007 to 2014 the net trend was for material to be moved in an eastwards direction to build up against East Pier Groyne. The full data set indicates, however, that beach levels have fluctuated over time, with beach levels at the toe if the wall fluctuating by up to 1.5m. This indicates that there is not a consistent movement of material in one direction, but that shingle moves from one of the bay to another, and back again.
- Between East Pier Groyne and the training wall, beach levels recorded at 6a01444 in the centre of this same bay, have not fluctuated as significantly over time, with the net difference in level recorded between 2007 and 2012 being around 0.5m. However, at East Pier groyne itself shingle accumulates at the groyne, forming a wedge of material at the top of the beach that is subsequently removed again. Between 2007 and 2012 there was a net increase in beach area at this location, but the previous data indicates that this is unlikely to remain permanently.

East Beach

- There are two profiles which cover East Beach: 6a01442 and 6a01441. Although 6a01442 indicates a net increase in beach volume over the period 2007 to 2012, the profile data shows that there has been a net retreat of the upper beach (above mean sea level) and accretion of the lower beach, which is associated with the build-up of sand and shingle against the eastern side of the training wall.

Table 5-8 Results of the CSA analysis for the BMP extent, from Jacob's Ladder Beach to East Beach. Red text denotes profiles with a reduction in CSA over the survey period.

Beach Section	PD 1995 to 1996 analysis	RH 2000 to 2005 Profile	PCO 2007 to Monitoring Profile	Survey period 1	1 - Net CSA Change (m^2)	Survey period 2	2 - Net CSA Change (m^2)
Jacob's Ladder Beach east	Not included	Not included	6a01463	2007 to 2012	+ 27	2012 to 2014	-10
	Not included	Not included	6a01462	2007 to 2012	+ 27		
Chit Rocks	Not included	Not included	6a01461	2007 to 2012	+ 39		
	Not included	Not included	6a01460	2007 to 2012	+ 26		
	Not included	Not included	6a01459	2007 to 2012	+ 37		
Sidmouth	A1	A	6a01458	2007 to 2012	+ 25		
	A2	B	6a01457	2007 to 2012	+ 25		
	A3	C	6a01456	2007 to 2012	+17	2012 to 2014	- 70
	B1	D	6a01455	2007 to 2012	+ 6		
	B2	No equivalent	6a01454	Not included	n/a		
	B2	E + E	6a01453A	Not included	n/a	2012 to 2014	+44
	B2	E + E	6a01453	2007 to 2012	- 9		
	B3	No equivalent	6a01452	Not included	n/a		
	B4	F	6a01451	2007 to 2012	+ 5		
	B5	G	6a01450	2007 to 2012	- 33		
	B6	H	6a01449	2007 to 2012	- 5	2012 to 2014	-15
	B7	I	6a01448	2007 to 2012	+ 31		
	C1	J	6a01447	2007 to 2012	- 60		
	C2	K	6a01446	2007 to 2012	+ 14	2012 to 2014	-9
	C3	L	6a01445	2007 to 2012	+ 10		
	D2	M	6a01444	2007 to 2012	+ 1		
	D3	N	6a01443	2007 to 2012	+ 25		
East Beach	Not included	Not included	6a01442	2007 to 2012	+ 22		
	Not included	Not included	6a01441	2007 to 2012	- 8	2007 to 2014	+13

- At profile 6a01441, a comparison of the 2014 data with 2007 indicates that the net change over this period has been a drop in beach levels, with a difference in beach level of around 0.5m across the shingle beach. However, the full data set indicates that beach levels here have tended to fluctuate over time and it is not possible to determine an ongoing trend of either accretion or erosion. Data from 2013 suggest that beach levels at this time were particularly high, but this is likely to relate to a cliff fall at this location: the data suggest that removal of this material occurred within only eight months, with beaches returning to levels pre-fall.

5.5.2.4 Results of volume analysis

A summary of the findings of the beach volumes analysis are presented in Figure 5-9 and Table 5-9, with the full table of results is presented in Appendix D. This covers the period 2007 to 2012, when the majority of profiles were surveyed.

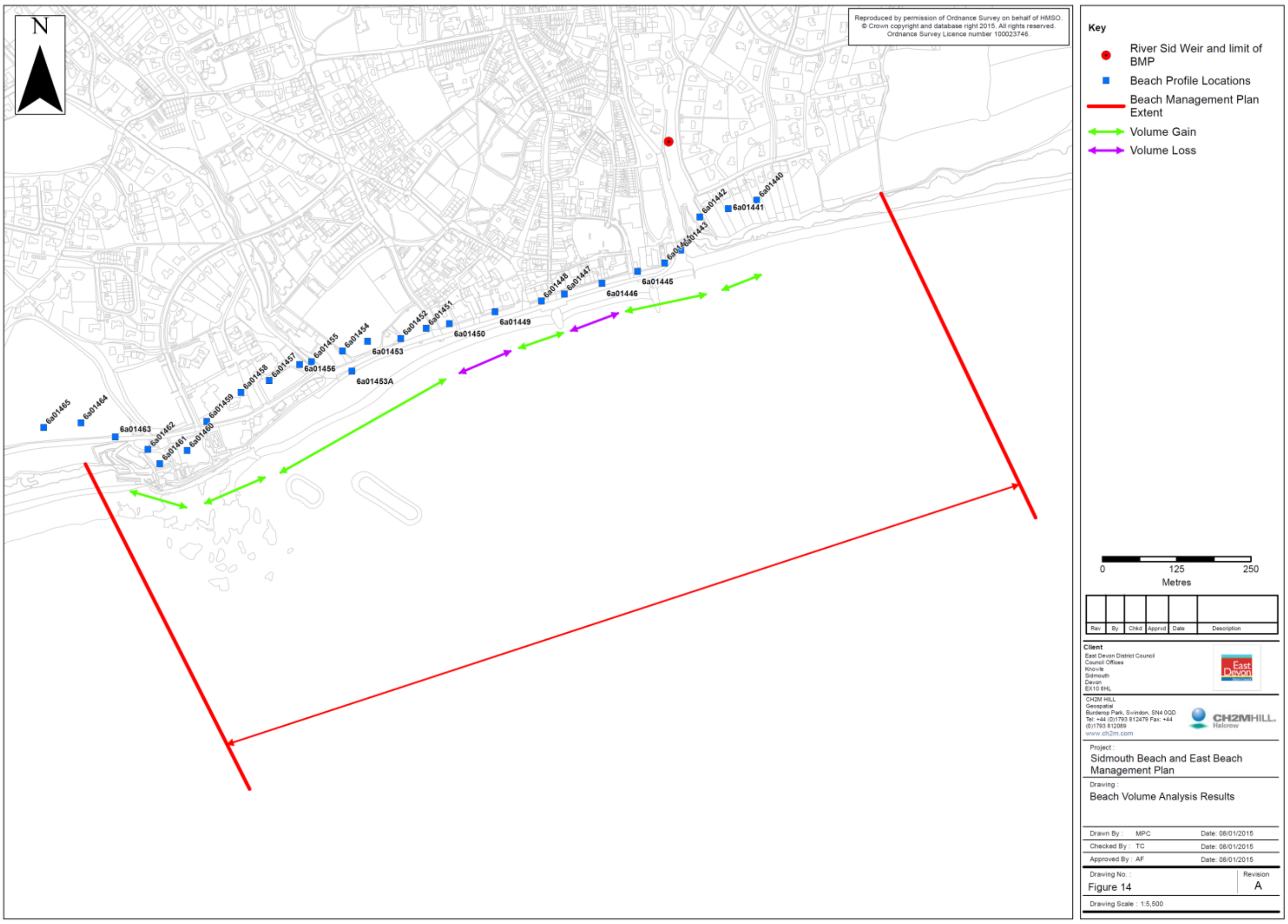


Figure 5-9 Map showing the results of the volumes analysis.

As the volume data is based on a simple interpolation of the CSA data for adjacent beach profiles it is unsurprising that the beach volume analysis shows similar trends across the frontage. For this analysis all available profiles have been used, with the exclusion of 6a1453A, for which surveys only started later. This data should be taken with some caution due to:

- the available data does not allow any assessment of whether the changes relate to sand or shingle; and
- the method of determining volumes is fairly crude due to the availability of data and the distribution of profile locations; this means that the volume analysis poorly replicates the movement of material from one end of the bay to the other. To gain a more accurate understanding of beach volumes and changes, either a Grid-based GPS survey or LiDAR would provide better coverage of the beach.

Despite these limitations, some trends can be concluded:

West of Sidmouth frontage, at Jacob's Ladder Beach

- At Jacob's Ladder Beach East, the beach volume increased between 2007 and 2012 by approximately 2,000m^3. However, much of this change apparently occurred between the first surveys in April and

August 2007, which is likely to relate to beach recovery following a storm recorded in March 2007 (see section 5.5.3). The profile and volume data indicate that the volume along this stretch does fluctuate, varying by between 100 and 500m^3 season to season. It is not possible from the data to identify whether material is moved around Chit Rocks along to the Sidmouth frontage. Given that it is reported that little if any sediment passes from the east to the west around Chit Rocks, this material is likely to have been supplied from further west, from cliff or beach erosion, but such a process was not evident from the analysis of the 2014 storm undertaken by PCO and reported in a later section. It is therefore assumed that shingle here is simply a redistribution of material from further west.

Table 5-9 Results of the beach volumes analysis for the BMP extent, from Jacob's Ladder Beach to East Beach. Data is shown for the period April 2007 to August 2012. Red text denotes profiles with a reduction in volume over the survey period. The shaded areas show where the sections cross the groynes.

Beach Section		PCO Profile Reference		Volume Change (m^3)
Jacob's Ladder Beach East		6a01463	6a01462	+2,063
Chit Rocks		6a01462	6a01461	+2,043
		6a01461	6a01460	+1,645
		6a01460	6a01459	+2,143
Sidmouth	*Lee of breakwaters to Bedford Steps Groyne*	6a01458	6a01457	+1,250
		6a01457	6a01456	+1,260
		6a01456	6a01455	+240
		6a01455	6a01454	-250
		6a01454	6a01453	-550
		6a01453	6a01452	-190
		6a01452	6a01451	+71
	Bedford Steps Groyne to York Steps Groyne	6a01451	6a01450	-660
		6a01450	6a01449	-1,580
		6a01449	6a01448	+1,010
		6a01448	6a01447	-600
	York Steps Groyne to East Pier Groyne	6a01447	6a01446	-1,500
		6a01446	6a01445	+760
	East Pier Groyne to training wall	6a01445	6a01444	+270
		6a01444	6a01443	+450
East Beach		6a01442	6a01441	+966

Chit Rocks

- At Chit Rocks, beach volume increased between 2007 and 2012 by between 1,600 and 2,100m^3. However, as shown by the full table of results in Table D.4 in Appendix D, and similar to Jacob's Ladder Beach east beach, much of this change is the result of a significant increase in beach volume between the April and August 2007 surveys. As discussed above, this may therefore relate to beach recovery following the March 2007 storm event. At this location the beach forms a veneer across the rock platform of Chitrocks and the earliest survey (April 2007) shows that at this time there appears to have been very little beach cover.

Sidmouth Frontage

- Between 2007 to 2012, the western part of the frontage gained in volume, with between a 4% and 17% change in volume recorded.
- Within the groyne bays, there was a volume loss at the western ends and a volume gain at the eastern ends over the period 2007 to 2012, which would infer an easterly movement of sediment within the groyne bays. However, as noted for the CSA analysis, in-between surveys show different trends, indicating the bi-directional nature of this frontage.
- When the volumes across the entire Sidmouth frontage are summed for April 2007 and August 2012, the difference between the two surveys is negligible (less than 1% change) suggesting no net loss or gain (but note limitations associated with the data specified above).
- Using the most complete data set from 2012 (which includes profile 6a01453A) the overall beach ‘volume’ along the Sidmouth frontage, from the seawall to a depth of -2m OD, has been calculated to be around 136,000m^3. It should be noted, however, that this is not the volume of mobile sediment (i.e. sand and shingle), as no consideration has been made of the bed level. In comparison, work recently completed by PCO for EDDC (*pers. comms*, 2014), calculated the ‘volume’ in July 2014 to be around 119,000m^3, based on a similar methodology but considering the profile down to -1.94mOD. This compares to a ‘design beach volume’ of 182,000m^3, calculated using the same method. This information would actually indicate that in both 2012 and 2014 the beach volumes appear to be lower than design levels, suggesting a loss of sediment from the system. It should be noted, however, that it is uncertain if the same design was used for the whole frontage (assumed in the PCO analysis) therefore the volume at the start of the scheme could have been less than the PCO calculation of 182,000m^3. To improve confidence, out-survey data from the original renourishment in the 1990s would need to be obtained and compared; no such data has been identified as part of this work.

East Beach

- The volume data suggests a net increase in beach volume, but as discussed for the CSA data, the profile data suggests that beaches here fluctuate in level and that from the full survey record it is not possible to differentiate a clear trend of either accretion or erosion and current beach levels lie within the envelope of change for the period 2007 to 2014. No seasonal trend in the data can be observed for the longer data record at location 6a01441.

To compare results here to the Royal Haskoning monitoring data discussed above (Sections 5.5.1.1 and 5.5.1.2), beach volume change has been calculated for each beach zone (see Figure 5-3):

- Zone A (A1 – A3) (equivalent to 6a01458 to 6a01455) Clifton Beach: +2,750m^3.
- Zone B (B1 to B4) (equivalent to 6a01455 to 6a01451) Former West Pier to Bedford Steps groyne: -900m^3 (*combined A1 to B4: +1,830 m^3*).
- Zone B (B5 to B7) (equivalent to 6a01451 to 6a01448) Bedford Steps groyne to York Steps groyne: --1,230m^3.
- Zone C (C1 – C3) (equivalent to 6a01448 to 6a01445) York Steps groyne to East Pier groyne: -1,338m^3 (*combined B5 to C3: -2,570m^3*).
- Zone D (D1 to D3) (equivalent to 6a01455 to 6a01443) East Pier groyne to River Sid training wall: +720m^3.

The volume changes show that between 2007 and 2012, beaches at the western and eastern ends of the Sidmouth frontage gained sediment, whilst those in the centre lost sediment. During this period (April 2007 to August 2012), the gains were of a similar magnitude to the losses, when the whole frontage is considered. This concurs with data for the first monitoring period (2000 to 2005), which concluded losses and gains were roughly in balance between zones A and B4 and zones B5 to C3, but found that losses (around 6,190m^3) were slightly greater than the gains (around 4,500m^3). The sediment accumulation behind the breakwater was larger in the first monitoring period, than between 2007 and

2012, and the losses also much greater. In comparison, losses and gains of sediment during the first three years of the scheme (1995 to 1998) (see Section 5.5.1.1), i.e. prior to construction of the Bedford Steps Groyne, were also much larger, but with a net gain of around 18,000m^3. From this it may be inferred that the beaches may becoming more stable. However, it is important to note that this latest analysis of volumes only includes data up to 2012 and there are significant limitations associated with the data available (see above). The storm analysis results discussed below also show that the situation in 2012 was significantly changed as a result of the 2014 storms.

It is not possible to determine from the data available, whether the gains and losses identified are shingle or sand fractions of the beach, which makes qualifying the source and fate of sediment very difficult.

5.5.3 Beach response to storms

Historical and anecdotal information indicates that this coastline is susceptible to storms, with beach drawdown in the past resulting in significant (albeit sometimes temporary) beach loss.

A high level storms analysis for the BMP extent has been completed, which has looked at the occurrence of storms in the historical record and assessed, where possible, the impact of those storms. The analysis has also considered the impact of more recent storm events, including the 2014 storms, drawing upon post storm report produced by Plymouth Coastal Observatory (PCO, 2014a; 2014b).

Information on historic storms and the impact on the beach at Sidmouth has been extracted from existing data and is summarised in Table 5-10.

5.5.3.1 Storm events

Table 5-10 Summary of existing information describing storms and beach behaviour at Sidmouth.

Date	Storm Description	Impact on Beach	Source of Information
1824	Storm event	Major erosion of chit rocks.	Posford Duvivier (1998).
1822 (April)	Storm event	No information.	Defence Assessment Baseline report.
1923	Storm event	No information.	Posford Duvivier (1998).
1924 (October)	Storm event	No information.	Posford Duvivier (1998). Defence Assessment Baseline report.
1963	Prolonged easterly storms	No information.	http://www.sidmouthherald.co.uk/news/news/sidmouth_cliff_erosion_a_sidmothian_s_views_1_461103
1989 / 1990	Storm event	Major depletion of the beach, no recovery. Substantial volumes of shingle moved to beaches to the east of Sidmouth and were drawn down seaward of the low water mark	Posford Duvivier (1998). Defence Assessment Baseline report.
1992/1993	Storm event	Further significant beach lowering.	Posford Duvivier (1998). Defence Assessment Baseline report.
1994	No storm recorded.	Erosion of Chit Rocks and shore platform	Defence Assessment Baseline report.
1995/1996 (winter)	Easterly storms	No information.	Posford Duvivier (1998).

Since 2006, wave data has been collected by the West Bay Directional Buoy. Table 5-11 shows analysis of wave height data from the West Bay Directional Buoy by PCO (2014a) for periods when wave conditions exceeded a pre-defined1 in 1 year return period. The data shows that particularly large storms were recorded on the 14th November 2009; 24th December 2013; 5th February 2014 and 14th February 2014, with the 5th February 2014 exceeding a 1 in 50 year event.

Table 5-11 Storms exceeding 1 in 1 year return period at West Bay since deployment in 2006 (PCO, 2014a).

Date	Wave Height (m)	Estimated Return Period
14th February 2014	6.22	> 1 in 10 years
8th February 2014	5.36	> 1 in 2 years
5th February 2014	7.08	Greater than 1 in 50 years
24th December 2013	6.42	> 1 in 30 years
28th October 2013	5.17	> 1 in 1 year
7th June 2012	5.07	> 1 in 1 year
3rd January 2012	5.55	> 1 in 3 years
14th November 2009	6.00	> 1 in 10 years
10th March 2008	5.05	> 1 in 1 year
6th March 2007	5.61	> 1 in 3 years

5.5.3.2 Beach response to previous storms

As part of the SWRCMP, the response of the beach to storms has been regularly assessed and post-storm profile data is available for 2008, 2009, 2010, 2012 and 2014. The data indicates that during storms there is significant redistribution across the frontage, with some profiles exhibiting build-up whilst others exhibit significant sediment loss. This process is very sensitive to the direction of the prevailing storm waves.

Table 5-12 summarises the characteristics and observed beach response, at selected profiles, for a number of recent storm events (Based on data from PCO). Figure 5-10 illustrates post-storm profiles at a number of locations, compared to the more normal year on year changes.

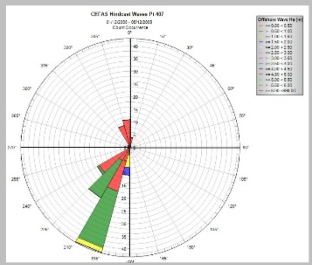
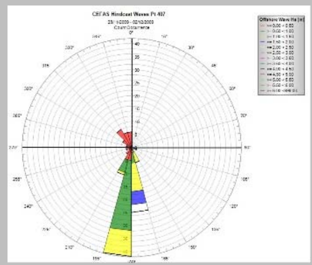
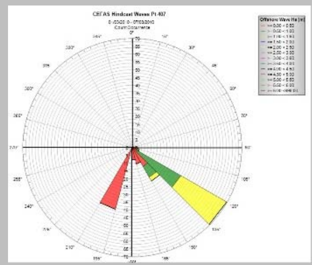
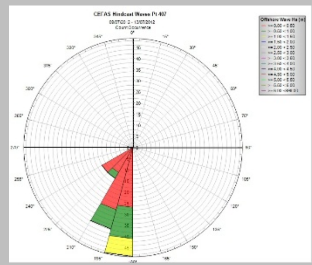
Some key observations have been made from the data:

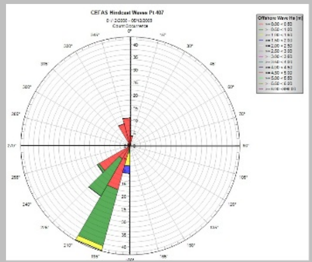
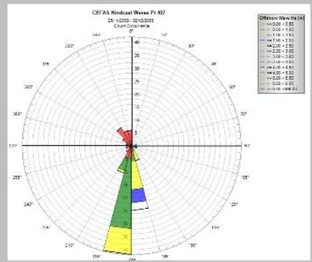
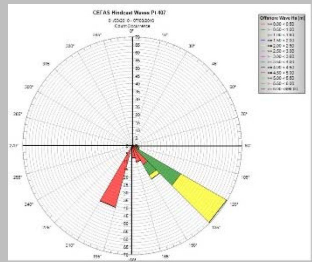
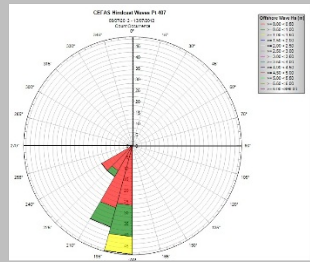
- Even with the scheme in place, the Sidmouth frontage remains sensitive to storms with beach levels changing significantly in response. It is, however, difficult to determine from the data available whether material from the beaches is significantly drawn down, or whether it is simply redistributed within the bays.
- In some situations material is pushed up the beach during storms creating a steeper beach and upper beach storm ridge or berm (such as experienced at 6a01453, in the lee of breakwaters, see Figure 5-11). Elsewhere, such as experienced at profile 6a01450 (see Figure 5-12), the beach has become drawn down from the upper beach, exposing the toe of the seawall.
- East Beach is also very dynamic and susceptible to beach drawdown; evidence collected by PCO indicates that the beach can become stripped of shingle during storms, as occurred in 2009 (see Figure 5-13). At profile 6a01442, Pennington Point, the post-storm survey for 11th July 2012 showed particular movement of the beach between MLWN and MLWS, with the formation of a berm, likely to be supplied by the cross-shore movement of material in that area. Changes here also affect the flow of the river, as shown in photographs. This change demonstrates the dynamic nature of the beach here, which was observed during various site visits undertaken for the present BMP. The photographs in Figure 5-14 and Figure 5-15 show that in December 2013 the shingle bank was narrow and low, whilst the beach around Pennington Point was high, so much so that the footings of

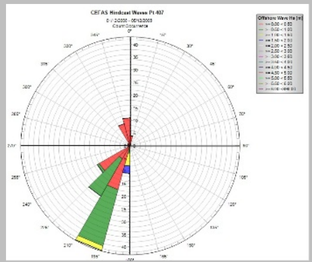
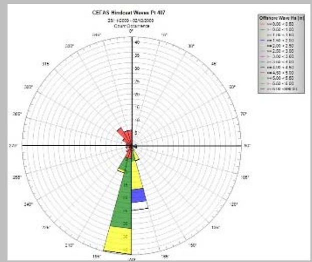
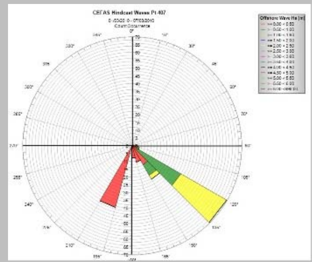
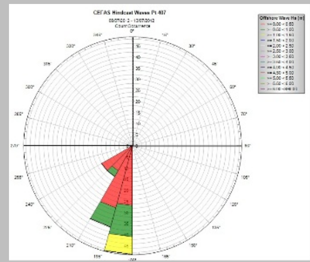
the Alma Bridge access ladder and the boulders were buried. However, in January 2014, the shingle bank is observed to have increased in width and height, whilst the beach around Pennington Point is lower exposing the access ladder footings and the boulders.

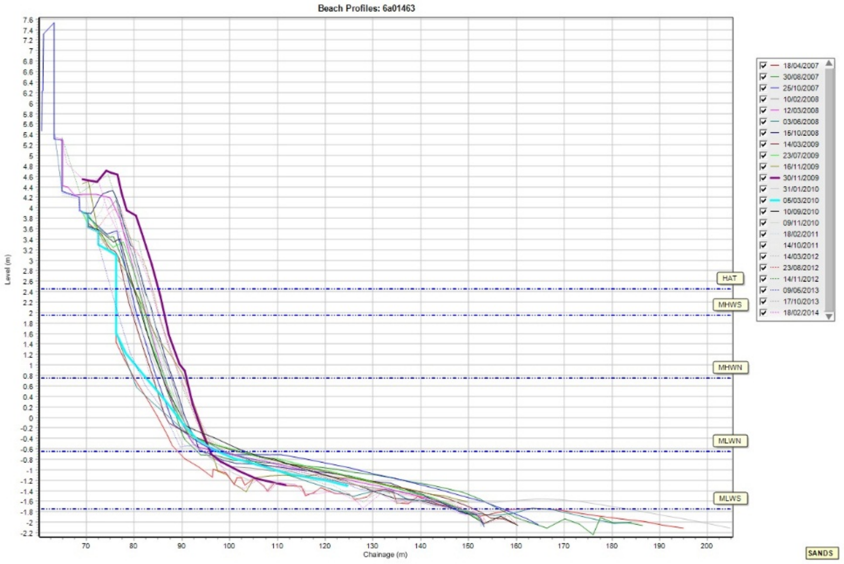
- The available data suggests that the beach at East Beach is particularly sensitive to storms from the south/south-west, with low beach profiles recorded in November 2009 and July 2012.
- Subsequent beach profile data indicates that beach recovery does occur following storms, with material redistributed across the beach; at some locations an area of beach which was eroded during one storm is observed to accrete in a following storm.

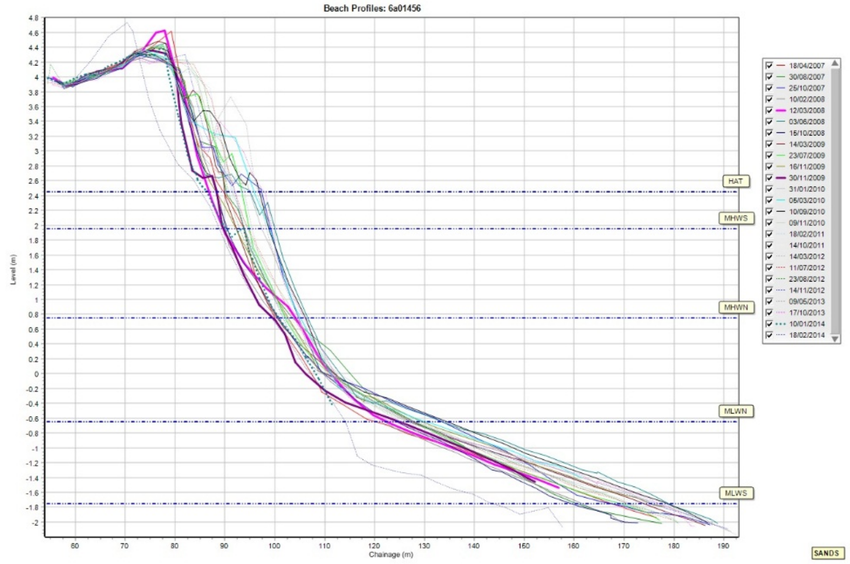
Table 5-12 Post storm beach profile analysis, from data collated by PCO.

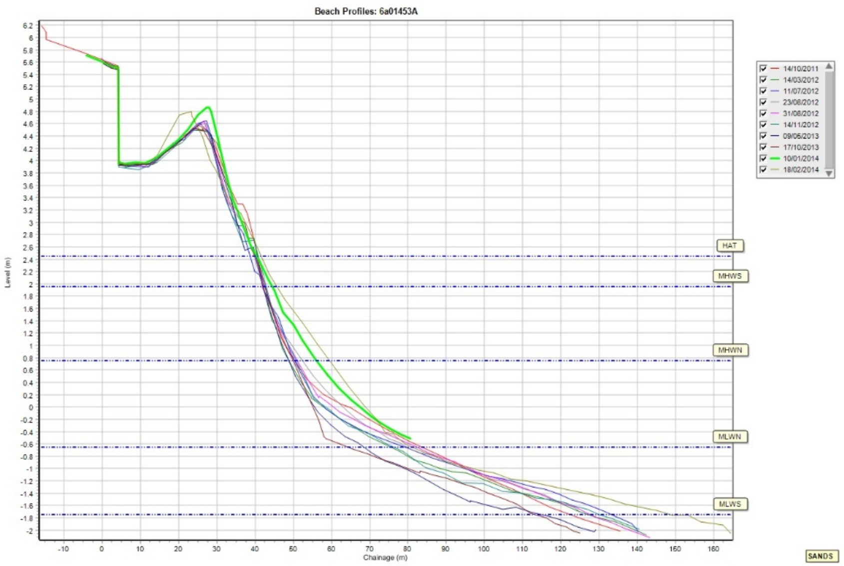
	Post storm profile				
	12.03.2008	**30.11.2009**	**05.03.2010**	**11.07.2012**	**10.01.2014**
Beach Profile + Wave Climate (from Met Office Hind Cast Data location '407)'	 **South-westerly. Note large waves (Hs>1.50m) from south**	 **Southerly. Note large waves (Hs>1.50m) from south**	 **South-easterly**	 **Southerly/south-westerly**	**No data**
6a01463 (Jacobs Ladder)	Change within profiles boundaries	Highest beach levels above MLWN recorded	Amongst lowest beach levels recorded above MHWN, exposing seawall toe		
6a01456 (Lee of breakwaters)	Amongst lowest beach levels recorded + second highest beach berm recorded	Amongst lowest beach levels recorded above MLWN	Change within profiles boundaries	Change within profiles boundaries	Amongst lowest beach levels recorded above MLWN. Note lowest ever levels, narrowest beach and highest berm recorded 18.02.2014.
6a01453A (Lee of breakwaters)				Change within profiles boundaries	Second highest beach levels at MHWN + highest beach berm crest recorded
6a01453 (Lee of breakwaters)		Highest beach levels below HAT recorded	Amongst lowest beach levels recorded below MHWN		
6a01450 (Bedford Steps Groyne)		Lowest beach levels recorded, exposing seawall toe	Amongst highest and widest beach levels recorded		

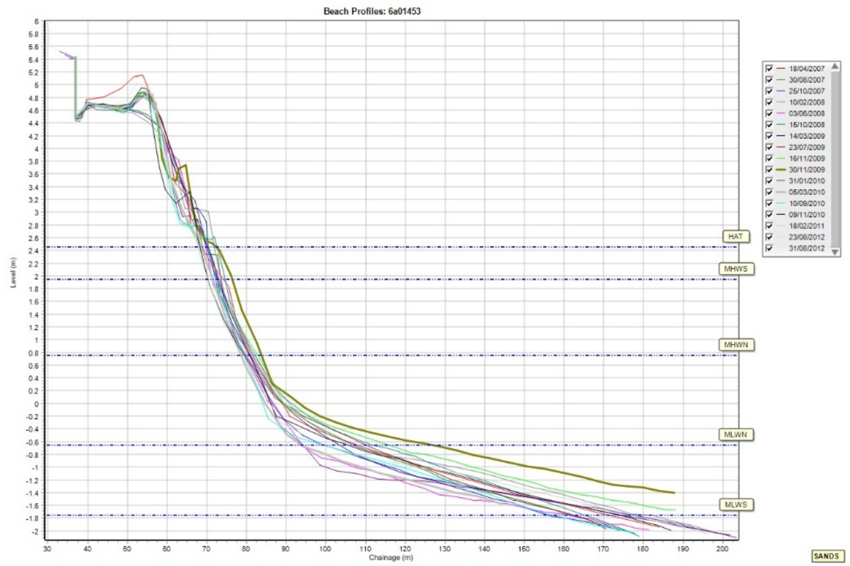
	Post storm profile				
	12.03.2008	**30.11.2009**	**05.03.2010**	**11.07.2012**	**10.01.2014**
Beach Profile + Wave Climate (from Met Office Hind Cast Data location '407)'	 **South-westerly. Note large waves (Hs>1.50m) from south**	 **Southerly. Note large waves (Hs>1.50m) from south**	 **South-easterly**	 **Southerly/south-westerly**	**No data**
6a01449 (Centre of groyne bay – Bedford Steps – York Steps)				Change within profiles boundaries	Change within profiles boundaries
6a01446 (Centre of groyne bay – York Steps – East Pier)				Change within profiles boundaries	Change within profiles boundaries
6a01445 (East Pier Groyne)		Amongst lowest beach levels recorded below MHWS	Lowest beach levels recorded above MLWN, exposing seawall toe		
6a01442 (Pennington Point)				Amongst lowest and highest beach levels recorded between MHWS and MHWN, with the formation of a bank at MLWS.	
6a01441 (East Beach)	Change within profiles boundaries	Lowest beach levels recorded	Change within profiles boundaries	Change within profiles boundaries	Change within profiles boundaries. Note highest ever levels, widest beach

	Post storm profile				
	12.03.2008	**30.11.2009**	**05.03.2010**	**11.07.2012**	**10.01.2014**
Beach Profile + Wave Climate (from Met Office Hind Cast Data location '407)'	 **South-westerly. Note large waves (Hs>1.50m) from south**	 **Southerly. Note large waves (Hs>1.50m) from south**	 **South-easterly**	 **Southerly/south-westerly**	**No data**
					and highest berm recorded 09.05.2013 and 17.10.2013.


Beach Profiles: 6a01463
Level (m)
Chainage (m)
HAT
MHWS
MHWN
MLWN
MLWS
SANDS


Beach Profiles: 6a01456
Level (m)
Chainage (m)
HAT
MHWS
MHWN
MLWN
MLWS
SANDS


Beach Profiles: 6a01453A
Level (m)
Chainage (m)
HAT
MHWS
MHWN
MLWN
MLWS
SANDS


Beach Profiles: 6a01453
Level (m)
Chainage (m)
HAT
MHWS
MHWN
MLWN
MLWS
SANDS

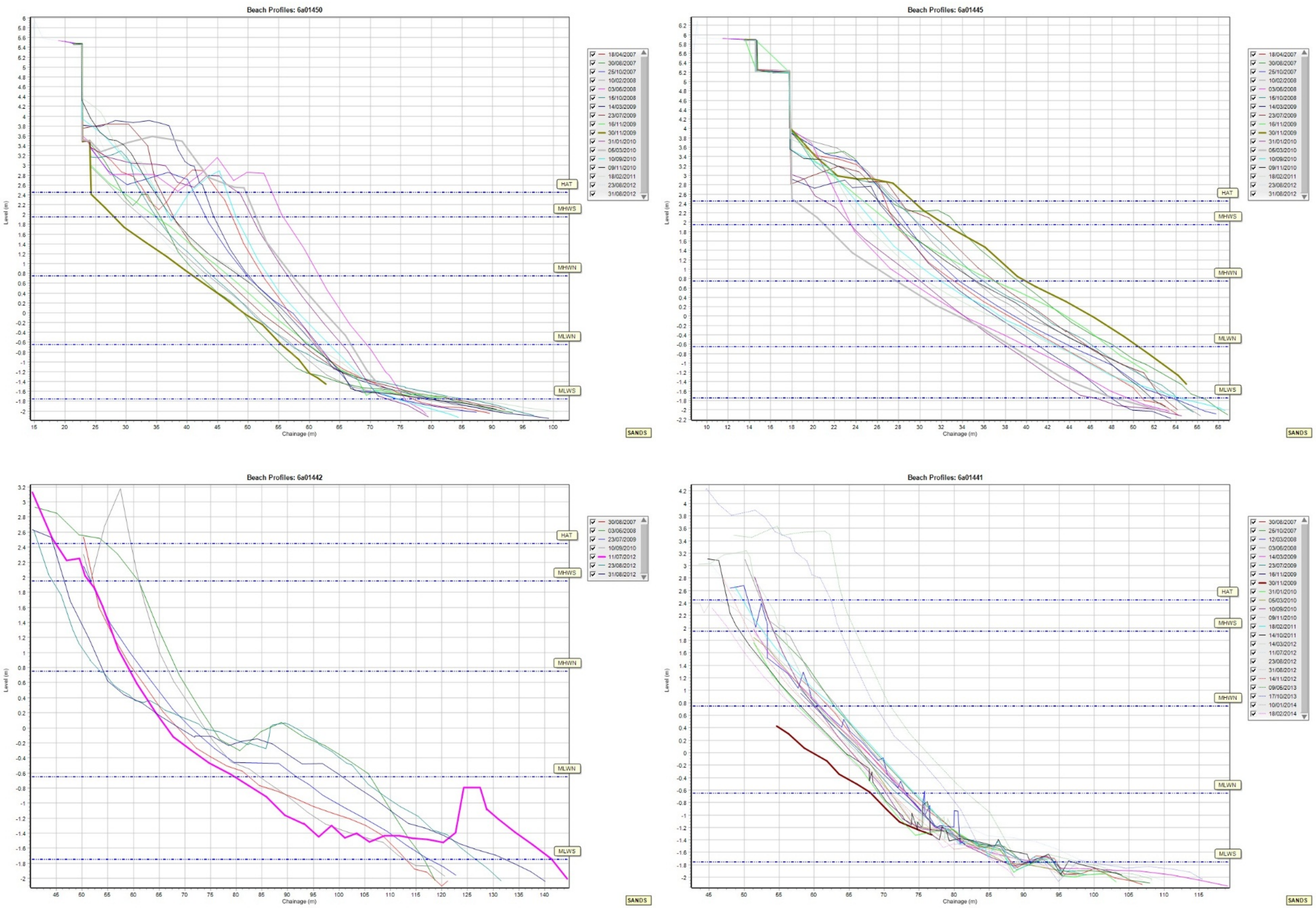


Figure 5-10 Beach profiles for post-storm surveys, where a notable change outside of the general profile change is marked by a profile in bold. Note the exaggerated y-axis (height) scale.

(a) Pre-storm (profile 6a01453 – in lee of breakwaters, west of Bedford Steps Groyne)

(b) Post-storm (profile 6a01453 – in lee of breakwaters, west of Bedford Steps Groyne)

Figure 5-11 Pre-and post-storm photographs taken at 6a01453 – in lee of breakwaters, west of Bedford Steps Groyne in November 2009 (PCO, 2010) showing how the beach has built up at this location, during the same storm as illustrated in the following Figures.

(a) Pre-storm (profile 6a01450 – western end of groyne bay between Bedford Steps Groyne and York Steps Groyne)

(b) Post-storm (profile 6a01450 – western end of groyne bay between Bedford Steps Groyne and York Steps Groyne)

Figure 5-12 Pre-and post-storm photographs taken at 6a01450 (western end of groyne bay between Bedford Steps Groyne and York Steps Groyne) in November 2009 (PCO, 2010) showing how the beach has become stripped of shingle, exposing the toe of the seawall.

(a) Pre-storm (profile 6a01441) (b) Post-storm (profile 6a01441)

Figure 5-13 Pre-and post storm photographs taken at 6a01441 (East Beach) in November 2009 (PCO, 2010) showing how the shingle veneer beach has been removed.

Figure 5-14 The east bank of the mouth of the River Sid, looking upstream: left, the shingle bank at Alma Bridge, and right; Pennington Point and Salcombe Hill Cliffs. Photographs taken during site visit 9th December 2013.

Figure 5-15 The east bank of the mouth of the River Sid, looking upstream: left, the shingle bank at Alma Bridge, and right; Pennington Point and Salcombe Hill Cliffs. Photographs taken during site visit 12th January 2014.

5.5.3.3 Beach response to the 2014 storms

Specific analysis was undertaken to investigate the impact of the series of severe storms in January and February 2014 (PCO, 2014b). Based on the change in beach elevation between 4th November 2013 and 9th February 2014, a number of key observations can be made:

- To the west of the BMP frontage, at Jacob's Ladder Beach east, there was erosion of the cliffs, but accretion of the fronting beach, with the formation of storm ridges.
- At Chit Rocks, the beach in front of the defences was eroded (and probably exposed the bedrock platform).
- At the western end of Sidmouth Beach, in the lee of the breakwaters, erosion of the beach occurred, particular the upper shingle beach, which is the area where previous monitoring had indicated had accreted since the scheme was introduced. There is evidence, however, that this material was moved to the eastern end of the groyne bay, between the eastern breakwater and Bedford Steps groyne.
- Within the two groyne bays to the east, Bedford Steps groyne to York Steps groyne and York Steps groyne to East Pier groyne, the data shows beach erosion at the western end of the groyne bay and accretion at the east, which is likely to represent a simple redistribution of the beach material. At East Pier Groyne, drawdown of the beach at the structure has occurred, suggesting the potential for sediment bypassing (although it is not possible to define whether this is sand or shingle).
- At the eastern end of Sidmouth Beach, between East Pier groyne and the River Sid training wall, a similar pattern of change occurred with erosion of the beach at the western end of the bay and accretion in the east. The data indicates some build-up of sediment at the seaward end of the training wall, suggesting potential for sediment bypassing.
- At Pennington Point, the data indicates cliff erosion and possible upper beach erosion. There was some accumulation of sediment around Mean Low Water, but it is not possible to determine whether this is material drawn down from the upper beach, material built up against the training wall transported from alongshore, or alternatively whether it is material that has bypassed the training wall from the Sidmouth frontage. There is evidence of material built up at the terminal end of the training wall and this, together with the west to east transport evident along the frontage, suggests at least some of this material may have been fed from bypassing of the training wall. Very little change occurred to the central portion of beach at East Beach.
- Further east there was erosion of Salcombe Hill cliffs, but a storm ridge appears to have developed to the east of East Beach, which increased in size to the east. Based on the direction of transport observed along the Sidmouth frontage it is likely that some of this material may have been derived from East Beach.

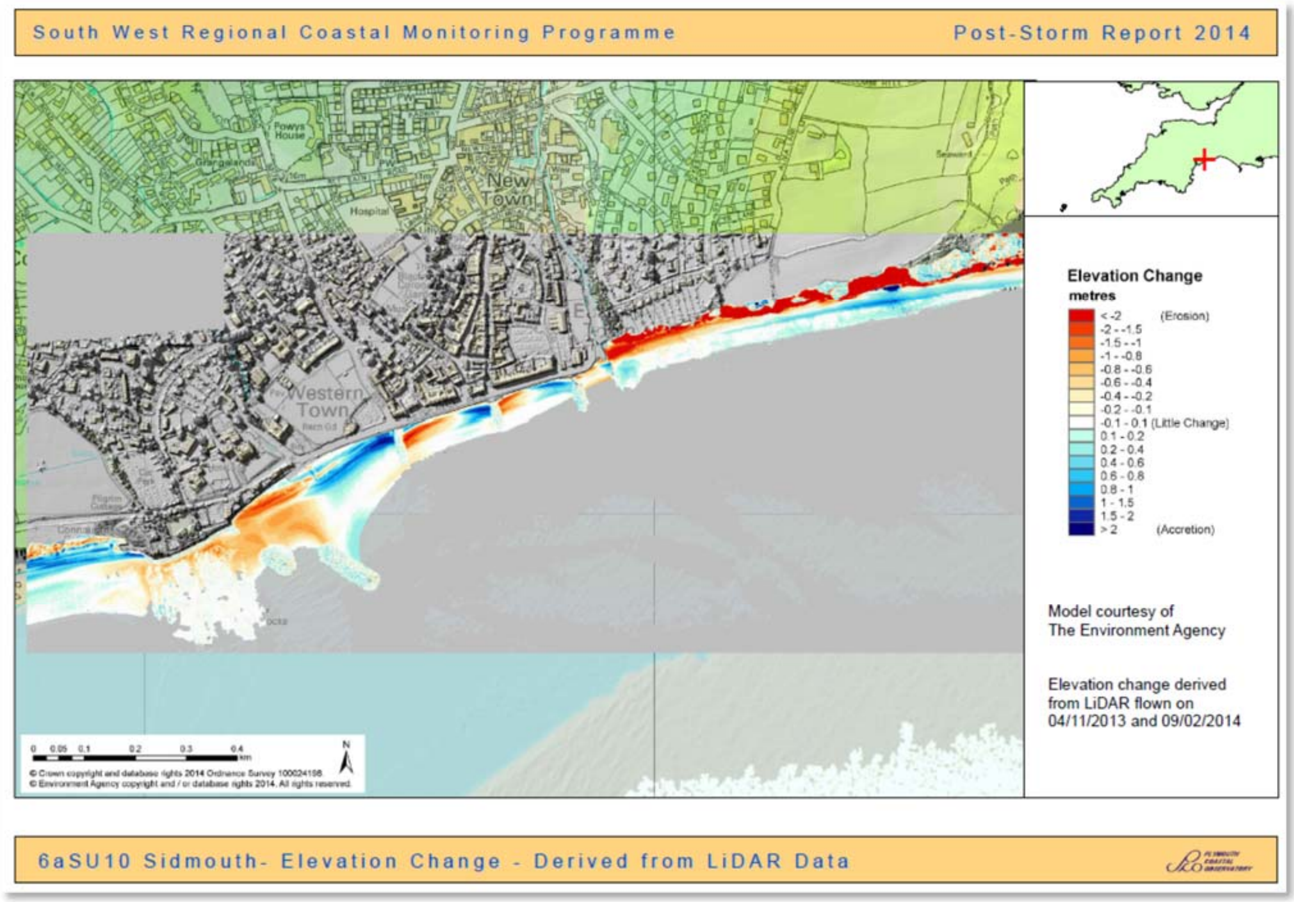


Figure 5-16 Topographic difference model for Sidmouth, showing the change in elevation between November 2013 (pre-storm) and February 2014 (post storm) (PCO, 2014b).

5.6 Anecdotal evidence

Photographs, postcards and locals' recollections has provided additional information how the state of the beach and cliffs from the late 1800s to the present day has changed to be developed, despite the fact that the records are patchy and many are undated. Although in some cases, it is possible to infer something about the condition of the beaches from the pictures, the width of exposed beach will obviously depend upon the state of the tide at the time of the photograph.

5.6.1 Review of available data

The earliest image of Sidmouth provided dates back to 1851 (refer to Appendix A) and the earliest photographs are also from the late 1800s. The image in Figure 5-17 shows the coastline in 1876, with a relatively wide beach fronting the town promenade. In the foreground of the image is Pennington Point, which appears heavily degraded with evidence of past slumping and development of vegetation. Despite the wide beach illustrated in this image, records indicate that severe storms affected the frontage in the 1820s and 1830s, prompting the construction of the first formal defences.

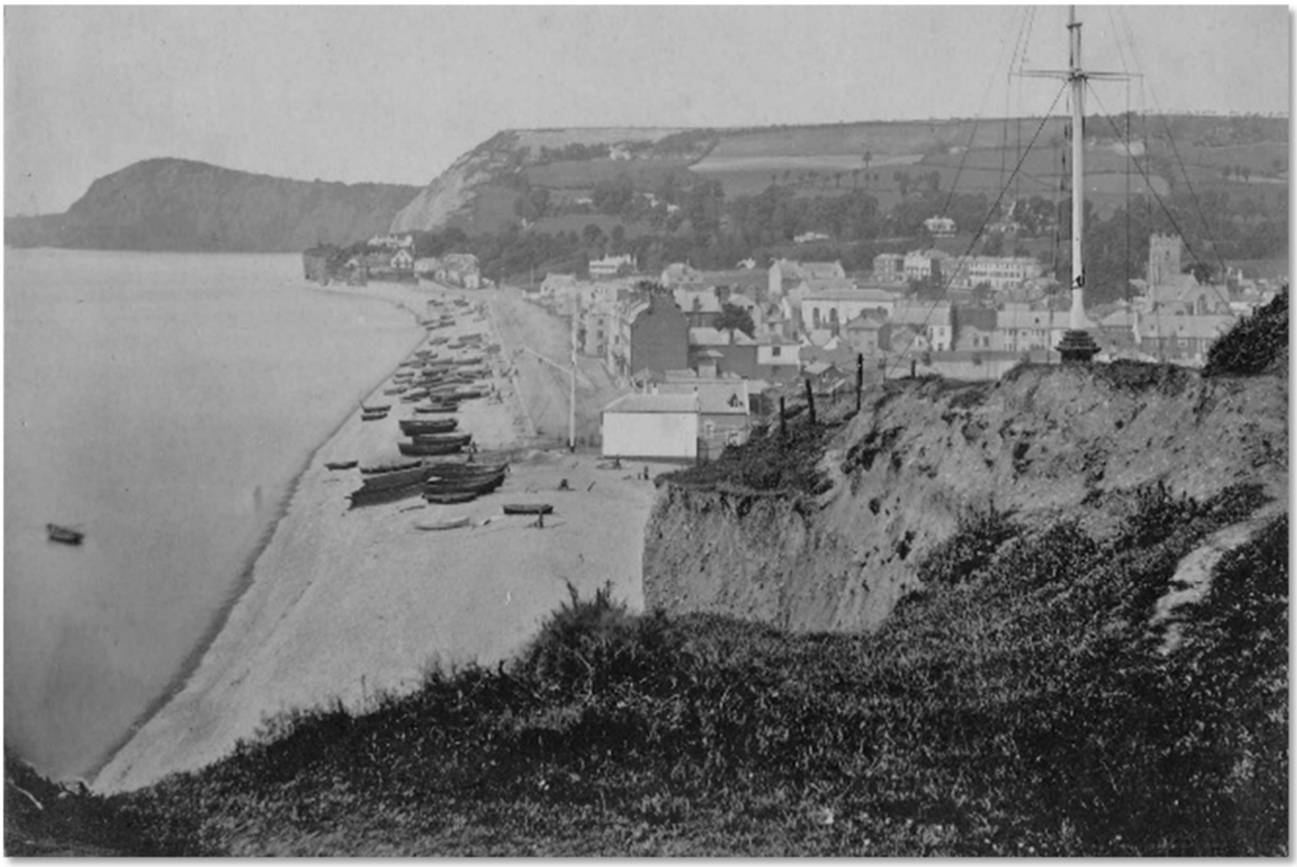


Figure 5-17 Historical photograph of Sidmouth in 1876 looking west from Pennington Point, showing a healthy and relatively wide gravel beach with boats; Pennington Point is in the foreground with evidence of erosion. Source: via David McCluskley, copyright Sidmouth Museum.

The slightly later photograph in Figure 5-18 shows the coastline in approximately 1905, with Dunning's Pier and the Alma Bridge in the foreground. The photograph shows there had been quite substantial development of the eastern end of the Sidmouth beach since 1876, with the construction of Dunning's Pier and buildings, extension of the road into the mouth of the River Sid and the upgrade of the Alma Bridge. This photograph predates the land reclamation and seawall construction at the southern end of the Esplanade. The shingle beach appears to be narrower, particularly at the western end, but this may simply reflect the state of the tide.

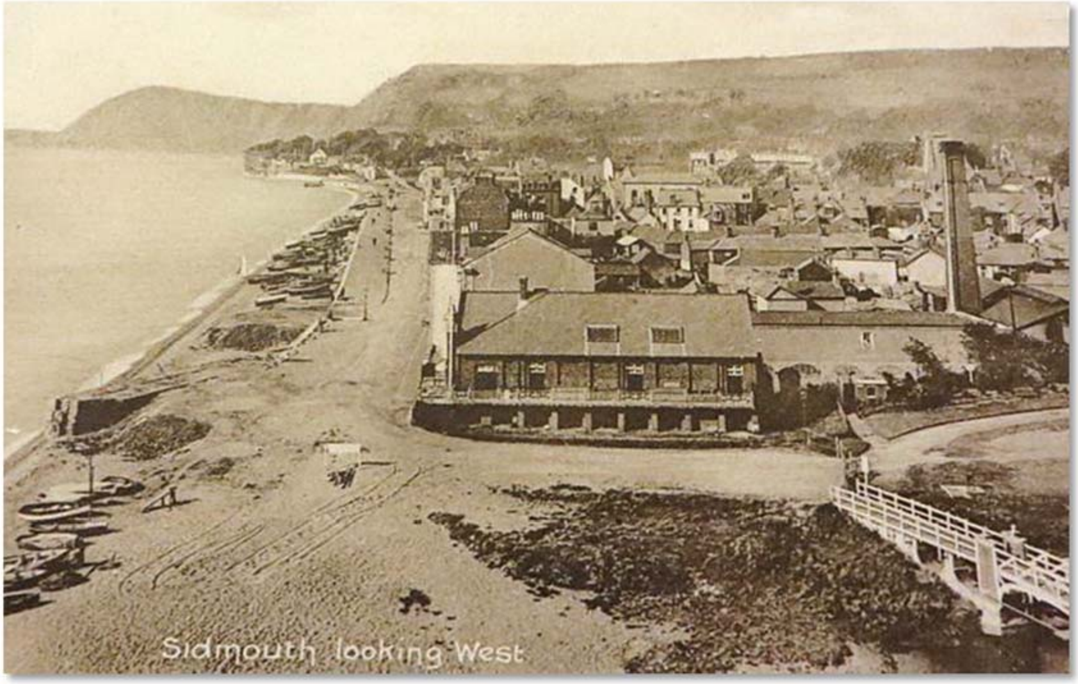


Figure 5-18 Sidmouth looking west in approximately 1905. Source: Mary Walden.

Little information has been found for the 1910s, but records indicate that by the 1920s there has been more development and construction of the seawall at the eastern end of Sidmouth Beach. The photograph from postmarked 1921 (see Figure 5-19) shows how the land on the western bank of the River Sid has been reclaimed to create the promenade and an access ramp has been constructed. It is notable that this photograph predates construction of the River Sid training wall.

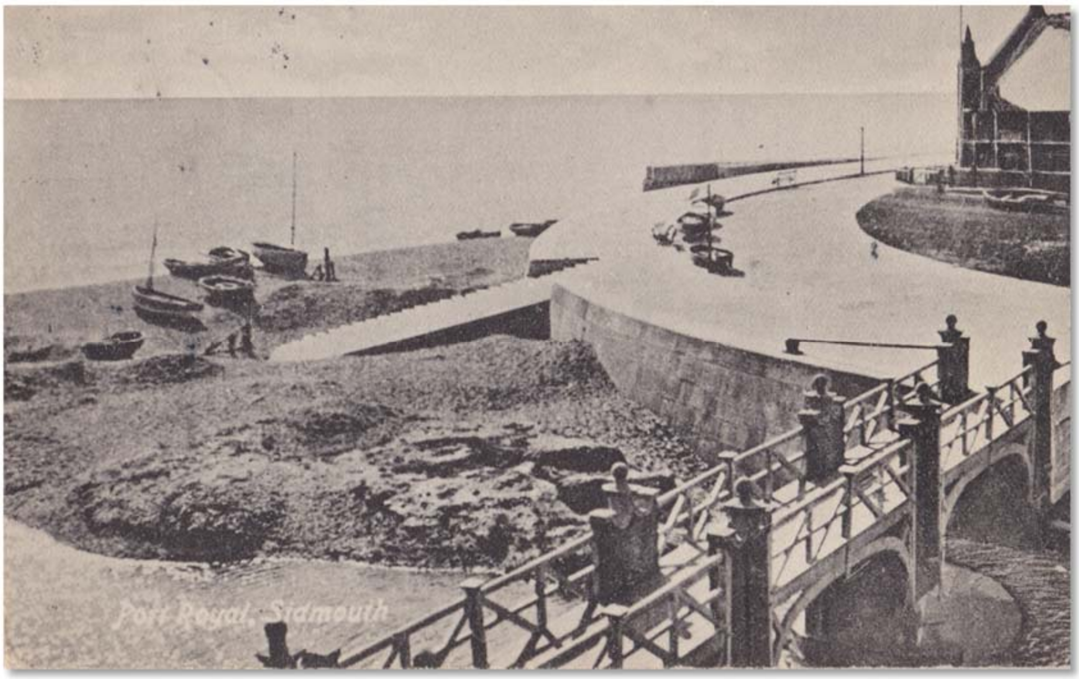


Figure 5-19 Eastern end of Sidmouth beach with new seawall and ramp, image postmarked 1921. Source: Mary Walden.

Sometime between 1921 and 1928 (see online historical photos from Francis Firth), a new training wall was constructed at the eastern end of Sidmouth Beach. The wall was positioned some distance away from the existing promenade, so that the channel now exited to the sea further to the east and the upper beach was fixed between the promenade and training wall. The photograph from 1932 (see Figure

5-22) shows an outfall extending from the training wall, so it is possible that they were constructed at or around the same time.

Records from the 1920s and 1930s (refer to Figure 5-20, Figure 5-21, Figure 5-22 and Figure 5-23) seem to indicate that the shingle beach fronting the town and East Cliff lowered and narrowed considerably over this period (which concurs with conclusions by Laver, 1981 who determined that beaches in the 1920s were lower than in the 1970s). The photographs show that the timber groynes and the face of seawall were exposed and beach levels either side of the training wall were low. Photographs shown in Figure 5-20 and Figure 5-23 appear to indicate debris at the toe of the cliffs along East Beach, indicating cliff failures, and records indicate that rock falls and collapses of weathered material from the cliff top occurred along East Cliff in 1925, 1927, 1928 and 1930.

Figure 5-20 The beach at Sidmouth looking east, image postmarked 1927. The upper shingle beach appears to be narrow and levels are low, based upon exposure of the seawall and timber groynes. Source: Mary Walden.

Figure 5-21 Aerial view of Sidmouth beach, looking west, image postmarked 1930. Source: Mary Walden.

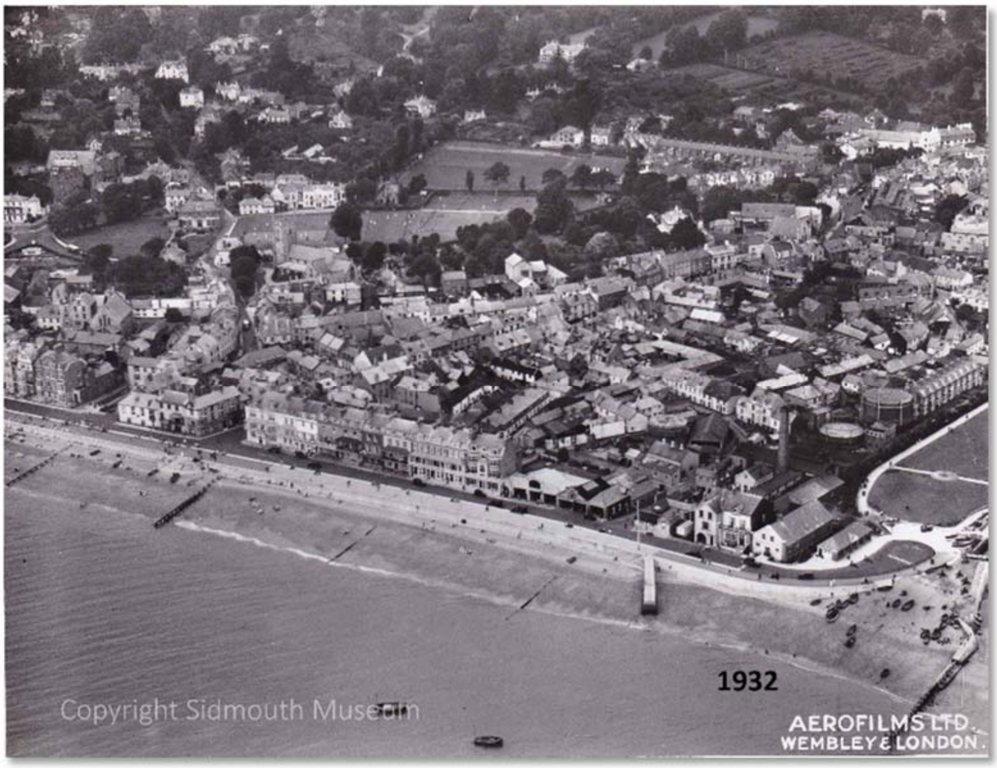


Figure 5-22 Aerial image of Sidmouth Beach in 1932 showing low and narrow beach, with new training wall and outfall structures at the eastern end of the beach. Source: David McCluskey, Sidmouth Museum.

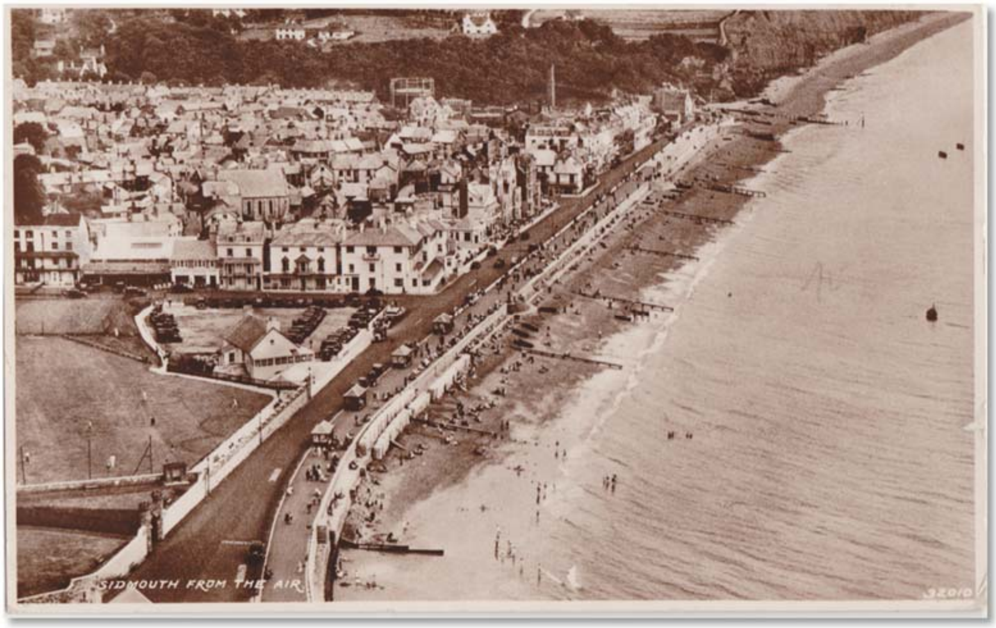


Figure 5-23 Aerial image of Sidmouth Beach, looking east, image postmarked 1937. Low and narrow beach levels are evident by the exposed groynes. Cliff failure at Pennington Point/East Cliff can been seen in the distance. Source: Mary Walden.

Records from 1940 suggest beach levels to the east of the River Sid may have recovered to some extent and remained higher, although 1937 was marked by a period of low beaches and a large collapse occurred at East Cliff in the early/mid 1930s (see Figure 5-24).

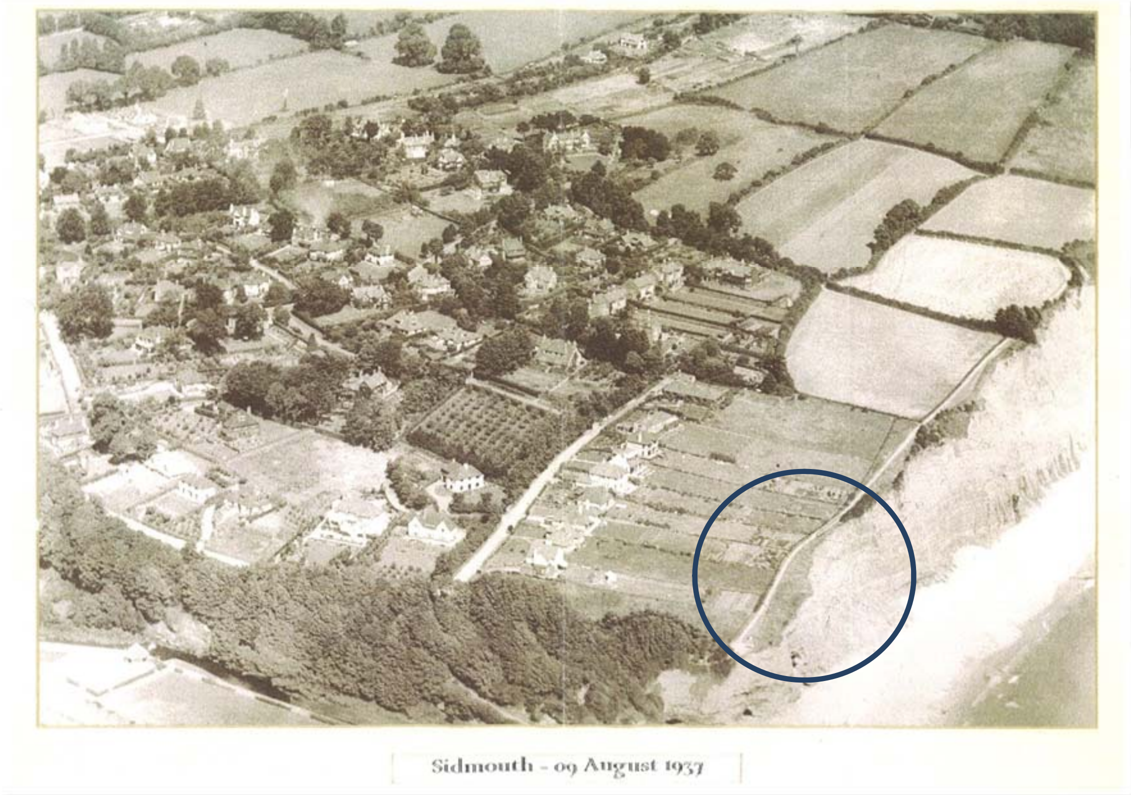


Figure 5-24 East Cliff 1937. Healthy beaches and large recent cliff failure that threatens the coast path (shown in circle). Source: Cliff Road Action Group (CRAG).

There are limited records from the 1940s and1950s, but a photograph from 1955 (refer to Figure 5-25) suggests beach levels were low and the upper shingle beach very narrow, at the time of this photograph. Build-up of shingle indicates that net drift was from west to east, although this may simply be indicative of the most recent conditions.

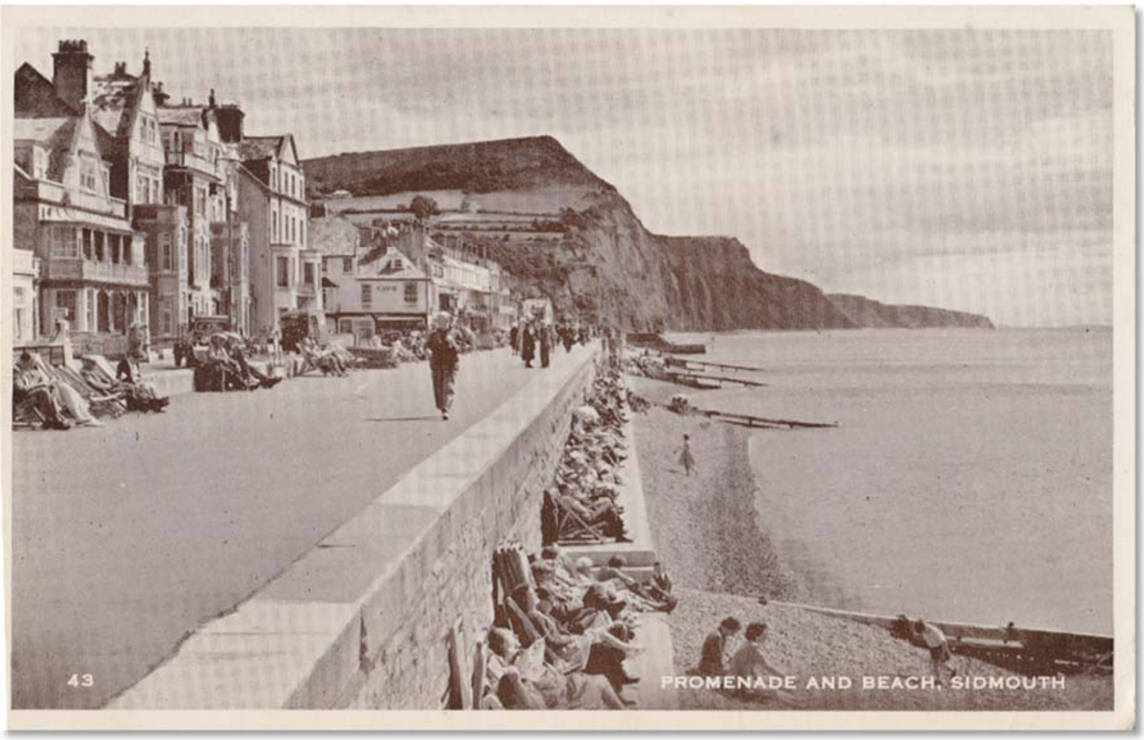


Figure 5-25 Sidmouth beach, looking east, image postmarked 1955. Source: Mary Walden.

Personal recollections of residents and photographs dating from the 1960s and 1970s suggests the decade was characterised by healthy beaches and stable cliffs. A postcard from 1966 (see Figure 5-26) and photograph of the beach in 1969 (Figure 5-27) supports these recollections and it is noted that beach levels at the eastern end of the beach between Dunnings Pier/East Pier and the training wall were high during this time. There is some evidence to suggest that the 1980s were also characterised by wider beaches (see Figure 5-28, Figure 5-29 and Figure 5-30), when again beach levels at the eastern end of the beach between Dunnings Pier/East Pier and the training wall appear to be high and the beach here is wide.

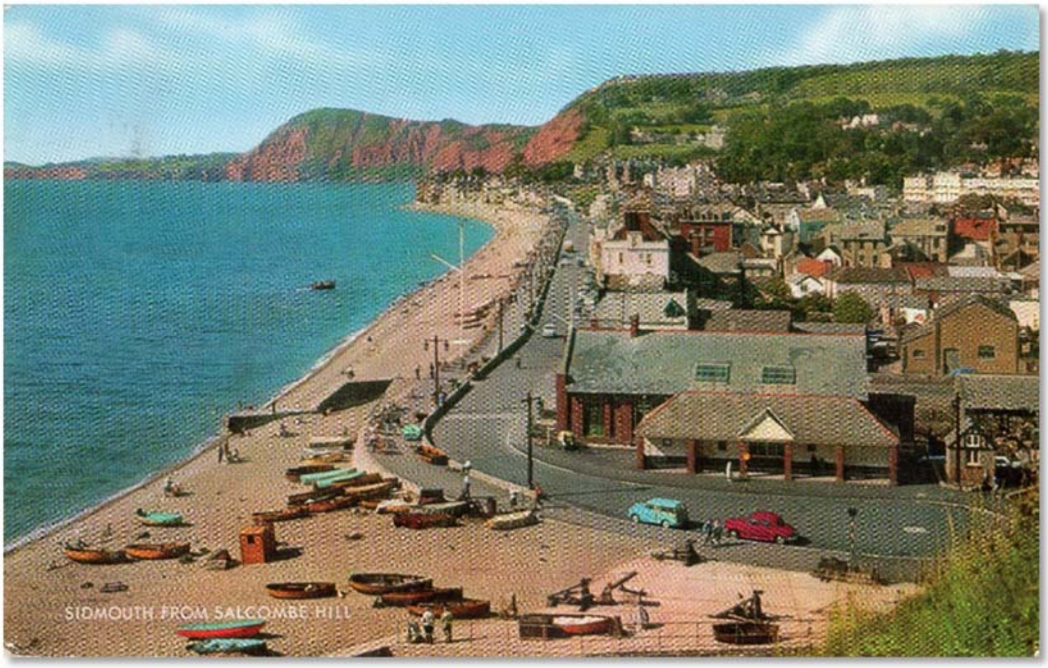


Figure 5-26 Sidmouth beach from Salcombe Hill, posted 1966. Health beach levels. Source: Mary Walden.

Figure 5-27 Sidmouth looking east in 1969, showing a wide beach and healthy beach levels at Sidmouth and East Beach. Source: Robin Bettridge.

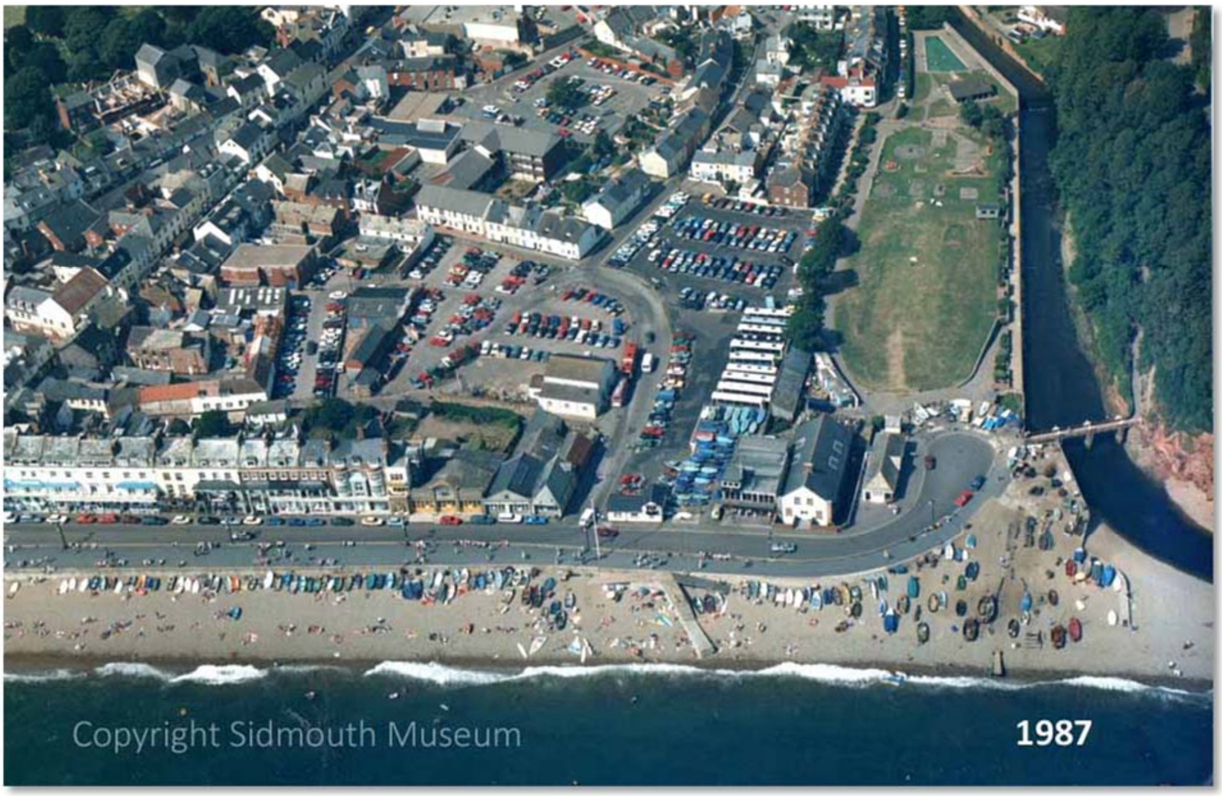


Figure 5-28 Aerial image of Sidmouth beach in 1987, showing healthy beach levels. Source: David McCluskey, Sidmouth Museum.

Figure 5-29 Photograph of Sidmouth beach, looking west, in 1983, showing a wide beach. Source: Robin Bettridge.

Figure 5-30 Photograph of East Beach, looking east, in 1983, showing wide beach and healthy beach levels. Source: Robin Bettridge.

During the early to mid-1990s, beach levels at Sidmouth dropped substantially, exposing the footings of the seawall and timber groynes once again (see Figure 5-31).

Along East Beach, photographs from 1989 and 1992 (Figure 5-32 and Figure 5-33) suggest that beaches had not suffered to the same extent as those along the Sidmouth frontage and that although talus was present at the toe of the cliffs, this was vegetated, suggesting that the beaches were preventing normal waves from reaching and removing this material. The 1992 photograph seems to show collapse of the cliff at Pennington Point and historical aerial photographs (discussed earlier in this report in Section 5.2), also provide evidence of cliff failure at the back of East Beach in the early 1990s, which would explain the presence of talus, but this may have been followed by a period of relative stability. It should be noted, however, that talus can become vegetated fairly rapidly and may therefore only indicate a year or so of stability.

A comparison can also be made between Figure 5-32 and Figure 5-24, which were taken from a similar position but 52 years apart, and suggest that between these two photographs (dating from 1937 and 1989) there had been significant retreat of the cliff top, resulting in loss of land and deposition of a large and partially-vegetated debris apron at the cliff toe.

Following this possible period of stability, the beaches along East Beach appear to have narrowed, based upon photographs dating from 2005 (for example see Figure 5-33), which show that the upper shingle beach fronting East Cliff was narrow but high, probably indicating a storm beach had recently developed.

Figure 5-31 Sidmouth beach in the early 1990s showing very low beach levels. Source: David McCluskey; Sidmouth Museum.

Figure 5-32 East Cliff, 1989. There is vegetated talus at the toe of the cliffs and a healthy fronting beach. This suggests a period of stability, which the beach being wide enough to prevent reworking of the talus by waves. Source: Cliff Road Action Group (CRAG). A comparison can be made to Figure 5.24 that shows retreat of the cliff top and formation of a debris apron at the cliff toe between 1937 and 1989.

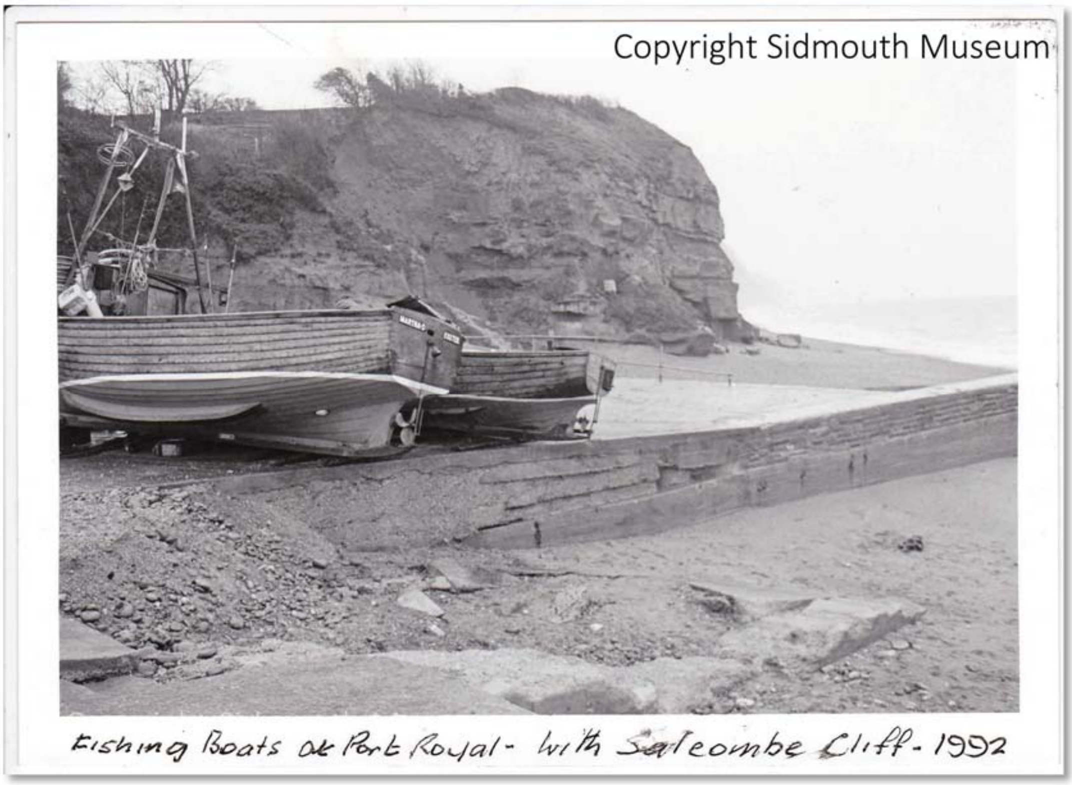


Figure 5-33 Collapse of weathered material from the upper part of Pennington Point / East Cliff in 1992. Source David McCluskey, Sidmouth Museum.

5.6.2 Key observations

Although it is difficult to make direct comparisons between the photographs presented above, because they are taken from different perspectives, at different states of the tide and each photograph only provides a snapshot of the beach and cliff condition, the information provides an interesting insight into how Sidmouth and the adjacent beaches and cliffs have looked in the past.

The photographs clearly show that beaches along this frontage are dynamic at timescales of years to decades and it is possible to distinguish a number of periods when the beach at Sidmouth has become depleted, notably the 1920s, 1950s and 1990s. Conversely, periods of full beaches can also be identified, namely, 1900s, 1940s and 1960s to 1980s. Past change shows a cycle of healthy beaches, beach depletion and beach recovery, with a period of anywhere between 20 and 40 years between. Distinguishing link between the behaviour of Sidmouth Beach and East Beach from the photographs has not been possible from this review. The causes of beach changes are also unclear from the photographs.

Anecdotal evidence and observations by local residents (Halcrow, 2014) suggests that accelerated cliff erosion at Pennington Point and East Cliff occurs during periods of low beaches, this cliff erosion is in turn threatening the integrity of Alma Bridge, River Sid Flood Defences and cliff-top properties. The review of anecdotal evidence presented here suggests that cliff erosion at Pennington Point has been ongoing at least since the earliest reliable evidence from the late 1800s. Periods of beach depletion in 1920s, 1950s and 1990s appear to correspond with when cliff failures have occurred, such as those in the 1920s, mid-1930s and 1990s. However, other large cliff failures recorded in the anecdotal records, particularly the erosion observed in the late 1800s, late 1920s, late 1980s and mid-1990s, occurred during periods of high beach level (at least along the Sidmouth frontage), suggesting that other factors, such as rainfall, may also be important in promoting cliff failure.

Figure 5-34 East Cliff beach in 2005 showing localised high gravel bank accumulated at the toe of the cliff immediately east of the Sid and very narrow upper beach further east. Source: Professor B Golding.

6 Conceptual understanding of shoreline behaviour and response

6.1 Timeline of change

A timeline of change has been produced (Table 6-1), which links both man-made and natural events to observed changes, based on the appraisal of available records, anecdotal information, historical maps, photographs, and aerial images.

Table 6-1 Contemporary change and impact on the coastline at Sidmouth.

Date	Description of Change	Impact on Coastline	Source of Information
Mid 1700s	Expansion of the town diverted the River Sid further east into a new channel cut into the sandstone bedrock that abuts the cliff. The river was in its present location by 1765 (Donn's map).	The new course of the river meant that the outflow of the river was located downdrift of the town frontage, so any fluvial inputs (albeit limited) were now deposited to the east. Expansion of the town onto the spit and associated coast protection trapped a considerable volume of beach sediment that had been temporarily stored in the spit.	Gallois (2011).
Early 1800s	Harbour development proposed in the western part of the town in 1836. Stone for construction was to be obtained from outcrops east of the town at Salcombe Regis and a narrow-gauge railway was constructed along the storm beach to transport this stone. The western-most section was constructed in a 540m tunnel excavated east of the River Sid.	The railway and harbour were never completed, but the tunnel appears to have acted as a point of weakness on the coast and contributed to several landslides along the majority of its length.	Gallois (2011).
1811	Landslide on eastern flank of Peak Hill (Jacob's Ladder Beach)	Loss of cliff top road requiring localised rerouting.	Diary of P.O. Hutchinson
April 1822	Storm event.	There is no record of the impact of this event.	Defence Assessment report.
November 1824	Catastrophic storm event.	Major erosion of Chit Rocks – proposed that this had a major impact on Sidmouth frontage.	Posford Duvivier (1998a); SCOPAC (2003).
1825 to 1826	Timber groynes and breastwork constructed along the length of the Sidmouth frontage.		Defence Assessment report.
1835	New seawall (420m) constructed Bedford Steps to the River Sid. The seawall was founded on the gravel bank and not on the bedrock.	Seawall was largely effective at protecting the town from erosion and flooding, but there was continued decline in sediment budget as beach material was either lost to long-shore drift or removed from the beach for construction purposes. Very little gravel was added by cliff recession due to the predominantly fine-grained nature of the cliffs.	Defence Assessment report.
1859	Significant storm on 25 October	Drove gravel beach inland and inundated much of the town	Diary of P.O. Hutchinson
1865	Significant storm on 23 November	Drove gravel beach inland and inundated much of the town	Diary of P.O. Hutchinson

Date	Description of Change	Impact on Coastline	Source of Information
1875	Dunnings Pier constructed at the eastern end of Sidmouth Esplanade to allow steamer access the town. It is assumed that West Pier was constructed at a similar time.	The solid construction of the pier means it will have acted as barrier to sediment transport towards the east.	Defence Assessment report. Gallois (2010)
1871	Breaches and remedial measures.	Unknown.	Gallois (2011).
1873	Breaches and remedial measures.	Unknown.	Gallois (2011).
1877	Breaches and remedial measures. 7th wettest year in SW England regional record	Unknown.	Gallois (2011). Met Office record
1878	Breaches and remedial measures.	Unknown.	Gallois (2011).
1882	3rd wettest year in SW region record		Met Office record
1887	Significant storm on 1 November	Drove gravel beach inland and inundated much of the town. High tides caused River Sid to burst its banks and flood the upper town.	Diary of P.O. Hutchinson
1903	5th wettest year in SW region record		Met Office record
1917 to 1919	Seawall between Bedford Steps and the River Sid repaired.	Unknown.	Defence Assessment report.
1918	River training wall constructed (original date of construction unknown).	Unknown.	Defence Assessment report.
1918 to late 1920s	Gravel removed from mouth of the River Sid for road construction and repairs to the seawall in 1924. The practice was discontinued in the late 1920s.	Unknown.	SCOPAC (2003)
1920 to 1921	New low level seawall constructed between West Pier (no longer exists) and Bedford Steps.	Unknown.	Defence Assessment report.
1921	Works undertaken on West Pier.	Unknown.	Defence Assessment report.
April 1922	Storm event. Dunnings Pier damaged.	Unknown.	Defence Assessment report.
1923	Storm event	Low beach levels arising from major storms in 1923 and 1924.	Posford Duvivier (1998a). SCOPAC (2003).
1924	New low level seawall extended from Bedford Steps to Dunnings Pier.	Unknown.	Defence Assessment report.
1924	Despite recognition that beach levels were low, gravel removal from the beach was still permitted and c. 300 tons were used for seawall repairs in 1924.	Unknown.	SCOPAC (2003).
October 1924	Storm event. West Pier damaged.	Low beach levels arising from major storms in 1923 and 1924.	Posford Duvivier (1998a).

Date	Description of Change	Impact on Coastline	Source of Information
			Defence Assessment report. SCOPAC (2003).
Winter of 1924/25	Significant storms caused 36.5m of seawall to collapse.	Unknown.	Defence Assessment report.
Oct 1925	Large rock fall at Pennington Point		Sidmouth Museum records
1926	6th wettest year in SW England regional record		Met Office record
1926	New seawall was constructed in 1926	Unknown.	Defence Assessment report.
1926	Dunnings Pier replaced by Port Royal Groyne, later known as East Pier.	Unknown. Suggested that this caused an interruption to alongshore drift, cutting off supply to East beach.	Defence Assessment report. Gallois (2011)
1927	Large rock fall at Pennington Point		Sidmouth Museum records
1927	Postcard shows beach levels fronting town and East Cliff remain low		Sidmouth Museum records
Oct 1928	Large rock fall at Pennington Point		Sidmouth Museum records
Feb 1930	Large rock fall at Pennington Point		Sidmouth Museum records
Aug 1937	Large rock fall midway along East Cliff that threatens the coast path		Sidmouth Museum records
1937	Postcard shows East Cliff beach is narrow, but widens towards Dunscombe Hill		Sidmouth Museum records
1950s to 1980s	A series of wooden groynes were constructed to entrain what little beach gravel remained.	A lack of up-drift sediment supply and no scheme for beach recharge meant beach levels continued to fall during this period.	Defence Assessment report.
1953 to 1957	Seawall between Bedford Steps and River Sid, timber groynes repaired.	Unknown.	Defence Assessment report.
1955	Postcard of Sidmouth shows beach is very narrow at MHW		Sidmouth Museum records
1957	New seawall and promenade (190m) constructed from Jacob's Ladder to Clifton Beach.	Unknown.	Defence Assessment report.
1960	2nd wettest year in SW region record		Met Office record
1963	Prolonged easterly storms	No information.	http://www.sidmouthherald.co.uk/news/news/sidmouth_cliff_erosion_a_sidmothian_s_views_1_461103

Date	Description of Change	Impact on Coastline	Source of Information
1989 and 1990.	Significant storms in 1989 and 1990. Storm event.	Major depletion of the beach, no recovery. Beach levels reduce further and exposed the footings of the seawall in places, which led to a localised breach. These storms also lead to the temporary disappearance of the beach fronting the East Cliffs (Frederick Sherrell Ltd, 1995), allowing waves to directly attack the cliff toe.	Frederick Sherrell Ltd (1995). Posford Duvivier (1998a). Defence Assessment report.
December 1989 / January 1990	Emergency works to seawall at Bedford Steps.	Unknown.	Defence Assessment report.
1990 to 1991	Phase I Sidmouth Coast Protection Scheme	The present seawall was constructed in 1991, but beach levels remained low.	Defence Assessment report.
1992	Storm	Further significant beach lowering.	Posford Duvivier (1998a). Defence Assessment report.
1993	Storm event. Emergency works, including construction of low level rock revetment at the foot of the seawall for approximately 400m from West Pier to York Steps and repairs to the seawall.	Unknown.	Defence Assessment report.
1994	8th wettest year in SW region record		Met Office record
Feb 1994	Cliff top collapse at Pennington Point		Sidmouth Museum record
1994	No information.	Erosion of Chit Rocks and shore platform	Defence Assessment report.
1994	**Connaught Gardens Coast Protection Scheme**	Created an additional barrier to eastwards sediment transport at Chit Rocks between the Jacob's Ladder Beach and the Town Beach. Gravel material removed from the beach for construction of the defences.	Defence Assessment report. Gallois (2011).
1995	**Phase II Sidmouth Coast Protection Scheme** In 1994 the two large rock groynes and two offshore breakwaters were constructed, and 325,000m^3 of gravel was imported to replenish the Town Beach	The rock groynes were designed to afford protection to the Sidmouth frontage from the dominant south-westerly waves and therefore limit drift towards the east. Under certain conditions, the rock groynes were ineffective at holding material between them so the beach cut back and reduced in profile in an easterly direction.	Posford Duvivier (1998a). Defence Assessment report.
1999	Wet year in local area		Met Office record
1999	**Clifton Walkway**	No information.	Defence Assessment report.
2000	4th wettest year in SW region record		Met Office record

Date	Description of Change	Impact on Coastline	Source of Information
2000	**Phase III Sidmouth Coast Protection Scheme**	Today, the seawall acts to reflect, rather than absorb, the energy of the most powerful waves, leading to draw down of the beach.	Defence Assessment report.
2002	10th wettest year in SW region record		Met Office record
2012	Wettest year in SW region record		Met Office record
2014	Severe storms in SW England from Dec 2013 to Feb 2014 9th wettest year in SW region record		Met Office record

6.2 Conceptual model of shoreline behaviour and response

Conceptual models of the coast pre and post-scheme have been developed based on a synopsis of the various data sources and are presented in Figure 6-1; this is a diagrammatic description of the following key points:

Controls and linkages

- At the large scale the configuration of this shoreline is controlled by the underlying geology. Which is defined by high coastal cliffs of predominantly of Otter Sandstone and Mercia Mudstone with localised outcrops of Upper Greensand and Clay-with-Flints. Failure of these cliffs is driven by two processes: rainfall and toe erosion through wave action.
- The legacy of how this coastline formed means that the beaches can be considered essentially relict, with very little natural supply of new sediment from the cliffs or River Sid. Construction of the town and promenade across the shingle beach, together with excavation of beach material in the past, has resulted in the local reserve of shingle being diminished further.
- The coastline is exposed to waves from the south-east, south and south-west. A review of wave height data shows that the predominant wave influence along the coastline at Sidmouth is from the south-west, and less frequent but sometimes large waves from the south-east, reflective of easterly storm conditions. This wave climate directly influences sediment transport along the coast, so that sediment transport is predominantly from west to east, however, the occurrence of south-easterly wave conditions/easterly storms has a significant influence by reversing the sediment transport direction from east to west for shorter periods of time. Tidal currents along the coast are small and not capable of moving shingle.
- Defences along the Sidmouth frontage have effectively fixed the position of the shoreline along this stretch since the 1820s and have fundamentally affected the sediment transport patterns and shoreline orientation: the early groynes and training walls would have reduced longshore transport, whilst the latest scheme is designed to specifically stabilise the recharged beaches. West and East of Sidmouth the coastlines remain undefended and there has been erosion of these cliffs over time, which has effectively advanced the line of the Sidmouth frontage and the current cliff line at Pennington Point/East Cliff has become set back from Sidmouth, resulting in a difference of 30 to 40m between the frontage of the town and the East Cliff.
- Historically the sandstone headland and rock platform of Chit Rocks has been a key control on this coastline and forms a headland separating Sidmouth from the bays to the west and east. Erosion of this feature in the early 1800s is believed to have resulted in significant erosion of the Sidmouth frontage and the construction of the esplanade at Jacob's Ladder in 1934 now fixes the shoreline at this location and has inhibited the western supply of beach shingle to the Sidmouth frontage (Gallois, 2011). There is not believed to be a significant contemporary littoral transport of shingle

across this area, and beach profile analysis supports this, on the basis of the nourished beaches not gaining significant sediment when the frontage is considered as a whole.

- Similarly, at the eastern end of the frontage an artificial barrier to transport has been created by the training wall/outfall. Storm profile data from the severe storm event in February 2014 suggests that there may be a possible leakage of sediment around this structure during storms, but there is little evidence to suggest a strong littoral connection. A training wall and outfall were in place during the 1920s, and further works were undertaken in the 1960s to lengthen both, and again in the 1990's to strengthen the training wall. The construction of a pier on the eastern side of Sidmouth (now the location of East Pier Groyne) was also believed to have interrupted longshore drift as far back as the late 18th Century (Gallois, 2011). Prior to this, shingle is likely to have passed more freely between the Sidmouth frontage and East Beach, although there is very little data to substantiate this beyond a limited number of photographs taken at different points in time.
- The design of the current scheme means that energy levels at the shoreline have been reduced, resulting in reduced sediment drift both behind the breakwaters and due to the rock groynes. Beach profile data has indicated that up to 2014, material appeared to be becoming trapped behind the breakwaters to form tombolo or salient beaches, due to waves from the south-south-west reduced by the breakwaters and therefore no longer enabling the eastwards longshore transport of material from behind the breakwaters; whilst storms from the east-south-east would continue to move material westwards. Pre-scheme modelling predicted that this accretion would occur, but not to the detriment of adjacent beaches. It was therefore recognised that the redistribution of the nourished beaches could be necessary (i.e. by beach recycling). During the 2014 storms, it appears, however, that shingle behind the breakwaters was eroded and redistributed to the eastern end of the groyne bay, between the eastern breakwater and Bedford Steps groyne.

Historical and contemporary shoreline change

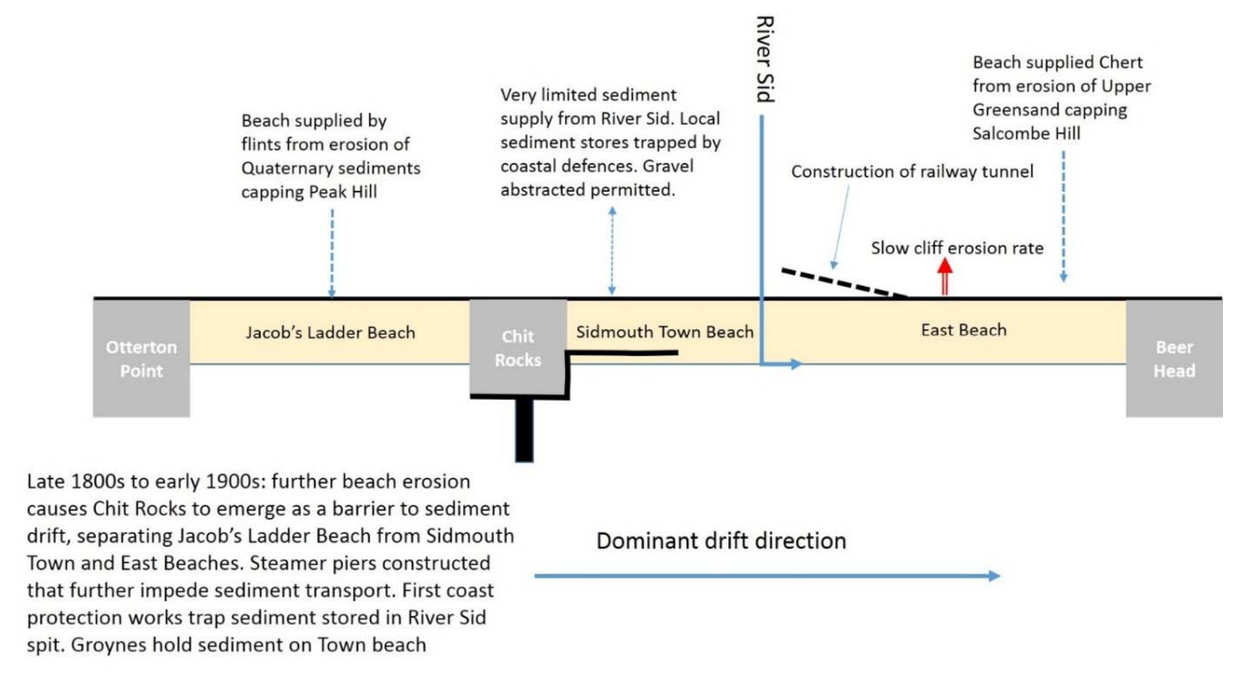
- Construction of the first defences along the River Sid sometime during the 18th century fundamentally altered the future of this frontage, through diverting the course of the river to permanently outflow along the toe of the Pennington Point cliffs.
- Subsequent construction of the promenade and seawall in the 1830s fixed the backshore position at Sidmouth, and may have advanced it slightly with defences reportedly being built on, rather than behind the gravel bank.
- Records indicate that the beaches have historically been very volatile, resulting in recorded damage to defences over time. The limited data available suggests that these periods have generally been associated with severe storms such as those between 1988 and 1990. Historical photographs also show periods when beach levels were high, followed by periods of very low beaches. Observations by made Laver (1981) over a 30 year period shows that beach levels were actually lower in the 1920s than in the 1970s. The anecdotal evidence also supports the view that beach levels in the 1920s were low, and that this period was marked by numerous cliff failures at Pennington Point and East Cliff.
- Despite the construction of defences between the 1880s and the 1990s, the beaches at Sidmouth suffered periodic depletion. From the late 1980s, beach levels and volumes steadily fell (SCOPAC, 2003) and following some of the most severe storm events in 1989/1990 (Posford Duvivier, 2001) the beach suffered from severe beach drawdown and loss of sediment to offshore sinks (SCOPAC, 2003). This led to the construction of the Sidmouth Coastal Defence Scheme in the mid-1990s to 2000, which was designed to reduce levels of wave energy reaching the beach face and to minimise reflective wave scour from the seawall fronting the low-lying area of Sidmouth (SCOPAC, 2003).
- Since construction of the defence scheme at Sidmouth and nourishment of the beach, the beach monitoring data shows that sediment appears to be redistributed within the frontage, with shingle from groyned sections tending to be moved and retained behind the rock reefs. The first Five Year Monitoring Programme (2000 to 2005) found there to be gains in the order of 4,000 to 5,000m^3 in the lee of the detached rock breakwaters and losses in the region of 5,000 to 6,000m^3 between the

three rock groynes; suggesting, when considered as a whole frontage, there had been no net loss or gain, with a net east to west movement of material. A similar pattern of net shingle redistribution had been indicated by the more recent data (between 2002 and 2012, prior to the 2014 storm (PCO, 2010) and is illustrated in Section 5, Figure 5-6.

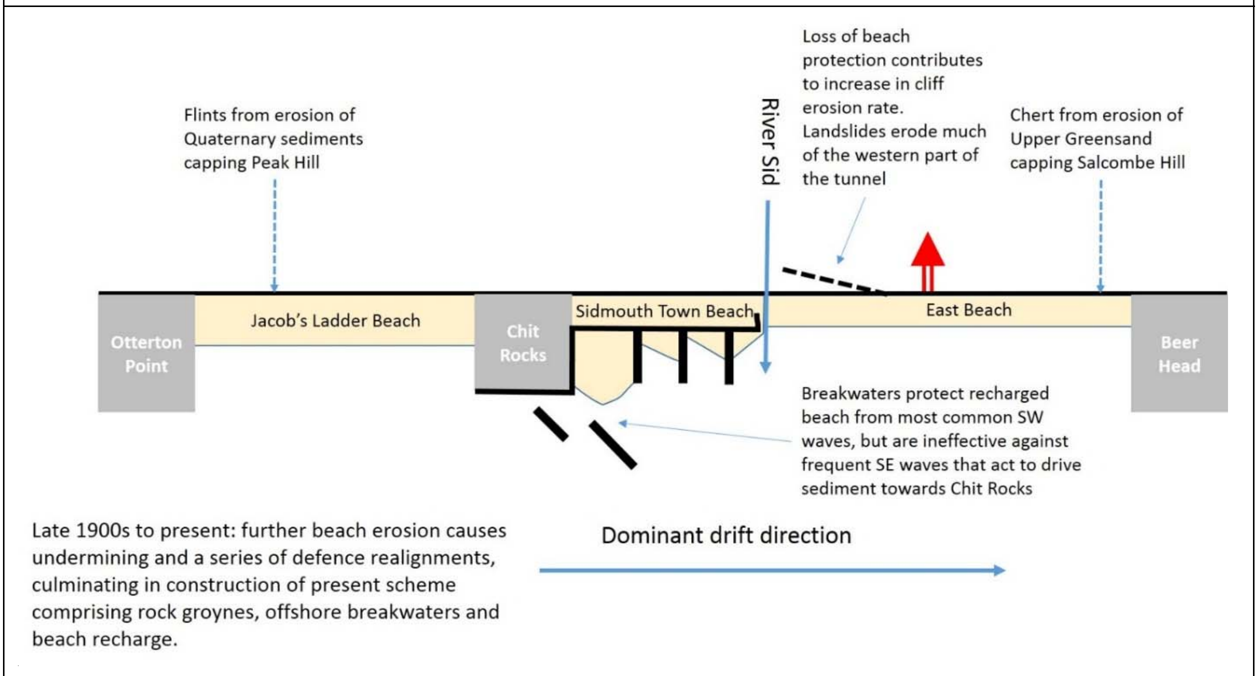
- More recent data, covering the period 2007 to present also shows that there has been a tendency for material to accrete in the lee of the breakwaters, but that the rate of this accretion over the period 2007 to 2012 was much less than previously. The profile data also indicates that shingle within the groyne bays tends to be moved back and forth between the groynes, although the net movement over the period considered was easterly, based on the net losses from the Bedford Steps groyne to York Steps groyne bay.
- Up to the 2014 storms, data suggested that once sediment ended up in the lee of the breakwaters it became trapped and was not returned eastwards under usual south-westerly conditions. However, the 2014 storms (discussed below) resulted in the erosion and redistribution of some of the material held behind the breakwaters. Future monitoring data will reveal the subsequent recovery of the beaches, but it is suspected that material will start to build behind the breakwaters over the next few years.
- A crude estimate of beach volumes, based on interpolating cross-sectional areas derived from the beach profile data, indicates that there appears to have been a net loss of sediment from the Sidmouth frontage, compared to the design profiles. Using data from July 2014, PCO have calculated that there has been a possible loss of around 63,000m^3. In comparison, a similar calculation undertaken using the 2007-2012 datasets suggested a loss of around 39,000m^3, using the design beach volume calculated by PCO. However, when compared to the beach data for 2007, the net change from 2007 to 2012 was negligible, and change in volumes between the two dates tended to be less than 10% of the volume along the frontage. However, these values should be used with caution for a number of reasons:
    - the available data does not allow any assessment of whether the changes relate to sand or shingle;
    - the method of determining volumes is fairly crude due to the availability of data and the distribution of profile locations; these means that the volume analysis poorly replicates the movement of material from one end of the bay to the other. To gain a more accurate understanding of future beach volumes and changes, either a Grid-based GPS survey or LiDAR data would provide better coverage of the beach; and
    - uncertainty regarding the placed beach volumes compared to the design beach volumes – records indicate that the quantity of beach material imported onto the Phase 2 scheme frontage during the course of the works was, in the event, less than the design requirement as determined by the physical model. The deficit was largely contained within the York Groyne to Bedford steps frontage - which is also the area which has tended to experience net losses over time.
- Historically the Sidmouth frontage and adjoining frontages have been susceptible to storms, with shingle becoming stripped from the beaches, leading to exposure and damage to defence structures. Storm analysis of beach behaviour indicates that the beaches remain vulnerable to storms, with material becoming redistributed within the groyne bays, depending upon the prevailing wave directions during this storm. This tends to result in material becoming stripped from one end of the bay and being moved alongshore. Analysis of post-storm profiles show that the beaches within the BMP extent do recover after storms and have even at some locations reached their highest recorded levels.
- Particularly severe storms were experienced in February 2014; the largest since the scheme was constructed. Data collected by PCO shows that during this storms there was significant redistribution of sediment across the frontage, with erosion of the beach behind the breakwaters; an area which previous monitoring indicated as a net store of sediment. The data also suggests that sediment

bypassing of the groynes may have occurred, indicated by beach accretion along the length of the groynes (although it is not possible to define whether this is sand or shingle). Through this mechanism material may be able to pass between groyne bays.

- To the east of Sidmouth, cliff recession events in the form of blocky rockfalls and muddy collapses from the upper cliff have occurred throughout the historical period. The anecdotal evidence suggests failures have been particularly common at Pennington Point, which is probably due its exposed position and the weaker materials exposed here. Pennington Point forms a cross section through the eastern valley side slope of the River Sid and consequently the materials exposed comprise a greater thickness of colluvium and a greater depth of weathering to than seen elsewhere along the coast.
- Based on anecdotal evidence and analysis of aerial photography, it is evident that cliff recession along East Beach over the last c.100 years is driven by two independent factors: (1) low beach levels, which allow toe erosion and undercutting of the lower cliff, and (2) higher than average rainfall, which weakens slope materials and promotes collapse of the upper cliff irrespective the beach condition. The cliffs have a history of episodic landsliding, but there is very limited data documenting the frequency or location of such events, particularly in the historical record. Many of the failures experienced in recent years have involved collapse of the cliff top, to form deep embayments in the gardens of properties along Cliff Road.
- Beach levels along this East Beach frontage have tended to fluctuate both historically and since the scheme has been introduced. Beach profile data for the frontage shows that in general this level fluctuates by up to a metre – but, unlike elsewhere, changes do not appear to be seasonal. During the February 2014 storms, the data indicates that the beach was particularly affected with erosion of the cliffs and drawdown of material to form a shingle-sand bank around the MLWS mark, along the training wall of the River Sid. Development of a storm ridge along beach to the east, suggests that some of the sediment removed from Pennington Point/East Cliff may also have been transported further east.
- Meteorological data shows that high rainfall years have become more common in recent years. The top 5 wettest years since 1873 have occurred in the last 20 years. High rainfall is a known contributor to cliff instability, particularly in weak materials such as the weathered Mercia Mudstone, Clay-with-Flints and colluvium that forms the upper part of the cliffs along much of the Sidmouth frontage. Large cliff falls at Pennington Point and East Cliff occurred in the mid-1920s and mid-1990s, which were exceptionally wet periods for the region.
- Along the beaches to the west of the Sidmouth frontage, cliff recession does not appear to relate to beach volumes, but instead the rapid change between 1890 and 1938 is associated with exceptionally wet years in 1882, 1903 and 1926, and the change indicated from 2006 onwards is associated with exceptionally wet years in 2002, 2012 and 2014.



Initiation of first defences in response to declining sediment budget, around 100 years ago.



Additional defences in response to recent storms and on-going declining sediment budget

Figure 6-1 Contemporary conceptual evolutionary model for the coastline between Otter Ledge and Beer Head.

6.3 Causes of increased cliff recession at East Beach

6.3.1 Introduction

A key concern from local residents has been the perceived acceleration in cliff recession at the western end of East Beach since construction of the defence scheme, which has been particular evident due to a number of cliff falls in recent years.

Previous estimates of cliff recession along this frontage have varied widely: from 0.03m/year (Gallois, 2011) to 2.3m/year. These variations can be attributed to use of different epochs of historical data, different locations of measurement or classification of cliff behaviour units and errors in the primary data. The landslide potential of these cliffs also means that spot measurements are not necessarily indicative of the whole cliff frontage.

Section 5.3 discusses the new analysis of cliff recession; for East Cliff the data indicates that when the entire frontage is considered the cliff experienced a phase of relatively more rapid recession from 1890s to 1950, limited change from 1950 to 2006, and more rapid recession thereafter. There has, however, been more rapid recession experienced at the western end of East Beach within 250m of the River Sid, with an average rate of 1.5m/year derived for the period 2006 to 2015, compared to 0.25m/year along the eastern end.

The cliffs have a history of landsliding that occurs either as collapse of the upper cliff, in response to intense and/or sustained rainfall, and/or through failure of the lower cliff by undercutting from wave attack. It is not possible to determine the frequency of large landslides as there are limited data but their contribution to the total amount of cliff recession is captured in the analysis. The beach profile data discussed in Section 5.5, indicates that the beaches here, like those to the west, are highly mobile and susceptible to beach loss during storm events; this leaves the cliff toe vulnerable to wave attack.

It should be noted, however, that the overall pattern of cliff recession along the coast has not changed since the late 19th Century. Over this time a generally linear cliff top with localised indentations from landslides has been a persistent form. However, the combination of recession of East Cliff and the fixed frontage of Sidmouth have had significant implications to sediment transport.

6.3.2 Possible causes of accelerated erosion

There are several possible explanations for the recent increase that appears to be occurring at the western end of East Beach:

- Downdrift erosion as a direct consequence of the defences at Sidmouth. This could be the result of the defences cutting off supply of sediment to East Beach, and/or the diffraction of waves around the end of the defended frontage. Both these impacts could potentially result in beach loss and cliff erosion.
- Impact of the remaining section of the former railway tunnel which was excavated parallel to the cliff toe in the 19th century.
- The location of natural geological fault lines in the cliff.
- Natural changes, such as changes in rainfall or reduction of sediment supply from the east.

6.3.2.1 Downdrift impact of defences

It is possible that the accelerated cliff recession at East Cliff directly results as a down-drift impact of the defences of the town (Brown et al., 2012). The so called ‘terminal groyne effect’ causes an interruption to sediment transport, leading to depletion of down-drift beaches and accelerated cliff erosion to form a characteristic set-back in the cliff edge. Such phenomena are widespread around the UK coastline, with notable examples at Lyme Regis, on the Holderness coast of East Yorkshire and at Barton-on-Sea in Hampshire. Under such circumstances and assuming that sediment transport is predominately in one direction, erosion of the beach and subsequent erosion of the cliffs would begin to form a bay shape. Where coastlines are exposed to a single predominant wave direction, it is possible for the coastline to retreat to a position in equilibrium with the incoming waves, known as a ‘stable bay’ or ‘zeta-form’ bay. In theory, a stable bay is formed when the beach and coastline becomes adjusted to the prevailing pattern of waves diffracted around a fixed point (i.e. a hard rock headland or fixed coastal defence structure). The sediment demand of the beach is met by local cliff erosion that ultimately forms the characteristic zeta bay shape.

Prior to any defences along the Sidmouth frontage, there would have been a continuous shingle barrier stretching along this coastline, linking East Beach to Sidmouth and the cliffed frontages further west. Based on the predominant wave directions along this frontage, it is likely that the relatively finite volume of shingle would have been moved periodically both eastwards and westwards, as observed currently within the groyne bays along Sidmouth frontage.

The earliest known interventions along this coast was the diversion of the River Sid in the 1700s. The implications of this are not known, but potentially flows within the River were increased by the throttling effect on the channel this would have caused, enabling the river to form more of a barrier to transport. The key change to the coastal landscape resulted from construction of defences along the Sidmouth barrier and at the western end of the frontage, which are believed to have effectively interrupted any potential shingle linkages from west of Chit Rocks (i.e. Jacob's Ladder Beach) to the Sidmouth town frontage. Further works to entrain the River Sid are likely to have had a similar impact at the eastern end of Sidmouth. Although historical photos indicate a beach extended across the end of the training wall in the past to link Sidmouth Beach and East Beach (pre-1989), in the present day bypassing of these structures may now only be possible during storm events, but during normal conditions it is not believed that shingle is able to move outside of the Sidmouth frontage to East Beach.

Defences along this frontage in the 1990's have therefore contributed to 'locking down' sediment within the Sidmouth frontage. However, the bi-directional transport of shingle along this frontage, means that the impact on adjacent beaches is not as severe as would occur on a coast exposed to a single predominant wave direction.

The Sidmouth Coastal Protection Scheme constructed in the 1990's involved nourishment of the beaches and was built at a time of very low beach levels, therefore it is unlikely that any naturally transported sediment that would have otherwise reached East Beach has been locked up within the Sidmouth frontage. Crude estimates of beach volume changes for Sidmouth suggest that although sediment moves within the frontage and the frontage experiences periods of low beaches and full beaches, the system appears to remain in relative balance. There is no evidence of significant gains in sediment, which would be expected if the frontage was retaining any additional supply from either the west, or from East Beach to the east.

Interpretation of aerial photographs and analysis of cliff recession data provides no indication that a curved bay is forming, instead a linear setback of the cliffs has been observed.

6.3.2.2 Impact of the former railway tunnel/ location of natural geological fault

The impact of a tunnel excavated parallel to the cliff toe of CBU 7 in the 19th Century (Gallois, 2011) and of geological faults in the cliff have been the subject of a detailed assessment by Frederick Sherrell Ltd (1995). The precise location of the tunnel as originally constructed and the location of any remaining sections are unclear and can only be inferred from a sketch map in Frederick Sherrell Ltd (1995) and descriptions in Gallois (2011). However, the c.250m running east from Pennington Point were lost by 1995, and probably as early as the 1950s (Gallois, 2011) (Figure 5-2).

Geological logging indicated that the location of many of the landslide embayments in this western section of CBU 7 were associated with the presence of geological faults that are orientated between approximately N-S and NW-SE. The information on faults and tunnel remnants have been superimposed on the aerial photograph and cliff recession data (Figure 6-2), which highlights several clear relationships:

- the embayment at transect 30 (Pennington Point) relates to mapped Fault 1;
- the embayment at transect 31 relates to mapped Fault 2;
- the embayment at transect 311 relates to mapped Fault 3;
- the embayment at transect 32 relates to mapped Fault 4, but may also be coincident with a section of tunnel that was revealed by a landslide in 2010 (Gallois 2011); and
- the embayment between transects 33 and 331, which appears to have widened towards the east, is coincident with the western limit of the tunnel.

As the majority of the tunnel in the western 250m of East Cliff had been eroded by the 1950s the rapid cliff recession of Pennington Point and East Cliff experienced in the last c.25 years is unrelated. However, rapid retreat east of transect 33, associated with an eastwards-widening embayment does appear to be associated with the entrance to the remaining section of the tunnel, suggesting it does have a localised impact that can be expected to progress towards the west.

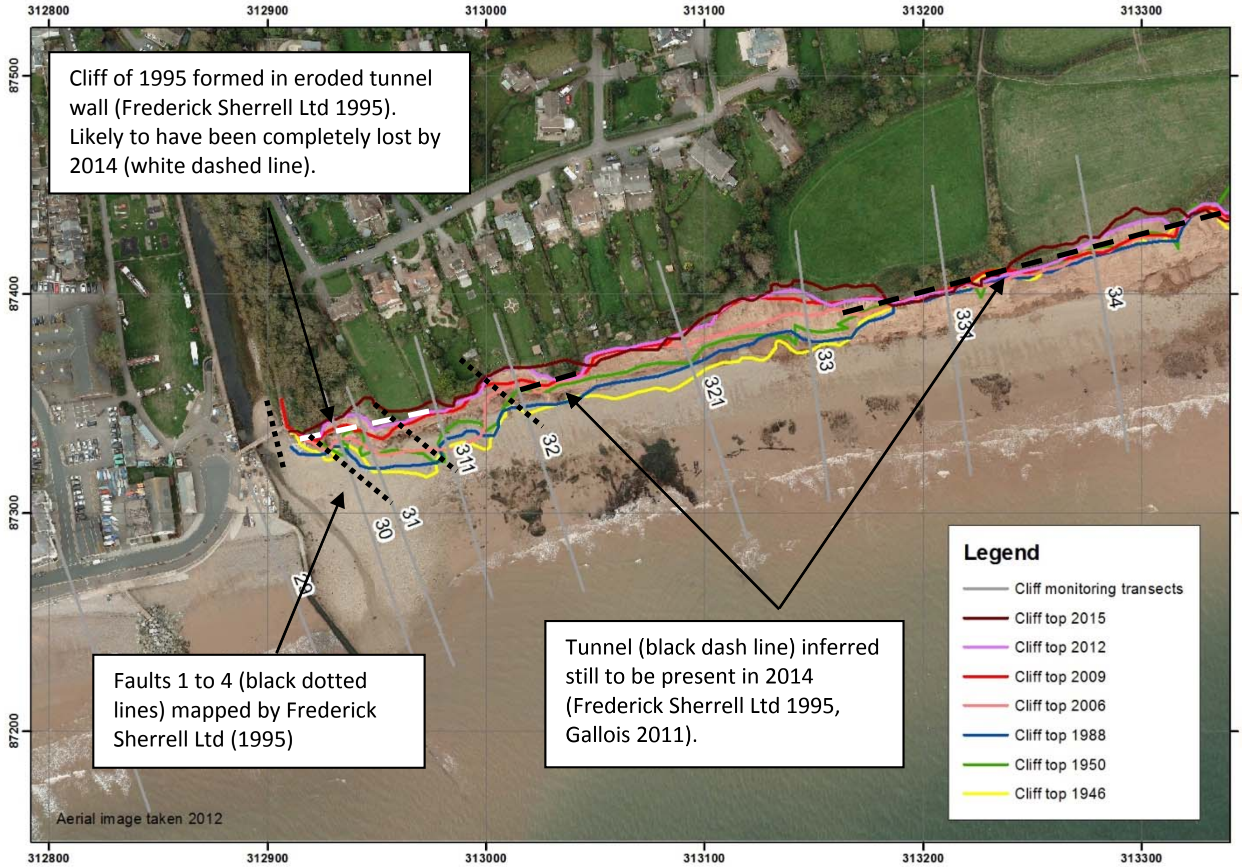


Figure 6-2 Cliff positions at East Cliff determined from aerial photos

6.3.2.3 Changes in rainfall

While the precise dates of all cliff failures along East Cliff are unclear, the 2012 and 2015 aerial images show there has been widespread and significant activity in this period. 2012 was the wettest year on record in the southwest region and 2014 was also extremely wet. The winter of 2013/14 was also exceptionally stormy. The fact that all periods of higher cliff recession do not coincide with periods of high rainfall supports the view that cliff failure is caused by a range of factors. Cliff failures in 'dry' years are likely to be triggered by toe erosion, particularly at a time of low beach levels. Consequently it is likely that high levels of rainfall and storminess have a significant impact on cliff stability.

6.3.2.4 Reduction in sediment supply from the east

Beach profile data for East Beach indicates beach levels here have fluctuated over the last few years (since 2007), and this is also evident in the historical record. This is likely to be in response to changes in net drift direction and the varying directions of any storm events. Data following the 2014 storms indicates sediment accretion and the development of beach ridges further east, which may have been supplied through erosion and subsequent transport of shingle from East Beach. Therefore it appears that the behaviour of East Beach may be dependent on linkages with beaches to the east, a conclusion that is supported by the sediment pathways assessment provided in Section 4.3.1. Small landslides periodically occur, which could have short term impact on sediment supply, but those formed in Mercia mudstones will be rapidly reworked, i.e. within a year; beach profile data indicate a small fall at East Beach had been removed within 8 months. In contrast, the large landslide at Dunscombe Cliff, further east, is formed in Greensand and therefore is more persistent and could be having a longer term impact on sediment supply to East Beach. There is, however currently a healthy beach between Pennington Point and Dunscombe Cliff, but material appears to be moved within this 'bay', with little or no replacement sediment arriving from Sidmouth (as has been the case since construction of defences along the River Sid), thereby under south-westerly conditions, beaches at East Beach will become periodically depleted, as observed in the data available.

6.3.3 Conclusions

Based on the data and reports presented here, it is not possible to definitively state that beach depletion and accelerated cliff recession are a direct result of coastal engineering at Sidmouth. However, it is evident that defences along this frontage (dating back to the 1700s) have fundamentally changed the evolution of this shoreline and altered its ability to respond to erosion. Evidence suggests that prior to the construction of the Sidmouth scheme in the 1990s, linkages between East Beach and Sidmouth were already diminished by a combination of the existing defences, in particular the River Sid training wall, and low-beach levels along the frontage that occurred following the 1989 storms (pre-1989 there is evidence of linkage when beach levels are elevated). Post scheme beach profile data for Sidmouth do not suggest that, when considered as a whole, the Sidmouth frontage is retaining any additional sediment further supporting this lack of current linkage. In addition, this coastline is characterised by two dominant wave directions, meaning that sediment transport is not uni-directional, so the beach at East Beach (even without defences in place) would rely on sediment feed from both east and west. Aerial photograph evidence showing the pattern of cliff recession at East Cliff also indicates retreat of a linear cliff top rather than progressive development of an embayment.

Cliff behaviour at East Cliff appears to be very strongly controlled by faults and the progressive erosion of the tunnel, which act as a lines of weakness or as a focus of groundwater flow, rainfall and beach levels. The faults and tunnel features control localised groundwater flows that can promote cliff top failures associated with peak rainfall events, and act as zones for preferential toe erosion if the beach levels is sufficiently low to allow wave erosion of the cliff toe.

Intense rainfall events have been clustered in the last 20 or so years, and while beach levels have fluctuated over the last 150 years, they have been persistently low over the last decade. Together, these factors have provided the necessary conditions for accelerated erosion.

The recent failures of the cliff top are therefore likely to have been triggered by periods of extreme weather. Intense rainfall causes saturation of the weak and unconsolidated upper cliff materials causing them to collapse, sometimes triggering joint-controlled failure of the basal mudstone. This has led to particularly rapid erosion at Pennington Point, which is for the most part characterised by particularly weak valley fill sediments that are particularly susceptible to failure through saturation. Storms, in combination with low beach levels, have caused rapid toe erosion, promoting block failure.

7 Projections of future change

7.1 Climate change and sea-level rise

Climate model projections suggest that the global average rate of sea level rise will increase in the 21st Century. A general assumption is that any increase in mean sea level is likely to cause an equal increase in all other water levels, including extreme water levels.

The latest advice from the Environment Agency is that beach management should take account of a ‘change’ factor covering the whole of the decision lifetime (see ‘Advice for Flood and Coastal Erosion Risk Management Authorities’, Environment Agency, 2011b). The change factor is defined as follows:

“The change factors quantify the potential change (as either mm or percentage increase depending on the variable) to the baseline. It is recommended that option are developed planning for the change factor covering the whole of the decision lifetime. However, rather than base options solely on the change factor the upper and lower end estimates can be used to refine the options to prepare for a rider range of future change.”

The guidance suggests that predictions of the future rate of sea level rise for the UK coastline should be taken from UKCP09 (Defra, 2009). Data downloaded from UKCP09 provides projections of sea level rise from 1990 for various scenarios and the Environment Agency advice is for coastal defence planning to use the upper end (95%) of the medium emissions scenario from UKCP09 as the ‘change’ factor. This is, however, advice, rather than a mandatory requirement. They also recommend that a range of sea level rise is be considered, not just the change factor, and define “lower end”, “upper end” and an extreme “H++” scenario.

Anticipated rates of relative sea level rise and surge estimates over three time periods for Sidmouth are presented in Table 7-1 for the following scenarios:

- Lower End Estimate: this is the low emissions scenario, 50% frequency, taken from the UKCP09 User Interface.
- Change Factor: this is the medium emissions scenario, 95% frequency, taken from the UKCP09 User Interface.
- Upper End Estimate: these are generic values of sea level rise provided in the climate change guidance; they are 4mm (up to 2025), 7mm (2026 to 2050), 11mm (2051 to 2080), and 15mm (2081 to 2115).
- H++ Scenario: these are generic values of sea level rise provided in the climate change guidance; they are 6mm (up to 2025), 12.5mm (2026 to 2050), 24mm (2051 to 2080), and 33mm (2081 to 2115).
- Upper End Estimate + Surge Estimate: This is the upper end estimate plus the upper end surge estimate. The surge estimate are generic values provided in the climate change guidance; they are 20cm (up to the year 2020s), 35cm (up to the year 2050s), and 70cm (up to the year 2080s). With regard to the surge increase, the uncertainty with surge increase is even greater than for sea level rise.

Table 7-1 Relative sea level rise estimates for Sidmouth.

Time Period	Various estimates of relative sea level rise and surge (m increase over time period)					
	Low Estimate 50%ile	Change Factor	Upper End	Upper End + Surge	Surge for Upper End	H++
2014 to 2025	0.04	0.04	0.06	0.26	0.20	0.08
2014 to 2055	0.15	0.17	0.29	0.64	0.35	0.52
2014 to 2105	0.42	0.49	0.94	1.64	0.70	1.94

7.2 Predictions of future cliff evolution

Assuming current coastal management continues, future coastal recession will continue, as a result of toe erosion, which occurs during most high tides with the currently depleted beach, and rainfall-driven failures of the upper cliff. The rate of annual erosion, and the magnitude and frequency of landsliding are likely to be increased by the forecast impacts of climate change, which include an acceleration in the rate of sea-level rise and increased levels of winter rainfall.

The precise relationship between climate change and coastal erosion is unclear, but increasing rates in the historical record by a factor of 10% used to approximate these effects. The Bruun rule is often used to model the impact of sea-level rise on shore profiles, but this approach is not appropriate for use on cliffs that fail through a complex series of process not exclusively driven by marine processes, or where there is limited sediment to maintain an equilibrium shoreline profile.

The inputs to the cliff recession projection are as follows:

- A long-term cliff recession rate that is deemed to be representative of the current environmental conditions (i.e. taking account of contemporary coastal engineering and sediment budget). This is typically the long-term rate of headscarp recession derived from aerial imagery. To account for the forecast impacts of climate change, this recession rate is increased by 10%. At East Cliff, where the cliff recession rate is influenced by beach level, the long-term erosion rate disguises periods of rapid loss associated with low beaches that have been seen in recent years. Therefore, the total projected erosion will not occur equally over each of the next 100 years, and rapid cliff retreat seen recently may continue for several years before a lower rate is experienced.
- An additional component to allow for random landslide events is included. While the effect of episodic events is included in the long-term cliff recession rate, an additional component has been added to account for gaps in historical record and uncertainty over the frequency of future landslides under projected sea-level rise and increased winter rainfall. This figure is judgement-based and is underpinned by the data on the size of past landslide events in each CBU.

A 100 year projection is presented in Table 7-2 for a lower estimate, which is simply a projection of the historical rates factored up by 10% to account for climate change, and an upper rate which includes additional headscarp recession based on the historical magnitude and frequency. The values presented are shown plotted in Figures 7-1 and 7-2 for East Cliff and Peak Hill respectively.

Table 7-2 Cliff recession projections for 100 years.

CBU	Assumed cliff recession rate	Additional headscarp recession	Lower Estimate Headscarp Recession	Upper Estimate Headscarp Recession
1	0.154	5	15.4	20.4
2	0.055	5	5.5	10.5
3	0.231	5	23.1	28.1
4	0.165	5	16.5	21.5
7	0.209	10	20.9	30.9
8	0.165	10	16.5	26.5

In all cases, the projections show the cumulative impact 100 years erosion and no attempt has been made to determine annual cliff losses or erosion rates. The actual erosion experienced in a given year is determined by the level of the beach, which is itself determined by the direction of waves that determines net drift direction; the timing, intensity and frequency of storms; and the amount of rainfall, none of which can be confidently predicted. Due to the current low beach levels, it is likely that the high rates of erosion seen in recent years will continue for several years, but that erosion will reduce in the near future once sediment has drifted back towards the west and a beach has accumulated.

The timing of a future reduction in cliff recession rate is uncertain, but several feedback mechanisms dictate that a continuation of a high rate of cliff recession for 100 years is not credible. Consistent accelerated erosion along a short section of coast would lead to formation of a set-back section of the cliff line where the cliff would become progressively further away from breaking waves causing erosion to reduce. Furthermore, a set-back section of coast would allow a pocket beach to accumulate, which would absorb wave energy and reduce erosion.

Figure 7-1 Cliff recession projection for 100 years at East Cliff. Note the projection is made from the 2015 cliff top, but are overlain on the 2012 image.

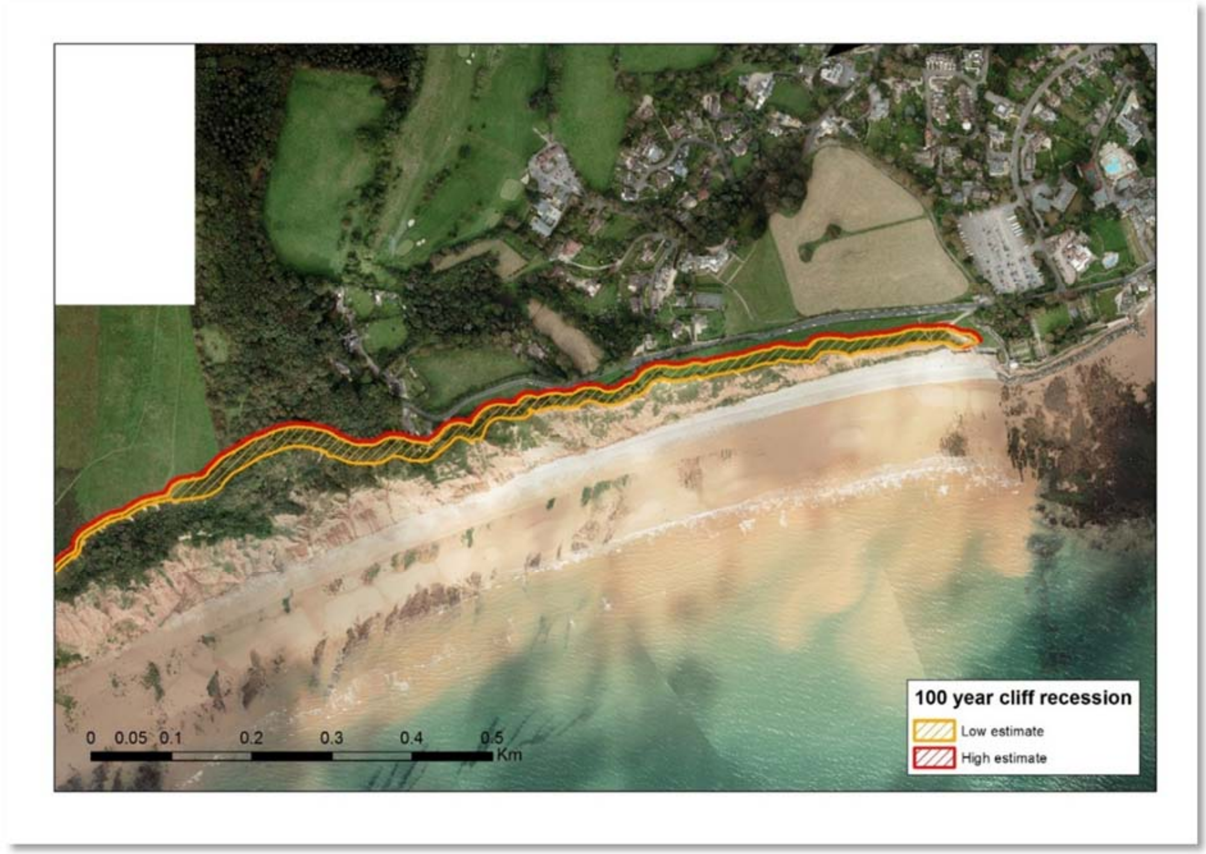


Figure 7-2 Cliff recession projection for 100 years at Peak Hill mapped. Note the projection is made from the 2012 cliff top and overlain on the 2012 image.

A review of the erosion rates predicted by the SMP2 (Halcrow, 2011), refer to Table 7-3, shows that they compare well with the cliff recession rates predicted for the present study.

Table 7-3 Comparison of predictions of shoreline change for a No Active Intervention scenario from the SMP2 and cliff recession rates estimated for the present study (in bold text).

Location	Short Term (to 2025)	Medium Term (to 2055)	Long Term (to 2105)
Beer Head to Salcombe Hill (West)	Total erosion in this area is predicted to be 5-6m by 2025.	Total erosion in this area is predicted to be 14-18m by 2055.	Total erosion in this area is predicted to be 29-53m by 2105.
CBU 8 (cliffs of Salcombe Hill)	-	-	**Total recession 100 years: 16.5 to 26.5m**
CBU 7 (cliffs immediately east of the River Sid)	-	-	**Total recession 100 years: 20.9 to 30.9m**
Sidmouth	No rates provided.	No rates provided.	No rates provided.
CBU6 and 5 (Chit Rocks and Sidmouth)	**n/a** **This coastline has been defended over the period covered by historical data.**	**n/a** **This coastline has been defended over the period covered by historical data.**	**n/a** **This coastline has been defended over the period covered by historical data.**
Chit Rocks to Big Picket Rock	Total erosion of 3-5m predicted by 2025 (SCOPAC, 2004).	Total erosion of 9-11m predicted by 2055 (SCOPAC, 2004).	Total erosion of 19-29m predicted by 2105 (SCOPAC, 2004).
CBU4 (eastern part of Jacob's Ladder Beach)	-	-	**Total recession 100 years: 16.5 to 21.5m**

8 Uncertainties and Recommendations

8.1 Uncertainty

The key uncertainties and limitations to our understanding of the behaviour of the coastline at Sidmouth include:

- The current monitoring of beach levels does not provide a good basis by which to assess volume changes, due to the distribution of profiles and the response of the beach, which is not very well replicated by interpolation of adjacent profile lines.
- Work completed by PCO for EDDC shows the design volume to MLWS (-2mOD) to be 182,062m^3. However, this is based on a relatively crude volume calculation, which does not account for the recorded difference in placed beaches compared to the design beaches. This means it is very difficult to assess the long term success of the scheme.
- The sediment pathway between the nearshore and offshore remains uncertain, particularly how much and where sediment may be being stored in the nearshore/offshore zone. More detailed and regular bathymetry surveys supported by sediment sampling would help to clarify this matter.
- Based on previous analysis, assumptions have been made regarding the transport of shingle across the River Sid, which are assumed to be small, in terms of shingle. A better understanding of this potential linkage would add confidence to the arguments presented in this report.
- The sediment links along the frontage from East Beach to Beer Head and potential interruption of sediment supply by periodic landslides. It would be useful to have beach monitoring data to improve understanding of the links between beach behaviour and response at East Beach and beaches further east.

8.2 Recommendations

The following recommendations are made for consideration in future management of the BMP frontage:

- To improve estimates of volume changes and sediment redistribution along the Sidmouth frontage, a recommended alternative to surveying linear beach profiles would be to undertake laser surveys or spot height surveys of the beach (possibly using quad bikes), the data from which could be used to produce DTMs. Difference plots generated from the DTM's could be used to identify precisely the location of areas of erosion and accretion. It is recommended that to make the best use of this data, regular surveys are undertaken, such as six-monthly. This data should also be extended to include East Beach and Jacob's Ladder Beach east, to improve understanding of sediment linkages.
- As a minimum, on-going analysis of PCO beach profile data is recommended following each new survey. This will, over time, provide a longer data set from which to determine trends in beach behaviour. At present, PCO monitor six profiles within the BMP extent as part of their annual summer survey. Increasing the number of profiles would provide an increased dataset to make more accurate assessments of beach profile change, CSA and volumes. It is recommended that additional beach profiles be located/surveyed to the western and eastern extents of the groyne bays.
- PCO undertake post-storm surveys of the beach at Sidmouth, however the same profile is not always surveyed after the storm. It is recommended that for consistency and to improve comparison between surveys, that the same locations are surveyed each time.
- Regular bathymetry surveys would help to improve the understanding of what is happening to material drawn down from the beach. Difference plots generated from surveys undertaken at difference time periods would provide an overview of areas of erosion/accretion. This would be further supported by regular seabed and beach sediment sampling and analysis.
- The findings of this report suggests that there is a strong link between reduced rates of beach accretion at Pennington Point/East Beach and the influence of the River Sid training wall and the

SWW outfall on the movement of material across the mouth of the River Sid. It is highly recommended that this is investigated in more detail with an in depth study completed to assess whether relocating or removing part of/all the River Sid training wall and the South West Water outfall will help to increase the volume of the beach at the mouth of the River Sid. Such as study would benefit from field-measurement of nearshore currents to inform analysis.

- It is recommended that high quality aerial photo/LiDAR surveys – similar to those collected in recent years – are continued on a regular basis (every 2 to 4 years) and that when undertaken, the survey specification should state the need to achieve a RMSE of better than +/-10cm.
- Furthermore, it is recommended that the East Cliff area be monitoring using dGPS surveys. This may comprise survey of the whole cliff edge position (if safe to do so), or setting up an inland datum and surveying distance to cliff edge. In both cases, a six-monthly survey is recommended.

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Appendix A – Review of Anecdotal Records

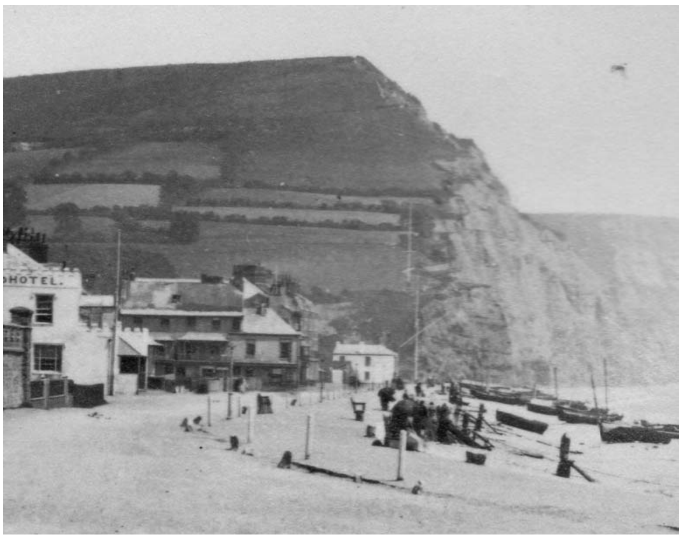
A review of the anecdotal evidence, in the form of photography, postcards and locals' recollections has allowed the state of the beach and cliffs over much of the 20th Century to be documented. While the records are patchy and many are undated, a pattern of change in the beach and cliffs can be documented that supplements the aerial photography and historical mapping database. The anecdotal records are summarised in Table A1 below. Where anecdotal evidence is in the form of a picture and has a known date, it has been included at the end of the appendix, refer to Table A.2.

Table A.1 Summary of Anecdotal Evidence

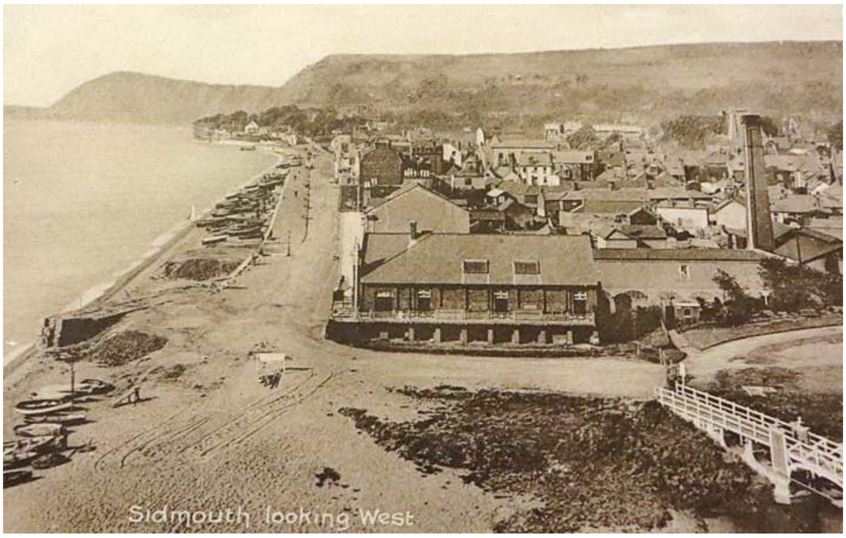
Record and date	Notes on cliff and beach
Photograph by Kathleen Nicholls in 1988 of East Cliffs and Ham Beach (Bagwell)	Shows boats on healthy beach west of River Sid (Ham Beach). Beach immediately East of river is also healthy, but narrows towards Salcombe Hill Cliff. Vegetated talus at base of East Cliffs shows failures occurred in recent past, but debris not yet reworked by waves.
Photograph of East Cliff dated 1966. (Bagwell)	Shows healthy state of beach fronting East Cliff and beach narrowing towards Salcombe Hill Cliff. Back of beach is a wide plateau for storage of boats
Photograph of East Cliff and Salcombe Hill Cliffs dated 1991. (Bagwell)	Shows active recession of these cliffs with 'fresh' faces and very limited vegetation cover. Beach evident but extent unclear.
Photograph of East Cliff and beach dated January 1996. (Bagwell)	Shows healthy beach used for storage of fishing boats and recent cliff collapse.
Photography of Each Cliff beach on 14 February 2015 (CRAG)	Shows low beach level with gravel cusps and exposure of boulders at cliff toe.
Photographs of Each Cliff on 14 February 2015 (CRAG)	Shows widespread erosion near the base of the cliff toe to form undercuts that appear to follow weak beds in the Mercia Mudstone. Joint controlled failures in the middle cliff are evident. Adit to former railway tunnel also shown, but location unclear.
Oblique aerial photography of East Cliff dated 9 August 1937 (CRAG)	Shows a very large cliff failure mid-way along the cliff, with talus present at the back of the beach. Also appears to be a large block failure near Pennington Point. The coast path (now lost) is fronted by perhaps 10m of land immediately north of Pennington Point, but only c. 1m at the failure. The beach is wide.
Oblique aerial photography of Each Cliff dated 1989 (CRAG)	Cliffs of Pennington Point have fresh toe erosion. Those further east are fronted by extensive and partially-vegetated talus slopes from previous significant cliff failures. Recent headscarp recession at the east end of Cliff Road where a footpath (marked by a hedge line) runs to the cliff edge. The coast path is obscured by vegetation, but appears to still be present, albeit very close to the cliff edge. The beach is wide and its healthy state is supported by the vegetated talus slopes that show waves rarely reach the cliff toe.
P.O. Hutchinson diary extracts (1859-1887)	Documents significant storms of : • 25 Oct 1859 that followed several day's frost. The beach was driven inland and much of the town was flooded. This was the most severe storm since November 1824. • 23 Nov 1865 drove the beach inland and flooded the town. • 1 November 1887 eroded beach and flooded much of the town. High tides impeded drainage of Rover Sid, which burst its backs and flooded upper town HAT occurred on 6 Oct 1869 but as strong winds came from SE, and not SW, no flooding occurred. A landslide on east flank of Peak Hill led to loss of cliff top road occurred in April 1811. In February 1882 Government prohibits removal of sand and gravel from the beach, much to the dissatisfaction of the town.
Photograph of Chit Rocks beach from Francis Frith Collection. Undated, but assumed to be 1930s.	Shows seawall, promenade and healthy beach (Symington)
Photograph of East Cliff and beach. Francis Frith Collection, 1928. (Symington)	Shows large recent rockfall at Pennington Point with debris reaching beyond MHW

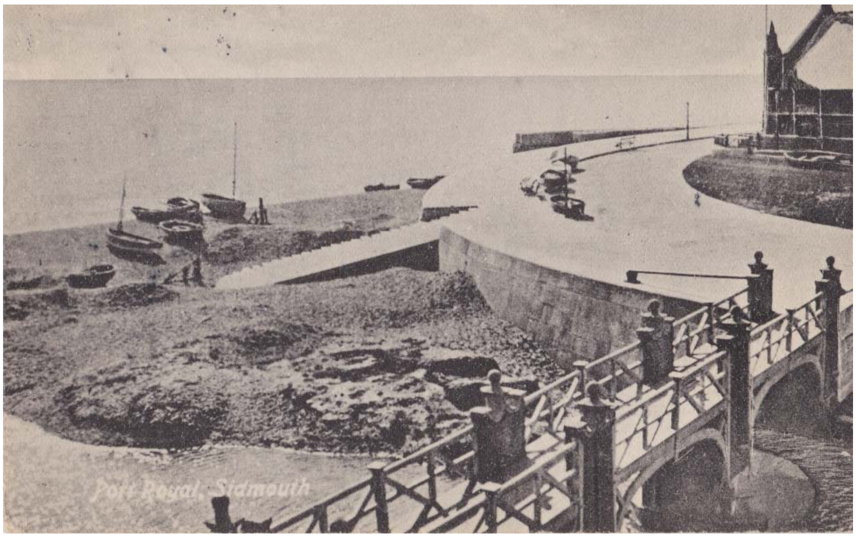
Photograph of original wooden Alma Bridge. Francis Frith Collection, 1895. (Symington)	Shows gravel accumulated on west bank of river.
Photograph of improved wood and brick three-arch Alma Bridge. Francis Frith Collection, 1904. (Symington)	No gravel on river bank, but significant gravel ridge on foreshore partially blocks the stream.
Photograph of improved wood and brick three-arch Alma Bridge. Francis Frith Collection, 1931. (Symington)	Significant gravel accumulation partially blocks eastern-most arch. Western-most arch appears to behave been boarded up to drive flows away from the town.
Sid Mouth and East Cliff Beach, 28 Oct 2005 (Golding)	Shows healthy beach with significant accumulation of gravel at cliff toe and large gravel bar at mid-beach that deflects river to east.
East Cliff and beach 27 Oct 2005 (Golding)	Taken near MHW, showing small section of high, steep-fronted beach that protects cliff toe and partially vegetated talus at Pennington Point, but lower and thinner beach immediately east, which allows waves to break at cliff toe.
East Cliff and beach 27 Oct 2005 (Golding)	Taken near MHW, showing very localised extent of high beach, which is c. 2m higher than adjacent area) at base of Pennington Point cliffs and mid-beach gravel bar deflecting flow to east.
Sidmouth Museum photos	The photos taken from the 1920s to 1990s document numerous large cliff collapses at Pennington Point and East Cliffs, often at times when the beach was healthy and at a high levels: • Large rockfall and high beach at Pennington Point Oct 1925 • Large rockfall and high beach at Pennington Point 1927 • Recent rockfalls and high beach at Pennington Point Oct 1928 • Recent rockfalls and high beach at Pennington Point Feb 1930 • Pennington Point degraded with numerous small failures of weathered material/head from upper cliff to healthy beach 1992. • Failure of weak materials from cliff top at Pennington Point in Feb 1994 Shows several times in the 1920s when Each Cliff beach was very thin, particularly immediately east of Pennington Point, allowing waves to break at cliff toe. Very healthy beaches are limited to area of Sid mouth. Aerial shots from 1987 show a healthy beach fronting East Cliff, with the gravel barrier deflecting the river to the east.
Account of long-time resident Marion Baker of the beach in 1960s	"Always a bank of pebbles at foot of Salcombe Hill...sea did not break against the cliffs". "River mouth very rarely open…huge bank of shingle usually across it"
Postcard of the Sidmouth and East Cliff frontage, 1927 (Walden)	Shows beach levels fronting the town and East Cliff are at a low level, with groynes and base of promenade exposed
Oblique photography of Sidmouth from 1937 (Walden)	Beaches relatively low at town with groynes and base of promenade exposed. Gravel platform at back of western part of East Cliff beach present, but narrows and then disappears by Salcombe Hill/
Postcard of Sidmouth beach, 1955 (Walden)	Town beach very narrow at MHW.
Undated (late 19th C?) postcard taken from Peak Hill towards Salcombe Hill (Walden)	Shows healthy gravel beach from Sid to Salcombe Hill and Dunscombe Cliff
Undated postcard photo (1930s?) from Chit Rocks to Salcombe Hill	Shows healthy gravel beach fronting town and narrower, but continuous beach east of the Sid.
Postcard showing East Cliff beach 1937	Shows beach is narrow fronting East Cliff and widens to east towards Dunscombe Cliff.
Undated postcard (1940s?) of East Cliff beach	Shows the high upper beach platform and healthy gravel beach as far as Dunscombe Cliff.
Undated postcard (late 19th C?) East Cliff	Shows wide beach fronting very degraded and deeply-weathered cliff.

Table A.2 Anecdotal Records

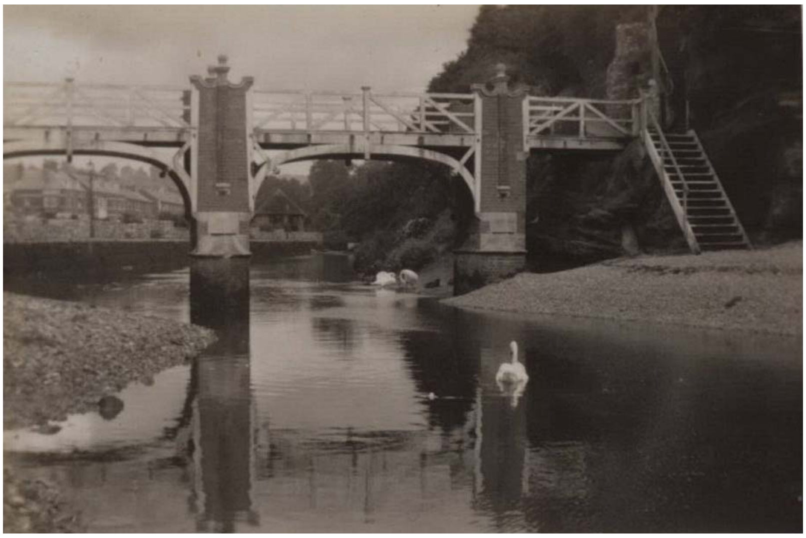
Date of Photograph	Name of Source	Image of Photograph
1851	http://issuu.com/ inthefootsteps/docs/final_hutch_vol01_2013	
1860s	Mary Walden	
1860s	Mary Walden	

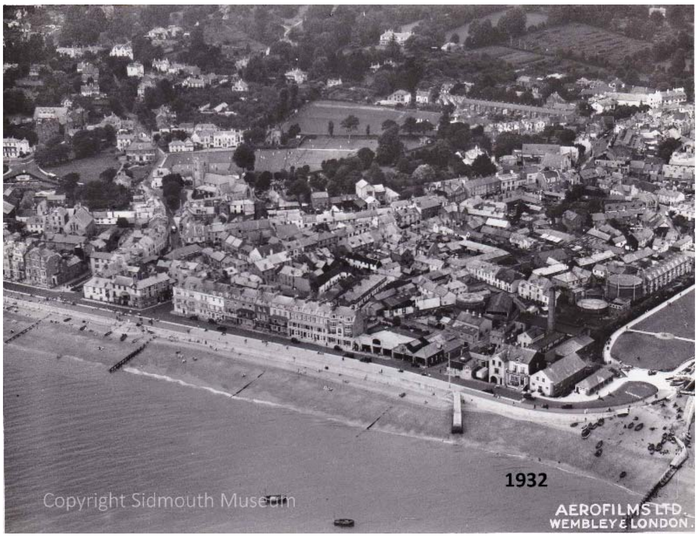
Date of Photograph	Name of Source	Image of Photograph
1860s	Mary Walden	
1860s	Mary Walden	
1876	David McCluskey	

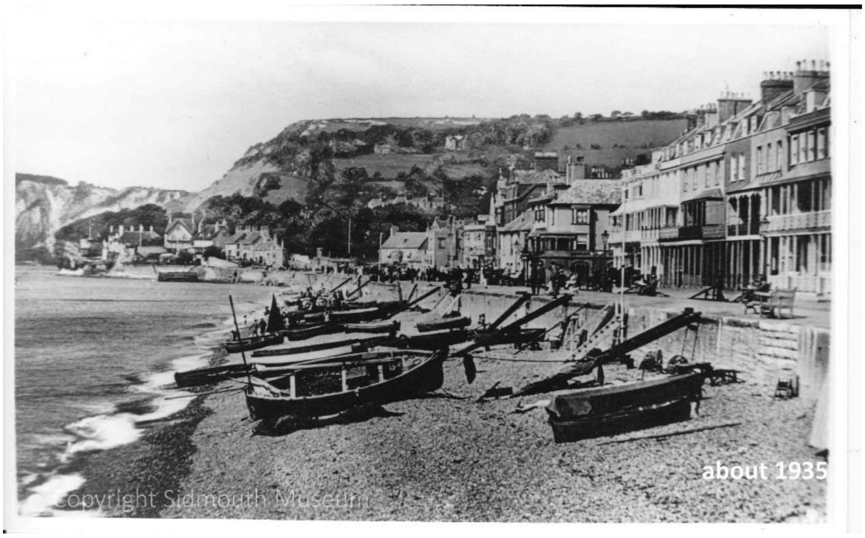
Date of Photograph	Name of Source	Image of Photograph
1876	Jo Frith	 Sidmouth in 1876. This photograph was taken before the esplanade was completed at Port Royal. Note the large amount of shingle at the eastern end.
1901	Mary Walden	
1905 (approximately).	Mary Walden	

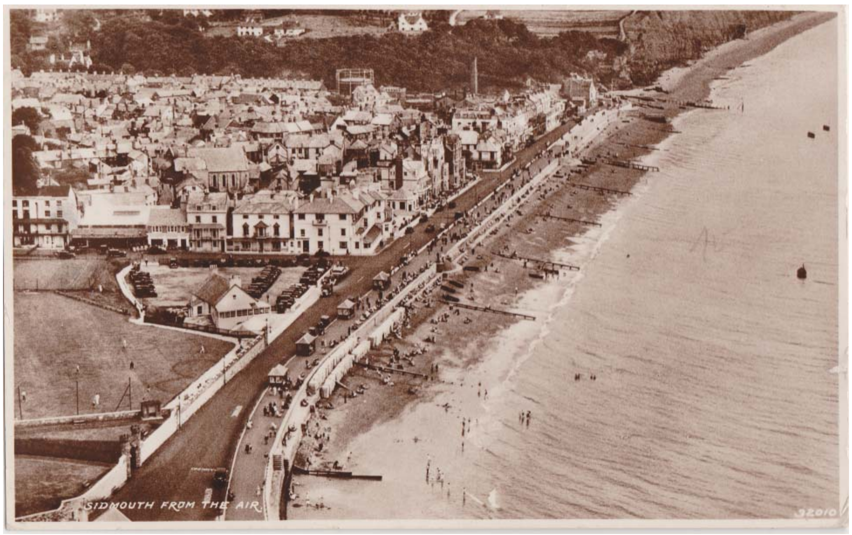
Date of Photograph	Name of Source	Image of Photograph
1906 (image postmarked)	Mary Walden	
1914 (image postmarked)	Mary Walden	
1921 (image postmarked)	Mary Walden	

Date of Photograph	Name of Source	Image of Photograph
1927 (image postmarked)	Mary Walden	
1930 (image postmarked)	Mary Walden	
1931	David McCluskey	

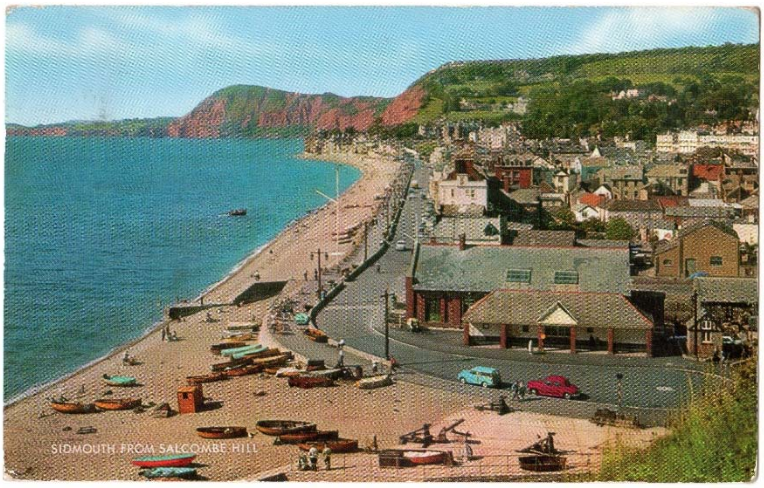
Date of Photograph	Name of Source	Image of Photograph
1931	Mary Walden	
1931	Mary Walden	
1931	Jo Frith	 uth, Alma Bridge 1931

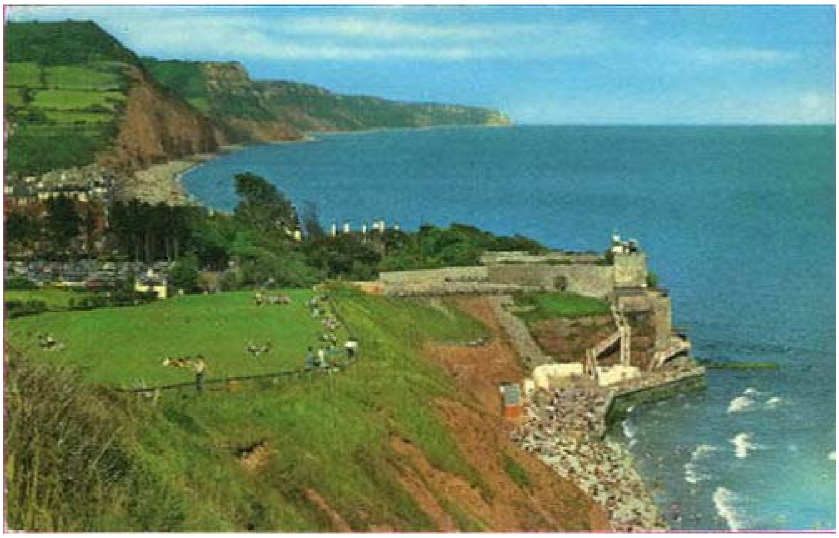
Date of Photograph	Name of Source	Image of Photograph
1932	David McCluskey	
1934	Mary Walden	
1934	Mary Walden	

Date of Photograph	Name of Source	Image of Photograph
1935	David McCluskey	
1937	Cliff Road Action Group (CRAG)	
1938	David McCluskey	

Date of Photograph	Name of Source	Image of Photograph
1937	Mary Walden	
1937 (image postmarked)	Mary Walden	
1954 (image postmarked)	Mary Walden	

Date of Photograph	Name of Source	Image of Photograph
1955 (image postmarked)	Mary Walden	
1956 (image postmarked)	Mary Walden	
1965 (image postmarked)	Mary Walden	

Date of Photograph	Name of Source	Image of Photograph
1966 (image postmarked)	Mary Walden	
1966 (image postmarked)	Mary Walden	
1966	Stan and Mary Bagwell	

Date of Photograph	Name of Source	Image of Photograph
Summer 1969	Robin Bettridge	
Summer 1669	Robin Bettridge	
1972 (image postmarked)	Mary Walden	

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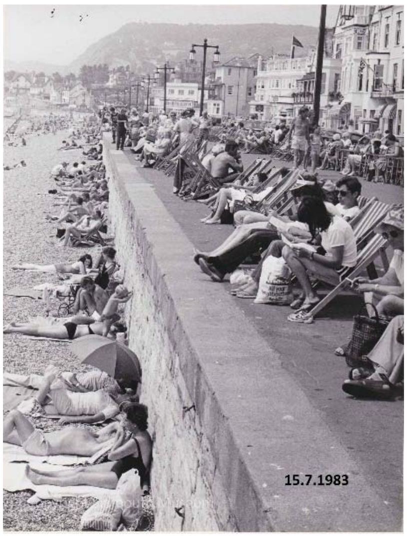
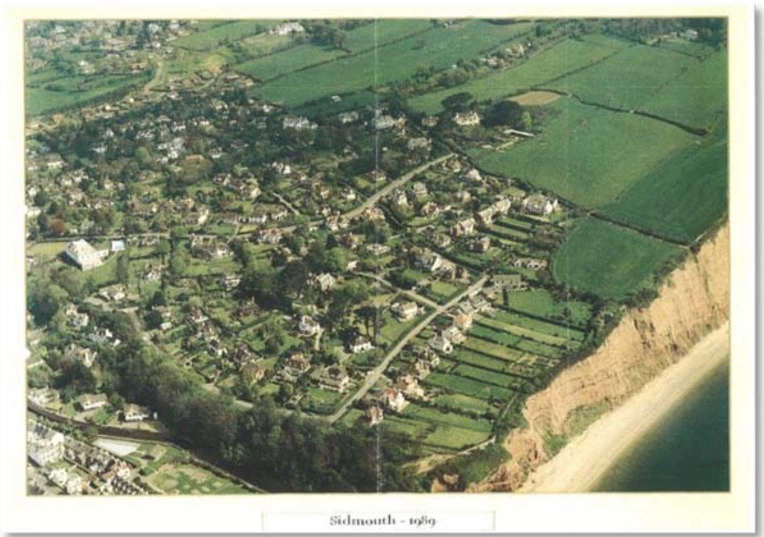
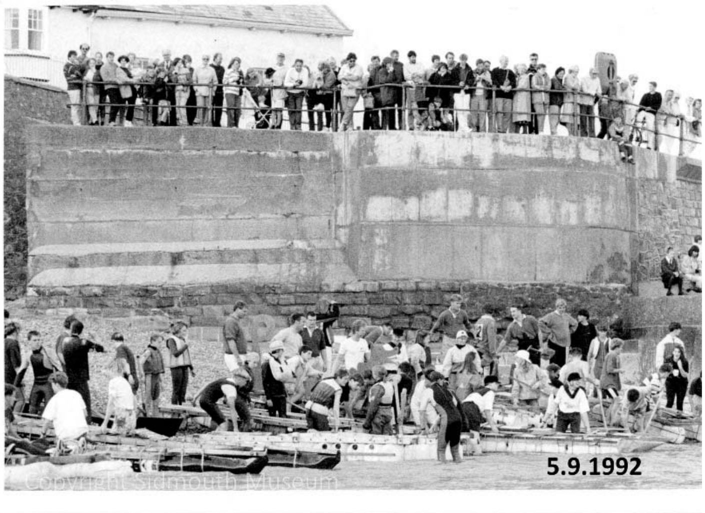
1983	David McCluskey	
1983	Robin Bettridge	

Date of Photograph	Name of Source	Image of Photograph
1983	Robin Bettridge	
1983	Robin Bettridge	
1983/1984 (approx.)	Robin Bettridge	

Date of Photograph	Name of Source	Image of Photograph
1983/1984 (approx.)	Robin Bettridge	
1983/1984 (approx.)	Robin Bettridge	
1986	David McCluskey	

Date of Photograph	Name of Source	Image of Photograph
1987	David McCluskey	
1988	Stan and Mary Bagwell	
1988	David McCluskey	

Date of Photograph	Name of Source	Image of Photograph
1988	David McCluskey	
1989	Cliff Road Action Group (CRAG)	
1991	K Bagwell	

Date of Photograph	Name of Source	Image of Photograph
1992	David McCluskey	
1992	David McCluskey	
1992	David McCluskey	

Date of Photograph	Name of Source	Image of Photograph
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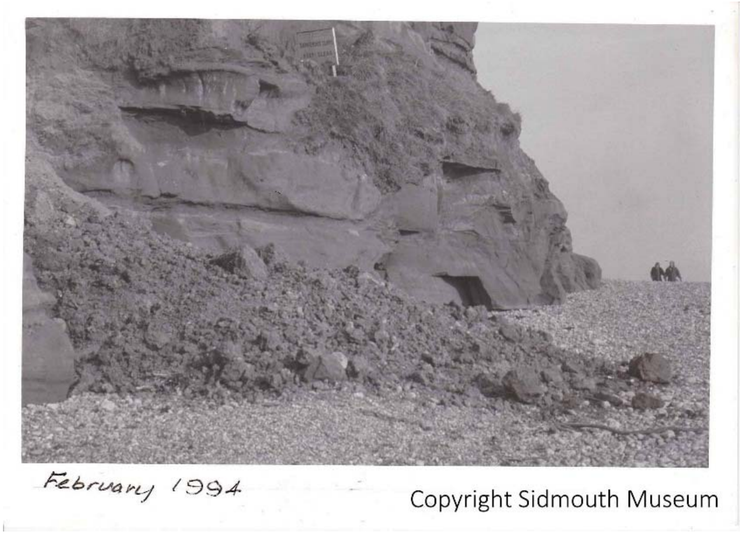
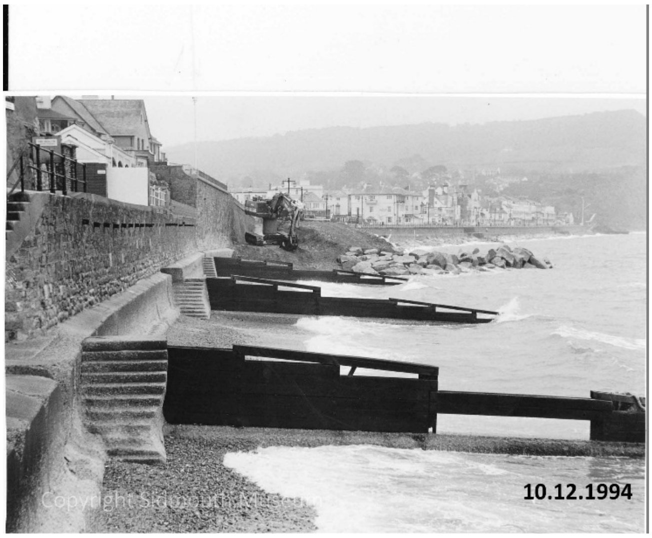
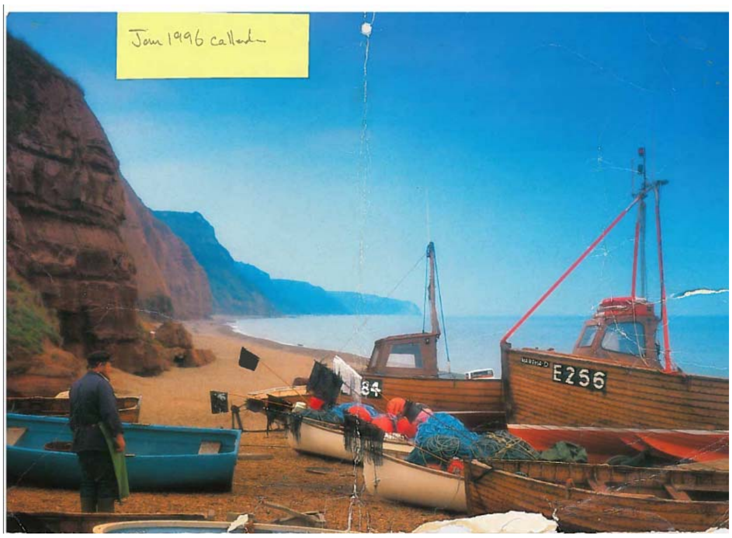
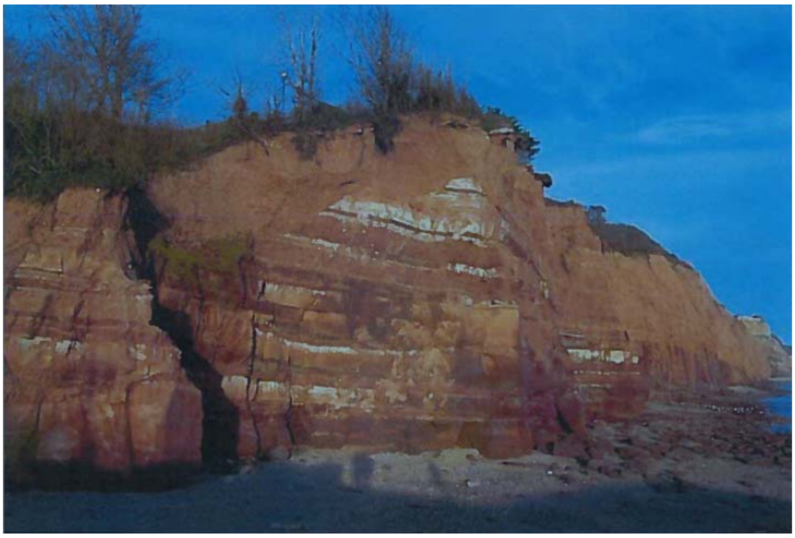
1994	David McCluskey	
1994	David McCluskey	

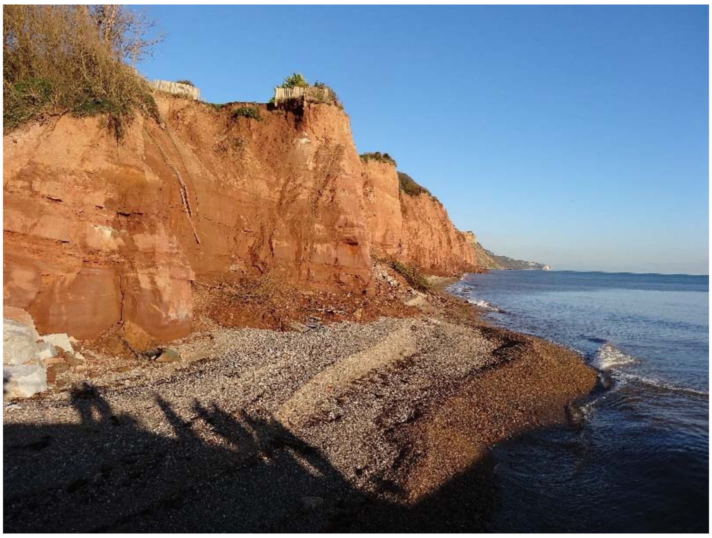
Date of Photograph	Name of Source	Image of Photograph
Jan 1996	Stan and Mary Bagwell	
Dec 2004	John Jones	
Oct 2005	Professor B Golding	

Date of Photograph	Name of Source	Image of Photograph
Oct 2005	Professor B Golding	
Oct 2005	Professor B Golding	
2008	Julia Burdekin	

Date of Photograph	Name of Source	Image of Photograph
Mar 2008	John Jones	
Mar 2008	John Jones	
Mar 2008	John Jones	

Date of Photograph	Name of Source	Image of Photograph
2008	Mary Walden	
Nov 2008	John Jones	
2009	Mary Walden	

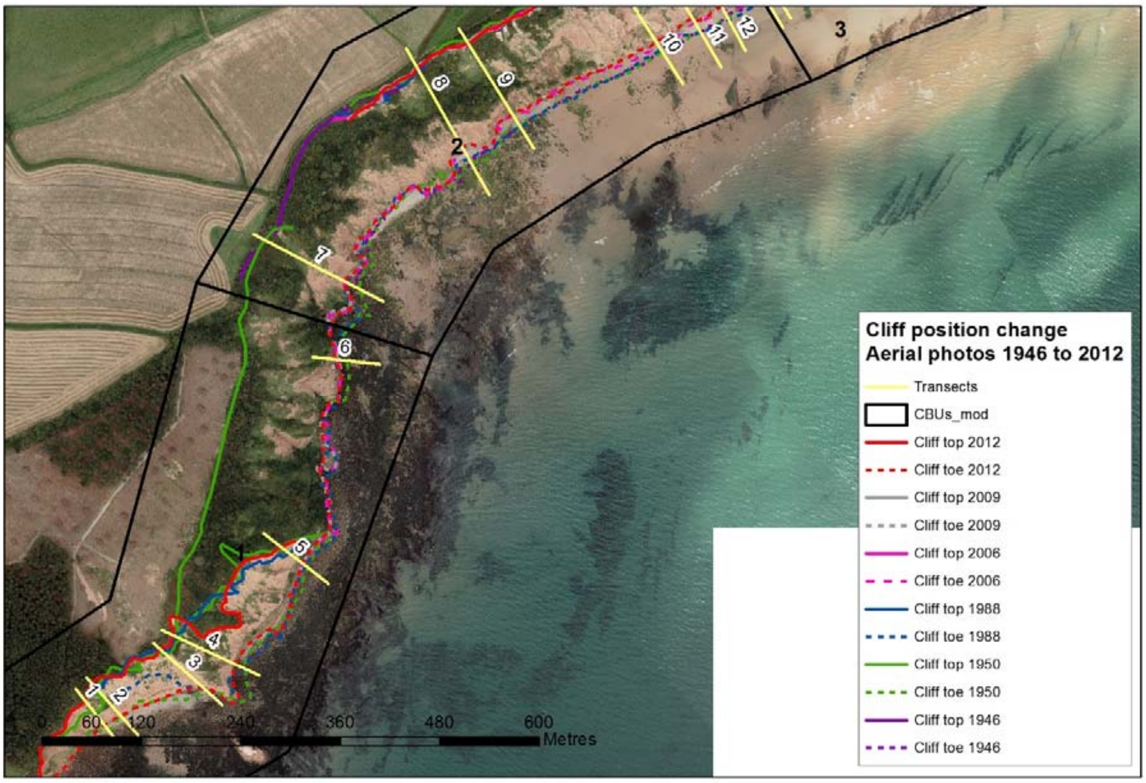
Date of Photograph	Name of Source	Image of Photograph
May 2010	John Jones	
2010	Mary Walden	
Mar 2011	Mary Walden	

Date of Photograph	Name of Source	Image of Photograph
2012	Mary Walden	
2012	Mary Walden	
Aug 2012	John Jones	

Date of Photograph	Name of Source	Image of Photograph
Sept 2012	Mary Walden	
Jan 2013	Mary Walden	
Jan 2013	Mary Walden	

Date of Photograph	Name of Source	Image of Photograph
Jan 2013	Mary Walden	
Feb 2013	Mary Walden	
Jan 2014	Mary Walden	

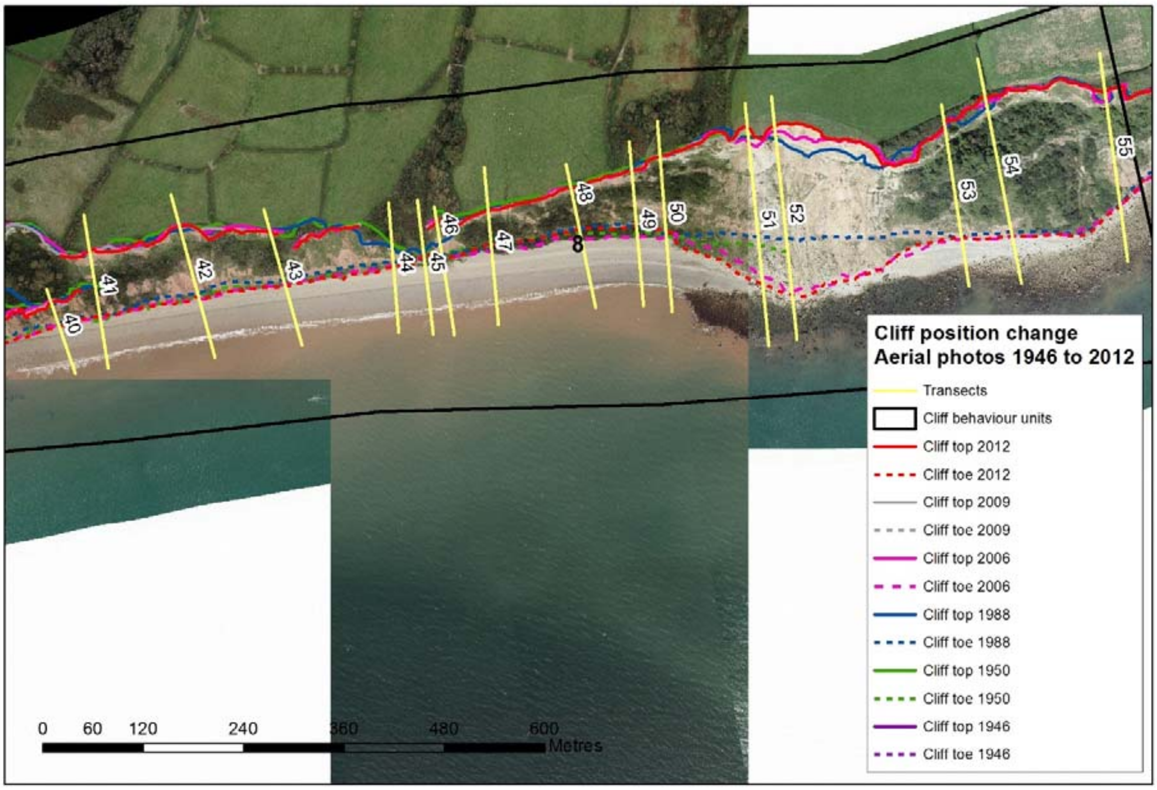
Appendix B – Cliff Recession Database & Transects



Cliff position change
Aerial photos 1946 to 2012
Transects
CBUs_mod
Cliff top 2012
Cliff toe 2012
Cliff top 2009
Cliff toe 2009
Cliff top 2006
Cliff toe 2006
Cliff top 1988
Cliff toe 1988
Cliff top 1950
Cliff toe 1950
Cliff top 1946
Cliff toe 1946
0 60 120 240 360 480 600
Metres

Cliff position change
Aerial photos 1946 to 2012
Transects
Cliff behaviour units
Cliff top 2012
Cliff toe 2012
Cliff top 2009
Cliff toe 2009
Cliff top 2006
Cliff toe 2006
Cliff top 1988
Cliff toe 1988
Cliff top 1950
Cliff toe 1950
Cliff top 1946
Cliff toe 1946
0 60 120 240 360 480 600
Metres


Cliff position change
Aerial photos 1946 to 2015
Cliff top 2015
Cliff top 2012
Cliff toe 2012
Cliff top 2009
Cliff toe 2009
Cliff top 2006
Cliff toe 2006
Cliff top 1988
Cliff toe 1988
Cliff top 1950
Cliff toe 1950
Cliff top 1946
Cliff toe 1946
0 50 100 200 300 400 500 600
Metres
6
7
8
29
30
31
311
32
321
33
331
34
341
342
35
36
37
38
39
40


Cliff position change
Aerial photos 1946 to 2012
Transects
Cliff behaviour units
Cliff top 2012
Cliff toe 2012
Cliff top 2009
Cliff toe 2009
Cliff top 2006
Cliff toe 2006
Cliff top 1988
Cliff toe 1988
Cliff top 1950
Cliff toe 1950
Cliff top 1946
Cliff toe 1946
0 60 120 240 360 480 600
Metres
8
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55

Cliff Top Position Changes

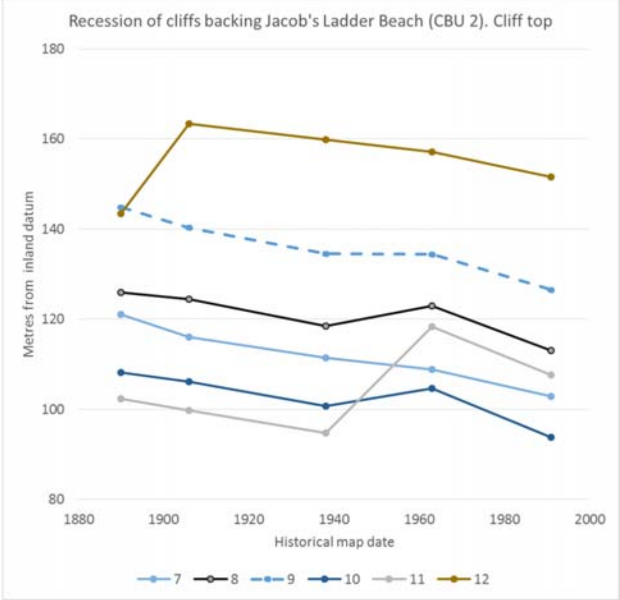


Figure B.1 Cliff top recession, CBU 2 (1890 to 1991)

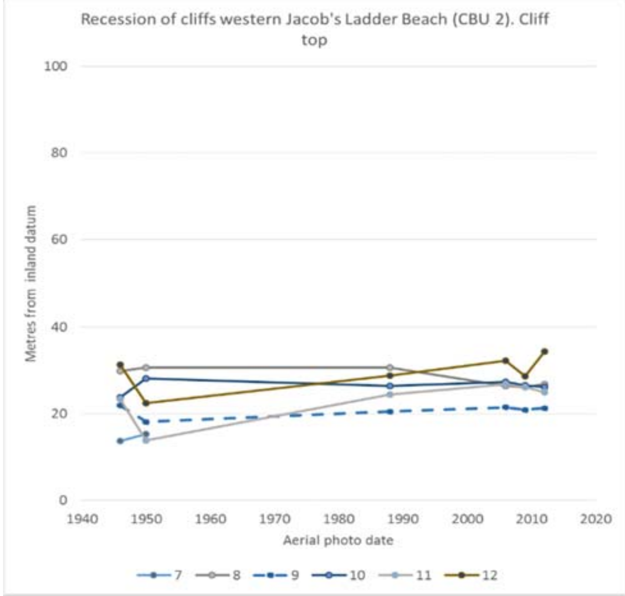


Figure B.2 Cliff top recession, CBU 2 (1946 to 2012)

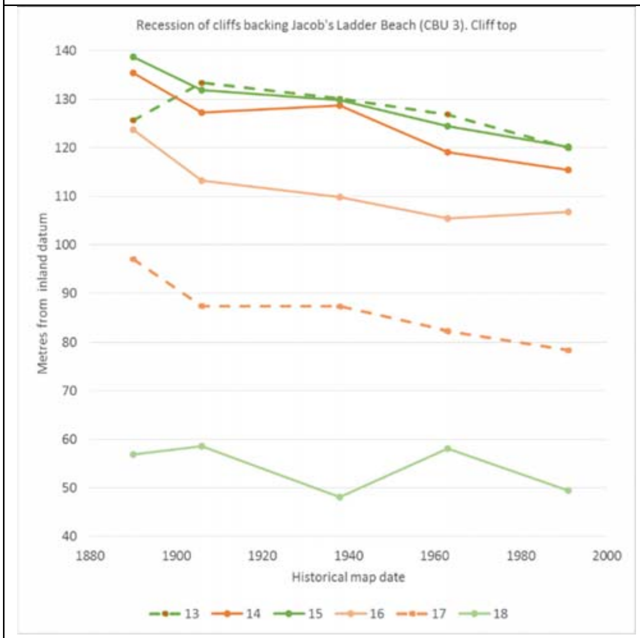


Figure B.3 Cliff top recession, CBU 3 (1890 to 1991)

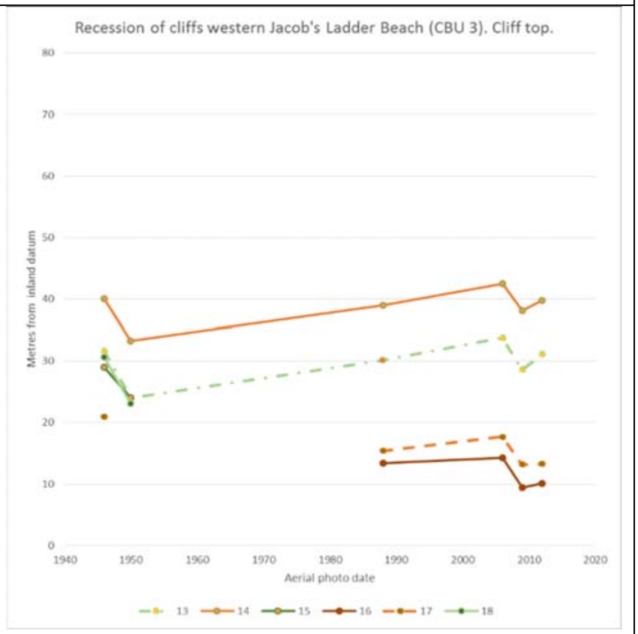


Figure B.4 Cliff top recession, CBU3 (1946 to 2012)

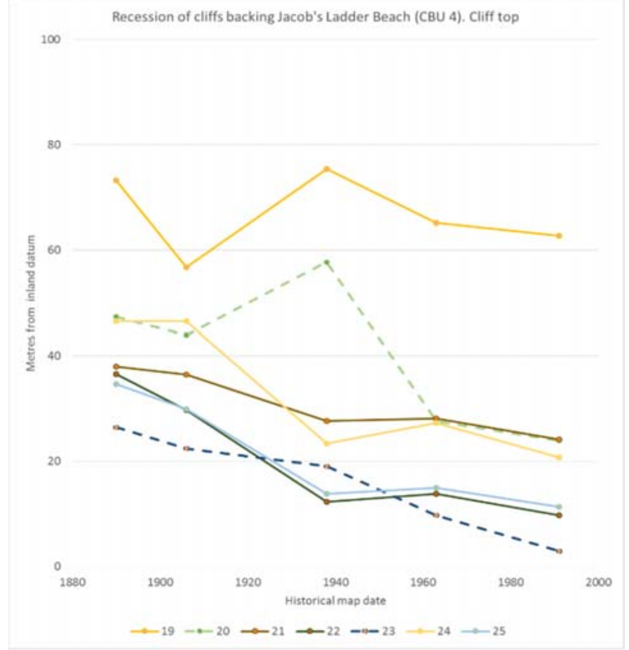


Figure B.5 Cliff top recession, CBU 4 (1890 to 1991)

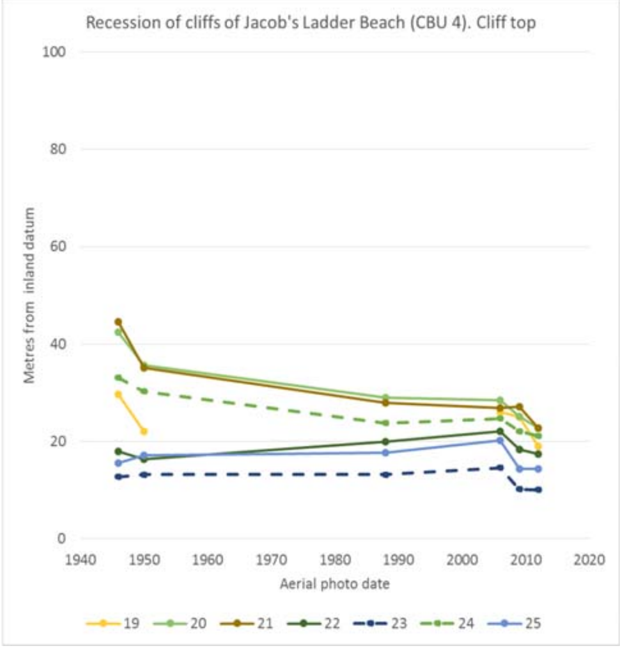


Figure B.6 Cliff top recession, CBU 4 (1946 to 2012)

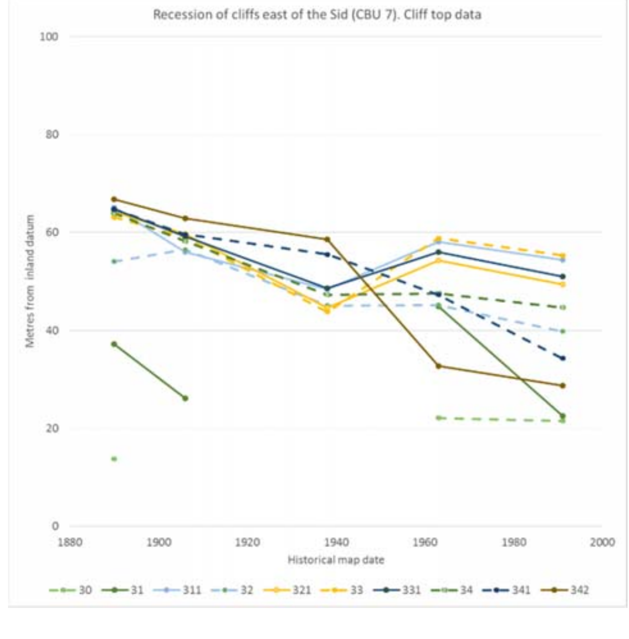


Figure B.7 Cliff top recession, CBU 7 (1890 to 1991)

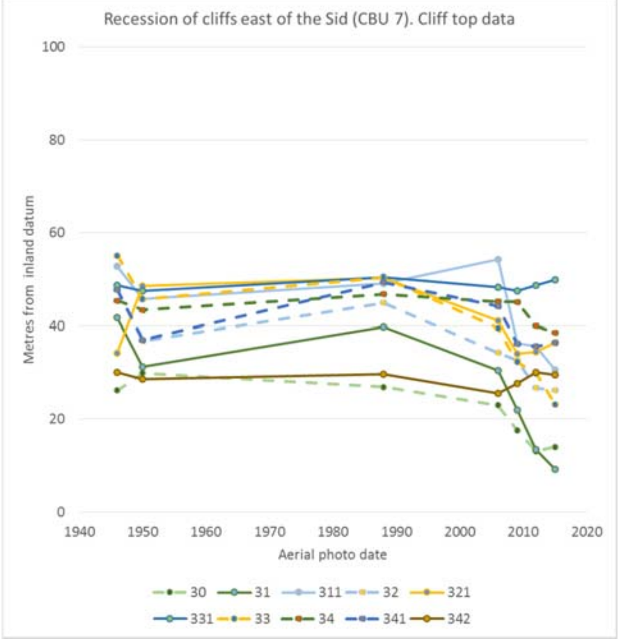


Figure B.8 Cliff top recession, CBU 7 (1946 to 2015)

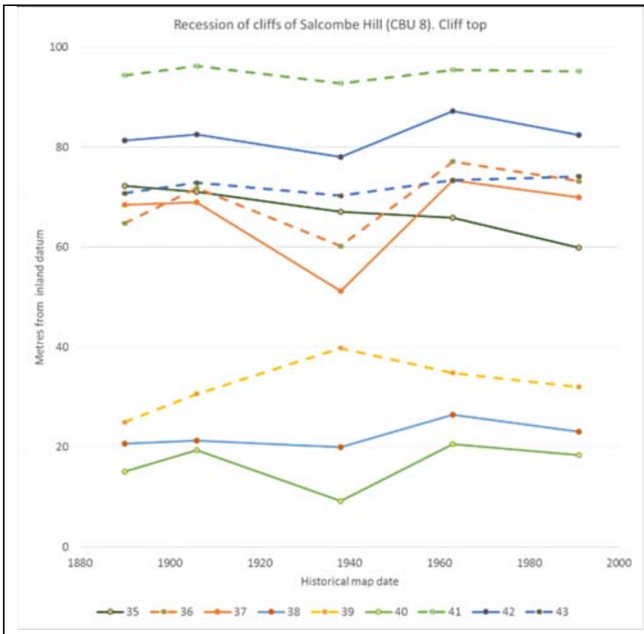
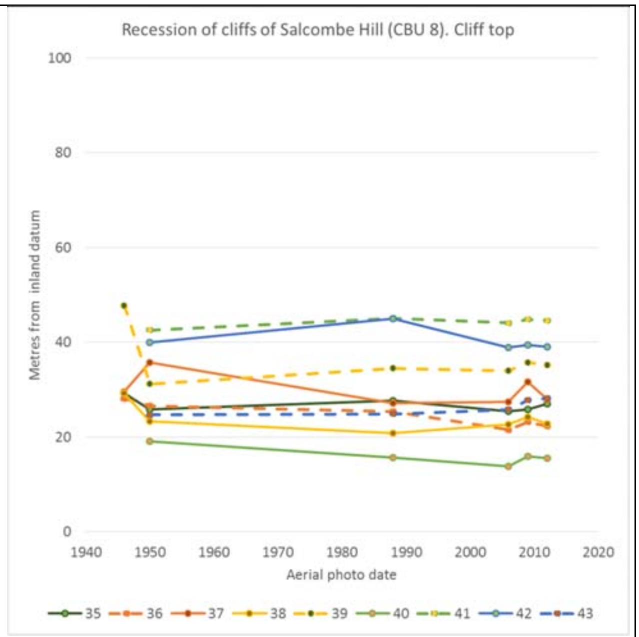
	

Figure B.10 Cliff top recession, CBU 8 (1890 to 1991)	*Figure B.11 Cliff top recession, CBU 8 (1946 to 2012)*

Cliff Toe Position Changes

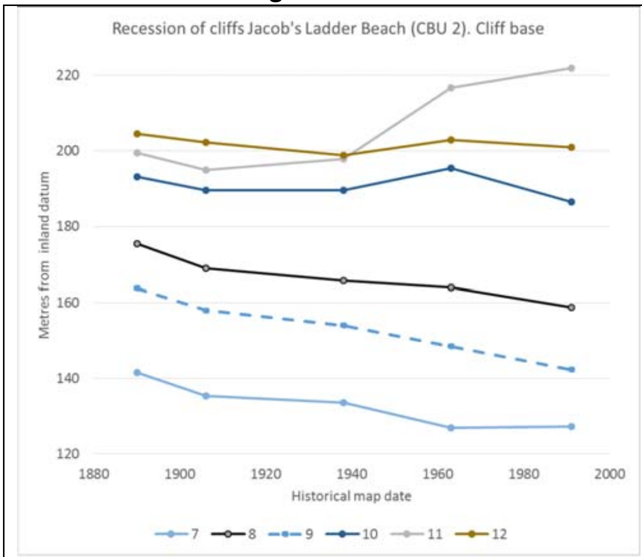


Figure B.12 Cliff toe recession, CBU 2 (1890 to 1991)

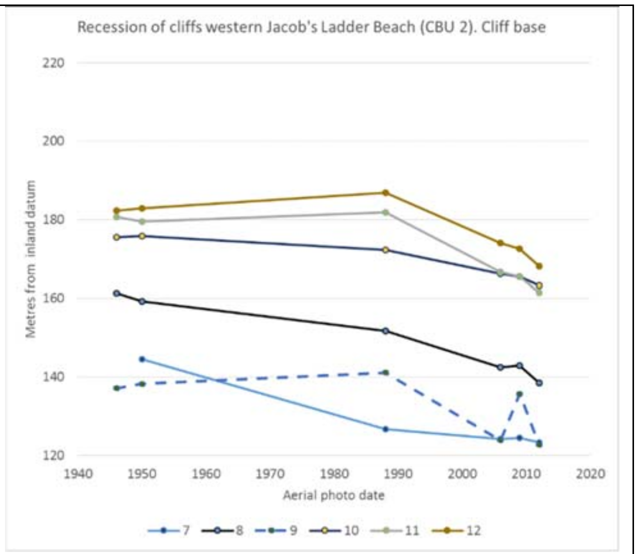


Figure B.13 Cliff toe recession, CBU 2 (1946 to 2012)

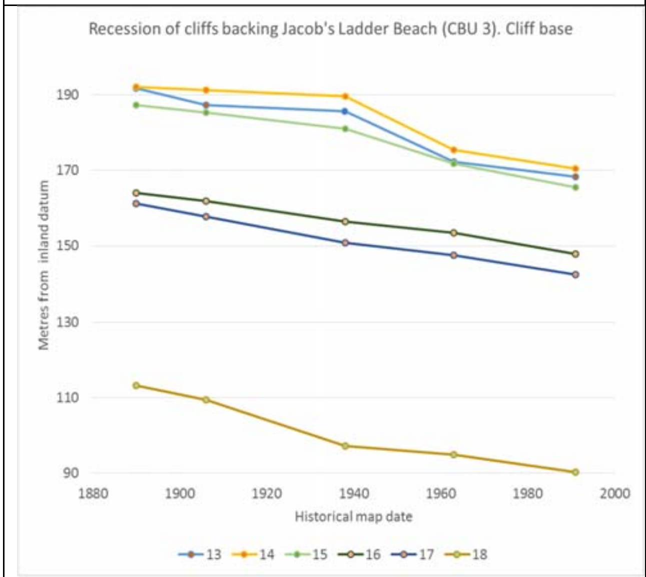


Figure B.14 Cliff toe recession, CBU 3 (1890 to 1991)

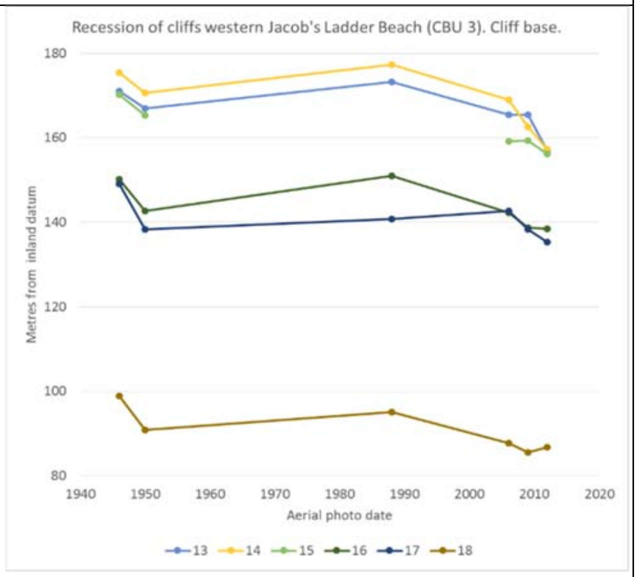


Figure B.15 Cliff toe recession, CBU 3 (1946 to 2012)

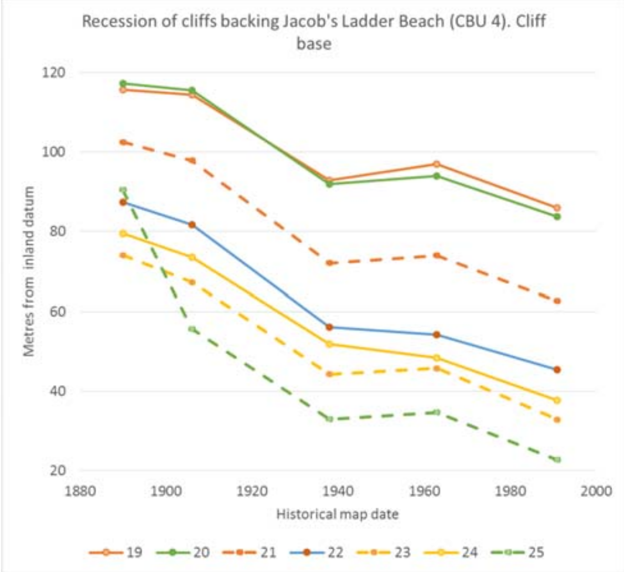


Figure B.16 Cliff toe recession, CBU 4 (1890 to 1991)

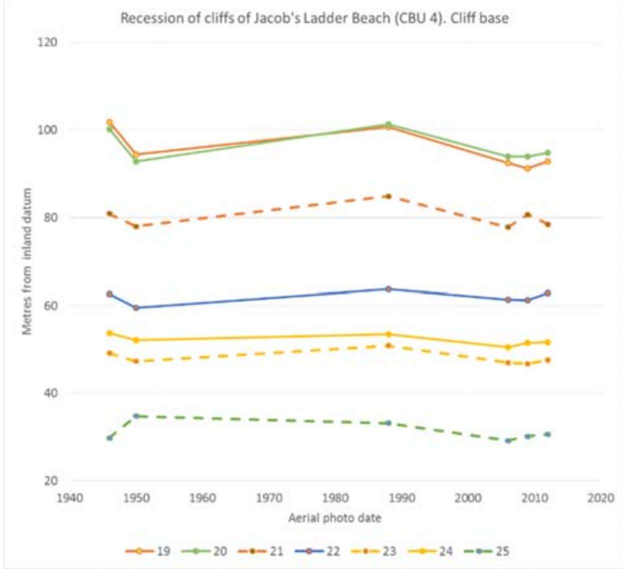


Figure B.17 Cliff toe recession, CBU 4 (1946 to 2012)

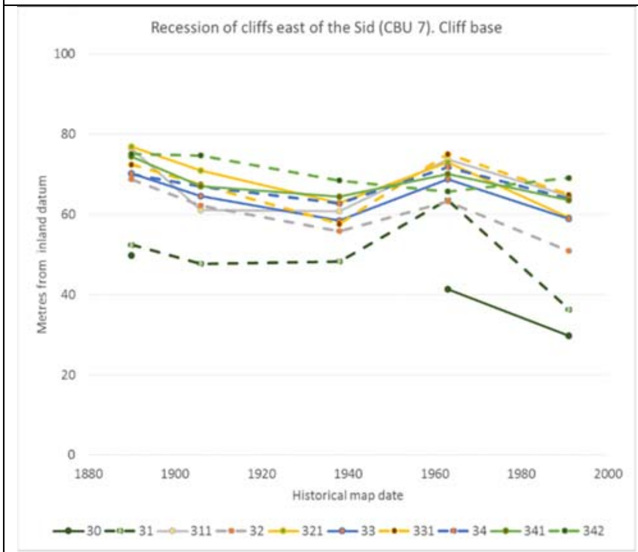


Figure B.18 Cliff toe recession, CBU 7 (1890 to 1991)

Figure B.19 Cliff toe recession, CBU 7 (1946 to 2012)

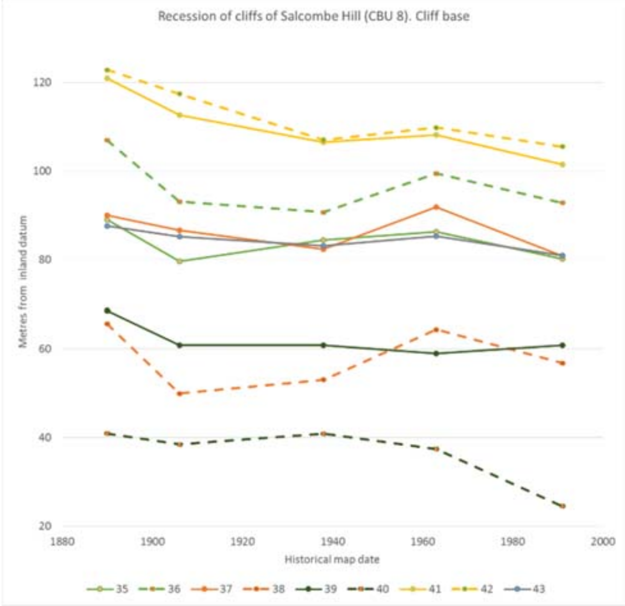


Figure B.20 Cliff toe recession, CBU 8 (1890 to 1991)

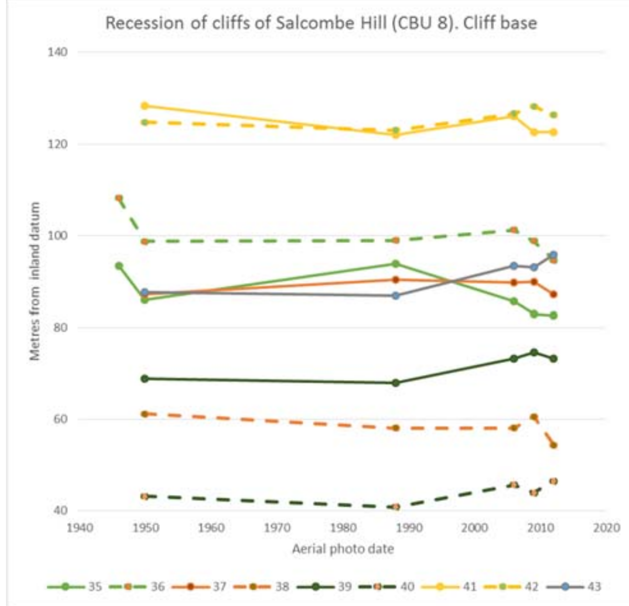


Figure B.21Cliff toe recession, CBU 8 (1946 to 2012)

Table B1. Cliff change data measured from aerial photos.

			DISTANCE FROM DATUM							TOTAL CHANGE							MEAN ANNUAL RATE OF CHANGE (m/year)								
Profile	CBU	Feature	1946	1950	1988	2006	2009	2012	2015	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	Profile	Feature
1	1	CT	*	34.6	*	*	*	17.5	*	*	*	*	*	*	*	-17.1							-0.28	1	CT
2	1	CT	*	18.5	14.7	*	*	9.3	*	*	-3.8	*	*	*	*	-9.2		-0.10					-0.15	2	CT
3	1	CB	*	90.6	83.5	*	*	81.7	*	*	-7.1	*	*	*	*	-8.9	*	-0.19	*	*	*	*	-0.14	3	CB
3	1	CT	*	16.9	12.4	*	*	10.2	*	*	-4.5	*	*	*	*	-6.7		-0.12					-0.11	3	CT
1	1	CB	*	62.9	*	*	*	56.7	*	*	*	*	*	*	*	-6.2	*	*	*	*	*	*	-0.1	1	CB
2	1	CB	*	59.3	*	*	*	61.1	*	*	*	*	*	*	*	1.8	*	*	*	*	*	*	0.029	2	CB
1	1	SBW	*	*	*	*	*	12.3	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	1	SBW
2	1	SBW	*	*	*	*	*	13.8	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	2	SBW
3	1	SBW	*	*	*	*	*	13.9	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	3	SBW
6	1	CB	*	60.4	27.9	29.2	30.7	27.1	*	*	-32.5	1.3	1.5	-3.6	*	-33.3	*	-0.86	0.072	0.5	-1.2	*	-0.54	6	CB
4	1	CB	*	112.1	109.4	*	*	97.3	*	*	-2.7	*	*	*	*	-14.8	*	-0.07	*	*	*	*	-0.24	4	CB
4	1	CT	*	22.9	16	*	*	14.4	*	*	-6.9	*	*	*	*	-8.5		-0.18					-0.14	4	CT
5	1	CB	*	67.9	64.5	60.3	59.6	59.6	*	*	-3.4	-4.2	-0.7	0	*	-8.3	*	-0.09	-0.23	-0.23	0	*	-0.13	5	CB
5	1	CT	*	29.4	38.9	*	*	27.5	*	*	9.5	*	*	*	*	-1.9							-0.03	5	CT
4	1	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	4	SBW
5	1	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	5	SBW
6	1	CT	*	*	*	*	*	*	*	*	*	*	*	*	*	*								6	CT
6	1	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	6	SBW
7	2	CB		144.5	126.7	124.2	124.5	123.3	*	144.50	-17.80	-2.50	0.30	-1.20	123.30	-21.20	36.13	-0.47	-0.14	0.10	-0.40	1.87	-0.34	7	CB
8	2	CB	161.4	159.2	151.7	142.4	142.9	138.5	*	-2.20	-7.50	-9.30	0.50	-4.40	-22.90	-20.70	-0.55	-0.20	-0.52	0.17	-1.47	-0.35	-0.33	8	CB
9	2	CB	137.1	138.2	141.1	123.8	135.7	122.7	*	1.10	2.90	-17.30	11.90	-13.00	-14.40	-15.50	0.28	0.08	-0.96	3.97	-4.33	-0.22	-0.25	9	CB
8	2	CT	29.9	30.6	30.7	26.4	26.2	26.8	*	0.70	0.10	-4.30	-0.20	0.60	-3.10	-3.80	0.00		-0.24	-0.07		-0.05	-0.06	8	CT
9	2	CT	21.9	18.1	20.5	21.5	20.9	21.3	*	-3.80	2.40	1.00	-0.60	0.40	-0.60	3.20	-0.95			-0.20		-0.01		9	CT
7	2	CT	13.7	15.3					*	1.60	-15.30	0.00	0.00	0.00				-0.40						7	CT
7	2	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	10	4	*	*	7	SBW
8	2	SBW	*	*	*	0	11.2	14.3	*	*	*	*	11.2	3.1	*	*	*	*	*	11	4	*	*	8	SBW
9	2	SBW	*	*	*	11.1	0	9.6	*	*	*	*	-11.1	9.6	*	*	*	*	*	12	4	*	*	9	SBW
11	2	CB	180.7	179.5	181.9	166.7	165.5	161.5	*	-1.20	2.40	-15.20	-1.20	-4.00	-19.20	-18.00	-0.30	0.06	-0.84	-0.40	-1.33	-0.29	-0.29	11	CB
12	2	CB	182.3	182.9	186.8	174	172.6	168.1	*	0.60	3.90	-12.80	-1.40	-4.50	-14.20	-14.80	0.15	0.10	-0.71	-0.47	-1.50	-0.22	-0.24	12	CB
10	2	CB	175.5	175.8	172.3	166.2	165.4	163.3	*	0.30	-3.50	-6.10	-0.80	-2.10	-12.20	-12.50	0.08	-0.09	-0.34	-0.27	-0.70	-0.19	-0.20	10	CB
10	2	CT	23.8	28.2	26.4	27.3	26.6	26.1	*	4.40	-1.80	0.90	-0.70	-0.50	2.30	-2.10		-0.05		-0.23	-0.17		-0.03	10	CT
11	2	CT	23.4	13.9	24.5	26.8	26.2	25	*	-9.50	10.60	2.30	-0.60	-1.20	1.60	11.10	-2.38			-0.20	-0.40			11	CT
12	2	CT	31.3	22.4	28.8	32.3	28.7	34.4	*	-8.90	6.40	3.50	-3.60	5.70	3.10	12.00	-2.23			-1.20				12	CT
10	2	SBW	*	*	*	8	5.8	*	*	*	*	*	-2.2	*	*	*	*	*	*	-0.733	*	*	*	10	SBW
11	2	SBW	*	*	*	11.8	11.5	16.4	*	*	*	*	-0.3	4.9	*	*	*	*	*	-0.1	1.633	*	*	11	SBW
12	2	SBW	*	*	*	11.7	13.8	14.4	*	*	*	*	2.1	0.6	*	*	*	*	*	0.7	0.2	*	*	12	SBW
14	3	CB	175.4	170.7	177.3	169	162.6	157.32	*	-4.70	6.60	-8.30	-6.40	-5.28	-18.08	-13.38	-1.18	0.17	-0.46	-2.13	-1.76	-0.27	-0.22	14	CB

			DISTANCE FROM DATUM							TOTAL CHANGE							MEAN ANNUAL RATE OF CHANGE (m/year)								
Profile	CBU	Feature	1946	1950	1988	2006	2009	2012	2015	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	Profile	Feature
13	3	CB	171	167	173.3	165.4	165.5	157	*	-4.00	6.30	-7.90	0.10	-8.50	-14.00	-10.00	-1.00	0.17	-0.44	0.03	-2.83	-0.21	-0.16	13	CB
15	3	CB	170.2	165.3		159.2	159.3	156.2	*	-4.90	-165.30	159.20	0.10	-3.10	-14.00	-9.10	-1.23	-4.35	8.84	0.03	-1.03	-0.21	-0.15	15	CB
14	3	CT	40.1	33.3	39	42.5	38.1	39.8	*	-6.80	5.70	3.50	-4.40	1.70	-0.30	6.50	-1.70			-1.47		-0.01		14	CT
13	3	CT	31.6	24	30.1	33.8	28.6	31.1	*	-7.60	6.10	3.70	-5.20	2.50	-0.50	7.10	-1.90			-1.73		-0.01		13	CT
13	3	SBW	*	*	*	9.9	12.4	13.7	*	*	*	*	2.5	1.3	*	*	*	*	*	0.833	0.433	*	*	13	SBW
14	3	SBW	*	*	*	9.3	20.5	14.5	*	*	*	*	11.2	-6	*	*	*	*	*	3.733	-2	*	*	14	SBW
15	3	CT	29	24.1					*	-4.90	-24.10	0.00	0.00	0.00	-29.00	-24.10	-1.23	-0.63				-0.44	-0.39	15	CT
15	3	SBW	*	*	*	13.1	16.9	14.6	*	*	*	*	3.8	-2.3	*	*	*	*	*	1.267	-0.767	*	*	15	SBW
16	3	CB	150.2	142.7	151	142.2	138.7	138.4	*	-7.50	8.30	-8.80	-3.50	-0.30	-11.80	-4.30	-1.88	0.22	-0.49	-1.17	-0.10	-0.18	-0.07	16	CB
18	3	CB	98.9	90.8	95.1	87.7	85.5	86.8	*	-8.10	4.30	-7.40	-2.20	1.30	-12.10	-4.00	-2.03	0.11	-0.41	-0.73	0.43	-0.18	-0.07	18	CB
17	3	CB	149.1	138.2	140.7	142.6	138.2	135.2	*	-10.90	2.50	1.90	-4.40	-3.00	-13.90	-3.00	-2.73	0.07	0.11	-1.47	-1.00	-0.21	-0.05	17	CB
17	3	CT	21		15.4	17.7	13.2	13.3	*	-21.00	15.40	2.30	-4.50	0.10	-7.70	13.30	-5.25			-1.50		-0.12		17	CT
16	3	CT			13.4	14.3	9.4	10.1	*	0.00	13.40	0.90	-4.90	0.70	10.10	10.10				-1.63				16	CT
16	3	SBW	*	*	*	10.9	20.7	12.4	*	*	*	*	9.8	-8.3	*	*	*	*	*	3.267	-2.77	*	*	16	SBW
17	3	SBW	*	*	*	9.2	19	15.6	*	*	*	*	9.8	-3.4	*	*	*	*	*	3.267	-1.13	*	*	17	SBW
18	3	CT	30.7	23.1					*	-7.60	-23.10	0.00	0.00	0.00	-30.70	-23.10	-1.90	-0.61				-0.47	-0.37	18	CT
18	3	SBW	*	*	*	15.1	22.8	19.9	*	*	*	*	7.7	-2.9	*	*	*	*	*	2.567	-0.967	*	*	18	SBW
20	4	CT	42.4	35.6	29	28.4	25.1	22.7	*	-6.80	-6.60	-0.60	-3.30	-2.40	-19.70	-12.90	-1.70	-0.17	-0.03	-1.10	-0.80	-0.30	-0.21	20	CT
21	4	CT	44.6	35.1	28	26.9	27.2	22.7	*	-9.50	-7.10	-1.10	0.30	-4.50	-21.90	-12.40	-2.38	-0.19	-0.06		-1.50	-0.33	-0.20	21	CT
19	4	CT	29.6	22.1		26.1	25	19	*	-7.50	-22.10	26.10	-1.10	-6.00	-10.60	-3.10	-1.88	-0.58		-0.37	-2.00	-0.16	-0.05	19	CT
19	4	CB	101.8	94.5	100.7	92.5	91.3	92.8	*	-7.30	6.20	-8.20	-1.20	1.50	-9.00	-1.70	-1.83	0.16	-0.46	-0.40	0.50	-0.14	-0.03	19	CB
21	4	CB	80.9	78	84.9	77.8	80.7	78.5	*	-2.90	6.90	-7.10	2.90	-2.20	-2.40	0.50	-0.73	0.18	-0.39	0.97	-0.73	-0.04	0.01	21	CB
20	4	CB	100.2	92.8	101.3	93.9	93.9	94.8	*	-7.40	8.50	-7.40	0.00	0.90	-5.40	2.00	-1.85	0.22	-0.41	0.00	0.30	-0.08	0.03	20	CB
19	4	SBW	*	*	*	16.2	25.4	16.7	*	*	*	*	9.2	-8.7	*	*	*	*	*	3.067	-2.9	*	*	19	SBW
20	4	SBW	*	*	*	19.9	27.6	19.7	*	*	*	*	7.7	-7.9	*	*	*	*	*	2.567	-2.63	*	*	20	SBW
21	4	SBW	*	*	*	17	25.4	20	*	*	*	*	8.4	-5.4	*	*	*	*	*	2.8	-1.8	*	*	21	SBW
24	4	CT	33.1	30.3	23.8	24.7	22.1	21.1	*	-2.80	-6.50	0.90	-2.60	-1.00	-12.00	-9.20	-0.70	-0.17		-0.87	-0.33	-0.18	-0.15	24	CT
25	4	CB	29.8	34.8	33.2	29.2	30.2	30.7	*	5.00	-1.60	-4.00	1.00	0.50	0.90	-4.10	1.25	-0.04	-0.22	0.33	0.17	0.01	-0.07	25	CB
23	4	CT	12.7	13.2	13.2	14.6	10.2	10.1	*	0.50	0.00	1.40	-4.40	-0.10	-2.60	-3.10				-1.47	-0.03	-0.04	-0.05	23	CT
25	4	CT	15.6	17.2	17.7	20.2	14.3	14.4	15.2	1.60	0.50	2.50	-5.90	0.10	-1.20	-2.80				-1.97		-0.02	-0.05	25	CT
24	4	CB	53.8	52.1	53.5	50.6	51.6	51.7	*	-1.70	1.40	-2.90	1.00	0.10	-2.10	-0.40	-0.43	0.04	-0.16	0.33	0.03	-0.03	-0.01	24	CB
23	4	CB	49.2	47.3	50.9	47	46.8	47.6	*	-1.90	3.60	-3.90	-0.20	0.80	-1.60	0.30	-0.48	0.10	-0.22	-0.07	0.27	-0.02	0.01	23	CB
22	4	CT	18	16.4	19.9	22.1	18.4	17.4	*	-1.60	3.50	2.20	-3.70	-1.00	-0.60	1.00	-0.40			-1.23	-0.33	-0.01		22	CT
22	4	CB	62.6	59.5	63.7	61.4	61.2	62.8	*	-3.10	4.20	-2.30	-0.20	1.60	0.20	3.30	-0.78	0.11	-0.13	-0.07	0.53	0.00	0.05	22	CB
22	4	SBW	*	*	*	17.7	30.3	23.8	*	*	*	*	12.6	-6.5	*	*	*	*	*	4.20	-2.17	*	*	22	SBW
23	4	SBW	*	*	*	68.2	79.7	75.2	*	*	*	*	11.5	-4.5	*	*	*	*	*	3.83	-1.50	*	*	23	SBW
24	4	SBW	*	*	*	74.1	87.4	83.3	*	*	*	*	13.3	-4.1	*	*	*	*	*	4.43	-1.37	*	*	24	SBW
25	4	SBW	*	*	*	50.1	66	67.6	*	*	*	*	15.9	1.6	*	*	*	*	*	5.30	0.53	*	*	25	SBW

			DISTANCE FROM DATUM							TOTAL CHANGE							MEAN ANNUAL RATE OF CHANGE (m/year)								
Profile	CBU	Feature	1946	1950	1988	2006	2009	2012	2015	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	Profile	Feature
26	5	CT	*	17.2	*	*	*	*	*	*	*	*	*	*	*	*								26	CT
26	5	CB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	26	CB
26	5	SBW	*	*	*	65.8	67.8	43.5	*	*	*	*	2	-24.3	*	*	*	*	*	0.667	-8.1	*	*	26	SBW
27	5	CT	*	*	*	*	*	*	*	*	*	*	*	*	*	*								27	CT
27	5	CB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	27	CB
27	5	SBW	*	*	*	52.8	64.4	12.4	*	*	*	*	11.6	-52	*	*	*	*	*	3.867	-17.333	*	*	27	SBW
28	5	CT	*	*	*	*	*	*	*	*	*	*	*	*	*	*								28	CT
28	5	CB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	28	CB
28	5	SBW	*	*	*	43.9	59.7	8.7	*	*	*	*	15.8	-51	*	*	*	*	*	5.267	-17	*	*	28	SBW
29	5	CT	*	*	*	*	*	*	*	*	*	*	*	*	*	*								29	CT
29	5	CB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	29	CB
29	5	SBW	*	*	*	58.1	49.5	7.1	*	*	*	*	-8.6	-42.4	*	*	*	*	*	-2.87	-14.13	*	*	29	SBW
31	7	CT	41.7	31.3	39.7	30.4	22	13.5	9.2	-10.40	8.40	-9.30	-8.40	-8.50	-28.20	-17.80	-2.60		-0.52	-2.80	-2.83	-0.43	-0.29	31	CT
31	7	CB	46.9	44.6	51.8	35.6	30.5	26.8	*	-2.30	7.20	-16.20	-5.10	-3.70	-20.10	-17.80	-0.58	0.19	-0.90	-1.70	-1.23	-0.31	-0.29	31	CB
30	7	CT	26.2	29.9	26.9	23	17.6	13.1	14	3.70	-3.00	-3.90	-5.40	-4.50	-13.10	-16.80		-0.08	-0.22	-1.80	-1.50	-0.20	-0.27	30	CT
30	7	CB	46.1	33.5	41.5	31.1	26	24.8	*	-12.60	8.00	-10.40	-5.10	-1.20	-21.30	-8.70	-3.15	0.21	-0.58	-1.70	-0.40	-0.32	-0.14	30	CB
311	7	CT	52.8	45.7	49.1	54.3	36.3	35.7	30.6	-7.10	3.40	5.20	-18.00	-0.60	-17.10	-10.00	-1.78			-6.00	-0.20	-0.26	-0.16		
311	7	CB	67.9	65.2	68.5	55.6	40.4	45.6	*	-2.70	3.30	-12.90	-15.20	5.20	-22.30	-19.60	-0.68	0.09	-0.72	-5.07	1.73	-0.34	-0.32		
321	7	CT	34.2	48.5	50.3	41.1	34.1	34.4	36.4	14.30	1.80	-9.20	-7.00	0.30	0.20	-14.10			-0.51	-2.33			-0.23		
321	7	CB	72	68.9	72.7	58.1	52.4	49.9	*	-3.10	3.80	-14.60	-5.70	-2.50	-22.10	-19.00	-0.78	0.10	-0.81	-1.90	-0.83	-0.34	-0.31		
331	7	CT	48.6	47.5	50.4	48.3	47.5	48.6	49.8	-1.10	2.90	-2.10	-0.80	1.10	0.00	1.10	-0.28		-0.12	-0.27					
331	7	CB	75.9	72.8	77.5	71	66.1	64.8	*	-3.10		-6.50	-4.90	-1.30	-11.10	-8.00	-0.78	0.00	-0.36	-1.63	-0.43	-0.17	-0.13		
341	7	CT	47.7	37	49.3	44.2	36.2	35.6	36.5	-10.70	12.30	-5.10	-8.00	-0.60	-12.10	-1.40	-2.68		-0.28	-2.67	-0.20	-0.18	-0.02		
341	7	CB	78.7	75.3	78.3	73.7	70.1	67.7	*	-3.40		-4.60	-3.60	-2.40	-11.00	-7.60	-0.85	0.00	-0.26	-1.20	-0.80	-0.17	-0.12		
342	7	CT	30	28.6	29.7	25.5	27.6	30	29.5	-1.40	1.10	-4.20	2.10	2.40	0.00	1.40	-0.35		-0.23						
342	7	CB	80.3	72.3	72.1	74.6	72.7	71	*	-8.00		2.50	-1.90	-1.70	-9.30	-1.30	-2.00	0.00	0.14	-0.63	-0.57	-0.14	-0.02		
30	7	SBW	*	*	*	81	90.1	108.9	*	*	*	*	9.1	18.8	*	*	*	*	*	3.033	6.267	*	*	30	SBW
31	7	SBW	*	*	*	77.9	78.1	105.3	*	*	*	*	0.2	27.2	*	*	*	*	*	0.067	9.067	*	*	31	SBW
32	7	CB	66.7	65.7	67	49.5	46.1	43.3	*	-1.00	1.30	-17.50	-3.40	-2.80	-23.40	-22.40	-0.25	0.03	-0.97	-1.13	-0.93	-0.36	-0.36	32	CB
33	7	CT	55.1	45.7	50.3	39.5	32.3	29.8	23.1	-9.40	4.60	-10.80	-7.20	-2.50	-25.30	-15.90	-2.35		-0.60	-2.40	-0.83	-0.38	-0.26	33	CT
33	7	CB	71.7	68.7	71.3	58.9	56.9	54.8	*	-3.00	2.60	-12.40	-2.00	-2.10	-16.90	-13.90	-0.75	0.07	-0.69	-0.67	-0.70	-0.26	-0.22	33	CB
32	7	CT	47.6	36.8	44.9	34.3	32.6	26.7	26.2	-10.80	8.10	-10.60	-1.70	-5.90	-20.90	-10.10	-2.70		-0.59	-0.57	-1.97	-0.32	-0.16	32	CT
34	7	CB	74	68.4	74.5	68.5	63	64.2	*	-5.60	6.10	-6.00	-5.50	1.20	-9.80	-4.20	-1.40	0.16	-0.33	-1.83	0.40	-0.15	-0.07	34	CB
34	7	CT	45.4	43.4	46.8	45.2	45.1	40	38.5	-2.00	3.40	-1.60	-0.10	-5.10	-5.40	-3.40	-0.50		-0.09	-0.03	-1.70	-0.08	-0.06	34	CT
32	7	SBW	*	*	*	87.5	71.1	71.6	*	*	*	*	-16.4	0.5	*	*	*	*	*	-5.47	0.167	*	*	32	SBW
33	7	SBW	*	*	*	90.9	75.9	80.5	*	*	*	*	-15	4.6	*	*	*	*	*	-5.00	1.533	*	*	33	SBW
34	7	SBW	*	*	*	96.4	78.5	94.1	*	*	*	*	-17.9	15.6	*	*	*	*	*	-5.97	5.2	*	*	34	SBW
37	8	CT	29.5	35.7	27.2	27.4	31.7	27.9	*	6.20	-8.50	0.20	4.30	-3.80	-1.60	-7.80		-0.22			-1.27	-0.02	-0.13	37	CT

			DISTANCE FROM DATUM							TOTAL CHANGE							MEAN ANNUAL RATE OF CHANGE (m/year)								
Profile	CBU	Feature	1946	1950	1988	2006	2009	2012	2015	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	Profile	Feature
36	8	CT	28.1	26.6	25.4	21.5	23.2	22.3	*	-1.50	-1.20	-3.90	1.70	-0.90	-5.80	-4.30	-0.38	-0.03	-0.22		-0.30	-0.09	-0.07	36	CT
36	8	CB	108.2	98.7	98.9	101.2	98.8	94.6	*	-9.50	0.20	2.30	-2.40	-4.20	-13.60	-4.10	-2.38	0.01	0.13	-0.80	-1.40	-0.21	-0.07	36	CB
35	8	CB	93.4	86	93.9	85.7	82.9	82.7	*	-7.40	7.90	-8.20	-2.80	-0.20	-10.70	-3.30	-1.85	0.21	-0.46	-0.93	-0.07	-0.16	-0.05	35	CB
37	8	CB		87.2	90.3	89.8	89.9	87.2	*	87.20	3.10	-0.50	0.10	-2.70	87.20	0.00	21.80	0.08	-0.03	0.03	-0.90	1.32	0.00	37	CB
35	8	CT	29.3	25.8	27.7	25.5	25.9	27	*	-3.50	1.90	-2.20	0.40	1.10	-2.30	1.20	-0.88		-0.12			-0.04		35	CT
35	8	SBW		*	*	118.4	*	112.8	*	*	*	*	*	*	112.8	*	*	*	*	*	*	1.709	*	35	SBW
36	8	SBW		*	*	132.4	*	119.5	*	*	*	*	*	*	119.5	*	*	*	*	*	*	1.811	*	36	SBW
37	8	SBW		*	*	122	*	110.9	*	*	*	*	*	*	110.9	*	*	*	*	*	*	1.68	*	37	SBW
38	8	CB		61.2	58.1	58.1	60.6	54.4	*	61.20	-3.10	0.00	2.50	-6.20	54.40	-6.80	15.30	-0.08	0.00	0.83	-2.07	0.82	-0.11	38	CB
40	8	CT		19.1	15.7	13.8	16	15.6	*	19.10	-3.40	-1.90	2.20	-0.40	15.60	-3.50		-0.09	-0.11		-0.13		-0.06	40	CT
38	8	CT	29.3	23.4	20.8	22.7	24.3	22.8	*	-5.90	-2.60	1.90	1.60	-1.50	-6.50	-0.60	-1.48	-0.07			-0.50	-0.10	-0.01	38	CT
40	8	CB		43.2	40.8	45.7	43.9	46.5	*	43.20	-2.40	4.90	-1.80	2.60	46.50	3.30	10.80	-0.06	0.27	-0.60	0.87	0.71	0.05	40	CB
39	8	CT	47.8	31.2	34.5	34	35.8	35.2	*	-16.60	3.30	-0.50	1.80	-0.60	-12.60	4.00	-4.15		-0.03		-0.20	-0.19		39	CT
39	8	CB		68.9	67.9	73.2	74.6	73.3	*	68.90	-1.00	5.30	1.40	-1.30	73.30	4.40	17.23	-0.03	0.29	0.47	-0.43	1.11	0.07	39	CB
38	8	SBW		*	*	89.5	*	83.1	*	*	*	*	*	*	83.1	*	*	*	*	*	*	1.26	*	38	SBW
39	8	SBW		*	*	104.7	*	98	*	*	*	*	*	*	98	*	*	*	*	*	*	1.49	*	39	SBW
40	8	SBW		*	*	80	*	75	*	*	*	*	*	*	75	*	*	*	*	*	*	1.14	*	40	SBW
41	8	CB		128.4	121.9	126	122.6	122.6	*	128.40	-6.50	4.10	-3.40	0.00	122.60	-5.80	32.10	-0.17	0.23	-1.13	0.00	1.86	-0.09	41	CB
42	8	CT		40	45	38.9	39.4	39	*	40.00	5.00	-6.10	0.50	-0.40	39.00	-1.00			-0.34		-0.13		-0.02	42	CT
42	8	CB		124.7	123	126.6	128.2	126.3	*	124.70	-1.70	3.60	1.60	-1.90	126.30	1.60	31.18	-0.05	0.20	0.53	-0.63	1.91	0.03	42	CB
41	8	CT		42.6	45.1	44.1	44.8	44.6	*	42.60	2.50	-1.00	0.70	-0.20	44.60	2.00			-0.06		-0.07			41	CT
43	8	CT		24.7	24.9	25.8	27.8	28.2	*	24.70	0.20	0.90	2.00	0.40	28.20	3.50								43	CT
43	8	CB		87.6	86.9	93.3	93	95.8	*	87.60	-0.70	6.40	-0.30	2.80	95.80	8.20	21.90	-0.02	0.36	-0.10	0.93	1.45	0.13	43	CB
41	8	SBW	*	*	*	161	*	154.1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	41	SBW
42	8	SBW	*	*	*	166.2	*	164.3	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	42	SBW
43	8	SBW	*	*	*	131.8	*	132.8	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	43	SBW
46	8	CB	*	56.8	59.2	61.6	61.3	63.8	*	*	2.4	2.4	-0.3	2.5	*	7	*	0.06	0.13	-0.10	0.83	*	0.11	46	CB
44	8	CB	*	69.3	72.1	75.9	76	77	*	*	2.8	3.8	0.1	1	*	7.7	*	0.07	0.21	0.03	0.33	*	0.12	44	CB
44	8	CT	*	48.7	54.4	*	*	*	*	*	5.7	*	*	*	*	*								44	CT
44	8	SBW	*	*	*	117.2	*	122.8	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	44	SBW
45	8	CT	*	63.8	62	*	*	*	*	*	-1.8	*	*	*	*	*		-0.05						45	CT
45	8	CB	*	*	73	71	70.5	66.5	*	*	*	-2	-0.5	-4	*	*	*	*	-0.11	-0.17	-1.33	*	*	45	CB
45	8	SBW	*	*	*	116.4	*	122.2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	45	SBW
46	8	CT	*	*	*	18.4	19	18.5	*	*	*	*	0.6	-0.5	*	*					-0.167			46	CT
46	8	SBW	*	*	*	105.9	*	108.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	46	SBW
49	8	CB	*	109.9	102.2	114.2	115.3	100.9	*	*	-7.7	12	1.1	-14.4	*	-9	*	-0.20	0.67	0.37	-4.80	*	-0.15	49	CB
48	8	CB	*	84.1	79	91.4	91.9	79.5	*	*	-5.1	12.4	0.5	-12.4	*	-4.6	*	-0.13	0.69	0.17	-4.13	*	-0.07	48	CB
47	8	CB	*	94.5	99.7	102.1	102.1	93.2	*	*	5.2	2.4	0	-8.9	*	-1.3	*	0.14	0.13	0.00	-2.97	*	-0.02	47	CB

			DISTANCE FROM DATUM							TOTAL CHANGE							MEAN ANNUAL RATE OF CHANGE (m/year)								
Profile	CBU	Feature	1946	1950	1988	2006	2009	2012	2015	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	1946-1950	1950-1988	1988-2006	2006-2009	2009-2012	1946-2012	1950-2012	Profile	Feature
49	8	CT	*	30.5	31.6	36.3	35.4	34.8	*	*	1.1	4.7	-0.9	-0.6	*	4.3				-0.30	-0.20			49	CT
47	8	CT	*	46.4	50.2	52	52	51.8	*	*	3.8	1.8	0	-0.2	*	5.4				0.00	-0.07			47	CT
48	8	CT	*	24.2	28.7	30.2	30.1	29.7	*	*	4.5	1.5	-0.1	-0.4	*	5.5				-0.03	-0.13			48	CT
47	8	SBW	*	*	*	143.3	*	150.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	47	SBW
48	8	SBW	*	*	*	*	*	142.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	48	SBW
49	8	SBW	*	*	*	*	*	169.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	49	SBW
51	8	CT	*	40.6	42	48	31.3	28.9	*	*	1.4	6	-16.7	-2.4	*	-11.7				-5.57	-0.80		-0.2	51	CT
50	8	CB	*	137.6	135.6	139.1	140.05	132	*	*	-2	3.5	0.95	-8.05	*	-5.6	*	-0.05	0.19	0.32	-2.68	*	-0.09	50	CB
50	8	CT	*	41.5	42.4	41.9	41.2	42	*	*	0.9	-0.5	-0.7	0.8	*	0.5			-0.03	-0.23				50	CT
51	8	CB	*	173	160.6	207.9	*	218.2	*	*	-12.4	47.3	*	*	*	45.2	*	-0.33	2.63	*	*	*	0.73	51	CB
50	8	SBW	*	*	*	*	*	195.5	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	50	SBW
51	8	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	51	SBW
52	8	CT	*	*	52.1	42.1	*	35	*	*	*	-10	*	*	*	*			-0.56					52	CT
52	8	CB	*	*	170.7	235.1	*	239.3	*	*	*	64.4	*	*	*	*	*	*	3.58	*	*	*	*	52	CB
52	8	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	52	SBW
53	8	CT	*	*	28.1	27.8	*	23.6	*	*	*	-0.3	*	*	*	*			-0.02					53	CT
53	8	CB	*	*	159.9	162.8	*	161.2	*	*	*	2.9	*	*	*	*	*	*	0.16	*	*	*	*	53	CB
53	8	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	53	SBW
54	8	CT	*	*	61.2	53.2	*	46.1	*	*	*	-8	*	*	*	*			-0.44					54	CT
54	8	CB	*	*	211.6	216.1	*	216.3	*	*	*	4.5	*	*	*	*	*	*	0.25	*	*	*	*	54	CB
54	8	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	54	SBW
55	8	CT	*	*	59.8	60	*	46.8	*	*	*	0.2	*	*	*	*								55	CT
55	8	CB	*	*	183.3	184.4	*	184.9	*	*	*	1.1	*	*	*	*	*	*	0.06	*	*	*	*	55	CB
55	8	SBW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	55	SBW

Appendix C – Beach Profiles

Data

Details of the timings and frequencies of each beach profile survey completed since 2007 under the current monitoring programme are included in Table C.1. For reference, the current beach profile name is tabulated against previous profiles names, including those of the Posford Duvivier 1995 to 1998 analysis, and the first monitoring campaign completed between 2000 and 2005. It became evident when undertaking the new analysis, that there are some inconsistences and data gaps in the beach monitoring profile data. These include:

- Within the BMP extent, PCO monitor all profiles from 6a01463 to 6a01441 annually during the summer, a process which has been completed since 2007. However, a review of the available beach profile data downloaded from the PCO website shows that:
- In 2011, the survey location for three of the profiles changed; namely 6a01453 to 6a01453A, 6a01450 to 6a01449, and 6a01445 to 6a01446. Therefore the beach monitoring data for the full survey period from 2007 to 2014 cannot be compared consistently.
- It is also evident from the review of the downloaded data that two of the annual surveys are missing for the years 2011 and 2013.
- In addition to the annual survey, six of the profiles are monitored twice a year during the spring and autumn; profiles, these include: profiles 6a01463, 6a011456, 6a01453A, 6a01449, 6a01446, and 6a01441.
- Profile 6a01441 and 6a01463 – the profile lines stop short of the SANDS master profile and therefore estimates of CSA, and thus volume, will be underestimated.
- Profile 6a01442 – for some profiles the SANDS master profile is positioned seaward of the start of the data, which will lead to an underestimate of CSA and thus volume.
- Profile 6a01448 and 6a01450 – it has not been possible to capture some of the profile that is positioned landward of the master profile (i.e. on top of the seawall) and therefore CSA and volume is underestimated.

Table C.1 Table showing historical and current beach profiles, specific profile frequency for the current monitoring campaign. Orange shading indicates spring survey, purple annual survey and orange autumn survey. No shading means survey type is unknown.

PD 1995 to 1996 analysis	RH 2000 to 2005 Profile	PCO 2007 to Monitoring Profile	2007-04-18	2007-08-30	2007-10-25	2008-02-10	2008-06-03	2008-10-15	2009-03-14	2009-07-23	2009-11-16	2010-01-31	2010-09-10	2010-11-09	2011-02-18	2011-10-14	2012-03-14	2012-08-23	2012-08-31	2012-11-14	2013-05-09	2013-10-17	2014-01-	2014-02-18
Not included	Not included	6a01463	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1		1
Not included	Not included	6a01462	1	1			1			1			1					1						
Not included	Not included	6a01461	1	1			1			1			1					1						
Not included	Not included	6a01460	1	1			1			1			1					1						
Not included	Not included	6a01459	1	1			1			1			1					1						
A1	A	6a01458	1	1			1			1			1					1						
A2	B	6a01457	1	1			1			1			1					1						
A3	C	6a01456	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1
B1	D	6a01455	1	1			1			1			1					1						
B2	No equivalent	6a01454	1	1			1			1			1					1	1					
B2	E + E	6a01453A														1	1	1	1	1	1	1	1	1
B2	E + E	6a01453	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1					
B3	No equivalent	6a01452	1	1			1			1			1					1	1					
B4	F	6a01451	1	1			1			1			1					1	1					
B5	G	6a01450	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1					
B6	H	6a01449	1	1			1			1			1			1	1	1	1	1	1	1	1	1
B7	I	6a01448	1	1			1			1			1					1	1					
C1	J	6a01447	1	1			1			1			1					1	1					
C2	K	6a01446	1	1			1			1			1			1	1	1	1	1	1	1	1	1
C3	L	6a01445	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1					
D2	M	6a01444	1	1			1			1			1					1	1					
D3	N	6a01443	1	1			1			1			1					1	1					
Not included	Not included	6a01442		1			1			1			1					1	1					
Not included	Not included	6a01441		1	1		1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
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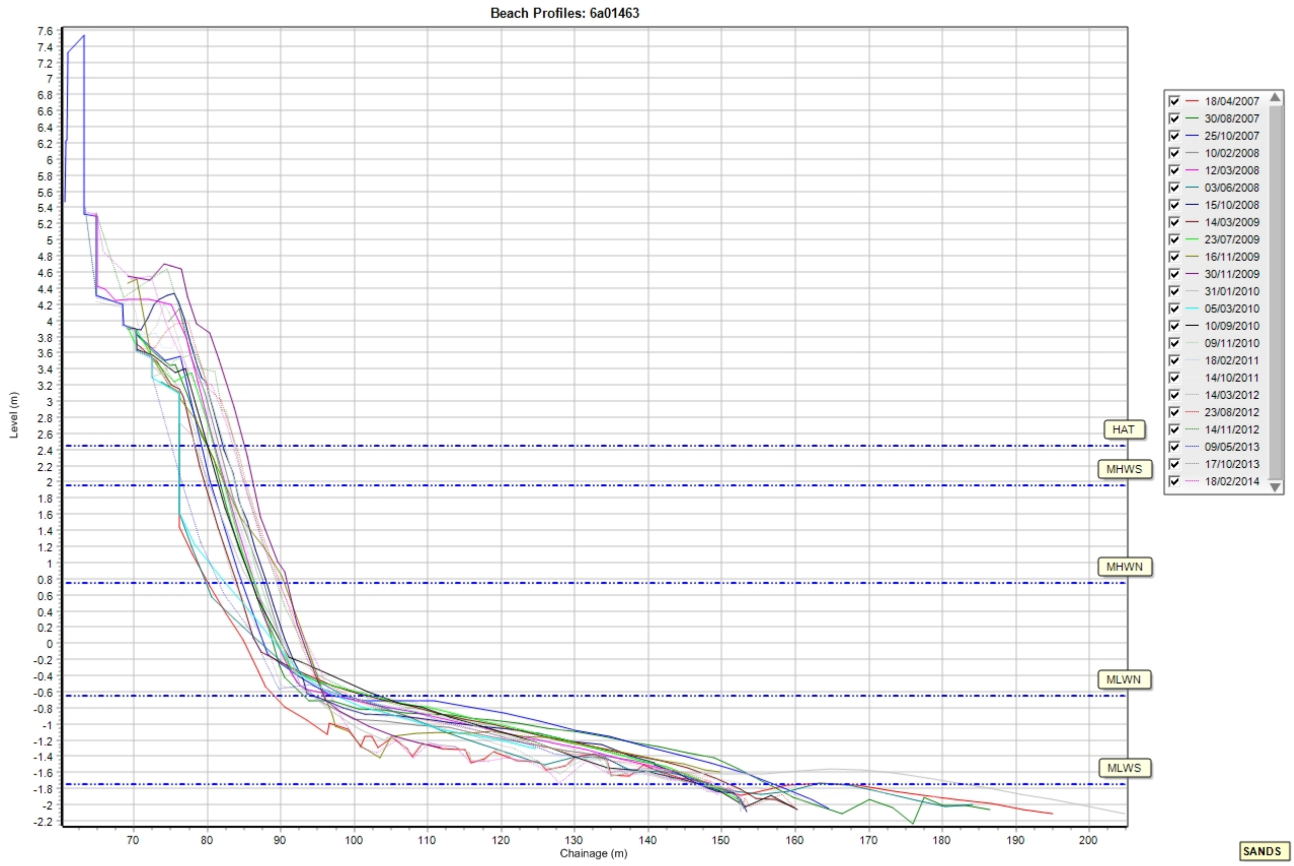
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10/02/2008
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03/06/2008
15/10/2008
14/03/2009
23/07/2009
16/11/2009
30/11/2009
31/01/2010
05/03/2010
10/09/2010
09/11/2010
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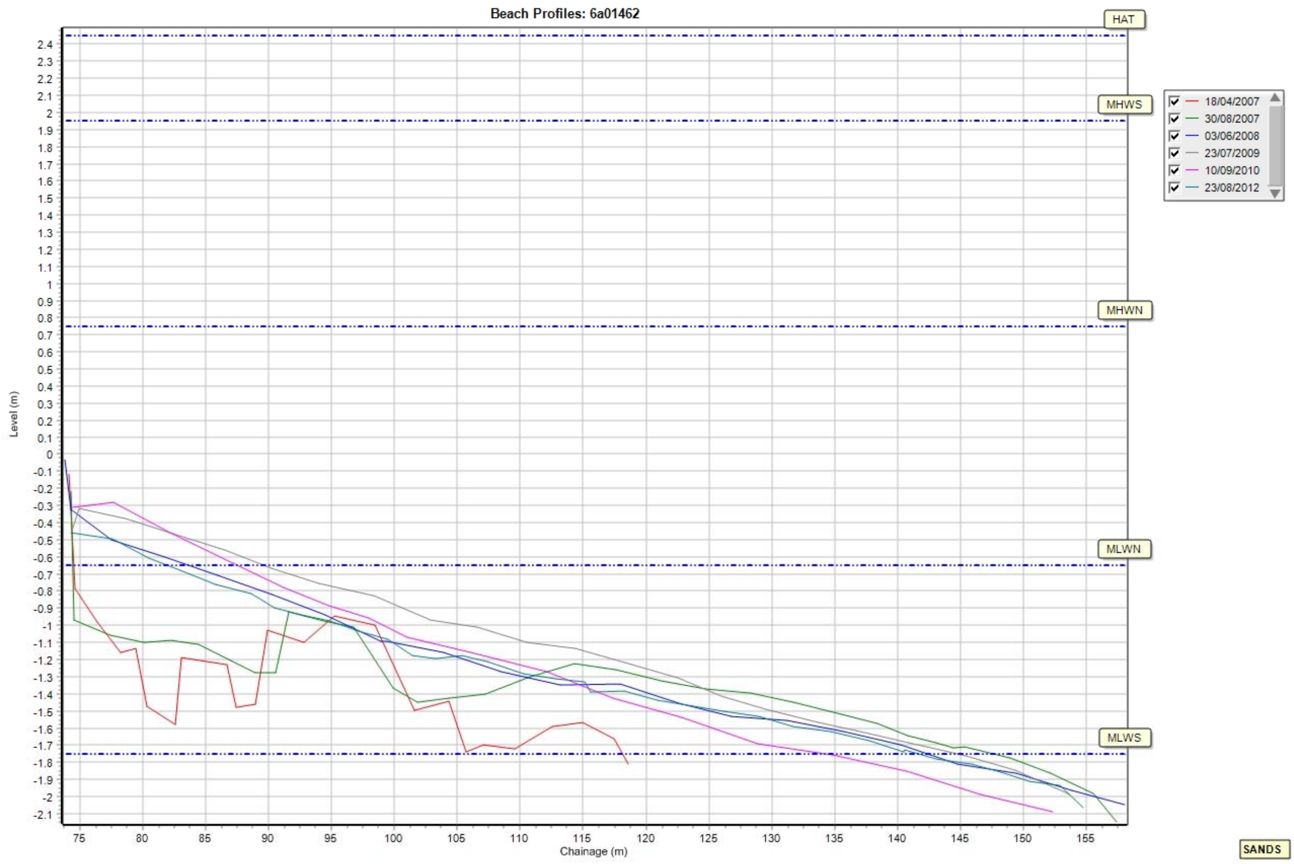
23/08/2012
14/11/2012
09/05/2013
17/10/2013
18/02/2014
SANDS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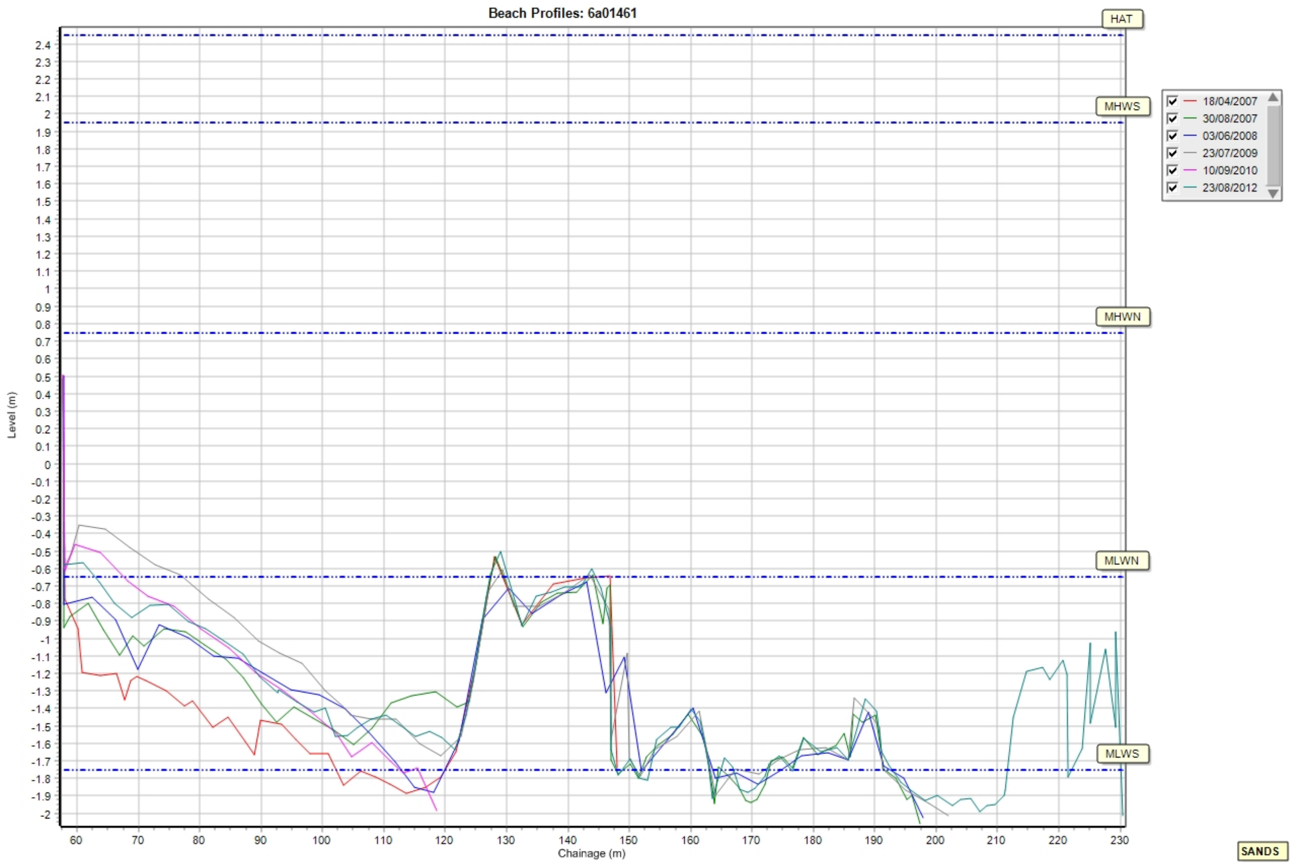
23/07/2009
10/09/2010
23/08/2012
SANDS



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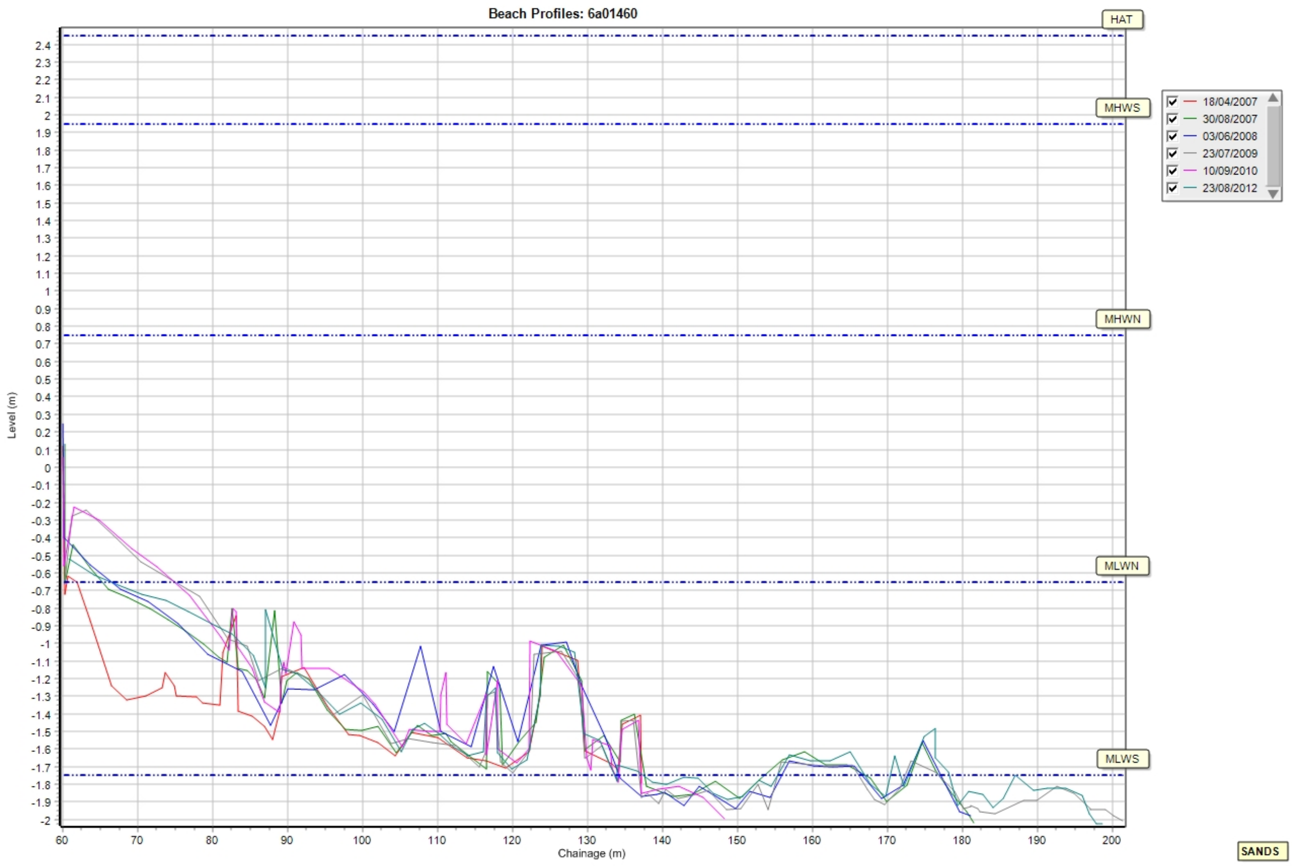
03/06/2008
23/07/2009
10/09/2010
23/08/2012
Level (m)
Chainage (m)
SANDS



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Level (m)
Chainage (m)
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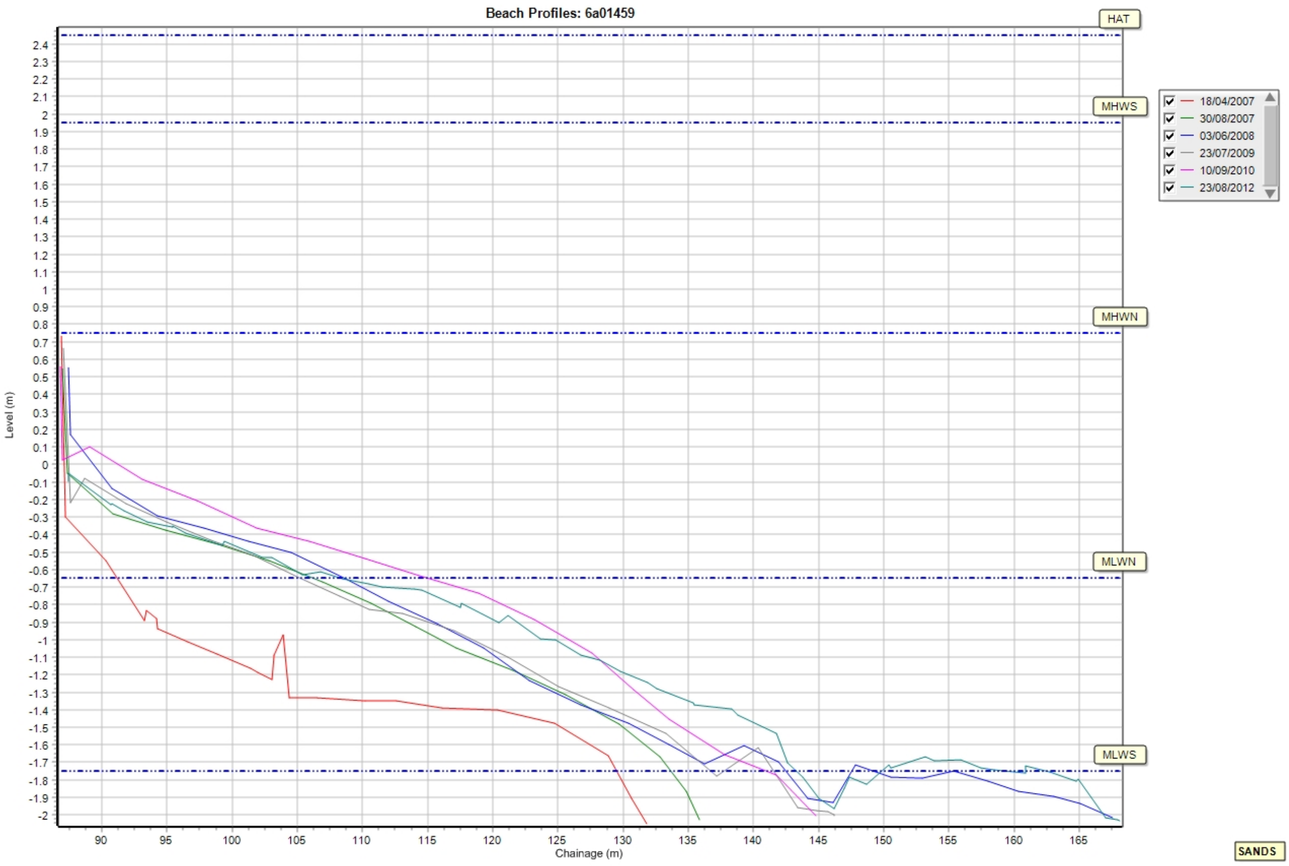

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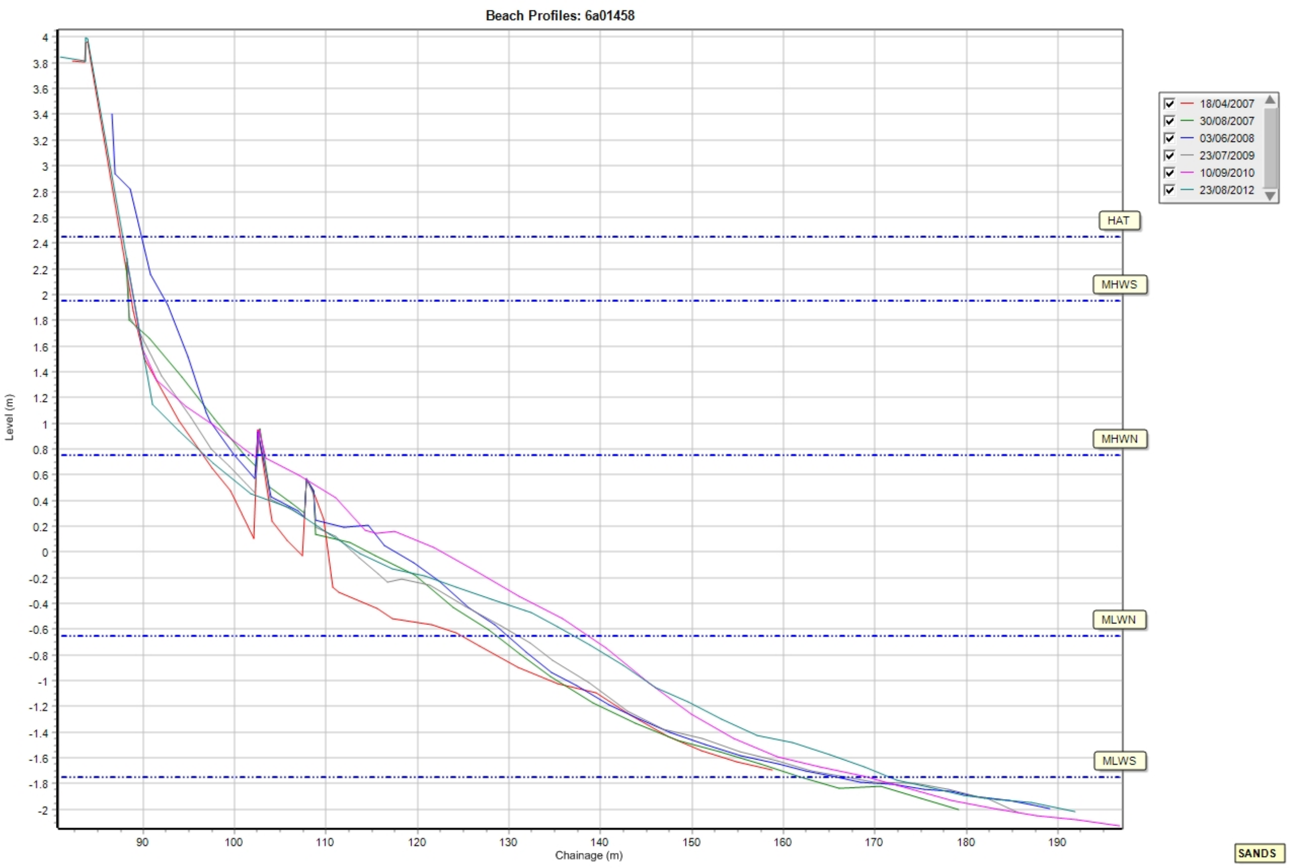

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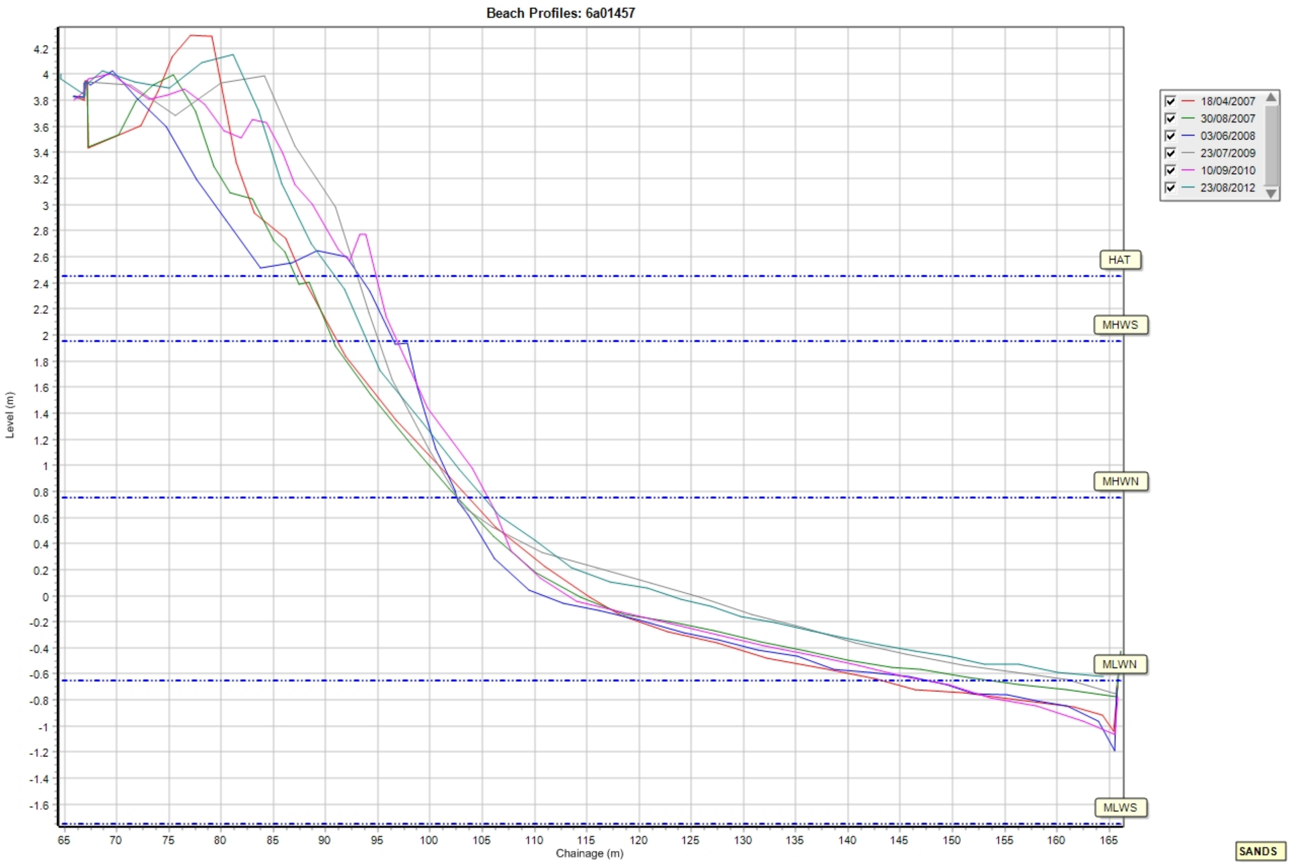
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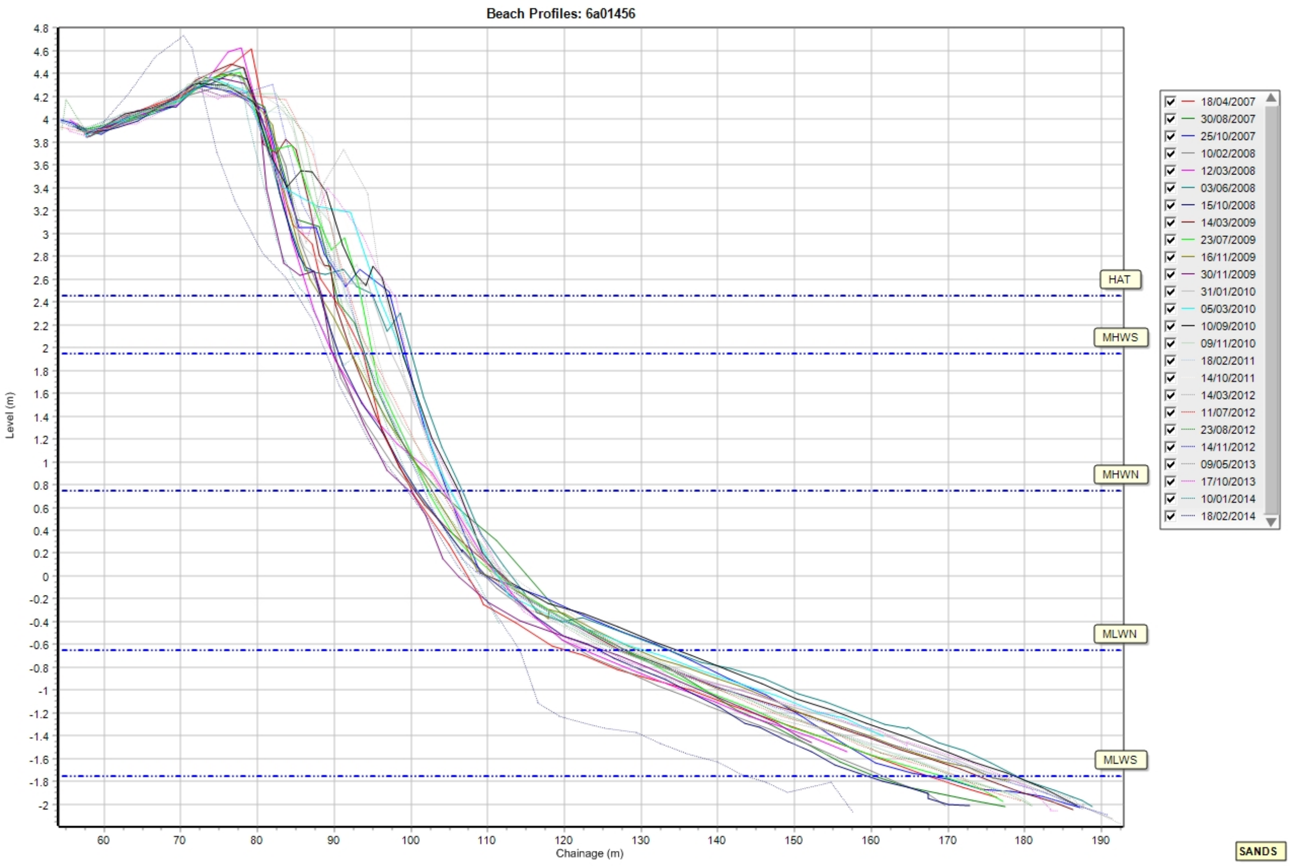
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10/01/2014
18/02/2014
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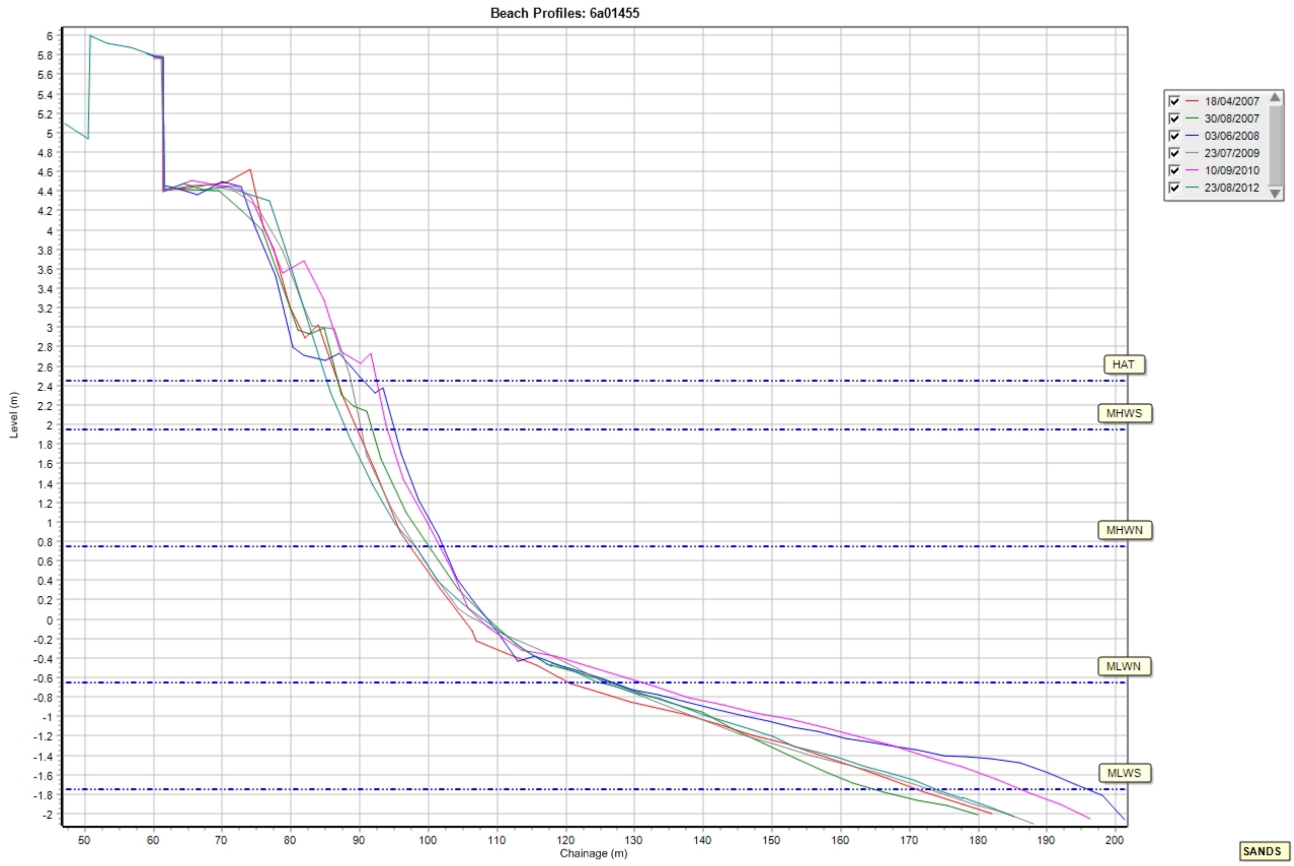
MLWN
MLWS
SANDS



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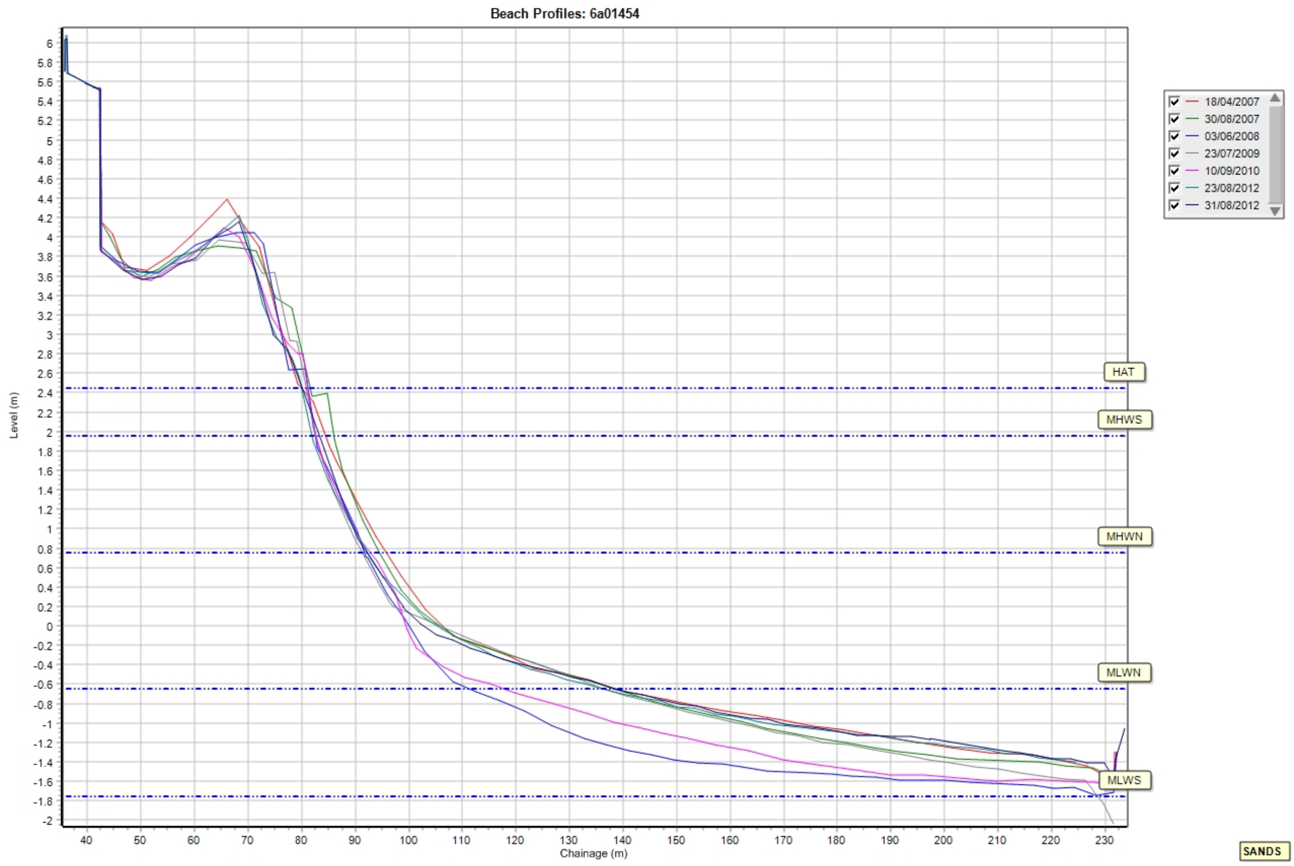

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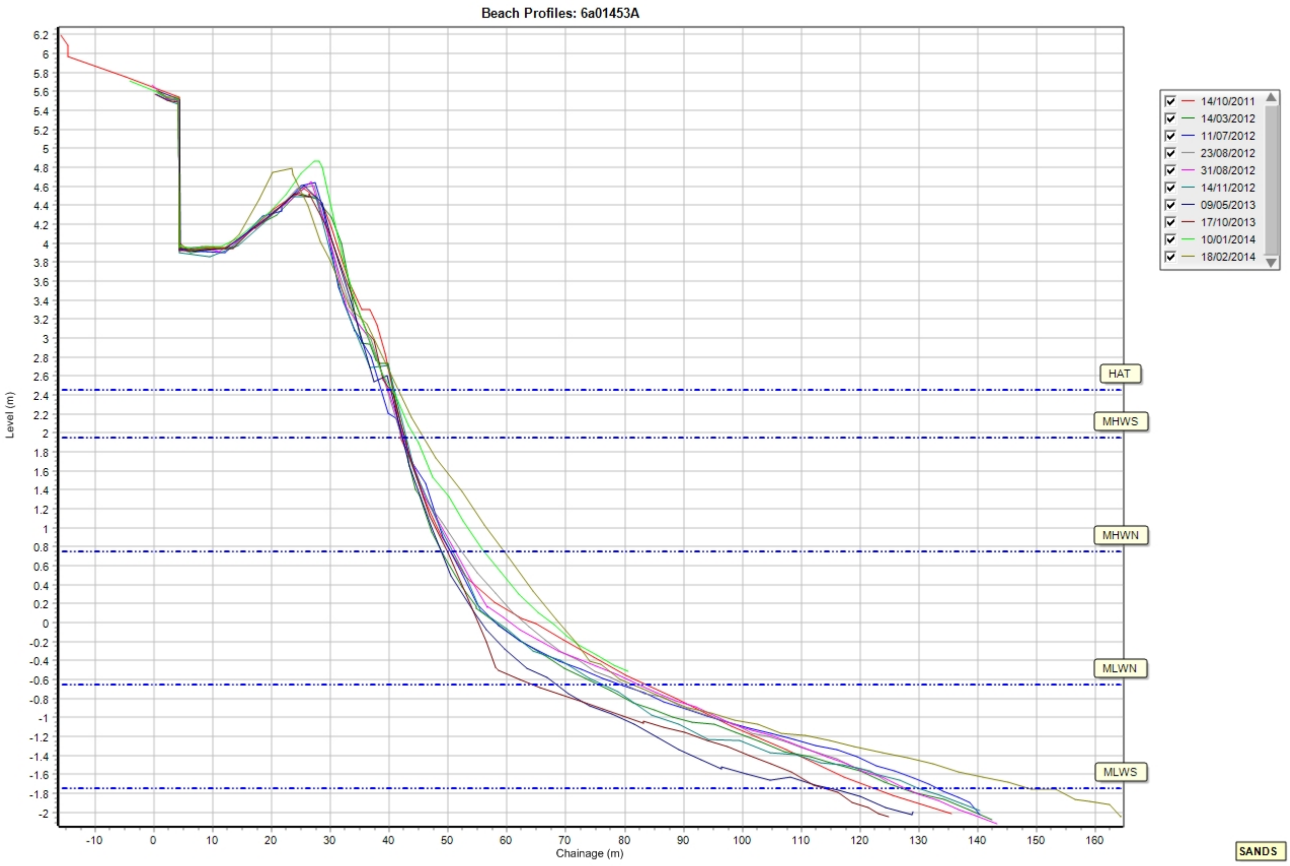
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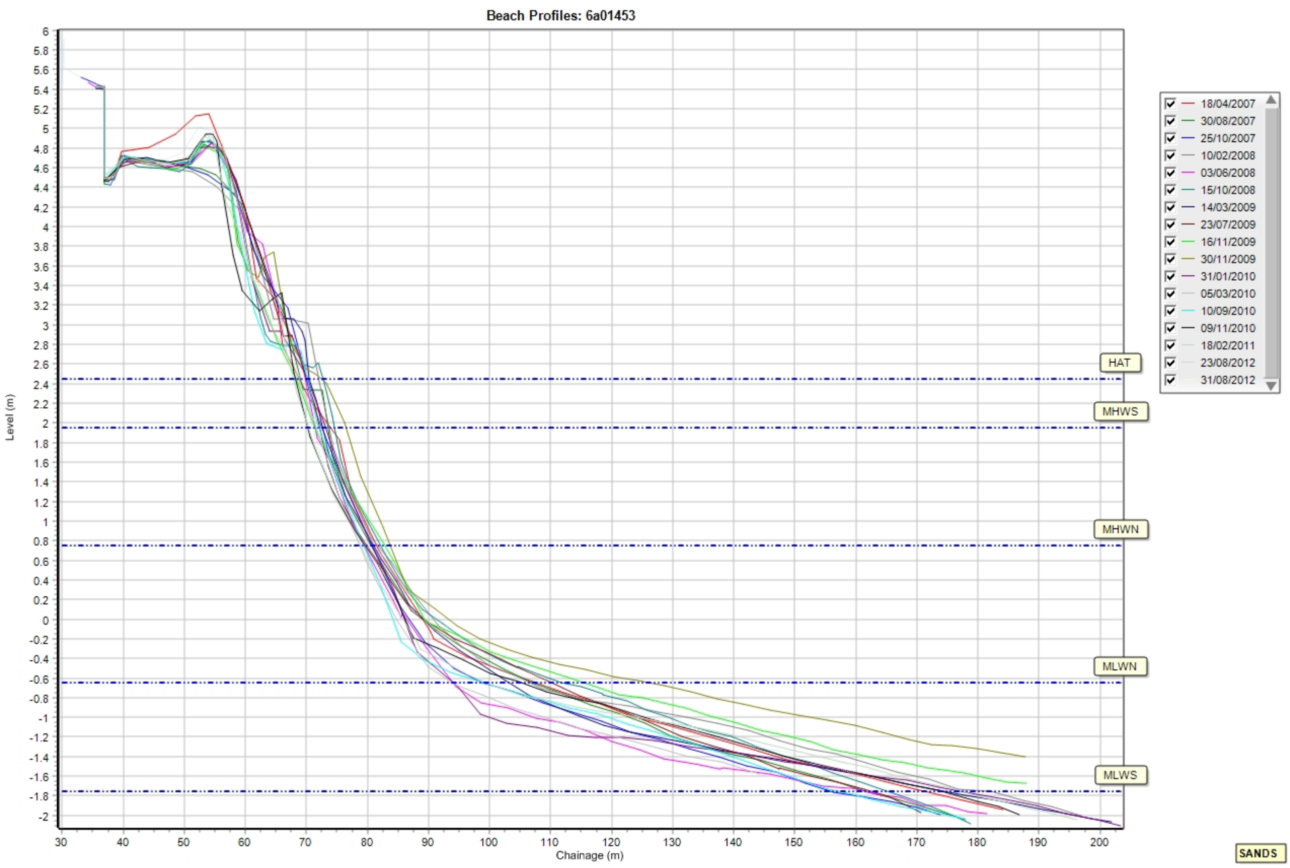
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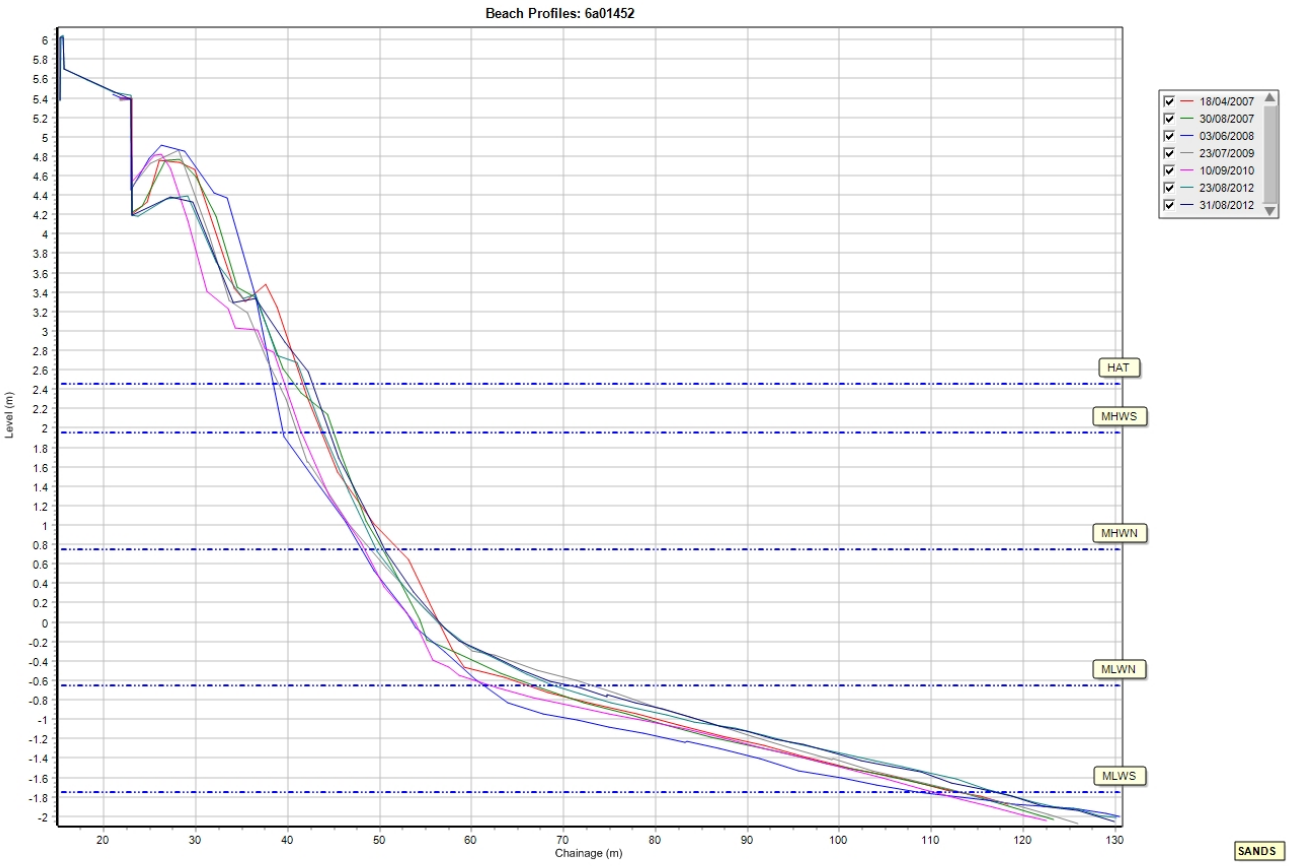
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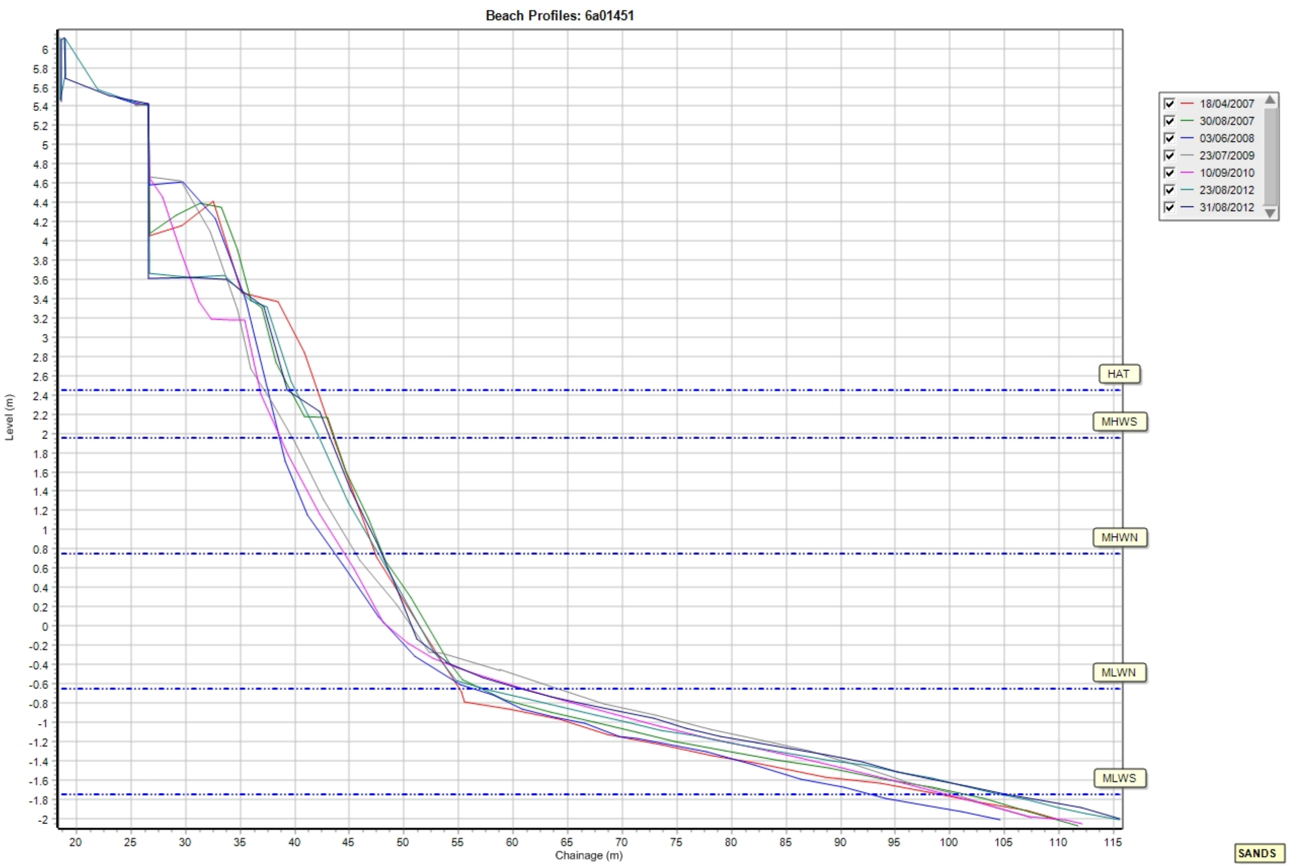
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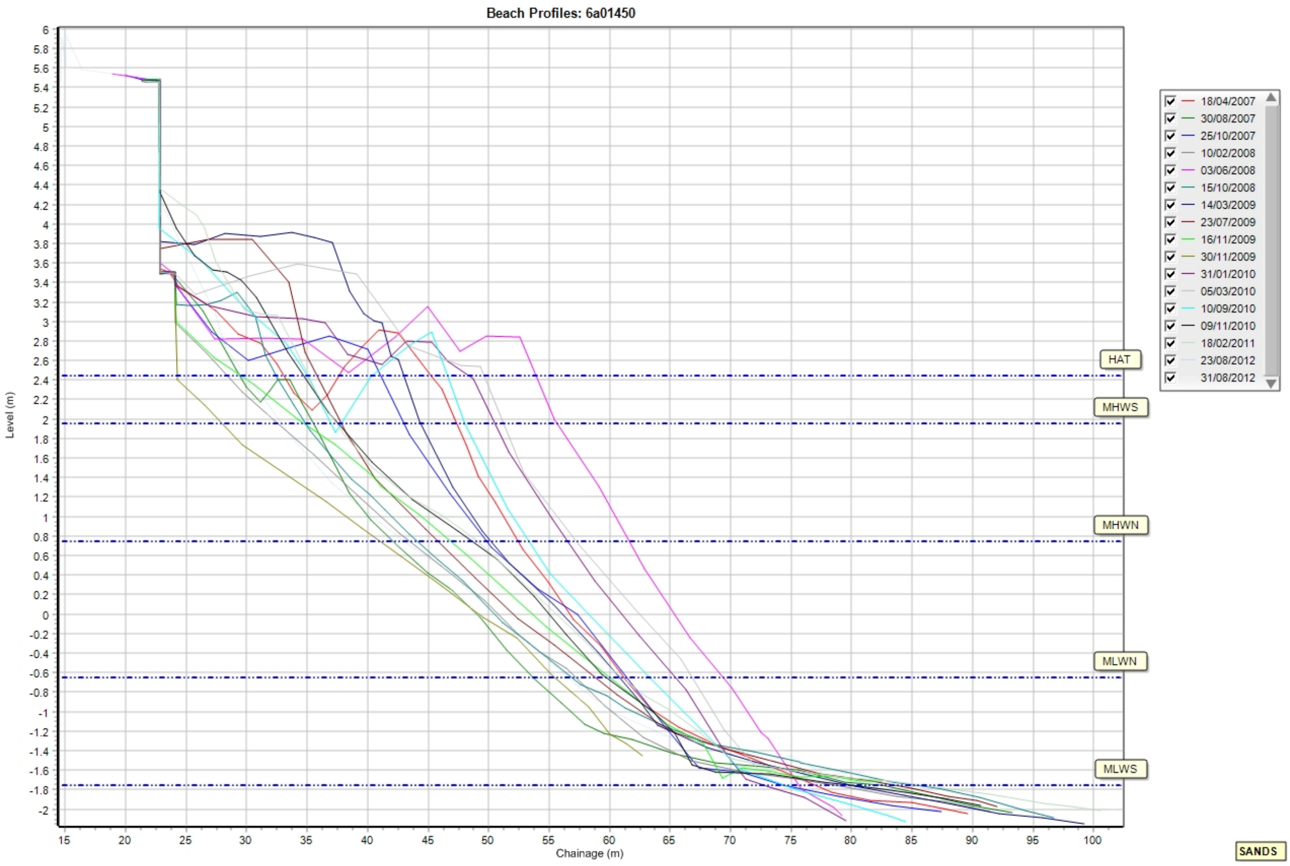
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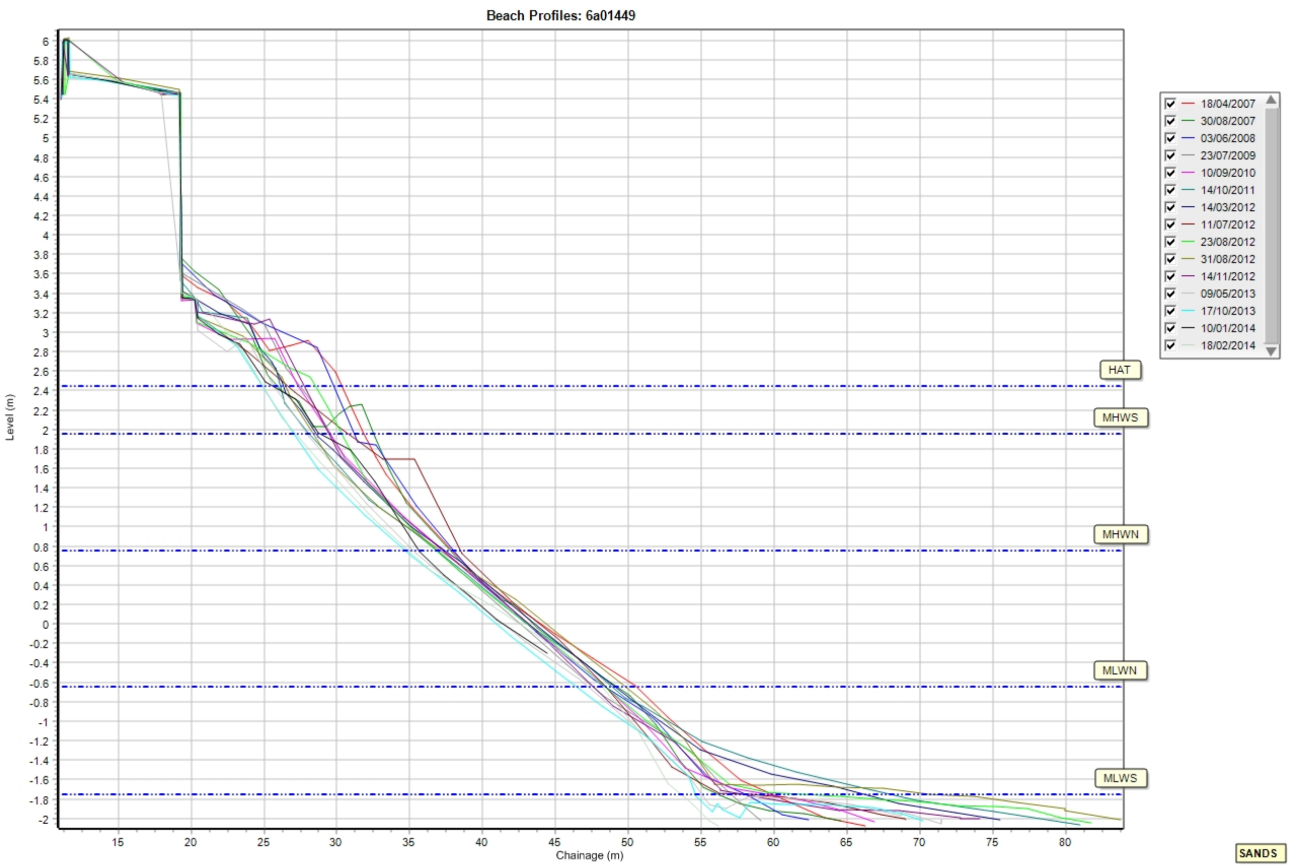
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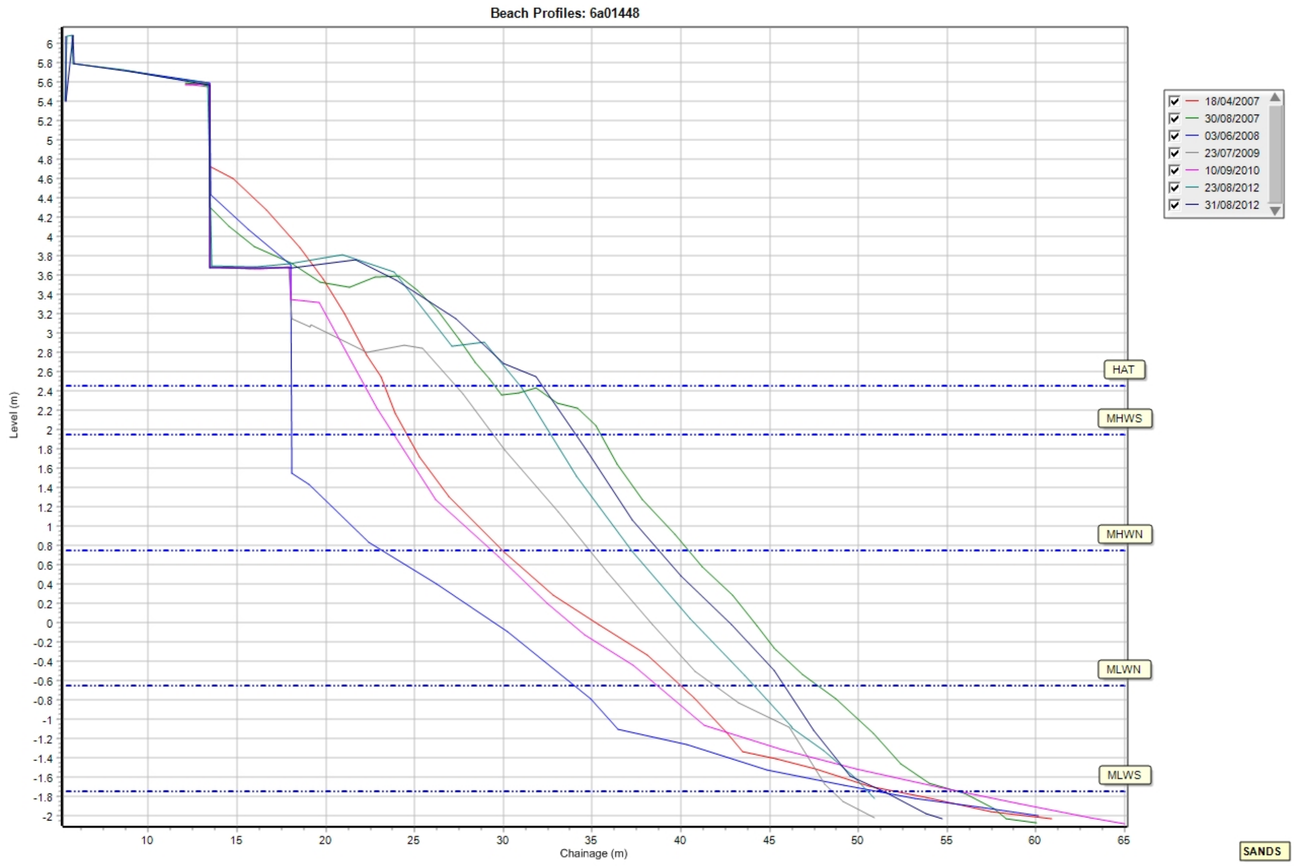
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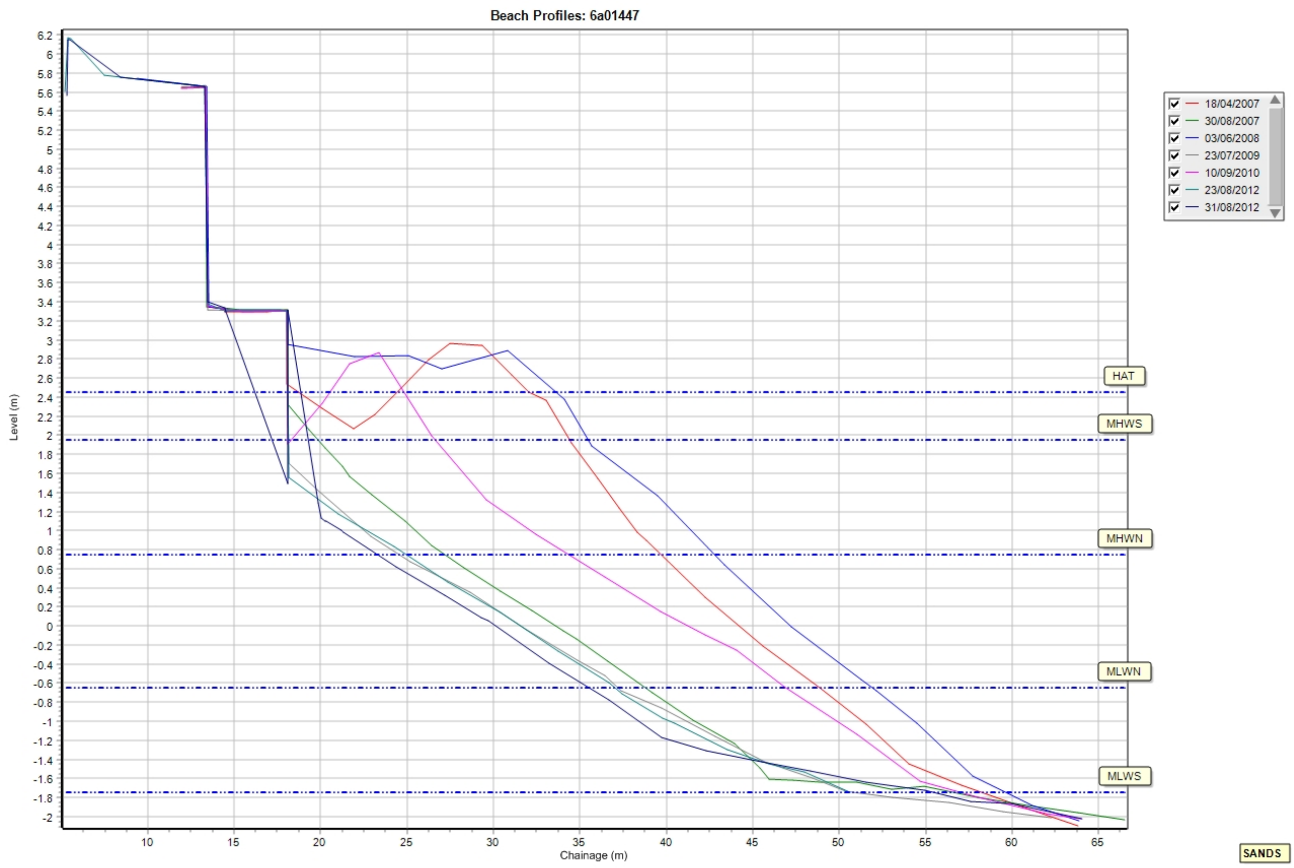
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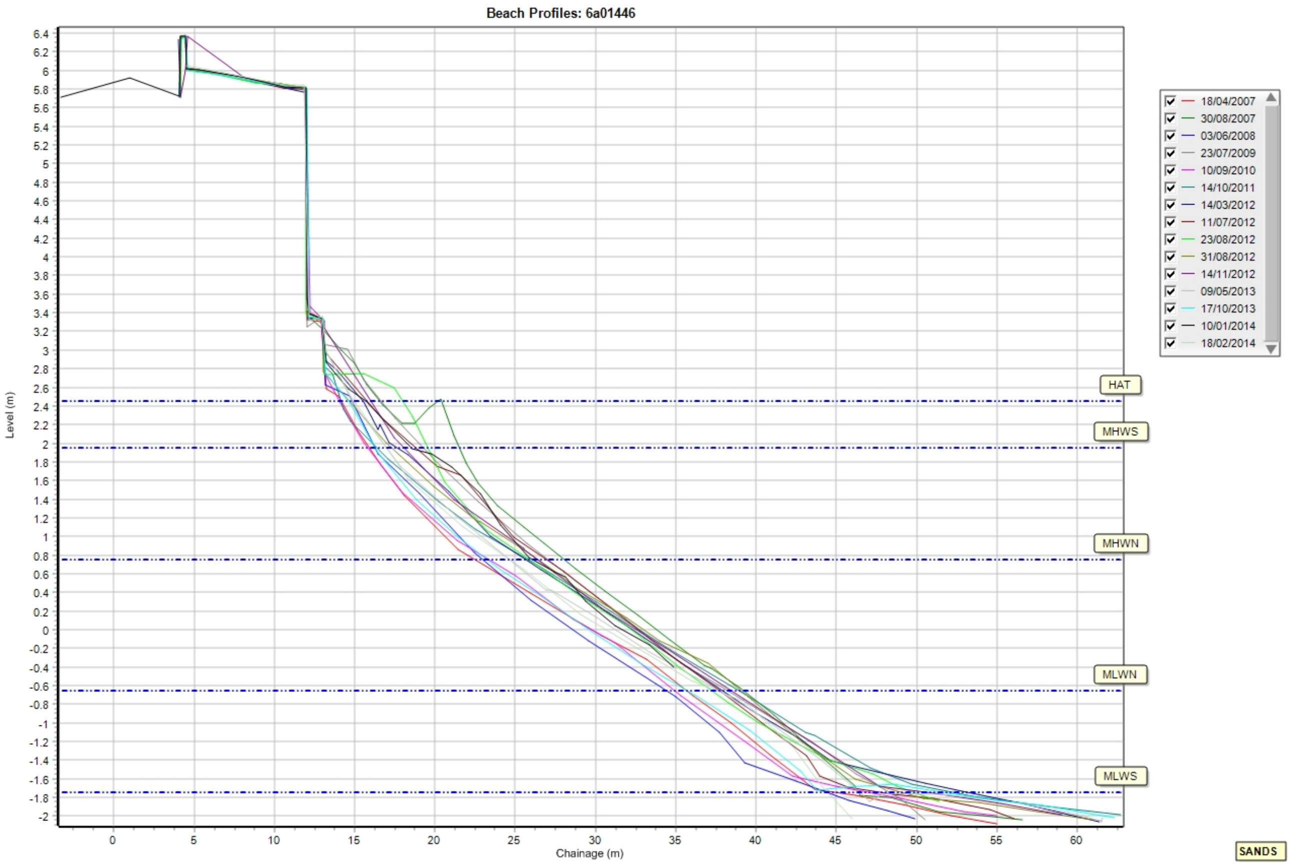
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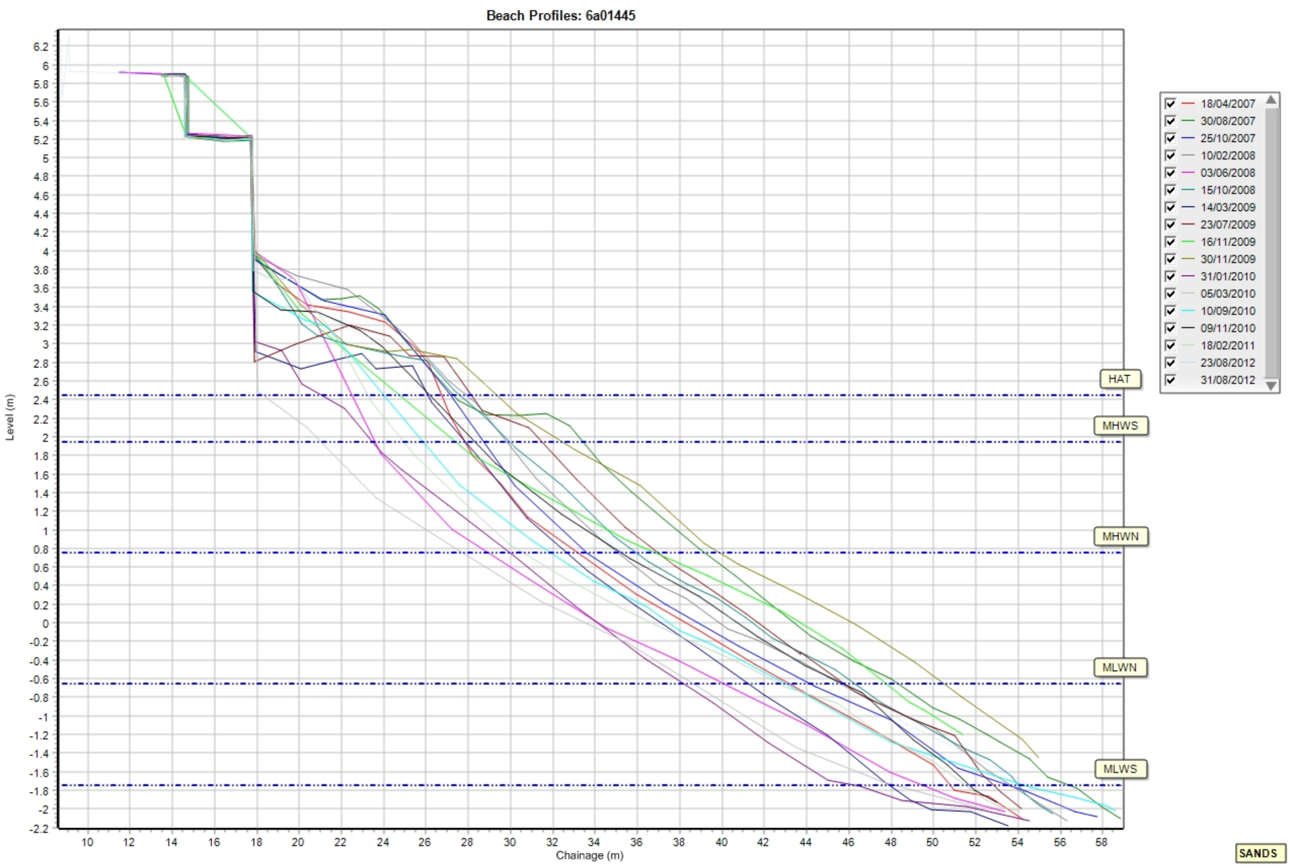
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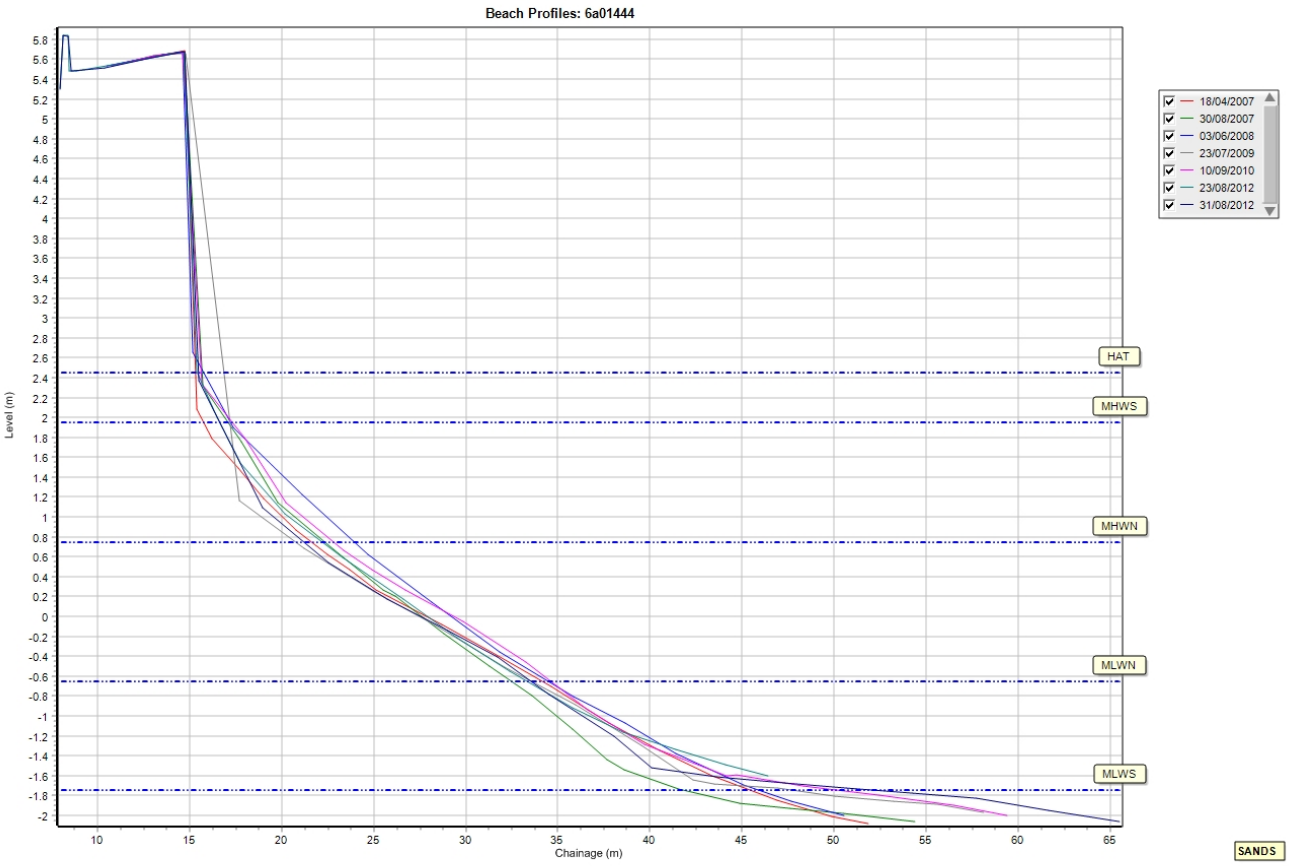
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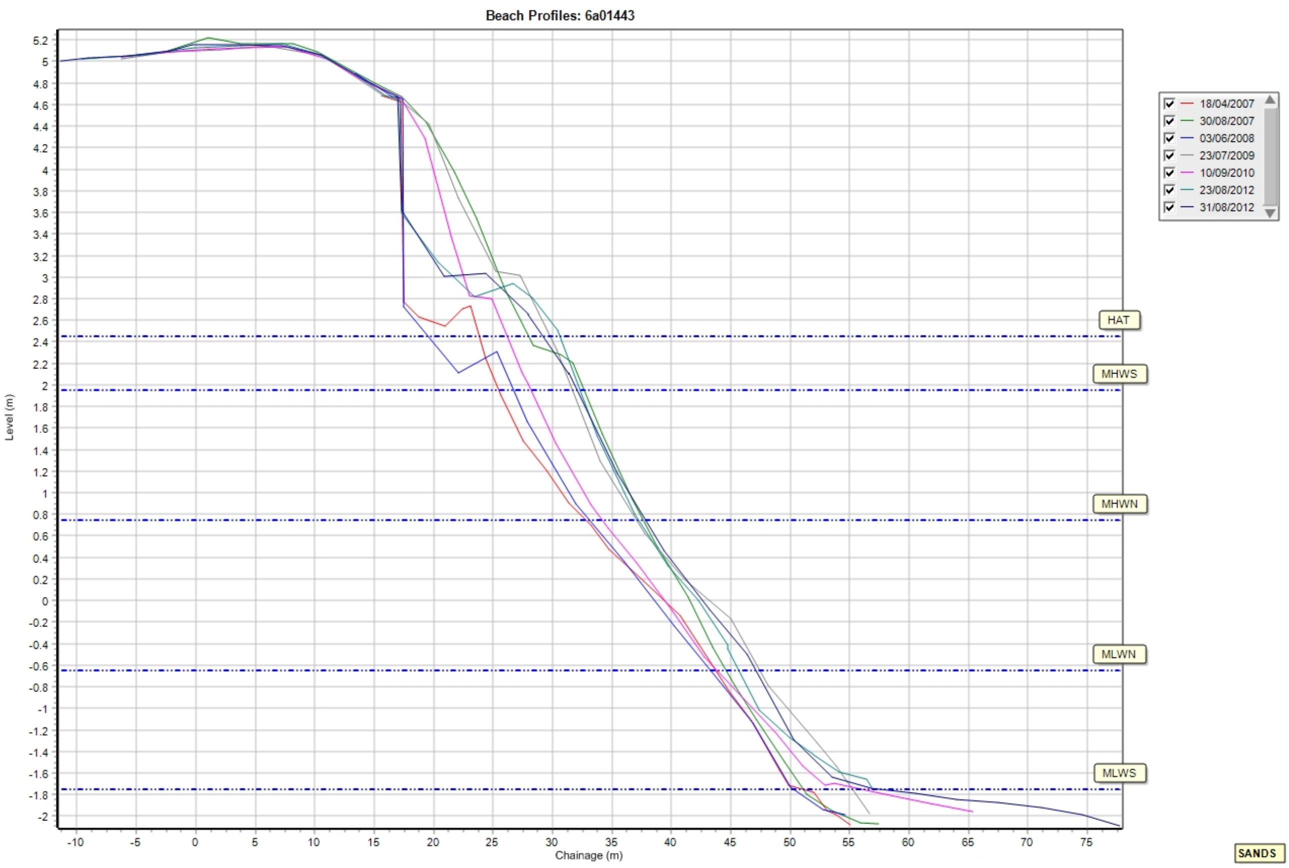
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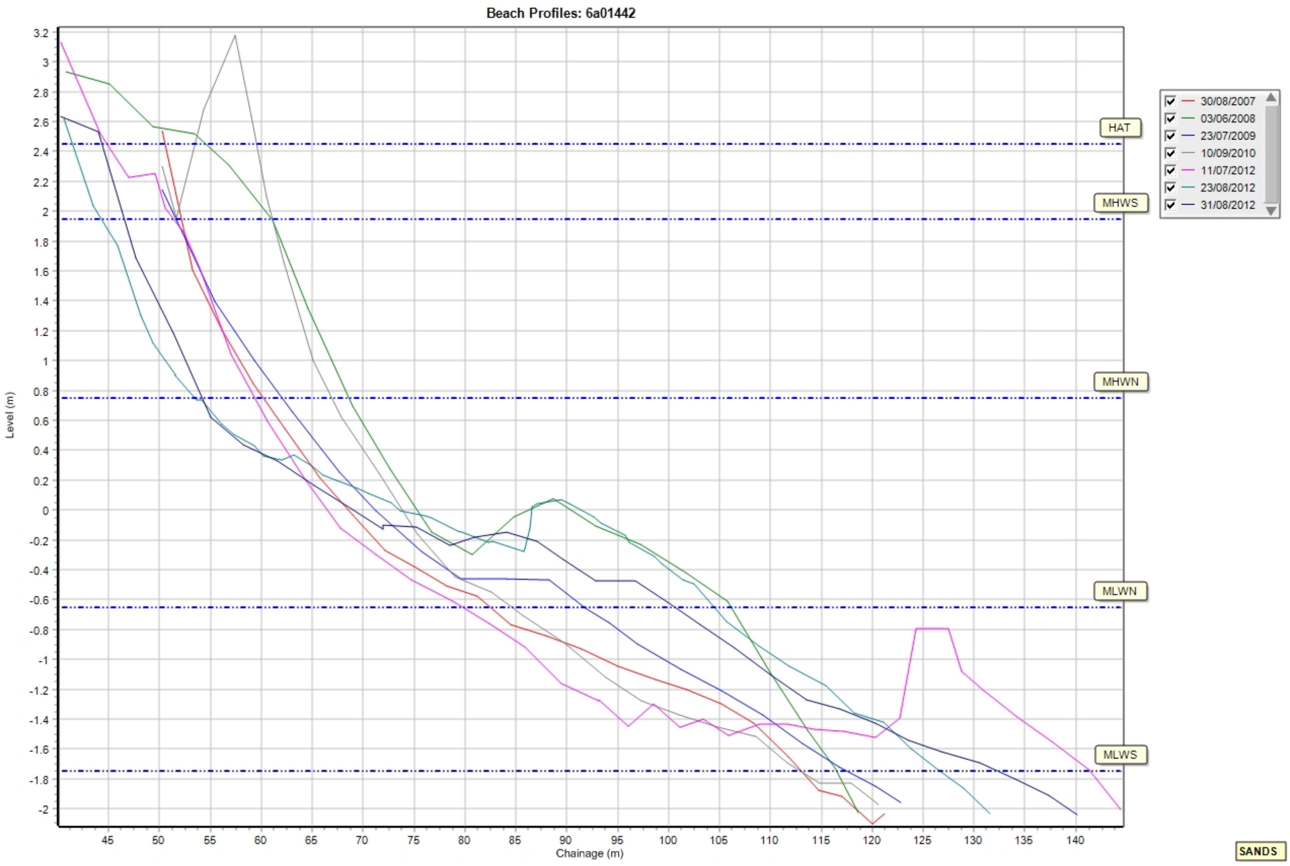
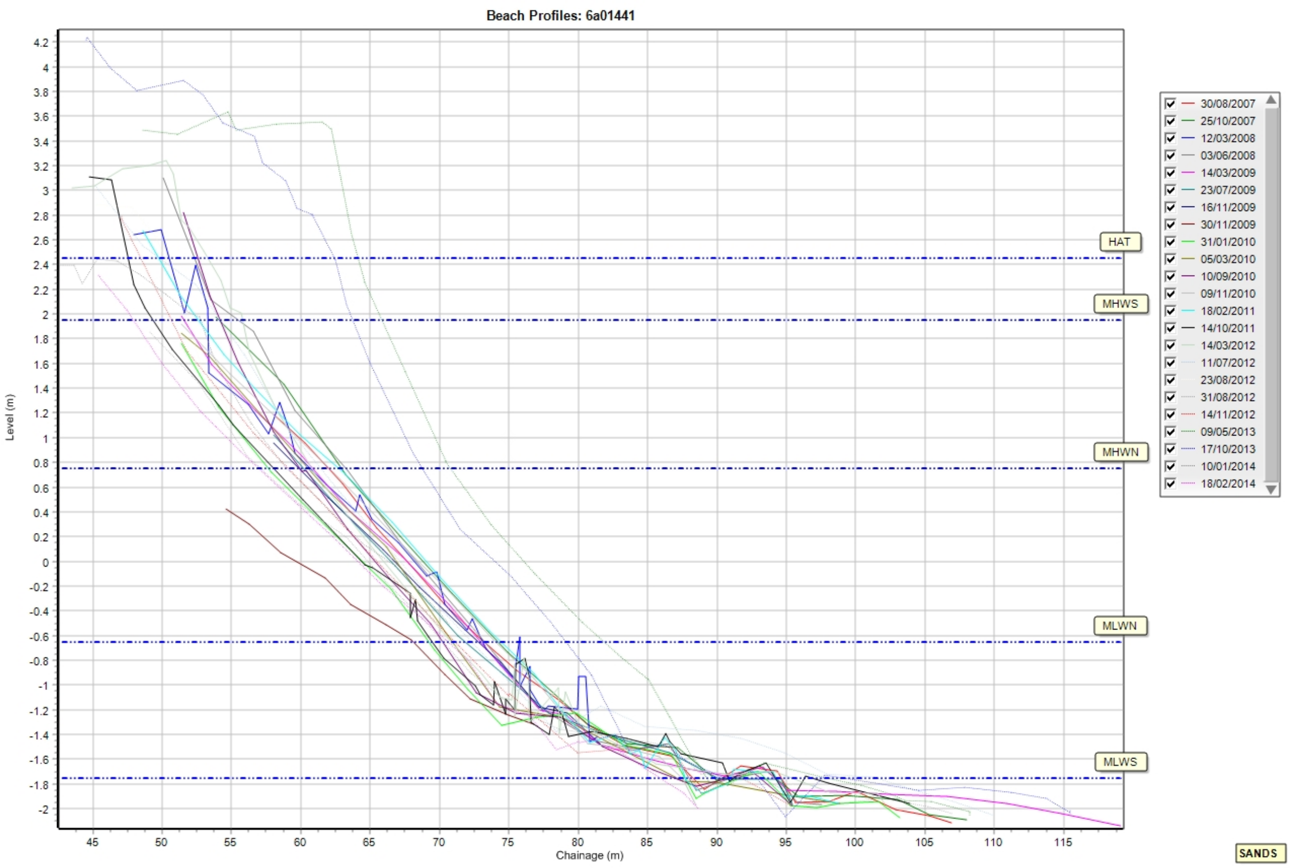
MLWS
SANDS


Beach Profiles: 6a01442
Level (m)
Chainage (m)
HAT
MHWS
MHWN
MLWN
MLWS
SANDS
30/08/2007
03/06/2008
23/07/2009
10/09/2010
11/07/2012
23/08/2012
31/08/2012


Beach Profiles: 6a01441
Level (m)
Chainage (m)
HAT
MHWS
MHWN
MLWN
MLWS
SANDS
30/08/2007
25/10/2007
12/03/2008
03/06/2008
14/03/2009
23/07/2009
16/11/2009
30/11/2009
31/01/2010
05/03/2010
10/09/2010
09/11/2010
18/02/2011
14/10/2011
14/03/2012
11/07/2012
23/08/2012
31/08/2012
14/11/2012
09/05/2013
17/10/2013
10/01/2014
18/02/2014

Appendix D – Beach CSA and Volume Analysis

Table D.1 Jacob's Ladder Beach east CSA

Locations		**PCO Jacob's Ladder Beach East - Cross Sectional Area (m2)**																				**Total Difference (above – 2007 to 2014 and below 2008 to 2014)**
Location		**2007-04-18**	**2007-08-30**	**2007-10-25**	**2008-02-10**	**2008-06-03**	**2008-10-15**	**2009-03-14**	**2009-07-23**	**2009-11-16**	**2010-01-31**	**2010-09-10**	**2010-11-09**	**2011-02-18**	**2011-10-14**	**2012-03-14**	**2012-08-23**	**2012-11-14**	**2013-05-09**	**2013-10-17**	**2014-02-18**	
6a01463		74.59	111.7	112.87	104.23	87.13	111.44	101.86	109.18	106.2	103.07	104.9	108.22	102.6	134.55	111.32	117.29	120.94	86.87	89.33	101.62	
6a01462		29.53	51.28			58.83			67.79			57.24					56.95					
	Total	104.12	162.98	112.87	104.23	145.96	111.44	101.86	176.97	106.2	103.07	162.14	108.22	102.6	134.55	111.32	174.24	120.94	86.87	89.33	101.62	
6a01463	Difference		37.11	1.17	-8.64	-17.1	24.31	-9.58	7.32	-2.98	-3.13	1.83	3.32	-5.62	31.95	-23.23	5.97	3.65	-34.07	2.46	12.29	27.03
6a01462			21.75			7.55			8.96			-10.55					-0.29					27.42

Table D.2 Jacob's Ladder Beach East Volume

Volume Between			**Volumes (m3)**																				**Total Difference**
Location 1	**Location 2**		**2007-04-18**	**2007-08-30**	**2007-10-25**	**2008-02-10**	**2008-06-03**	**2008-10-15**	**2009-03-14**	**2009-07-23**	**2009-11-16**	**2010-01-31**	**2010-09-10**	**2010-11-09**	**2011-02-18**	**2011-10-14**	**2012-03-14**	**2012-08-23**	**2012-11-14**	**2013-05-09**	**2013-10-17**	**2014-02-18**	**(above – 2007 to 2014 and below 2008 to 2014)**
6a01463	6a01462		3064	4796			4295			5208			4771					5128					
		Total	3064	4796			4295			5208			4771					5128					
6a01463	6a01462	Difference		1732			-501			913			-437					356					2063
																							331

Table D.3 Chit Rocks Beach CSA

Locations		**PCO Chit Rocks - Cross Sectional Area (m2)**						**Total Difference**
Location		**2007-04-18**	**2007-08-30**	**2008-06-03**	**2009-07-23**	**2010-09-10**	**2012-08-23**	
6a01462		29.53	51.28	58.83	67.79	57.24	56.95	
6a01461		58.89	92.1	90.54	107.58	47.89	97.88	
6a01460		48.81	69.78	72.65	75.22	69.7	74.45	
6a01459		34.44	54.96	63.94	59.2	70.13	71.14	
	Total	171.67	268.12	285.96	309.79	244.96	300.42	
6a01462	Difference		21.75	7.55	8.96	-10.55	-0.29	27.42
6a01461			33.21	-1.56	17.04	-59.69	49.99	38.99
6a01460			20.97	2.87	2.57	-5.52	4.75	25.64
6a01459			20.52	8.98	-4.74	10.93	1.01	36.7

Table D.4 Chit Rocks Beach Volume

Volume Between			Volumes (m3)						Total Difference (2007 to 2012)	Total Difference (2008 to 2012)
Location 1	Location 2		2007-04-18	2007-08-30	2008-06-03	2009-07-23	2010-09-10	2012-08-23		
6a01462	6a01461		2524.82	4288.15	4398.27	5109.99	2772.63	4568.04		
6a01461	6a01460		2741.14	4120.19	4153.47	4652.91	2992.93	4386.12		
6a01460	6a01459		2776.71	4186.78	4595.22	4511.82	4680.56	4919.50		
		Total	8042.66	12595.12	13146.96	14274.72	10446.17	13873.65		
6a01462	6a01461	Difference		1763.31	110.12	711.72	-2337.36	1795.40	2043.22	279.89
6a01461	6a01460			1379.06	33.28	499.43	-1659.98	1393.19	1644.98	265.92
6a01460	6a01459			1410.07	408.44	-83.40	168.74	238.94	2142.80	732.72

Table D.5 Sidmouth Beach CSA

	PCO and Posford Annual Profiles - Cross Sectional Area (m2)																						Sum Difference	Beach Zone
Location	2007-04-18	2007-08-30	2007-10-25	2008-02-10	2008-06-03	2008-10-15	2009-03-14	2009-07-23	2009-11-16	2010-01-31	2010-09-10	2010-11-09	2011-02-18	2011-10-14	2012-03-14	2012-08-23	2012-08-31	2012-11-14	2013-05-09	2013-10-17	2014-01-10	2014-02-18		
6a01458	101.53	116.55			123.58			118.19			134.52					126.71								
		15.02			*7.03*			*-5.39*			*16.33*					*-7.81*							*25.18*	*A1*
6a01457	189.98	190.02			189.51			216.87			205.17					215.23								
		0.04			*-0.51*			*27.36*			*-11.7*					*10.06*							*25.25*	*A2*
6a01456	290.34	300.54	315.87	282.29	326.77	283.58	305.32	305.4	304.81	315.33	329.92	312.03	310.92	306.43	316.54	307.25		308.67	319.2	320.24	231.21	246.33		
		10.2	*15.33*	*-33.58*	*44.48*	*-43.19*	*21.74*	*0.08*	*-0.59*	*10.52*	*14.59*	*-17.89*	*-1.11*	*-4.49*	*10.11*	*-9.29*		*1.42*	*10.53*	*11.57*	*-87.99*	*-73.91*	*-44.01*	*A3*
6a01455	273.83	277.38			306.14			281.79			310.19					280.14								
		3.55			28.76			-24.35			28.4					-30.05							6.31	B1
6a01453A														346.53	335.66	344.21	345	334.14	312.06	315.59	321.73	379.69		
															-10.87	*8.55*	*0.79*	*-10.86*	*-22.08*	*3.53*	*6.14*	*57.96*	*33.16*	*B2*
6a01453	350.25	337.68	326.89	358.13	318.88	348.51	343.49	339.36	363.22	327.38	321.55	336.13	337.07			341.41	346.44							
		-12.57	*-10.79*	*31.24*	*-39.25*	*29.63*	*-5.02*	*-4.13*	*23.86*	*-35.84*	*-5.83*	*14.58*	*0.94*			*4.34*	*5.03*						*-3.81*	*B2*
6a01451	156.14	159.33			140.6			157.32			145.3					157.25	161.06							
		3.19			*-18.73*			*16.72*			*-12.02*					*11.95*	*3.81*						*4.92*	*B4*
6a01450	155.83	116.85	146.11	116.91	192.79	129.74	166.45	143.41	128.44	172.33	160.82	141.37	147.88			121.44	122.98							
		-38.98	*29.26*	*-29.2*	*75.88*	*-63.05*	*36.71*	*-23.04*	*-14.97*	*43.89*	*-11.51*	*-19.45*	*6.51*			*-26.44*	*1.54*						*-32.85*	*B5*
6a01449	116.72	110.61			113.88			107.57			107.76			112.68		111.36	113.01	108.76	99.97	97.36	89.75	97.66		
		-6.11			*3.27*			*-6.31*			*0.19*			*4.92*		*-1.32*	*0.33*	*-3.9*	*-11.39*	*-15.65*	*-19.01*	*-2.31*	*-19.06*	*B6*
6a01448	79.9	124.09			51.17			92.79			76.75					110.51	117.4							
		44.19			*-72.92*			*41.62*			*-16.04*					*33.76*	*6.89*						*37.5*	*B7*
6a01447	117.11	67.21			132.25			59.31			97.79					56.99	56.98							

		-49.9			*65.04*			*-72.94*			*38.48*					*-40.8*	*-0.01*						*-60.13*	*C1*
6a01446	74.78	94.62			72.82			90.64			75.43			88.74	89.03	88.78	88.36	90.26	84.47	79.01	75.22	80.33		
		19.84			*-21.8*			*17.82*			*-15.21*			*13.31*	*0.29*	*-0.25*	*-0.38*	*1.23*	*-4.31*	*-9.35*	*-15.04*	*-4.14*	*+5.55*	*C2*
6a01445	95.46	119.43	100.42	106.4	76.37	106.06	85.17	107.04	104.1	69.48	89.57	100.17	85.99			105.33	109.48							
		23.97	*-19.01*	*5.98*	*-30.03*	*29.69*	*-20.89*	*21.87*	*-2.94*	*-34.62*	*20.09*	*10.6*	*-14.18*			*19.34*	*23.49*						*+14.02*	*C3*
6a01444	56.91	54.88			62.57			60.1			63.63					58.29	59.29							
		-2.03			*7.69*			*-2.47*			*3.53*					*-5.34*	*1*						*2.38*	*D2*
6a01443	87.34	113.82			86.29			119.82			102.86					111.96	115.45							
		26.48			*-27.53*			*33.53*			*-16.96*					*9.1*	*3.49*						*28.11*	*D3*
Total	2146.12	2183.01	889.29	863.73	2193.62	867.89	900.43	2199.61	900.57	884.52	2221.26	889.7	881.86	854.38	853.89	2536.86	1635.45	841.83	815.7	812.2	717.91	804.01		
Difference																							217.41	

Table D.6 Sidmouth Beach Volume

Volume Between			Volumes (m3)																							Total Difference (2007* to 2012 **)	Total Difference (2008 to 2012)	Beach Zone	2007 to 2012 By Zone
Location 1	Location 2		2007-04-18*	2007-08-30	2007-10-25	2008-02-10	2008-06-03	2008-10-15	2009-03-14	2009-07-23	2009-11-16	2010-01-31	2010-09-10	2010-11-09	2011-02-18	2011-10-14	2012-03-14	2012-08-23**	2012-08-31	2012-11-14	2013-05-09	2013-10-17	2014-01-10	2014-02-18				
6a01458	6a01457		7310.21	7682.49			7846.01			8394.47			8510.48					8562.44										
6a01457	6a01456		14268.75	14575.46			15349.64			15521.99			15906.62					15529.67										
6a01456	6a01455		5795.90	5937.16			6501.83			6032.47			6576.08					6034.26										
6a01455	6a01453A																	28340.04										
6a01453A	6a01453																	14351.57	14446.47									
6a01453	6a01451		25688.02	25207.94			23308.09			25195.15			23681.99					25295.46	25743.93									
6a01451	6a01450		6194.97	5483.78			6620.25			5971.65			6078.75					5534.01	5640.43									
6a01450	6a01449		10841.46	9047.48			12198.21			9983.10			10683.39					9260.12	9387.44									
6a01449	6a01448		7882.79	9409.82			6616.98			8032.90			7397.55					8895.38	9237.58									
6a01448	6a01447		4012.13	3896.99			3735.74			3098.45			3555.49					3412.09	3552.05									
6a01447	6a01446		6254.95	5278.29			6682.95			4890.98			5647.33					4755.04	4739.82									
6a01446	6a01445		5412.28	6809.52			4742.60			6287.80			5247.06					6174.00	6292.50									
6a01445	6a01444		3658.78	4185.52			3336.32			4013.28			3678.55					3928.74	4051.36									
6a01444	6a01443		2519.28	2946.36			2596.14			3142.18			2907.84					2971.70	3050.10									
		Total	99839.52	100460.82	0	0	99534.76	0	0	100564.43	0	0	99871.15	0	0	0	0	143044.53	86141.69	0	0	0	0	0				
6a01458	6a01457	Difference		372			164			548			116					52							1,252	880	A	
6a01457	6a01456			307			774			172			385					-377							1,261	954	A	
6a01456	6a01455			141			565			-469			544					-542							238	97	A	2,752
6a01455	6a01453A			0			0			0			0					0							-	0	A	
6a01453A	6a01453			0			0			0			0					0	95						95	95	B	
6a01453	6a01451			-480			-1,900			1,887			-1,513					1,613	448						71	536	B	

6a01451	6a01450			-711			1,136			-649			107					-545	106						-660	157	B	-404
6a01450	6a01449			-1,794			3,151			-2,215			700					-1,423	127						-1,581	340	B	
6a01449	6a01448			1,527			-2,793			1,416			-635					1,498	342						1,013	-172	B	
6a01448	6a01447			-115			-161			-637			457					-143	140						-600	-345	B	-559
6a01447	6a01446			-977			1,405			-1,792			756					-892	-15						-1,500	-538	C	
6a01446	6a01445			1,397			-2,067			1,545			-1,041					927	119						760	-517	C	
6a01445	6a01444			527			-849			677			-335					250	123						270	-134	C	-242
6a01444	6a01443			427			-350			546			-234					64	78						531	104	D	531

Table D.7 East Beach CSA

		PCO East Beach - Cross Sectional Area (m2)																		
Location		**2007-08-30**	**2007-10-25**	**2008-06-03**	**2009-03-14**	**2009-07-23**	**2009-11-16**	**2010-01-31**	**2010-09-10**	**2010-11-09**	**2011-02-18**	**2011-10-14**	**2012-03-14**	**2012-08-23**	**2012-08-31**	**2012-11-14**	**2013-05-09**	**2013-10-17**	**2014-01-10**	**2014-02-18**	
6a01442		103.69		152.72		115.9			124.47					131.4	125.46						
6a01441		48.15	67.36	82.02	70.42	44.18	39.72	59.47	64.92	69.67	79.89	68.03	78.83	74.29	66.19	67.79	132.79	120.35	56.48	60.77	
	Total	151.84	67.36	234.74	70.42	160.08	39.72	59.47	189.39	69.67	79.89	68.03	78.83	205.69	191.65	67.79	132.79	120.35	56.48	60.77	
6a01442	Difference			49.03		-36.82			8.57					6.93	-5.94						**21.77**
6a01441			19.21	14.66	-11.6	-26.24	-4.46	19.75	5.45	4.75	10.22	-11.86	10.8	-4.54	-8.1	1.6	65	-12.44	-63.87	4.29	**12.62**

Table D.8 East Beach Volume

Volume Between		**Volumes (m3)**																		
Location 1	**Location 2**	**2007-08-30**	**2007-10-25**	**2008-06-03**	**2009-03-14**	**2009-07-23**	**2009-11-16**	**2010-01-31**	**2010-09-10**	**2010-11-09**	**2011-02-18**	**2011-10-14**	**2012-03-14**	**2012-08-23**	**2012-08-31**	**2012-11-14**	**2013-05-09**	**2013-10-17**	**2014-01-10**	**2014-02-18**	
6a01442	6a01441	3704.67		5729.01		3903.83			4626.97					5012.57	4670.51						
	Total	3704.67	0	5729.01	0	3903.83	0	0	4626.97	0	0	0	0	5012.57	4670.51	0	0	0	0	0	
	Difference			2024.34		-1825.18			723.14					385.59	-342.05						965.84

Appendix E – Extreme wave and water level data

Extreme Water levels

The Environment Agency's R&D project 'Coastal Flood Boundary Conditions for UK Mainland and Islands' (Environment Agency, 2011a) provides the most recent assessments of Extreme water levels – these are shown in Table E.1.

Table E.1 Extreme water levels for a range of return periods at Sidmouth (Environment Agency, 2011a).

Year	Assumed increase in Sea Level (m)	MHWS Level (mOD)	Extreme Water Levels (mOD) by return period (1 in X years) and APO (%)								
			1 (100%)	5 (20%)	10 (10%)	20 (5%)	50 (2%)	100 (1%)	200 (0.5%)	500 (0.2%)	1000 (0.1%)
2013	*0*	1.95	2.72	2.88	2.95	3.02	3.12	3.18	3.26	3.37	3.44
2025	*0.05*	2	2.77	2.93	3.00	3.07	3.17	3.23	3.31	3.42	3.49
2050	*0.15*	2.1	2.87	3.03	3.10	3.17	3.27	3.33	3.41	3.52	3.59
2075	*0.27*	2.22	2.99	3.15	3.22	3.29	3.39	3.45	3.53	3.64	3.71
2100	*0.41*	2.36	3.13	3.29	3.36	3.43	3.53	3.59	3.67	3.78	3.85

Extreme swell waves

The most recent estimate of extreme swell waves for this area is provided by the Environment Agency's R&D project 'Coastal Flood Boundary Conditions for UK Mainland and Islands' (Environment Agency, 2011a). The data relevant to Sidmouth is shown in Table E.2.

Table E.2 Extreme swell wave conditions levels for a range of return periods at Sidmouth (Environment Agency, 2011a).

	Swell Wave Directions								
	Southeast			South			Southwest		
Return Period (1inX yrs)	Wave Height (m)	Confidence Limit (+/- m)	Wave Period (s)	Wave Height (m)	Confidence Limit (+/- m)	Wave Period (s)	Wave Height (m)	Confidence Limit (+/- m)	Wave Period (s)
1	2.6	0.2	8	3.7	0.2	12	2.9	0.1	8
2	2.8	0.2	8	3.99	0.3	12	3.03	0.1	12
5	3.03	0.3	12	4.34	0.4	12	3.17	0.1	12
10	3.18	0.3	12	4.58	0.4	12	3.27	0.2	12
20	3.32	0.4	12	4.8	0.5	12	3.35	0.2	12
25	3.36	0.4	12	4.87	0.6	12	3.37	0.2	12
50	3.48	0.5	12	5.07	0.7	12	3.44	0.2	12
75	3.55	0.5	12	5.18	0.7	12	3.48	0.2	12
100	3.59	0.6	12	5.25	0.8	12	3.5	0.2	12
150	3.65	0.6	12	5.36	0.8	12	3.54	0.2	12
200	3.69	0.6	12	5.43	0.9	12	3.56	0.2	12
250	3.72	0.7	12	5.48	0.9	12	3.57	0.2	12
300	3.74	0.7	12	5.52	0.9	12	3.59	0.2	12
500	3.8	0.7	12	5.63	1	12	3.62	0.3	12
1000	3.87	0.8	12	5.78	1.1	12	3.66	0.3	12

Extreme Resultant Waves

The most recent estimate of extreme resultant waves for this area, which reflect the combined influence of wind-waves and swell waves, is provided by the Environment Agency commissioned project 'Parameters for Tidal Flood Risk Assessment – Wave Parameters' (Royal Haskoning, 2012). The data relevant to Sidmouth is shown in Table E.3.

Table E.3 Extreme resultant wave conditions levels for a range of return periods at Sidmouth (Royal Haskoning, 2012).

	Resultant Wave Directions					
	Southeast		South		Southwest	
Return Period (1inX yrs)	Wave Height (m)	Wave Period (s)	Wave Height (m)	Wave Period (s)	Wave Height (m)	Wave Period (s)
1	4.16	8	5.68	10	4.73	8
2	4.29	8	5.91	10	4.93	8
5	4.42	8	6.18	10	5.16	10
10	4.49	8	6.35	10	5.31	10
20	4.54	8	6.51	10	5.44	10
25	4.55	8	6.55	10	5.48	10
50	4.59	8	6.68	10	5.59	10
75	4.61	8	6.75	10	5.65	10
100	4.62	8	6.79	10	5.69	10
150	4.63	8	6.85	10	5.74	10
200	4.64	8	6.89	10	5.78	10

	Resultant Wave Directions					
	Southeast		South		Southwest	
Return Period (1inX yrs)	Wave Height (m)	Wave Period (s)	Wave Height (m)	Wave Period (s)	Wave Height (m)	Wave Period (s)
250	4.65	8	6.92	10	5.8	10
300	4.65	8	6.95	10	5.82	10
500	4.66	8	7.01	10	5.88	10
1000	4.68	8	7.08	10	5.94	10

Joint Probability Analysis (Extreme Waves vs Extreme Water Levels)

A joint probability analysis assessing the combinations of extreme water levels and extreme wave heights that provide a range of extreme return period conditions has been completed as part of this project. This analysis was undertaken using the simple desk based approach provided in the Environment Agency's R&D project 'Joint Probability Dependence Mapping and Best Practice' (Environment Agency, 2003).

This joint probability analysis has been undertaken by comparing directional extreme swell waves and extreme resultant waves, with extreme water levels (E.5). The outputs of this analysis are presented in Table E.4 to Table E.9.

Table E.4 Joint probability analysis results for south-westerly extreme swell waves vs EWLs.

2013 EWLs offshore of Sidmouth (mOD)	Joint exceedance return period (years)							
	1	2	5	10	20	50	100	200
	Offshore swell wave height off Sidmouth (m) from South West direction by RP							
2.49	2.51	2.67	2.89	3.05	3.18	3.33	3.42	3.50
2.52	2.42	2.58	2.80	2.96	3.11	3.27	3.37	3.46
2.64	2.21	2.37	2.58	2.75	2.91	3.11	3.24	3.34
2.72	2.08	2.24	2.45	2.62	2.78	3.00	3.13	3.26
2.78	#N/A	2.11	2.32	2.49	2.65	2.87	3.03	3.16
2.88	#N/A	#N/A	2.15	2.32	2.48	2.69	2.86	3.02
2.95	#N/A	#N/A	#N/A	2.19	2.35	2.56	2.73	2.89
3.04	#N/A	#N/A	#N/A	#N/A	#N/A	2.39	2.55	2.72
3.12	#N/A	#N/A	#N/A	#N/A	#N/A	2.26	2.42	2.59
3.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	2.35	2.51
3.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	2.29	2.46
3.26	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	2.33
3.37	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.44	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Table E.5 Joint probability analysis results for south-westerly extreme resultant waves vs EWLs.

2013 EWLs offshore of Sidmouth (mOD)	Joint exceedance return period (years)							
	1	2	5	10	20	50	100	200
	Offshore resultant wave height off Sidmouth (m) from South West direction by RP							
2.49	4.13	4.38	4.71	4.96	5.17	5.40	5.55	5.68
2.52	3.99	4.24	4.57	4.82	5.06	5.32	5.48	5.61
2.64	3.66	3.91	4.24	4.50	4.75	5.06	5.26	5.43
2.72	3.46	3.71	4.04	4.30	4.55	4.88	5.10	5.30
2.78	#N/A	3.51	3.84	4.10	4.35	4.68	4.93	5.15
2.88	#N/A	#N/A	3.58	3.83	4.08	4.41	4.66	4.91
2.95	#N/A	#N/A	#N/A	3.63	3.88	4.21	4.46	4.71
3.04	#N/A	#N/A	#N/A	#N/A	#N/A	3.95	4.20	4.45
3.12	#N/A	#N/A	#N/A	#N/A	#N/A	3.75	4.00	4.25
3.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	3.88	4.13
3.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	3.80	4.05
3.26	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	3.85
3.37	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.44	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Table E.6 Joint probability analysis results for southerly extreme swell waves vs EWLs.

2013 EWLs offshore of Sidmouth (mOD)	Joint exceedance return period (years)							
	1	2	5	10	20	50	100	200
	Offshore swell wave height off Sidmouth (m) from South direction by RP							
2.49	2.83	3.19	3.67	4.03	4.36	4.74	5.00	5.24
2.52	2.63	2.99	3.47	3.84	4.18	4.59	4.87	5.11
2.64	2.15	2.52	3.00	3.36	3.72	4.18	4.50	4.78
2.72	1.86	2.23	2.71	3.07	3.43	3.91	4.25	4.56
2.78	#N/A	1.94	2.42	2.78	3.14	3.62	3.99	4.32
2.88	#N/A	#N/A	2.03	2.40	2.76	3.24	3.60	3.97
2.95	#N/A	#N/A	#N/A	2.11	2.47	2.95	3.31	3.68
3.04	#N/A	#N/A	#N/A	#N/A	#N/A	2.57	2.93	3.29
3.12	#N/A	#N/A	#N/A	#N/A	#N/A	2.28	2.64	3.00
3.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	2.47	2.83
3.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	2.35	2.71
3.26	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	2.42
3.37	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.44	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Table E.7 Joint probability analysis results for southerly extreme resultant waves vs EWLs.

2013 EWLs offshore of Sidmouth (mOD)	**Joint exceedance return period (years)**							
	1	**2**	**5**	**10**	**20**	**50**	**100**	**200**
	Offshore resultant wave height off Sidmouth (m) from South direction by RP							
2.49	4.99	5.28	5.66	5.94	6.19	6.46	6.64	6.78
2.52	4.83	5.12	5.50	5.79	6.06	6.36	6.55	6.71
2.64	4.45	4.74	5.12	5.41	5.70	6.06	6.29	6.49
2.72	4.22	4.51	4.89	5.18	5.47	5.85	6.11	6.34
2.78	#N/A	4.28	4.66	4.95	5.24	5.62	5.91	6.16
2.88	#N/A	#N/A	4.36	4.65	4.93	5.31	5.60	5.89
2.95	#N/A	#N/A	#N/A	4.42	4.70	5.08	5.37	5.66
3.04	#N/A	#N/A	#N/A	#N/A	#N/A	4.78	5.07	5.36
3.12	#N/A	#N/A	#N/A	#N/A	#N/A	4.55	4.84	5.13
3.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	4.70	4.99
3.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	4.61	4.90
3.26	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	4.67
3.37	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.44	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Table E.8 Joint probability analysis results for south-easterly extreme swell vs EWLs.

2013 EWLs offshore of Sidmouth (mOD)	Joint exceedance return period (years)							
	1	2	5	10	20	50	100	200
	Offshore swell wave height off Sidmouth (m) from South East direction by RP							
2.49	2.00	2.25	2.58	2.83	3.04	3.28	3.44	3.58
2.52	1.86	2.11	2.44	2.69	2.93	3.19	3.36	3.51
2.64	1.53	1.78	2.11	2.37	2.62	2.93	3.13	3.30
2.72	1.33	1.58	1.91	2.17	2.42	2.75	2.97	3.17
2.78	#N/A	1.38	1.71	1.97	2.22	2.55	2.80	3.02
2.88	#N/A	#N/A	1.45	1.70	1.95	2.28	2.53	2.78
2.95	#N/A	#N/A	#N/A	1.50	1.75	2.08	2.33	2.58
3.04	#N/A	#N/A	#N/A	#N/A	#N/A	1.82	2.07	2.32
3.12	#N/A	#N/A	#N/A	#N/A	#N/A	1.62	1.87	2.12
3.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.75	2.00
3.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.67	1.92
3.26	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.72
3.37	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.44	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Table E.9 Joint probability analysis results for south-easterly extreme resultant waves Vs EWLs.

2013 EWLs offshore of Sidmouth (mOD)	Joint exceedance return period (years)							
	1	2	5	10	20	50	100	200
	Offshore resultant wave height off Sidmouth (m) from South East direction by RP							
2.49	3.77	3.93	4.15	4.30	4.43	4.52	4.58	4.62
2.52	3.68	3.84	4.06	4.22	4.36	4.49	4.55	4.60
2.64	3.47	3.63	3.84	4.01	4.17	4.36	4.47	4.53
2.72	3.34	3.50	3.71	3.88	4.04	4.26	4.39	4.48
2.78	#N/A	3.37	3.58	3.75	3.91	4.13	4.29	4.41
2.88	#N/A	#N/A	3.41	3.58	3.74	3.95	4.12	4.28
2.95	#N/A	#N/A	#N/A	3.45	3.61	3.82	3.99	4.15
3.04	#N/A	#N/A	#N/A	#N/A	#N/A	3.65	3.81	3.98
3.12	#N/A	#N/A	#N/A	#N/A	#N/A	3.52	3.68	3.85
3.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	3.61	3.77
3.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	3.55	3.72
3.26	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	3.59
3.37	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.44	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A