UNIVERSITY OF SOUTHAMPTON

HYDRODYNAMIC INFLUENCES ON BEACH VOLUME CHANGE IN A CRENULATE BAY: SWANAGE BAY, UK

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Declaration

I, Toby Miller declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

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2. Where any part of this thesis has previously been submitted for any other qualification at this University or any other institution, this has been clearly stated;

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Abstract

Sandy/Shingle beaches are naturally dynamic, with sediment being moved over all time and length scales due to coastal processes such as waves, wind, nearshore currents and human interventions (Farris and List, 2007). Beaches are highly valued for several reasons such as tourism and coastal defence meaning that the management of these systems is important in order to maintain social, economic and environmental implications. The crenulated Bay in Swanage is unique along the south coast due to its orientation, as although Swanage is located on the south coast, it is eastward facing. Despite being sheltered to the dominant waves, the beaches experience rapid volume change across the Bay. It is imperative that the causes for such change are better understood to guide the next Beach Management Plan. Swanage Beach has 42 topographic survey locations with most profiles being sampled bi-annually since 2007. These surveys were used to calculate beach volume change, so that changes in beach profiles can be assessed against time and compared with the wave climate. Wave data is available from the Channel Coastal Observatory, CEFAS and a study carried out by HR Wallingford using AWAC buoys. A nearshore model was set up to model nearshore wave height and direction in order to predict the wave climate in Swanage Bay. Multivariate was also used to analyse which wave parameters cause a change in the beach volume. The results showed that the northern section of Swanage was accreting between 2007-18 while the central and southern section of the beach were eroding. Analysis shows that during times of high wave energy, beach volume falls, and during quiescent periods, beach volume is restored. There are two-time frames causing a change in beach volume. Extreme events caused a rapid draw down of sediment in the cross-shore direction while more longer time scale change was seen due to longshore transport causing a clockwise rotation of the bay driven by the wave climate itself.

Keywords: Swanage; Beach Volume change; Waves; Storm Events.

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Chapter 1 – Introduction

1.1 General Overview

Sandy/Shingle beaches occur all over the world and are the dominant feature on open coastlines (Bascom, 1980). These environments are naturally dynamic, with sediment being moved over all time and length scales due to coastal processes such as waves, wind, nearshore currents and human interventions (Farris and List, 2007). These beaches are highly valued environments (Whitmarsh et al., 1999) because of their rich resources; logistical reasons, such as access points for marine trade and transport; for recreational and cultural use; or simply for the special sense of place at the interface between land and sea (Neumann et al., 2015). In total, tourism represents 10% of the worlds GDP, corresponding to $7 trillion and 300 million jobs (WTTC, 2017). Of this, roughly 53% corresponds to "Leisure, recreation and holidays" category, with beaches being considered a major influence in the tourism market (Houston, 2008). Although economic benefits are important, beaches offer; a diverse ecosystem for flora and fauna; provide natural coastal protection; water catchment; and sediment storage (Barbier et al., 2011).

In England 520,000 properties are at risk of coastal flooding and 8,900 from coastal erosion. Damages are approximately £260 million per year (ChannelCoast, 2019). Climate change is increasing risks and the potential cost, meaning by 2080, property numbers at risk may be more than triple. This does not consider the additional risk to coastal infrastructure (ChannelCoast, 2019). In the coastal zone, impacts are mainly due to two factors: Sea level rise (SLR) and the increase in extreme weather events. Both processes act to increase water levels and incoming energy, which may cause flood events and inundations which will damage coastal infrastructure and coastal features causing a landward shoreline migration (Zhu et al., 2010). These extreme events can mobilise sediment which can cause beach drawdown. Beach drawdown is the movement of sediment from the beach onto an offshore bar. Flooding may also occur, if storm events are large enough to breach the defence line. This is an issue for Swanage Bay as the coastal defence line has been breached a number of times while the beach has been eroded. Other than environmental forcing, the coastline is affected by human activities such as mass tourism (Davenport and Davenport, 2006), land reclamation and coastal squeeze (Doody, 2013; Pontee, 2013).

In order to maintain and manage coastal zones for future demand in a sustainable way, beach management plans (BMP) need to be created and implemented. A BMP is a plan for managing a beach at a local level for the purpose of flood and coastal erosion risk management. They take into account and try to promote or enhance other uses and functions of the beach. Consideration is often given to the current conditions of the beach and coastal defences and try and plan for the long-term future (Eastdevon.gov, 2019). Swanage Bay experiences rapid beach volume change, and it is imperative that the cause for such change are better understood to guide the BMP which is currently being planned.

Beaches are very dynamic systems and understanding how they behave to environmental forcing can be key to managing the area. Coastal processes such as waves and nearshore currents, can drive changes in the beach in both long and cross shore directions. These processes can lead to changes in the beach volume as well as beach rotation over both short and long timescales. Studies in changing beach profiles have been carried out extensively (e.g. Thom and Hall 1991; Winant et al., 1975; Larson and Kraus, 1994). Many models have also been set up to help try and understand beach profile response such as the Bruun Model and the Edelman Model II (Dean and Maurmeyer, 2018). This report investigates what drives rapid changes in beach volumes in a crenulate bay using Swanage Bay as a case study and understand what mitigation strategies can be put in place to help protect the coast for future events.

1.2 Motivation

Beach Management Plans (BMPs) are constantly being changed and updated to fit the needs of the specific site in question. These plans can only be implemented correctly if the environment at the site is properly understood. Currently, it is still unclear as to what drives rapid beach volume change at Swanage due to complex hydrodynamic conditions. The motivation for this project comes from the need to understand the cause of rapid beach volume change to help in the implementation of a new BMP.

1.3 Aim and Objectives

The aim of this project is to assess the role of hydrodynamic regime on the beach response within a crenulate bay in Swanage. The crenulated Bay in Swanage is unique along the south coast due to its orientation, as although Swanage is located on the south coast, it is eastward facing. To fulfil the aim of this report, several objectives have been set.

These objectives are:

1. Examine wave diffraction around Durlston Point and the resulting hydrodynamics within Swanage Bay;
2. Assess how beach volume change varies during storm events and seasonal variation; and
3. Examine how the hydrodynamic regime causes a change in the beach volume.

1.4 Outline of the thesis

This thesis will be divided into chapters, being Chapter 2: looking at the background and literature for the subject; Chapter 3: looks at the site that is analysed and the methods used in order to analyse the data; Chapter 4: looks at the results of the thesis; Chapter 5: looks into discussing the results and Chapter 6: Concludes the thesis.

Chapter 2: Background and Literature Review

To understand how beaches respond to environmental variables, a variety of concepts are needed to be understood. These concepts range from the necessary requirements to shape crenulate bays; generation and influence waves have on the coastline; seasonal and annual variation of beach topography. This section brings together the key concepts for the purpose of providing the background knowledge needed to comprehend the study. This section will then bring together relevant literature that accesses the topic in questions and shows limitations in the current literature which this study tries to fill.

2.1 Formation of Crenulate Bays

Crenulate-shaped bays are rather common on exposed sedimentary coasts (Hsu et al., 1989). Crenulate bay beaches occur with the presence of two consecutive headlands and a predominant wave approach oblique to the alignment of the up-coast and down-coast headlands (Silvester, 1970). Oblique persistent swell striking a shoreline transports sediment along the beach and sculptures a headland dominated coast into crenulate shaped bays (Finkelstein, 1982). A highly concave portion of shoreline forms on the downdrift side of the headland where the coastline is shadowed from the dominant wave direction subject to waves that diffract around the headland.

The physiographic feature of crenulate bays was first recognised by Jennings (1955), with theoretical models concerning beach morphology on crenulate bays being carried out by Yasso (1965). Yasso's (1965) study examined the plan forms of several prototype bays and reported their equivalence to the logarithmic spiral (Silvester 1970; LeBlond, 1972). Theoretically, a crenulate bay is formed in response to an updrift headland and its beach will take the shape of a logarithmic spiral (Finkelstein, 1982). However, using computer simulations of a crenulate bay, it was shown that its equilibrium configuration is governed by its pattern of offshore wave refraction and diffraction and the distribution of wave energy which governs the equilibrium configuration (Silvester, 1970, Rea and Komar 1975). Once a beach has reached equilibrium, the waves approaching the shore will no longer be at an angle to the coastline so no alongshore sediment transport will occur. However, if a bay is not in equilibrium or in dynamic equilibrium, waves will break at an angle to the shore and sediment transport will occur throughout the bay subject to man-made features such as groynes. This makes it easy to distinguish whether a beach is in equilibrium as alongshore transport will cease (Silvester, 1976).

To fully understand how these bays are formed, it is important to understand how waves are generated and propagate in the ocean as well as how these waves influence beach transport.

2.2 Waves in the Ocean

Waves in the ocean can have a large spectrum of frequencies. Waves can vary in wavelengths from high frequency capillary waves to large wavelength waves such as tides (Kinsman, 1984) (Figure 1). However, when dealing with coastal systems and how they vary over annual time series, we usually deal with a group of waves known as surface gravity waves which have a period of 1-30s. These waves are generated by wind blowing over the surface of the ocean and are equilibrated by the gravitational force. These waves are generated based on three factors: wind velocity; duration of the wind; fetch distance. These features will define the wave characteristics with one or more of these features being a limiting factor (Ewans, 1998).

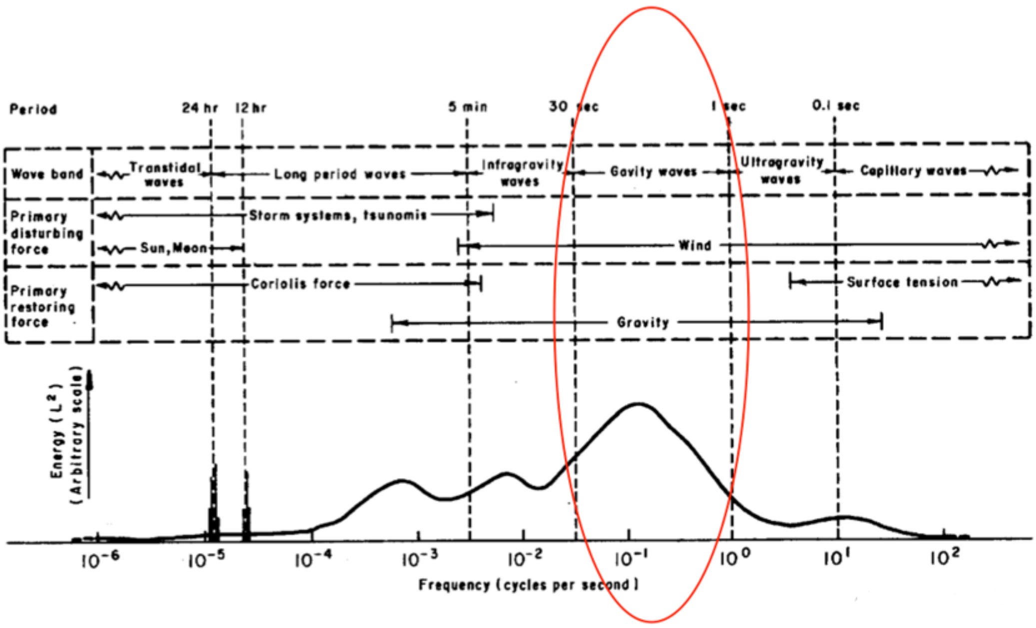


Figure 1 - An indication of waves which will be assessed in this report highlighting that gravity waves and wind waves will have the main effects on this report. Source: Kinsman, (1984).

Surface waves are described using the following measures: wave height (H) or the vertical distance between the crest and trough of a wave; wavelength (L) or the distance between two consecutive wave crests; wave Period (T) or the time between two successive crests (Figure 2). Near the formation area, the wave field includes all measures including wavelengths, periods and directions, creating a chaotic surface that is known as seas. Once the waves travel away from the formation zone, they will separate into groups based on their celerity (C), which depends on their wavelengths. Once waves propagate away from the formation area, they are referred to as swell (US Army Corps of Engineers, 1984).

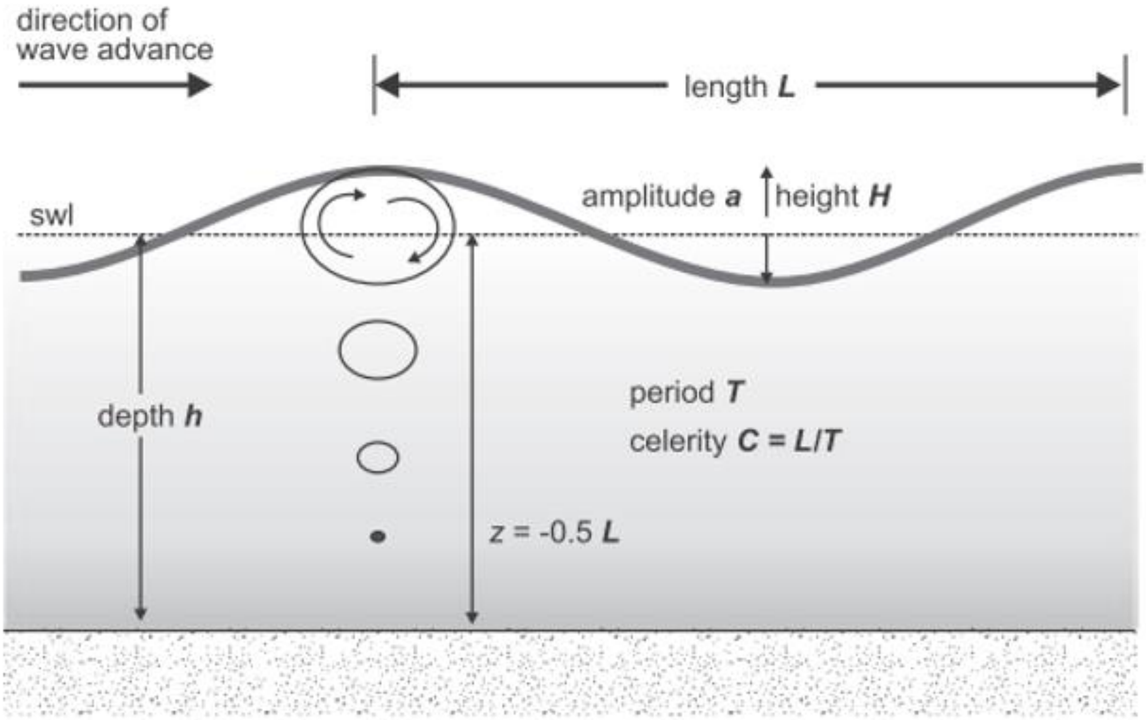


Figure 2 - Different wave parameters discussed, such as wave height, length, period, celerity and water depth. Source: Davidson-Arnott (2009).

As these waves are generated by wind forces, they can often show seasonal effects. This is due to winds usually being greater over winter periods and smaller over summer periods. Winter waves tend to be more energetic, with longer periods and larger waves, compared to summer waves which are typically smaller with a shorter period. The main incoming wave direction will play a large role on seasonal effects. The orientation of the coast to the wave direction can also be important leading to some areas being more exposed whilst other areas will be more sheltered.

Storms are defined by atmospheric perturbations where strong winds or large pressure gradients or a combination of both are seen. As wind is the main generator of these waves, the stronger the wind, the larger the wave. These waves are called storm waves and are defined when the wave height reaches a certain threshold. In the case of Swanage, a storm threshold of 1.2m is applied. This threshold was calculated using return periods with a wave height of 1.2m expected to occur 1:0.25 years, or 4 times a year. Storm waves are different to swell waves as swell waves are generated far from the coastline, whereas storm waves can be generated both near and far from the coast. Swell waves also usually have smaller wave amplitudes and large wavelengths and periods whereas storm waves tend to have higher amplitudes and smaller periods, meaning the waves are likely to be steeper than normal conditions. This will influence the breaking parameters.

2.2.1 Wave Energy

When waves start to approach the coastline, they are transformed due to the wave's interaction with the bottom, and the coastal morphology. The waves will start to feel the friction effects of the bottom when the water depth is roughly half the wavelength. When the waves start feeling these effects, the wavelength, velocity and direction can change, but the peak period will remain constant. This leads to a dissipation of energy meaning as waves approach onshore, the wave energy reduces. To calculate wave energy flux, linear wave theory is used in its simplest form. The equation used to calculate wave inshore wave energy flux is:

$$E = g . \rho_w . \frac{{H_s}^2}{8} . c_g$$

Where ρ_w is the density of water, g is gravity and c_g is the group celerity.

It is important to understand wave energy, as larger energies mean that more sediment can be transported which can lead to a change in beach volumes. If energies are small, only fine sediments may be transported, or no sediment transport will be seen. The main processes acting on these waves in the nearshore are: shoaling; refraction; diffraction and wave breaking.

2.2.1.1 Wave Shoaling

Wave shoaling is the effect by which surface waves entering shallow water change in wave height. It is caused by the fact that the group velocity, which is also the wave-energy transport velocity changes with shallowing water depth. A reduction in transport speed must be compensated by an increase in energy density in order to maintain a constant energy flux which in turn leads to an increase in wave height (Kennedy et al., 2000).

2.2.1.2 Refraction

Refraction is a change in the wave direction due to the bottom bathymetry. Waves tend to arrive at shore perpendicularly to the depth contours. This is caused due to waves travelling slower in shallower water allowing the section of waves in deeper water to catch up. Refraction usually focuses waves onto headlands, as the change in depth is more rapid around a headland. This means that the wave energy is dissipated once it reaches a bay.

2.2.1.3 Diffraction

Wave diffraction is the bending of waves due to edges such as a breakwater or a headland. Diffraction is regarded as a key process capable of modifying the wave direction around headlands and structures (Daly et al., 2014). Diffraction redistributes wave energy in the shadow zone of embayed beaches thereby causing curvature of the shoreline (LeBlond 1979). Laboratory experiments have been carried out to investigate these hypotheses; however, these experiments are prone to scale effects. Bed slope in the shadow zone is often not reduced below the critical angle of repose of the sediment, indicating that hydrodynamic effects are weak in comparison with to slope stability effects (Daly et al., 2014). Analytic models have been used to determine the shoreline embayment, if waves break uniformly (Dean, 1978; Rea and Komar, 1977). However, periodic changes in the wave climate can also alter the energy distribution in and around the shadow zone. Therefore, the variability of the wave climate can in theory have an equally large effect on the equilibrium morphology of crenulate-shaped bay environments. Many studies have shown that a variability of wave climates can lead to different types of beach response which may affect the morphodynamic equilibrium of shoreline position (Tukri et al., 2013; Yates et al., 2009).

2.2.1.4 Wave Breaking

When the wave enters shallow waters, the wave will continually steepen. Once the steepness limit is reached and exceeded, the wave will break. The breaking wave can have different forms which are influenced by, the offshore wave steepness, and the slope of the seabed.

A way to categorise the breaker type is known as the Iribarren number (Battjes, 1974), defined as:

$$Ir = \frac{tan\alpha}{\sqrt{H/_{L_0}}}$$

Where α is the beach slope and L_0 indicates the deep-water wavelength. The Iribarren number divides the breakers into 3 distinct categories. When H is used in the equation, the classifications will be:

- Surging/collapsing: Ir >2
- Plunging: 0.4> Ir ≥ 2
- Spilling: Ir ≤ 0.4.

These breaker types can be visualised in Figure 3.

The higher the Iribarren number is, determines the type of wave breaking on the beach. If the wave breaking on the beach is a plunging breaker, the beach experiences much higher energies which can mobilise sediment. Plunging breakers often have a strong backwash meaning sediment is transported offshore, which will lead to a steepening of the beach and a volume loss. In comparison, a spilling wave has a more balanced swash and backwash and occurs under less energetic conditions. These waves cause less sediment movement and are often less damaging to the beach. Collapsing and surging waves also cause damage to the beach; however it is unlikely to see these types of waves at the study site.

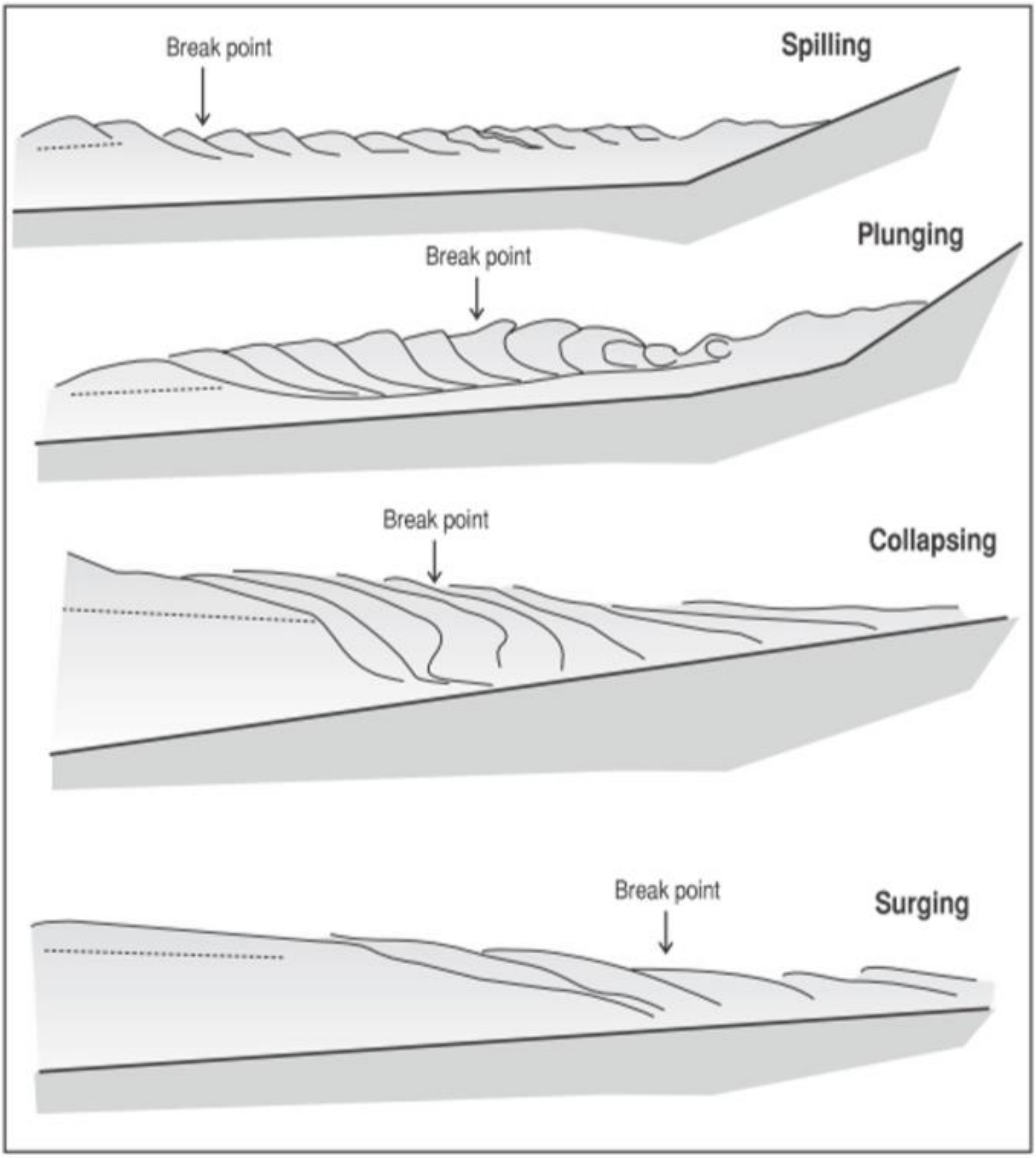


Figure 3 - An image depicting the different breaker types based on the Iribarren number: Ir > 2, Surging/ collapsing; 0.4 >Ir >2, Plunging; Ir <2, Spilling wave. Source: Davidson-Arnott (2009)

Waves play a large role in sediment transport in the nearshore zone. Waves are responsible for oscillatory fluid motions which cause currents, sediment mobilisation and bed level changes (Van Rijn, 1998). As waves enter a shallow basin, they undergo a transformation which lines up the crest of the waves to the beach. However, in many circumstances, the waves are unable to align fully parallel, so break at a slight angle on the beach. As the waves break at an angle to the beach, material is pushed up the beach at an angle in the swash zone causing along-shore sediment transport. The rate and amount of sediment transport along the beach is dependent on the size of the waves, and the angle at which the waves break. The larger the waves, implies more energy, so a larger amount of sediment able to be transported. If the angle of the wave breaking is small, the rate of along-shore sediment transport is increased, as each wave will move a body of sediment further along the beach. Once sediment is moved up the beach in the waves swash, sediment is then moved back towards the water, perpendicular to the beach due to gravity. This causes a zig-zag motion along the beach. Drift reversal is also possible, if the wave angle changes past 90˚, where sediment is moved back against the main sediment transport direction (Masselink and Pattiaratchi, 2001).

2.3 Coastal Morphodynamics

The cause of rapid beach volume change is still relatively unknown, so it is critical to understand how the wave and current climate affects the beach. The sediment at the study site is a mix of sand and shingle, which is both non-cohesive and non-consolidated. To understand how the beach volume varies, it is important to understand how sediment in both the cross-shore and longshore is transported.

2.3.1 Cross-shore sediment transport

Cross-shore sediment transport is carried on the shoreface. The shoreface is split into two sections, with the upper shoreface (or active zone) to the lower shoreface. Figure 4 shows the shoreface and the temporal scale by each depth. The active zone stretches from the beach dunes to the depth of closure. Beach dunes are driven be aeolian processes, but the remainder of the sediment transport is driven by waves and currents. The upper shoreface is dynamic and can change seasonally with winter and summer conditions changing the beach morphology. The depth of closure is the boundary between the upper and lower shoreface (Nicholls et al., 1998). The depth of closure is the significant seaward limit, beyond which repetitive beach-nearshore profiles show negligible change. The depth of closure can be as far as 1km away from the coastline in depths of waters up to 8m as seen on the Duck coast (Nicholls et al, 1998). In contrast, the lower shoreface is the boundary between the depth of closure and the inner shelf. In this area, some sediment transport is possible, but can take years or even decades to see a noticeable change. The lower shoreface can stretch up to 20km long and have water depths up to 20m.

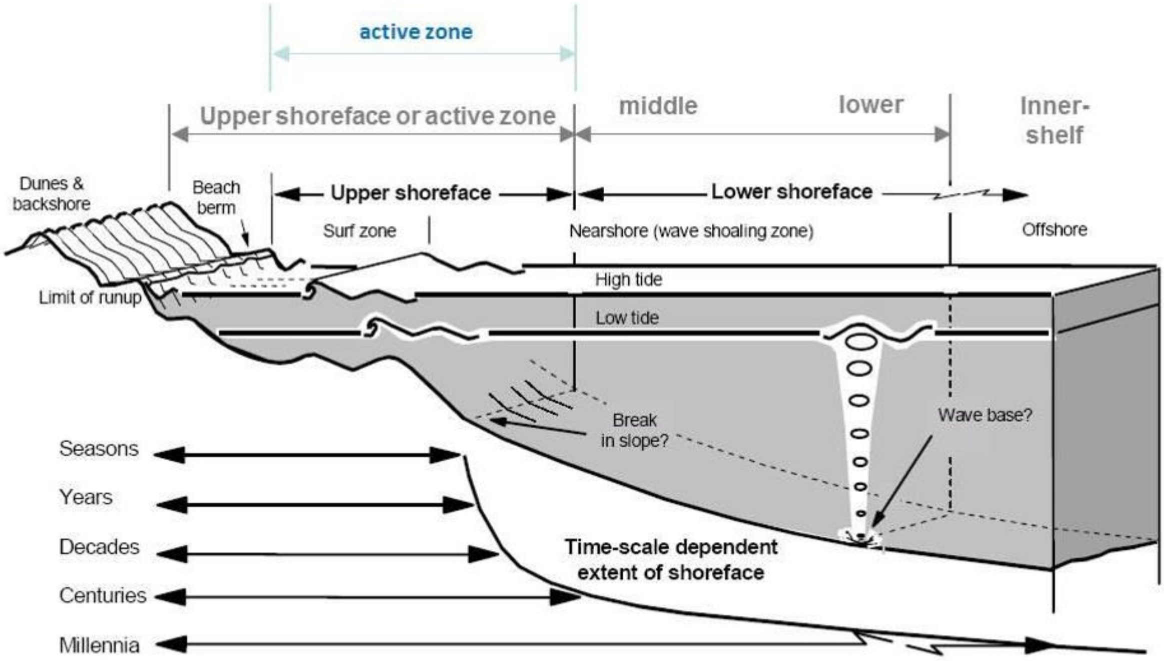


Figure 4 - An image showing a beach in the cross-shore direction. The figure shows how different timescales influence the profile. Source: Cowell et al., (1999).

2.3.1.1 Seasonal Variability

Cross-shore sediment transport plays a large role in beach profile change. This is because the beach morphology can change drastically over seasons. During summer conditions, beaches experience low energy waves. This results in a gradual onshore sediment transport direction leading to onshore berm formation. As the wave climate is low energy, and the onshore sediment transport is gradual, the gradient of the beach is likely to become shallower. In contrast, during winter conditions, high energy waves can quickly remove sediment from the beach. As the waves are destructive, the backwash parameter of the waves is much larger than the swash characteristic leading to offshore sediment movement. During winter conditions, an offshore bar is formed within the depth of closure. As the wave climate is energetic and destructive, the beach gradient is likely to steepen during these events. The sediment on the beach is also likely to change with finer sediments being deposited on the beach during summer conditions and removed during winter conditions (Winant et al., 1975). The time for these conditions to have a notable change on the beach slope is known as the recovery time.

When studying beach profile change, many variables are used. The most commonly used variables are shoreline position and beach volume. This parameter is useful for when we have a long profile of topographic surveys. This is because beach volumes offer information about the amount of sand, and how it varies over time. Beach profile volumes can give useful information on how a profile along a beach is fluctuating both seasonally and over longer time series. Beach volumes can be used to see if a beach is eroding or accreting, which can be very useful for the derivation of BMPs. Another widely used proxy in literature is shoreline position. Typically, both the beach volumes and shoreline positions will be well correlated. Figure 5 shows a profile from Swanage Bay, with both the shoreline position and the beach volume plotted. As they are closely correlated, beach volume can be used in this analysis.

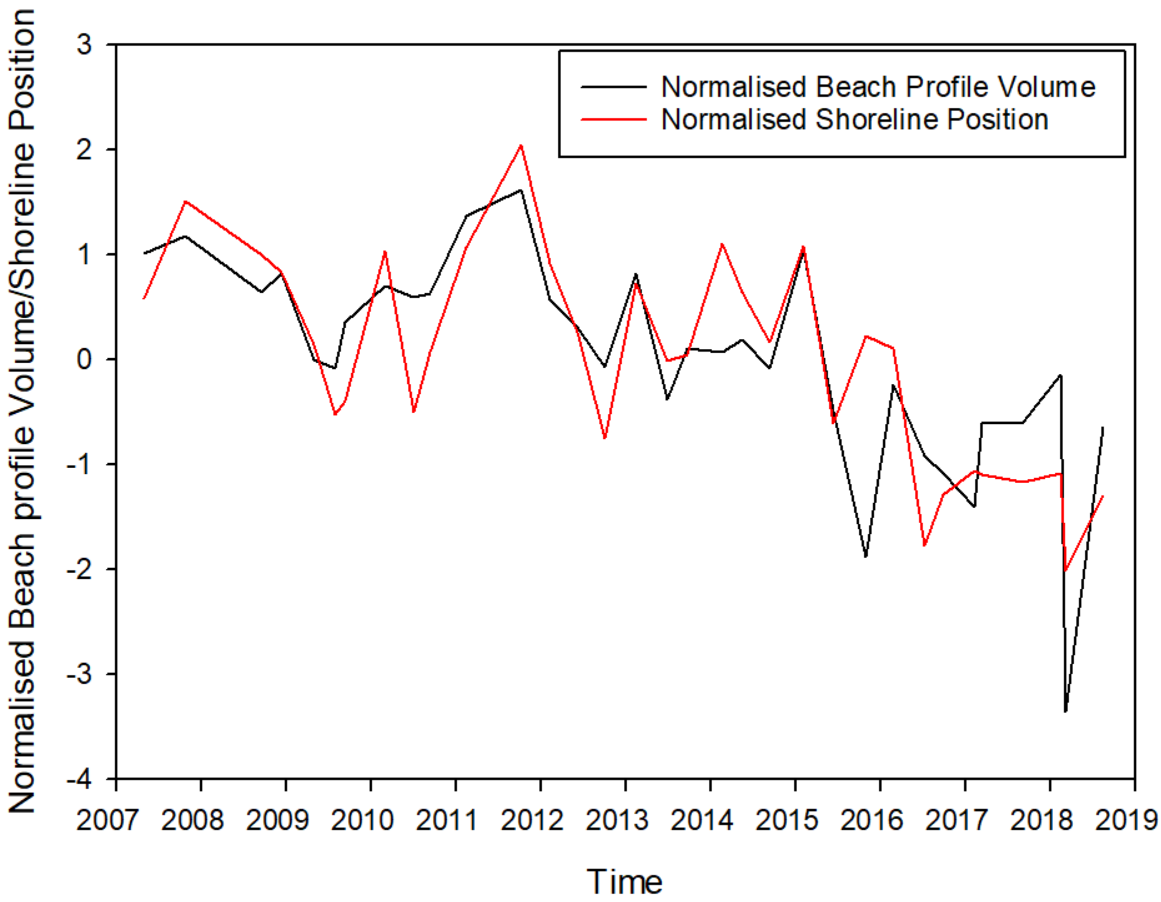


Figure 5 - A plot of normalised beach volumes against shoreline position. Profile P5f00764 was used.

2.3.2 Beach Centroid

The centroid is the geometric centre of an area, or a measure of the volumetric centre of the profile (Villamarin, 2017). The variable X1 represents the variation of the centroid in the x axis, cross-shore coordinate, and is calculated using the first moment of the volume in x. In a similar way, Z1 is the vertical variation of the centroid and is calculated using the first moment in z (Townend, 2019). The centroid is unique as it can give us an idea of the likely change the beach is experiencing with accretion, erosion, flattening and steepening being the basic cases. In general terms, you can use beach centroid plots to say that based on the previous point, a shift NE shows accretion with no rotation, a shift SW shows erosion with no rotation, a shift SE shows flattening rotation, a shift NW shows steepening rotation (Figure 6).

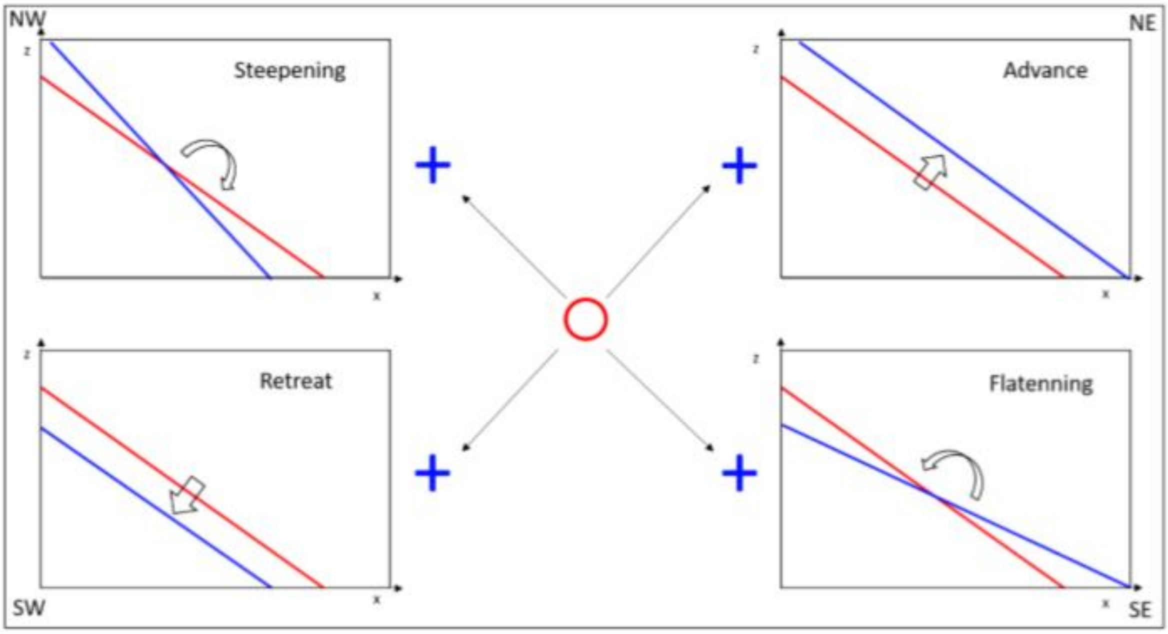


Figure 6 - An illustration of how a change in beach centroid can show a change in beach profile. Source Townend, 2019.

2.3.3 Longshore Sediment Transport

Longshore sediment transport is the rate and direction of sediment movement along the beach. Sediment can be transported once the threshold of motion is reached. This means that the greater the flow velocity, the greater the sediment transport. The relationship between velocity of flow and the movement of different sized sediments was first proposed by Hjulstrum (1935). A non-linear relationship between flow velocity and grain size was seen. Shields (1936) examined the threshold at which sediment becomes mobile. He did this by using a dimensionless parameter in relation to mean grain size: (θ = shields parameter, $\tau_{\circ}$ = shear stress, g = gravity, ρs =density of the sediment, ρ = density of water, d = water depth.)

$$\theta = \tau_{\circ}\ g(\rho s - \rho)$$

When the wave and current conditions exceed the threshold of motion, sand is transported as bed load. These grains are transported by rolling, sliding or a hopping motion. This occurs on a flat bed with low flows, meaning less energy is required. Suspension occurs once the threshold of suspension is met. The threshold of suspension is met when there is greater energy in the system, sand is suspended off the seabed and is carried at the same velocity of the water (Soulsby 1997).

Longshore sediment transport occurs over a longer timescale than cross-shore sediment transport. This is because the movement of sediment along the shore is less affected by extreme events, meaning that rapid drawdown has less affect.

2.4 Review of the literature

There is a wealth of literature available explaining how beach morphology and crenulate bays are measured. The literature available gives a good understanding of the common practices applied to many different case studies, but also shows the limitations in some of the methods used.

2.4.1 Shoreline Morphology and position change

Understanding the main drivers of beach profile change and beach behaviour is difficult to measure in a time series. Due to technological advances, beach profiles and natural events can be converted into digital expressions. Parameters can then be created to explain how the beach is changing as well as using statistics and processing to analyse other elements. For example, in order to analyse the beach characteristics before and after storm events, beach profiles can be measured by littoral detectors, geological beach volumes, or by using a numeric simulation (Kriebel and Dean, 1985; Larson and Kraus, 1989). To further understand what causes recovery, research was carried out by Long et al (2011) who used a LIDAR (light detection and ranging) method on the coast of Florida to see the impacts on beach change during a hurricane period. This kind of test measures the distance of vertical movement more accurately and shows more details of coastal change. However, this method can be expensive so cannot be applied to all beaches.

Shoreline position can be defined as height against elevation, and to evaluate the shoreline position change, the horizontal distance is compared to a standard elevation line. It is understood that the shoreline wants to enter a state of equilibrium and it is said to achieve this during non-storm conditions (Miller and Dean 2004; Swart 1974). The shoreline position is measured by equilibrium during the length of a storm period, with the rate of change of the profile being measured. This allows to see how the beach has behaved to the storm event as profile pre and post storm are shown. However, this just shows elevation compared to the standard elevation line and does not include the change in beach volume which can lead to limitations in using shoreline position to measure beach behaviour.

Understanding how coastal profiles vary under certain conditions is a key objective for coastal engineers and researchers. Understanding these concepts can help aid engineers in the design of coastal structures, and new BMPs. Storm events can have both an immediate and long-term effect on beach processes and patterns (Sabitar et al., 2009). Bruun (1954) proposed a method to predict the offshore extent of sediment transport which still keeps the profile in equilibrium as the total volume of the profile does not change, but the location of sediment does. Beach slope is also used to see the affects storms may have on the beach steepness. Beach slope can change by over 2-3˚ during a storm event (Koslow and Anthony, 1978), with recovery occurring after, during periods of low wave energy. Not only is beach slope assessed, but in many recent papers, beach volume is also measured. Although storm events are thought to have the main effect on beach drawdown, other investigations suggest other parameters including storm events may be more effective in controlling beach morphology.

2 4 2 Beach Volume

Models have been created and applied to explore storm erosion and recovery. A numerical model XBeach (Rovelink et al., 2009), is used to estimate storm erosion on the beach. The model can also be used to evaluate wave energy impact on beach erosion (Splinter et al 2014). The model showed the insignificant impact of storm sequence observed on storm cluster erosion.

Many studies argue how the environment influences the beach volume. Beach characteristics such as the pre storm profiles, sediment type and coastline direction determine the impact a storm may have on the beach (Mendoza and Jimenez, 2006). Other studies show that beach morphology is determined by tidal range, wave climate and sediment type (Chappell, 1983). It is understood that a combination of many factors such as time of storm event, tide times and sediment type decide the coastal morphology (Kriebel and Dean, 1993). Many models have been created in order to predict the changes in beach profiles under certain conditions such as the model created by Yates et al (2009). The model can only predict sediment moving in the cross-shore direction meaning that if the beach also experiences longshore sediment transport, the model may be discarded. Also, studies investigating the impact of storm variability connecting to beach morphology is still scarce and needs further improvement (Ferreira, 2005; Morton 2002). Alongside the improvements needed to understand storm effects on beach profiles, very little is understood on what causes beach recovery and the rate at which it can occur.

2.4.3 Response of Crenulate bays to wave climate

Hurst et al (2015) explored how wave conditions influence the morphology of embayed beaches using a one-line model for coastline evolution. One-line models are models that depict the coastline as a single line. This model is built around an assumption that the cross-shore beach profile maintains some average morphology, which is only temporarily affected by storm events (Masselink et al., 2015). These bays occur in the lee of headlands or man-made coastal structures where erosion and littoral drift is inhabited in the face of the dominant direction of wave incidence (Yasso, 1965). To generate a wave climate, Hurst et al (2015) transformed an offshore wave into the nearshore using rules to allow for diffraction and refraction for when the coast is shadowed (Rea and Komar, 1975).

For a 2000m headland separation, the coastline approached equilibrium form in <40 years in all wave climate cases. The formation of crenulate-bays is favoured by a strong asymmetric wave climate, meaning that they are sensitive to wave direction and spread. Small bays are thought to recover from events more rapidly than larger bays. Daly et al (2015) saw recovery times much larger than those of Hurst et al (2015), which showed strong dependency on sediment transport formula used. These sediment transport formulas carry significant uncertainties. Another issue with the model is based on the grain size with different grain sizes showing different response times. The shoreline may also fluctuate about an average state in response to fluctuations in the wave climate and the reversal of sediment transport (Hurst et al, 2015). This causes sediment to be shifted from one end of the model to another which causes beach rotation (Harley et al., 2011; Turki et al., 2013).

Variations in beach morphology have previously been attributed to changes in the external forcing e.g. shifting wave climates at a seasonal and decadal timeseries (Harley et al., 2011; Thomas et al., 2011). Although increasingly, Ratliff and Murray (2014) identify that similar timescales for morphological fluctuation emerge from internal dynamics of coastlines forced using a constant wave climate. Ratliff and Murray (2014) saw rotation caused by alongshore sediment transport, but rotation may also be caused by alongshore gradients in cross-shore sediment transport (Harley et al., 2011). Cross-shore sediment dynamics may play a vital role in the evolution of nearshore bathymetry, which will influence the delivery of wave energy into the system. In order to further explore the cause of rotation, models using both cross and along shore sediment directions are needed.

Chapter 3: Site description, materials and Methods

This section will be broken down in to two main parts. The first section will be a complete site description, which brings together background information on Swanage, the BMP in action currently, and the available data sources for the area. The second section will mainly focus on the processes taken to analyse this data.

3.1 Study Site: Swanage Bay

Swanage is a coastal town in the south east of Dorset, England. Swanage is approximately 6 miles south of Poole and 25 miles east of Dorchester. The population of Swanage is nearly 10,000, however in a typical year, over 2,000,000 people visit Swanage as tourists (Swanage.gov, 2019). The main attraction for these tourists is the beach. According to the Swanage council, Swanage's pride and joy is its "gently shelving, golden sandy beach", which has achieved the blue flag award for the 17th consecutive year (Swanage.gov, 2019), making it an asset to maintain and protect.

Swanage is located within the SCOPAC region (Standing Conference on Problems Associated with the Coastlines) and the southern coastal group. The role of SCOPAC is to work with local authorities and other key organisations to sustainably manage the Southern coast of England. To manage this, the area is split into different sections which are controlled by local authorities. Swanage Bay lies within the shoreline management plan (SMP) Sub-cell 5f which used to be within the Bournemouth Borough Council (Bournemouth Borough Council, 2011). SMPs are large scale reports assessing the risks associated with coastal processes. It aims to help reduce these risks to people, property and the historic and natural environment. The England and Wales coastline is broken down into 11 cells. These cells are then broken down into sub-cells for more local management. These local management strategies consist of forming beach management plans. However, since the last BMP was created, Bournemouth council has merged with Christchurch and Poole council to form the BCP council. Sub-cell 5f encompasses two bays, Swanage Bay and Durlston Bay, with the limit of sediment transport being stated between Durlston Head to the South and Handfast Point to the North (Figure 7).

Swanage Bay is situated on the south coast of England, with the beach facing eastward. Handfast Point through to Ballard Point and continuing along the southern flank comprises of high, resistant chalk cliffs. The cliffs are near vertical with no intertidal foreshore, with irregular cliff falls. To the south of the headland, the coastal slope changes, reflecting its softer composition or Wealden Clays. The change in cliff marks the change in coastal form, beginning the crenulate shape of Swanage Bay (New Forest District Council, 2017).

Figure 7 - An overview of the Swanage area showing the location of Swanage Bay, Durlston Head, Peveril Point, Ballard Point, Handfast Point, Poole Bay and Christchurch Bay.

3.1.1 Beach Profiles

Swanage Bay is regularly surveyed as part of the regional monitoring program. The bay is surveyed to understand how profiles change along Swanage to help inform management decisions. In total, Swanage Bay has 42 topographic survey locations covering the full extent of the bay. These profiles are used to measure elevation levels and allow to see how the full extent of Swanage is varying over time. These sections have been broken down into three distinct sections: The northern section encompasses topographic profiles north of the most northward groyne; The centre section which includes all the profiles which received re-nourishment in 2005/06; The south section includes profiles south of the re-nourishment, to the southern extent of the beach (Figure 8). These sections have been pre-determined by the Channel Coastal Observatory (CCO) as the central section received the re-nourishment and the other two sections did not. The profiles extend from Pf500728-Pf500770 from north to south of the bay. The samples accessed are from 2007-2018 with many profiles being surveyed bi-annually. This data timeframe has been chosen as it is post re-nourishment meaning variations in the profile over the time series will be caused by natural processes. Surveys are also occasionally taken post storm event. 7 topographic profiles have been extended to 1998, where occasional beach surveys have been taken place using past CCO data. All these profiles have been carried out by the CCO and all the data used is open source (ChannelCoast, 2019).

Figure 8 - An aerial image of Swanage Bay with all topographic surveys. The image has been split into three sections: A northern section (red), a central section (blue), and a southern section (green). Aerial Image source: CCO (2019)

3.1.2 Wave Climate

The dominant wave direction is from the south to south-west, corresponding with the longest fetch and longer period swell waves originating from the Atlantic Ocean. However due to Swanage bay facing eastward, this section of coastline may be subject to significant shorter period wind waves originating from the south-east (Bournemouth Borough Council, 2011). These waves can be generated with a fetch of around 250Km, which may drive inshore sediment movement. Due to diffraction of waves around Durlston Head and Peveril Point, the dominant south-westerly waves also tend to approach Swanage Bay shoreline from the southeast.

Wave data has been collected from three different sources. The first source is from the Channel Coastal Observatory, where nearshore wave data can be collected. The closest wave data to Swanage is collected by a Rosemount WaveRadar Rex which is located on Swanage Pier and samples at 30-minute intervals (Table 1) (Figure 9). This WaveRex collects data including significant wave height, peak period and max height (ChannelCoast, 2019) It is stated by CCO that the storm threshold for the area is 1.2m for significant wave height. This is calculated using probability matrix which predicts that a 1 in 0.25 year storm event breaches a significant wave height of 1.2m. The limiting factor of this WaveRex is that it does not measure wave directions. This is because the WaveRex's main function is to measure water levels. The Swanage Pier WaveRex measures continuous water levels since 2008. The WaveRex measures water levels in 20-minute intervals. Water levels will be used in the analysis in order to carry out a joint analysis between tidal levels and extreme events. The time series for this data starts in January 2012 and is running to the present day.

Another CCO buoy used is located at Boscombe with a water depth of 10m OD. This buoy collects data in 30-minute intervals and has annual data from 2007-2018. This buoy collects wave parameters including, wave height, direction and period. The second wave buoy used is from CEFAS, which is another open source data provider. The buoy is in mid-deep water off the coast of Swanage. The CEFAS wave buoy measures, wave height, direction and period. This buoy is used as the water here may not be subject to diffraction around headlands. The CEFAS Poole Wavenet buoy is situated in waters with a depth of 28mOD. This data is also sampled every 30 minutes and has an annual timescale meaning the full study time can be analysed. The final wave data used in this report is from an acoustic wave and current profiler (AWAC) study carried out in 2017-18 by HR Wallingford. This study used 12 different AWAC systems located between Swanage and the Isle of White. These AWAC systems were deployed from 04/12/2017 till 30/01/2018 meaning only two months of data were collected. The data is sampled in 30-minute intervals and surveys wave height, direction and period. Although the measuring period is short, the data can be used to validate wave models for the specific conditions they were deployed as well as give visual representations of likely wave angles and heights. Figure 9 shows the location of these buoys.

Table 1 Location of wave Buoys used in thesis.

Buoy Name	Easting	Northing	Sampling Interval (mins)
Boscombe WaveRider	581911.2	5618385	30
Swanage Pier WaveRex	574348.5	5606913	30
poole Bay Wavenet	590603.6	5609872	30
Swanage AWAC Buoy	574921.1	5607765	30

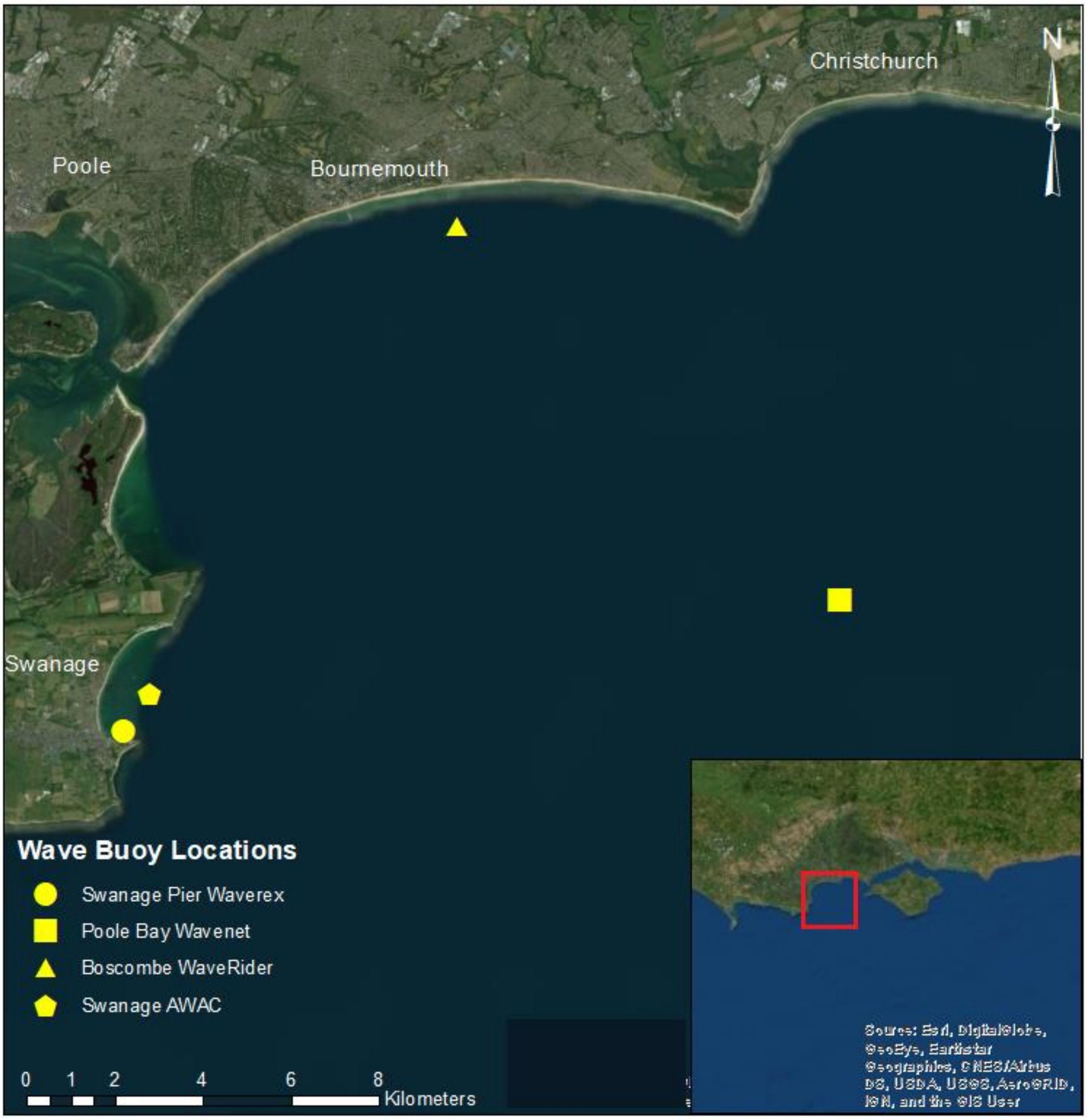


Figure 9 - An aerial image showing the location of all the wave data used in the report. This includes the Swanage Pier Waverex, Poole Bay Wavenet, Bosconbe WaveRider and Swanage AWAC.

As discussed in sections 2.2.1.2 and 2.2.1.3, wave refraction and diffraction can play a huge part in the direction of the waves entering a bay. As the dominant wave direction comes from the Southwest, some form of diffraction must take place for waves to reach Swanage Bay. It is clear to see that the dominant wave direction changes based on the location observed (Figure 10). The Poole Wavenet buoy suggests the dominant wave direction comes from the South West at an angle of roughly 200˚. This is because this buoy is less likely to have been affected by diffraction and refraction processes. The main angle at the Boscombe Wave Buoy is 180˚ as the waves have lined up to the coastline. Diffraction will have taken place around Durlston Head, but the main process lining up the waves will be refraction. At the Swanage AWAC buoy, the predominant wave angle is 150˚ as the waves have had to diffract around Durlston Head to then align with the bay. This rapid rate of diffraction around the headland makes it tricky to model the hydrodynamics in the region.

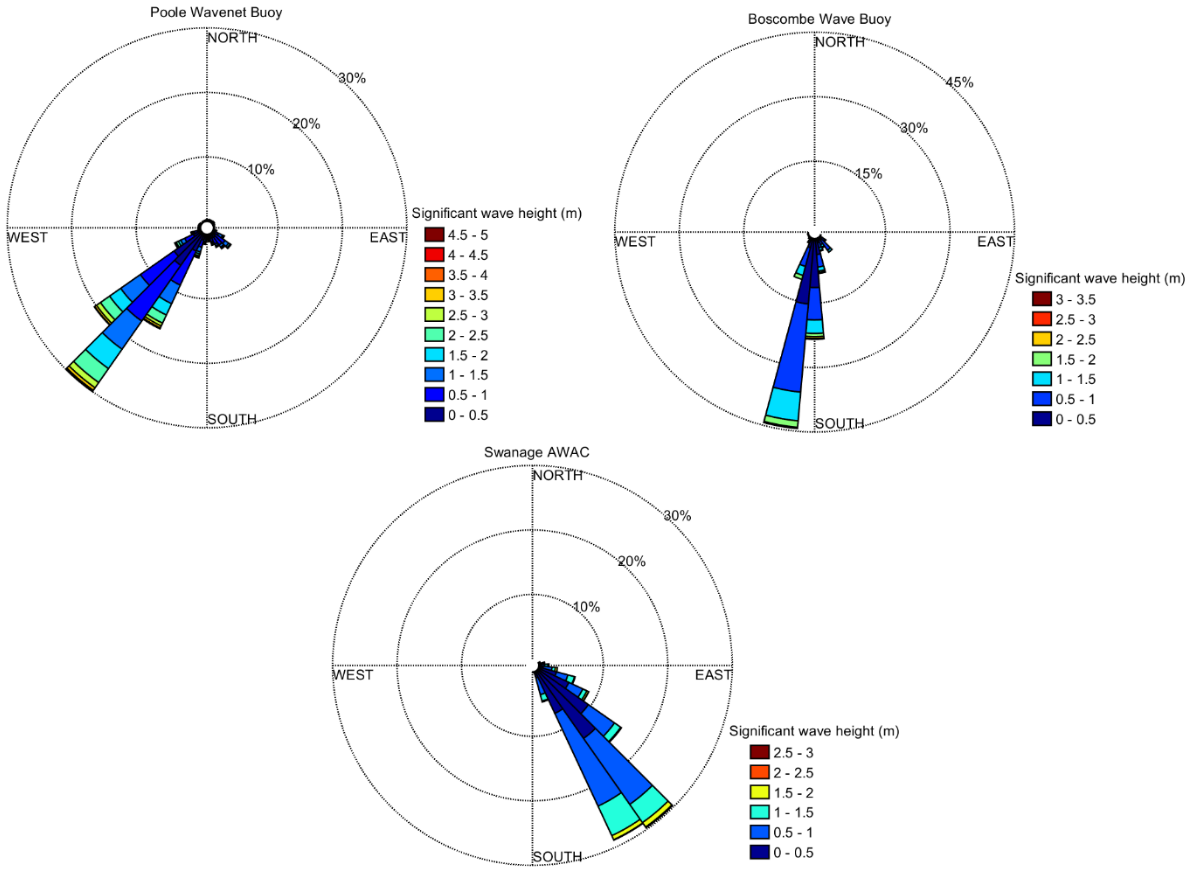


Figure 10 - A wave rose of wave data from Swanage Pier, Boscombe buoy and Poole wavenet buoy showing how wave direction varies based on the location between 04/12/2017-30/01/2018.

3.1.3 Tidal Flow

Swanage bay experiences relatively low tidal flows due to a micro-scale tidal range. As tidal flows are small, the main inshore sediment movement is caused by wave action. During spring tides, the tidal range is approximately 1.7m. During neap tides, the tidal range can be as low as 0.5m. At spring high tide, the tide typically reaches a height of 0.6m OD, or 2m CD.

Although Swanage bay experiences low tidal flows, tidal flows are slightly higher along Durlston bay. Although flows are low inshore, there are strong rip currents, particularly on the ebb past Handfast Point and Durlston Head (Bournemouth Borough Council, 2011). There is generally a strong south west dominant flow field in the deep water offshore of Durlston Bay during the ebb tide. The ebb tide brings sediments offshore of Handfast point back down to the southside of Durlston Bay (SCOPAC.org, 2004).

3.1.4 Control Features

The main control features of the site are Ballard point to the north and Peveril Point to the south. Although the south headland anchors the coast, and influences the wave climate, the southern headland, due to its orientation, acts to retain sediment fully within the bay. The beach tends to run out to an intersection of the hard cliff and the softer coastal slope to the northern end. Therefore, the bay tends to leak sediment to the offshore zone (Bournemouth Borough Council, 2011). There are local control features within Swanage Bay such as the pier. The pier provides a physical barrier that will trap northward moving sediment, and hence starve the north end of the beach of sediment.

3.1.5 Existing Defences

Swanage Bay has had a large amount of work done to limit the effect of flooding and beach volume loss. Defences commence part way along the soft coastal slope at the northern extent of the bay. The defence comprises a groyned beach with a sea wall starting at the southern extent of the first groyne system. The main section of Swanage Bay has a new 19 timber groyne field and recharged beach in-front of a promenade. According to the local council, the beach is said to be in good condition after these defences were put in place (Bournemouth Borough Council, 2011). To the South of Swanage Bay defences, there is a series of seawall sections said to be in a reasonable condition. Although all these defences are in a relatively good condition, in extreme water levels, these defences can be severely overtopped, which may affect areas behind the beach. The standard of protection of Swanage is 1:300 years, however this is expected to be over predicted due to recent storm events breaching the defence line (Purbeck District Council, 2005).

3.1.6 Re-Nourishment

During the winter of 2005/06, approximately 1.1million m^3 of sand dredged from Poole harbour channels was used to replenish beaches at Swanage, Poole and Bournemouth to protect from erosion (Poolebay.net, 2019). The current sediment size at Swanage is mainly sand with a small percentage of shingle along the southern and central parts of Swanage. The northern part is comprised of sand with 50% or more shingle. The re-nourishment was based on the existing beach but also took into consideration the commercial market (Halcrow Maritime, 2005). The construction of seawalls over the course of the last century limits the natural supply of beach material from cliff erosion. This combined with a natural loss of beach material from wind and wave induced transport makes it necessary to occasionally replenish beaches. Although Poole and Bournemouth beaches have previously been re-nourished, the 2005-06 re-nourishment was the first re-nourishment scheme for Swanage. In total, 90,000m^3 of sediment was placed in the central section of the bay (Figure 8). The crest level was risen to 1.2m ODN which was 0.7m higher than previous levels. The beach was also given a gentle slope of 1:20. Figure 11a shows the beach in the 1930s, compared to Figure 11b which shows the beach post nourishment. It is clear to see in the images that the beach level has greatly increased due to the height of the sediment compared to the sea wall.

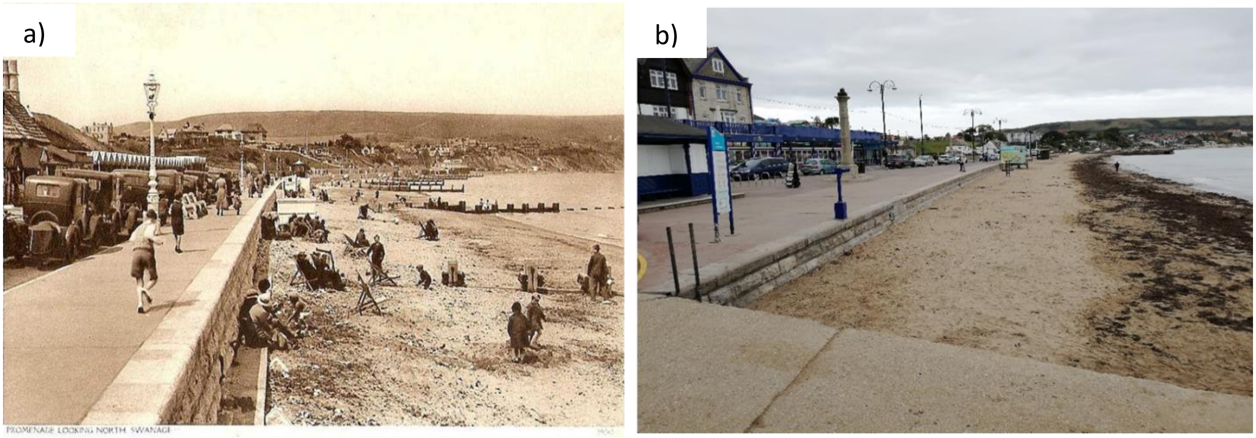


Figure 11 - shows two figures pre and post re-nourishment to see how the beach level has changed a) taken in the 1930s and b) in 2007. Source: Environmental Agency.

3.1.7 Recent Flooding Events

Although the standard of protection at Swanage is stated as 1:300 years, this is likely to be overpredicted. In the last 8 years, three storms have caused flooding in Swanage. In 2014, the Valentine's day storm caused significant damage to the sea wall, with approximately 25m of the top of the sea wall being displaced due to wave action. In 2016, Storm Angus caused the sea wall to be overtopped by waves along the southern end of Swanage. There was also flooding of local businesses and roads along the eastern end of the High Street, with 7 properties being flooded in total (Picksley, 2019; pers comm). Other storms such as Beast from the East also caused flooding with debris being thrown into the promenade in the central part of Swanage. Although the damage is yet to be significant, these storm events show that Swanage is still susceptible to flooding and needs to be managed accordingly.

3.1.8 Sediment Processes

Figure 12 shows the general sediment transport pathways between Durlston Head and Handfast Point. Changes in bathymetry carried out by SCOPAC.org (2004) identify a net sediment drift from south to north along the two bays. The drift along Swanage Bay tends to work along a narrow section of the intertidal beach, but there is also some drawdown of the upper beach. The Swanage Bay strategy study suggests that there may be feed to the bay from offshore to the southern parts of the bay, which is then fed northwards along Swanage Bay (SCOPAC.org, 2004). This is likely to occur during major storms which are capable to mobilise sediment in the deep offshore area. This may explain why there may have been periods of accretion along the frontage in the past. Due to near continuous northward drift, erosion from cliffs in the northern parts of the bay is unlikely to provide a significant sediment supply to the bay. The slightly advanced position of the hard defences to the southern end of the bay, limits the amount of sediment retention available. The slightly deeper bay to the east of the pier can trap sediment to form a wider beach.

Durlston Bay has no opportunity for sediment to build. Any material eroded from the cliffs is quickly transported northward along the shore by wave action. Only large boulders remain on the narrow intertidal foreshore. Studies have shown that Durlston Bay may benefit from a greater degree of protection from wave action at the southern extent of the bay (SCOPAC.org, 2004). This protection would not stop northward sediment transport, but would help to limit the rate of transport, so sediment retention would increase (Bournemouth Borough Council, 2011). Figure 12 shows the predicted sediment transports along Swanage Bay (Scopac.org, 2019). It shows that there is limited sediment input from the river and cliffs especially due to coastal defences protecting Swanage. This means that the main sediment input comes from circulation within the bay.

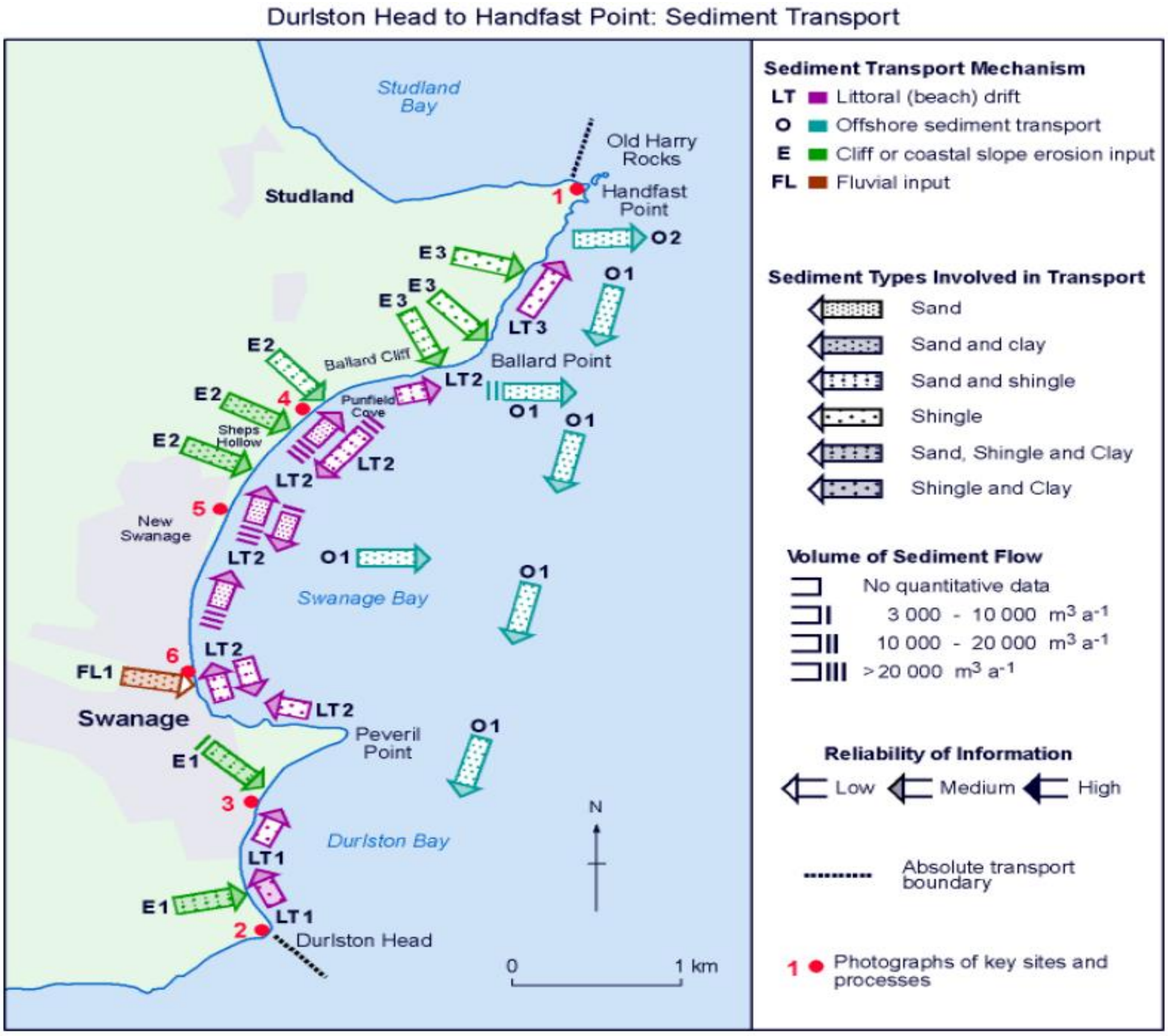


Figure 12 – Surveyed data predicting sediment transport along Swanage Bay. Source: SCOPAC, (2004).

3.2 Data Analysis and Modelling

The beach profiles and wave data were analysed with the help of CoastalTools (Townend, 2019). Beach profiles from 2007-18, sampled to low spring tide, were used to calculate beach volumes, shoreline positions and slope. The beach volume is the cross-sectional area per unit length of the beach and the shoreline position is defined as the crossing of the 0m OD contour for each vertical datum.

3.2.1 Beach Volumes and Centroid

Although beach volume and shoreline positions are considered as good proxies for measuring beach change, neither of these parameters take into consideration rotation. Rotation is the steepening or flattening of the beach which can be critical to maintain shorelines and modify beach volumes. A way to account for these rotations is to use beach centroids (Villamarin, 2017). Cross-shore sediment transport mainly occurs during extreme events meaning that a rapid change in beach volume can occur in a very short period. This means that the cross-shore component of sediment transport occurs over a shorter timeframe than longshore transport.

The volumetric centroid is calculated using the cross-sectional area by a rectangle that creates a control area (Townend, 2019) (Figure 13). Inside this control area, the following parameters are calculated:

Volume: $V = \int z'dx'$

Horizontal centroid: $X_1 = \int {x'z'dz'}/{V}$ (first moment in x)

Vertical centroid: $Z_1 = \int {x'z'dz'}/{V}$ (first moment in z)

where x and z are the raw profile data. x' is the horizontal distance from the origin of the control area and z' is the elevation above the same origin. For each profile, the points on the profile nearest the defined minimum x or minimum z are found and used to define the two end points for the profile (Townend, 2019; Villamarin, 2017).

These values are then subtracted from the profile x-z co-ordinates, such that:

$$x' = x - x_{min}; x' \geq 0 and z' = z - z_{min}; z' \geq 0$$

The range of x and z is then defined as: L_x = max(x') and L_z = max(z').

These are used to define non-dimensional variables $x''=x'/L_x$ and $z''=z'/L_z$. The non-dimensional moments are then:

Non-dimensional volume: $m_0 = \int z''dx'$

Non-dimensional x centroid: $x_1 = \int {x''z''dx''}/{m_0}$

Non-dimensional z centroid: $z_1 = \int {x''z''dz''}/{m_0}$

The centroid was analysed making use of the non-dimensional x and z coordinates: x_1 and z_1. Non-dimensional x and z coordinates are used so that there can be a direct comparison between profiles along Swanage Bay.

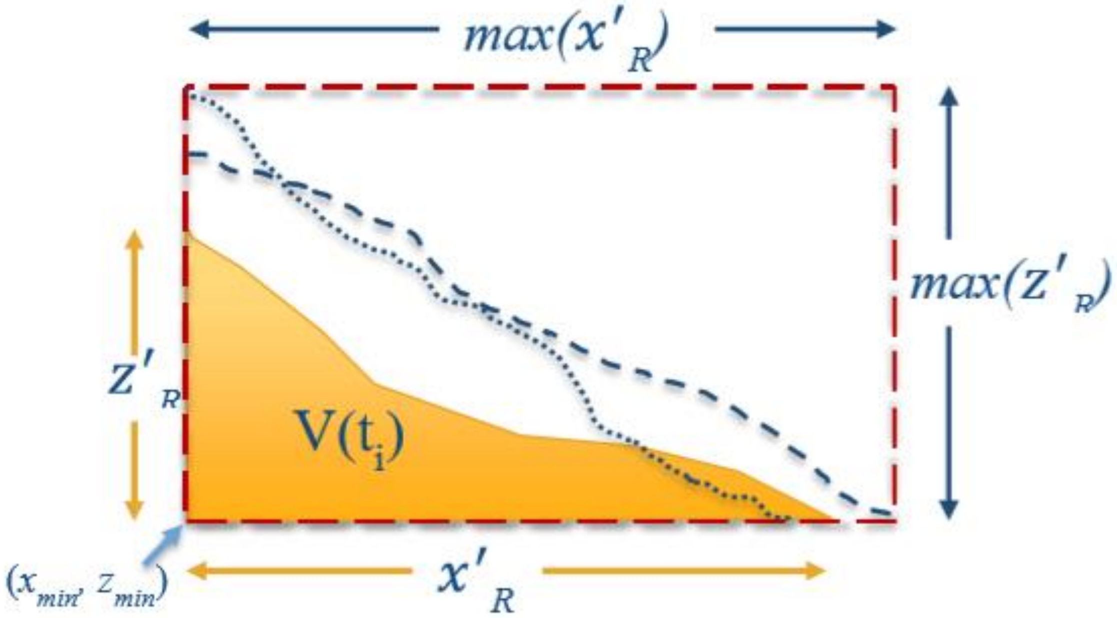


Figure 13 - Volumetric centroid calculation matrix. Source: Townend, 2019.

3.2.2 Inshore Wave model

A key problem for predicting the hydrodynamic regime within Swanage Bay is the lack of a long-term directional wave data. Although the AWAC was deployed within Swanage, the deployment was only for 2 months during winter. Only winter wave directions are monitored rather than over an annual period. This means that if the time series is extended, the wave heights will likely be over predicted as no quiescent periods had been monitored. In order to increase the time series for waves in Swanage, a model must be set up in order to predict nearshore wave directions and wave height.

Models such as Swan models and Tomerwac, can model wave refraction and diffraction in 2-D. These models, require large amounts of time to set up in order to be accurate, meaning a more simple model was used in this report.

In order to create a model to predict nearshore waves, an offshore and nearshore point must be selected. The offshore point selected was the CEFAS Poole wavenet buoy as the buoy was unlikely to have been affected from refraction and diffraction processes. The nearshore point which is modelled was the same location as the Swanage AWAC Buoy. This was chosen because it means a direct comparison can be taken in order to see if the model predictions match real world readings. The wave model used, propagates wave from the offshore into the nearshore. For this point to be accurate, site parameters must be set to match the nearshore buoy location. The water depth at the buoy is -9.5m OD, and the bottom contours are 15˚ off direct north. A friction coefficient of 1 was used in order to match the wave heights seen from the Swanage AWAC buoy. Changing the friction coefficient changes the wave height as greater frictions will cause waves to become steeper and break earlier.

For each time interval, the model uses offshore values of wave height, period and direction (Townend, 2019). Wave refraction and shoaling are computed to either the specified inshore depth in this case. The model outputs a time series of inshore wave heights and directions at the inshore depth used. In this model, wave period is assumed to be constant as there is little variation over an annual time series (Fournier and Reeves, 1986).

Inshore waves are calculated using linear wave theory and plane bed refraction and shoaling:

$$H_{si} = k_r k_s k_f h_{so}$$

where H_s is the significant wave height offshore and inshore, k_r is the refraction coefficient, k_s is the shoaling coefficient, k_f is the friction coefficient. These coefficients are defined as:

$$k_r = \sqrt{\frac{\cos(a_o)}{\cos(a_i)}}\, and\ a_i = sin^{-1}\left(\frac{c_i}{c_o}\sin a_o\right)$$

$$k_s = \sqrt{\frac{c_{go}}{c_{gi}}}\ where\ c_g = \frac{c}{2}\left(\frac{1+\frac{4\pi d}{c.T_p}}{sinh\left(\frac{4\pi d}{c.T_p}\right)}\right)$$

where d is water depth, c is wave celerity, c_g is group celerity, g is gravity and T_p is peak wave period (Townend, 2019). In this model, the inshore and offshore celerity are calculated using the equations proposed by Hunt (1979):

$$c = \sqrt{gdA}$$

$$with\ A = (y + (1 + 0.6522y + 0.864y^2 + 0.0864y^4 + 0.0675y^5)^{-1})^{-1}$$

$$where\ y = \left(\frac{2\pi}{T}\right)^2 \frac{d}{g}$$

This model originally only takes refraction into consideration. Diffraction is added to the model by adding a stiff boundary as to which only certain angle waves can enter the nearshore. If the wave has too great of an angle in the offshore, it is expected to continue offshore so will not enter the nearshore zone. The limit put on this value was 200˚ meaning any offshore wave with a direction greater than 200˚ will continue offshore. To validate this model, it was compared to the 2-month long AWAC dataset.

3.2.3 Model Validation

The model output of inshore waves was validated using the Swanage AWAC dataset. Both inshore wave directions and wave heights were modelled and compared with the AWAC data. Figure 14 shows a timeseries of AWAC data in blue and the modelled data in orange. The model predicts significant wave height (Hs) relatively accurately, However, the peaks are slightly lower than the AWAC data (Figure 14). Also, daily fluctuations in Hs are under predicted in the modelled data suggesting that other factors may be influencing the wave height such as the water level.

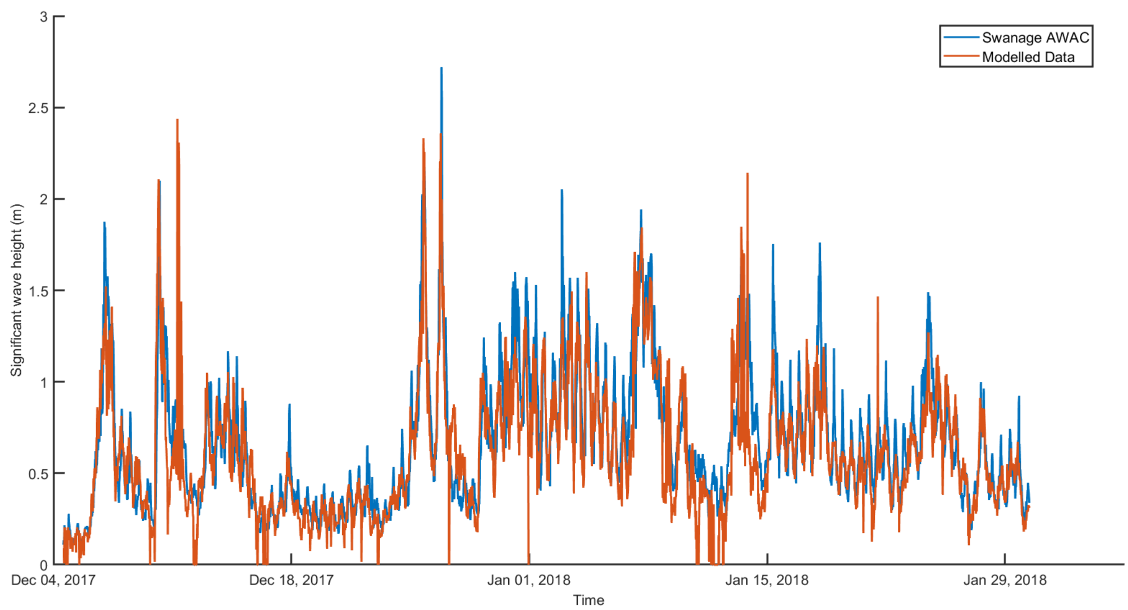


Figure 14 - Swanage AWAC data compared to Modelled data for significant wave heights from 04/12/2017-30/01/2018.

Wave directions are notoriously more difficult to model compared to Hs. Figure 15 shows the AWAC data in blue and the modelled data in orange. The trend of both data sets follows a similar pattern, there is a significantly greater variability in the AWAC data. As the modelled data is only using offshore wave height, period and wave directions to predict the inshore wave direction, it is expected that other factors such as wind and water level will also contribute to the wave direction meaning that the AWAC data will see greater variability. Although the modelled data does under predict the real-world data, it is assumed that the change will not have too large of an effect on the directions itself. A more complex model is recommended to be set up in the future to predict a more accurate wave climate.

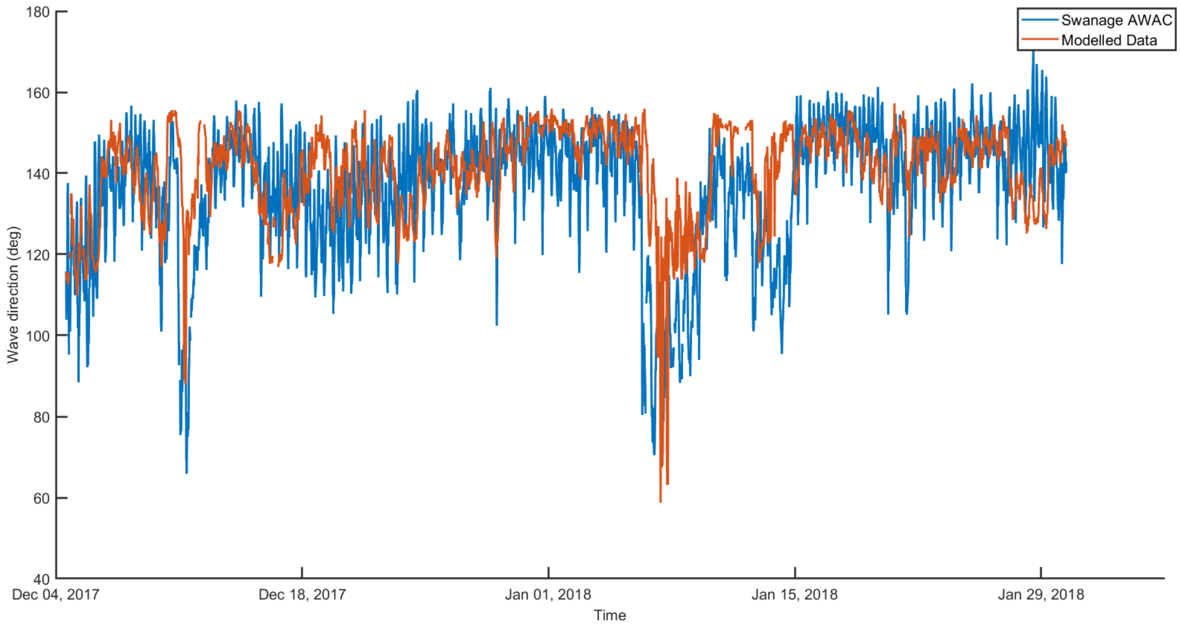


Figure 15 - Swanage AWAC data compared to modelled data for wave direction between: 04/12/2017-30/01/2018.

A Taylor diagram was used to analyse the statistics of the model runs in order to validate the model (Figure 16). A Taylor diagram uses standard deviation, correlation coefficient and route mean squared difference to assess the modelled runs against the measured data (Taylor, 2000). The Taylor diagram shows both inshore wave direction and Hs compared to the real-world data. Although both points are off, it is clear to see that Hs is closer to the reference point compared to wave direction. Inshore Hs has a correlation coefficient of 0.82 and a normalised standard deviation of 0.8 compared to inshore wave direction which has a correlation coefficient of only 0.45 and a normalised standard deviation of 0.65. For a simple model, these values are classed well predicted meaning that both the inshore Hs and wave directions can be used in analysis.

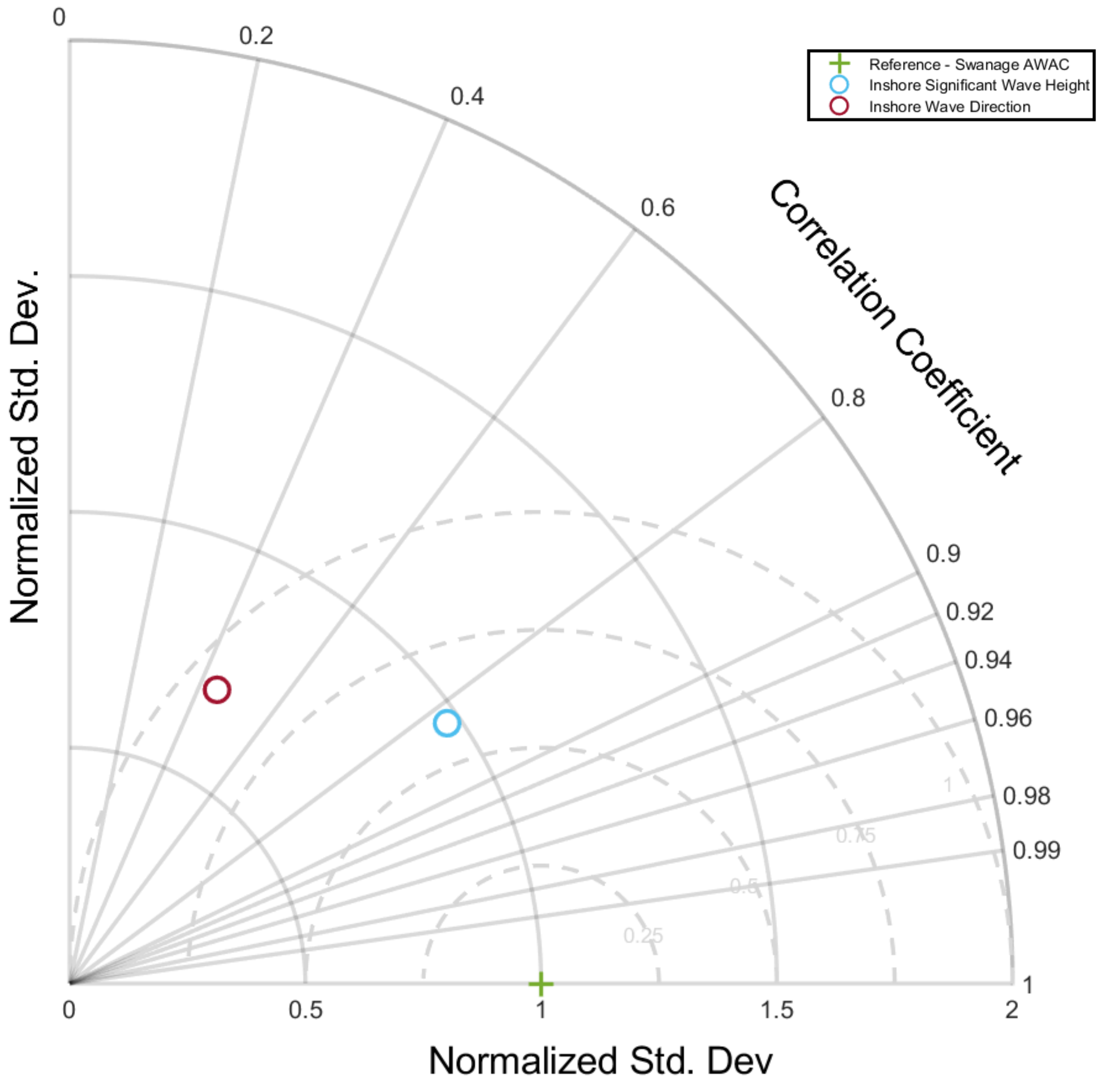


Figure 16 - A Taylor diagram showing how the model outputs for both wave direction and wave height compare to the Swanage AWAC data

The regression line below shows the Swanage AWAC data compared to the Modelled Data (Figure 17). The regression line fits a 1 to 1 trend with points being scattered either side of the regression line. An R^2 value of 0.68 indicates that the model is predicting similar significant wave heights. The regression plot does show that the model over predicts wave heights above 1.5 meaning the peak significant wave height may be over predicted during storm events.

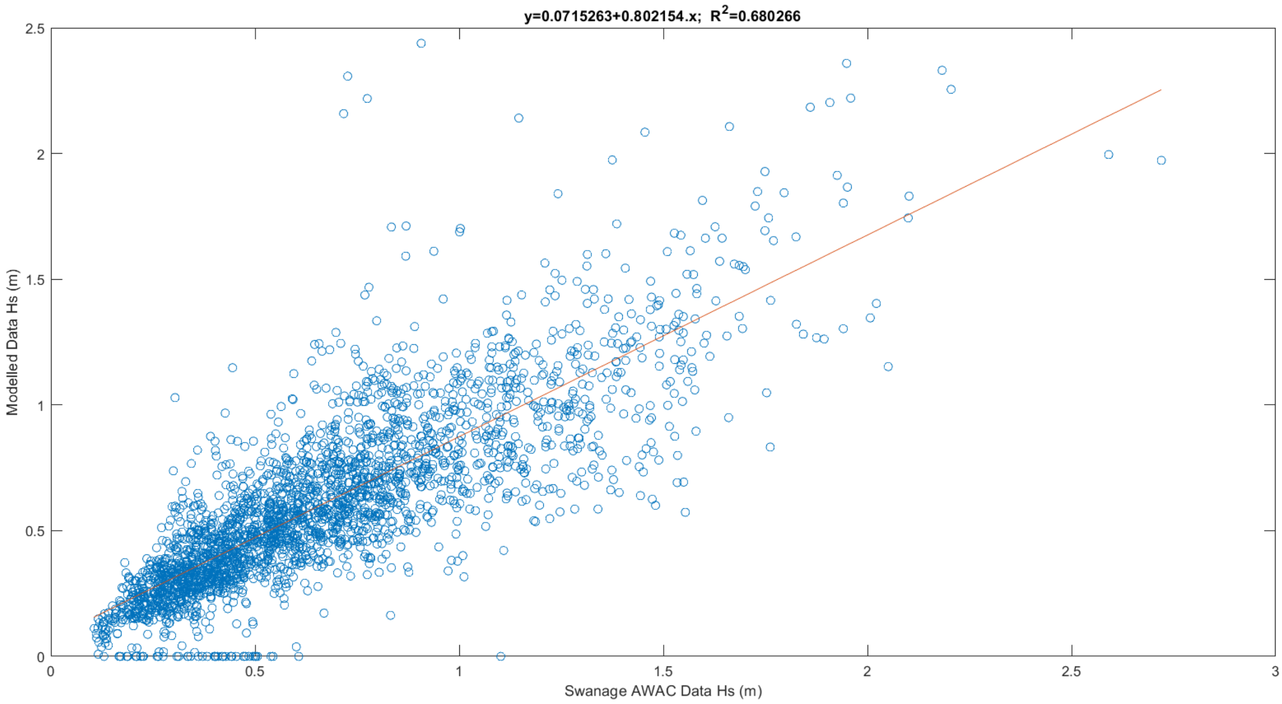


Figure 17 - A regression line comparing the Swanage AWAC significant wave heights with the Modelled datas significant wave heights.

3.2.4 Principal Component Analysis

Principal Component analysis (PCA) is the most popular multivariate statistical technique and can be used by most scientific disciplines (Abdi and Williams, 2010). Although it is classed as one of the oldest multivariate techniques, its modern instantiation was formalized by Hotelling (1933). PCA analyses data described by several dependant variables, which are inter-correlated. PCA extracts the important information from the data and expresses them as new variables called principal components. PCA is used to understand which wave parameter influences beach volume change. If no single parameter has an effect on beach volume, it is assumed that the system will be complex, with further multivariate analysis being required to understand the cause of beach volume change.

The dependant variables used in this analysis includes beach volume, significant wave height, peak wave period and inshore wave direction. Each dataset was two weeks before the next topographic profile. Due to limited wave data, only one beach profile has been analysed. This is because there is only one dataset which include significant wave height, wave directions and peak period meaning that these values cannot change around the beach. Profile Pf500747 was chosen for this analysis as it is central on the beach and that it is surveyed frequently allowing more data to be analysed.

Chapter 4: Results

This section will be broken down into four sections. The first section breaks down the overview of the beach, looking at frequency of storm events and how the beach will be broken down into distinct sections. The second investigates the three beach sections in more detail looking into how beach volumes change over time as well as looking at beach centroid plots and the effects of the re-nourishment. The third section then brings in the hydrodynamics and investigates possible causes into why we see a change in the beach volumes over time. this section will go into detail on different storm events as well as possible recovery conditions.

4.1 General Overview

As mentioned in section 3.1.2, the storm threshold at Swanage Pier is 1.2m for significant wave height. Figure 18 shows times that this limit has been reached. Since 2012, this threshold has been met 21 times (Figure 18). Figure 18 also shows recorded storm events by workers for the Environmental Agency, which listed the impacts of the storm. Although these only states that 4 storms took place, it is likely that other storms have also impacted Swanage but were not categorised due to budget and time restraints within the EA and CCO.

The storm threshold is usually breached during winter months. In winter, the wave climate is more energetic, with greater winds and swells meaning that significant wave height is expected to be higher. The largest recorded significant wave height at Swanage Pier was in February 2018 with a wave height of over 1.8m. In February 2018, the storm known as Beast from the East hit the South coast affecting many areas. This coincides with the largest significant wave heights. Other notable storms such as the 2013-14 storm and storm Angus record high significant wave heights. Although these storm events caused flooding in many areas, due to the location of Swanage, the effects of the impacts on the beach may be different. Other storms have also been seen and recorded but are not plotted on this figure.

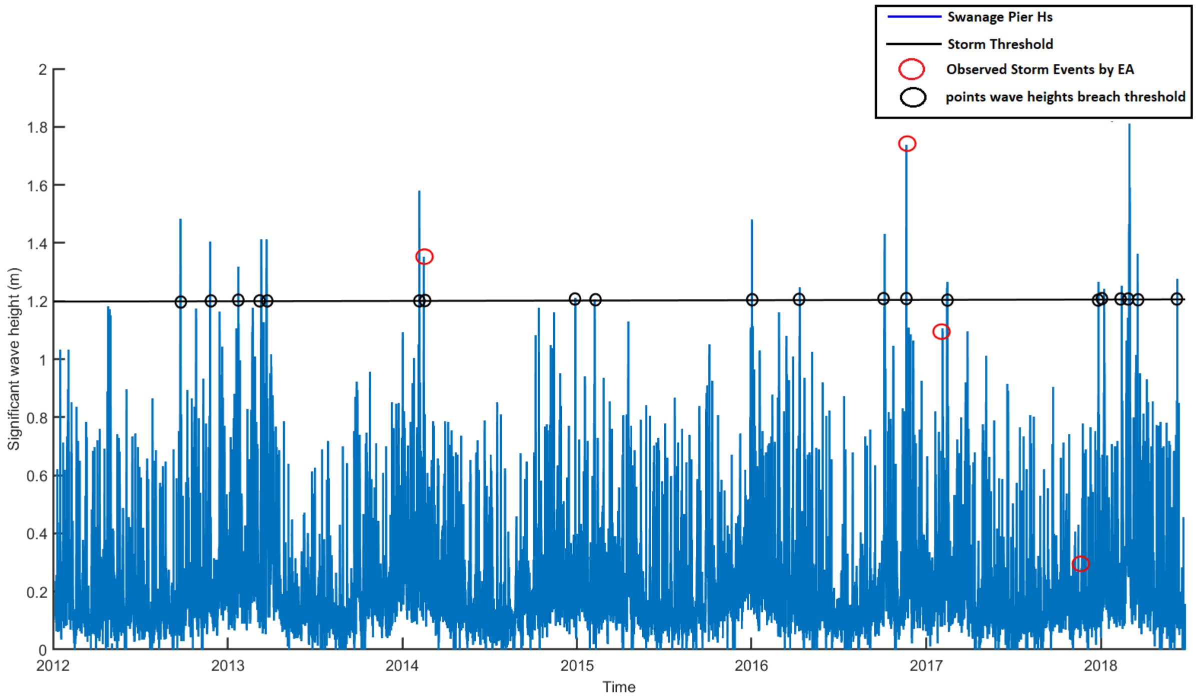
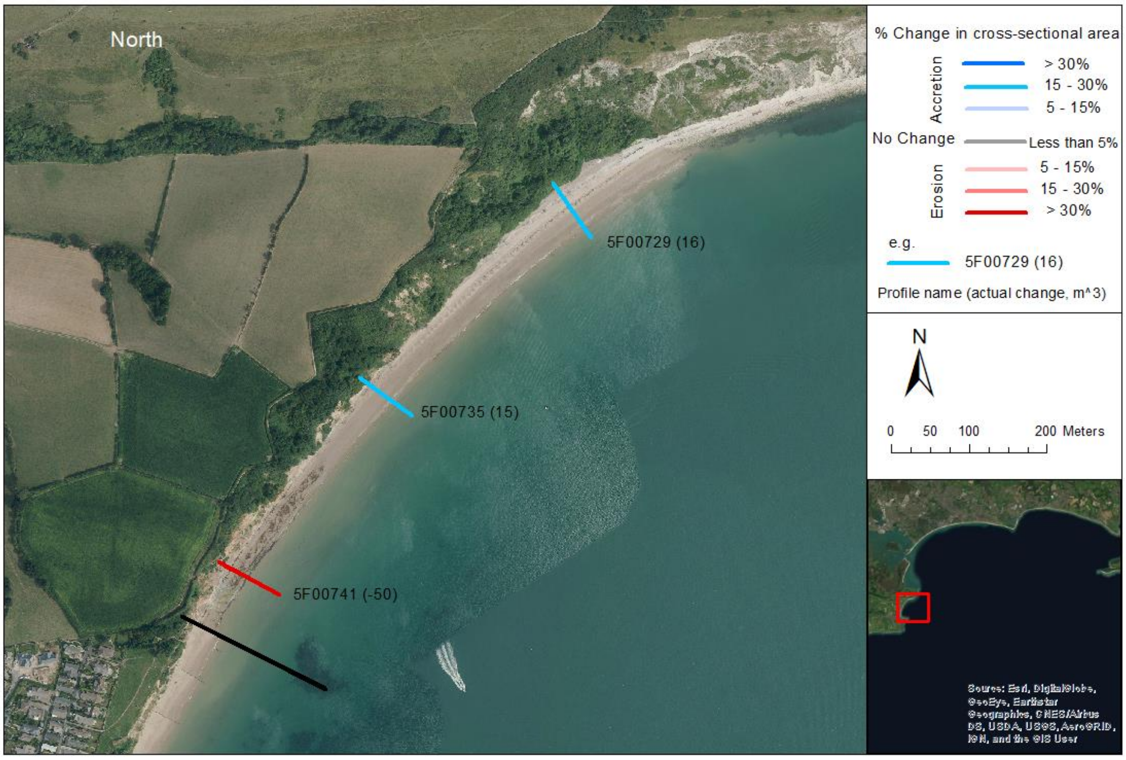


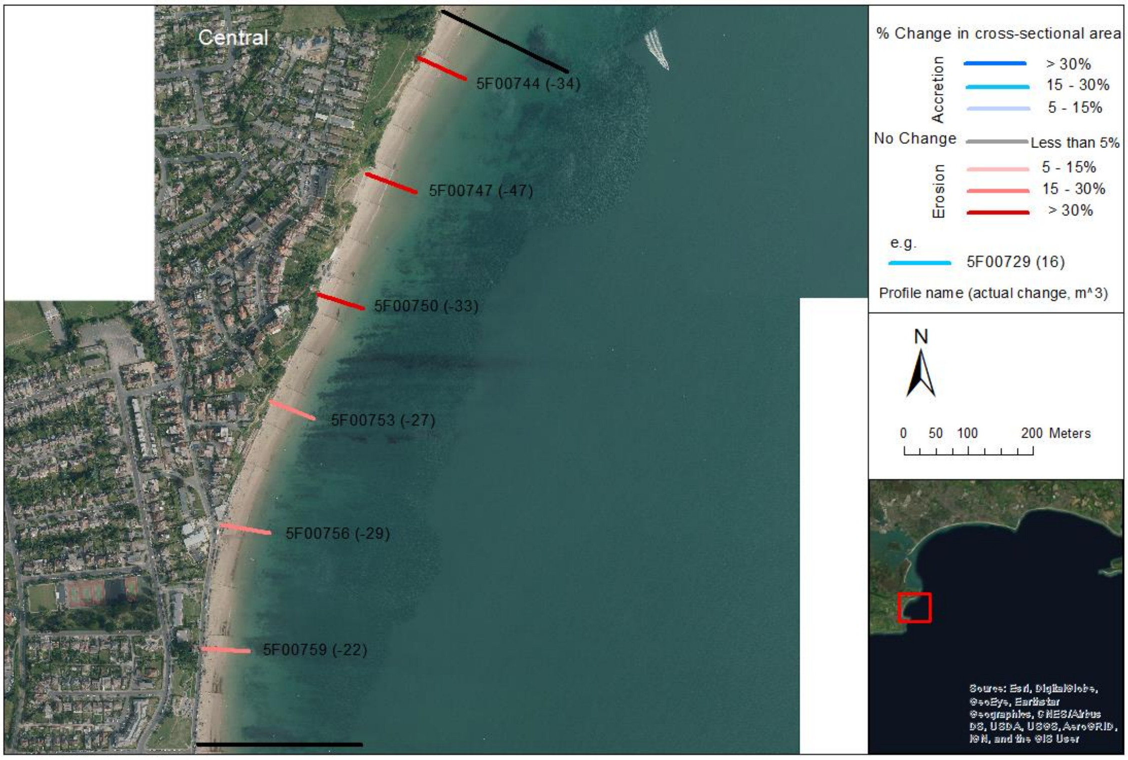
Figure 18 - A timeseries of significant wave height measured at Swanage Pier, with the storm threshold of 1.2 plotted as well as observed flood events. The black circles indicate positions that the storm threshold was breached.

4.2 Beach Profiles

In section 3.1.1, we decided to split Swanage Bay into 3 distinct sections. The reason the bay has been split into these sections is due to the nature of the profiles. These distinct sections experience different affects from the hydrodynamic regime as well as how they are managed. The top section of the beach is found north of the most northward groyne. This section of the beach is not protected as has large resistant cliffs behind. The middle section is the most protected section and covers the most profiles. This section is within the protected groyne field and lies in-front of the main town of Swanage. This area received the 90,000m^3 re-nourishment in 2006 to help protect the town from future flooding events. The final section mainly includes profiles south of the Banjo Pier. Although this section lies in-front of the town, there has been no active beach management plan for this section meaning there are no groynes and has received no nourishment.

Figure 19 has broken the beach into the three distinct sections. The percentage change in beach volume from the first profile surveyed in 2007 to 2018. It is clear to see the only accreting area of Swanage Bay is the north section with only one profile seeing an accretion (Figure 19). The north profiles have accreted by over 15% since 2007. Both the central and southern parts of the beach see high erosion rates suggesting that the beach volumes in these areas is decreasing. As Swanage is a crenulate bay between two headlands it is understood that there will be little loss out of the system. This means that if the northern section of the bay is accreting while the southern side of the bay is eroding, the beach is not in equilibrium and there will be a clockwise rotation of the beach.





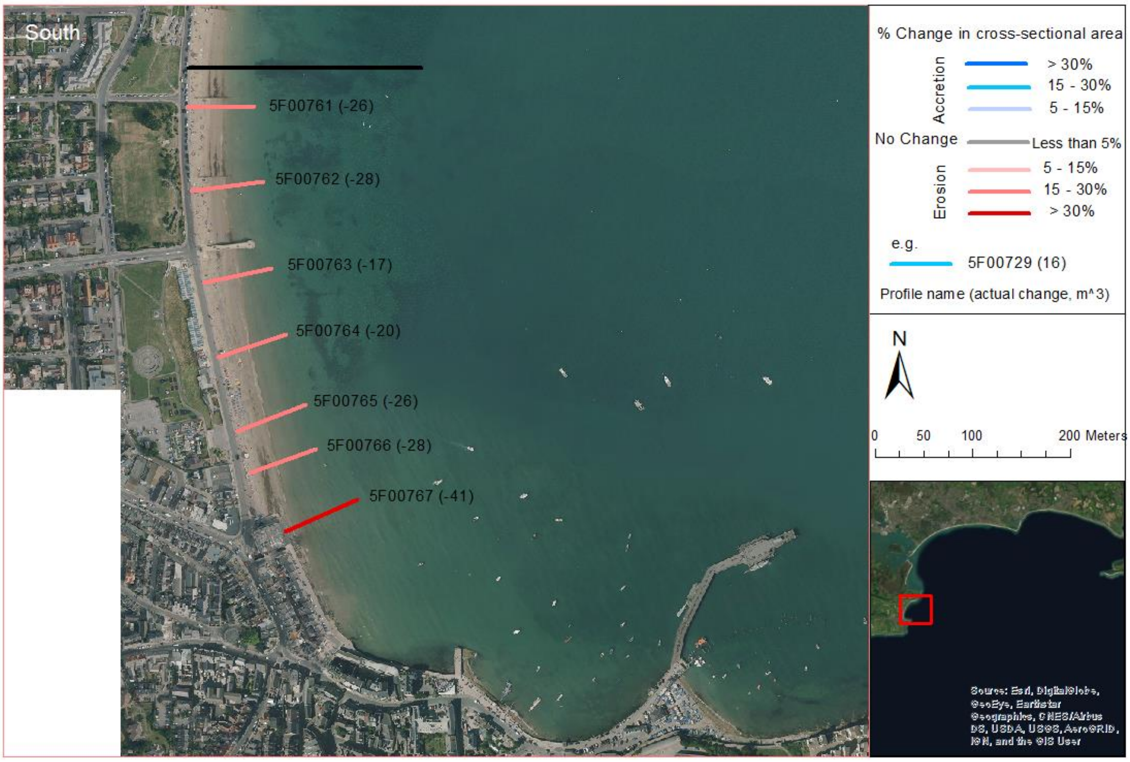


Figure 19 - Splits the beach into the three-section starting at the north end and moving south. The profile colour indicates the percentage erosion/ accretion seen at the profile between 2007-2018.

The main direction for sediment transport is northwards through the sections meaning that the analysis will start at the southern end and proceed northwards. Beach volumes were calculated for all 42 profiles along Swanage bay, but to show the results in a concise manner, only one profile has been selected from each section to be analysed. The samples chosen are P5f00735 for the northern section, P5f00747 for the central section and P5f00763 for the southern section (Figure 20). These profiles have been chosen as they are the profiles with the most frequent surveys including post storm surveys and pre-nourishment surveys.

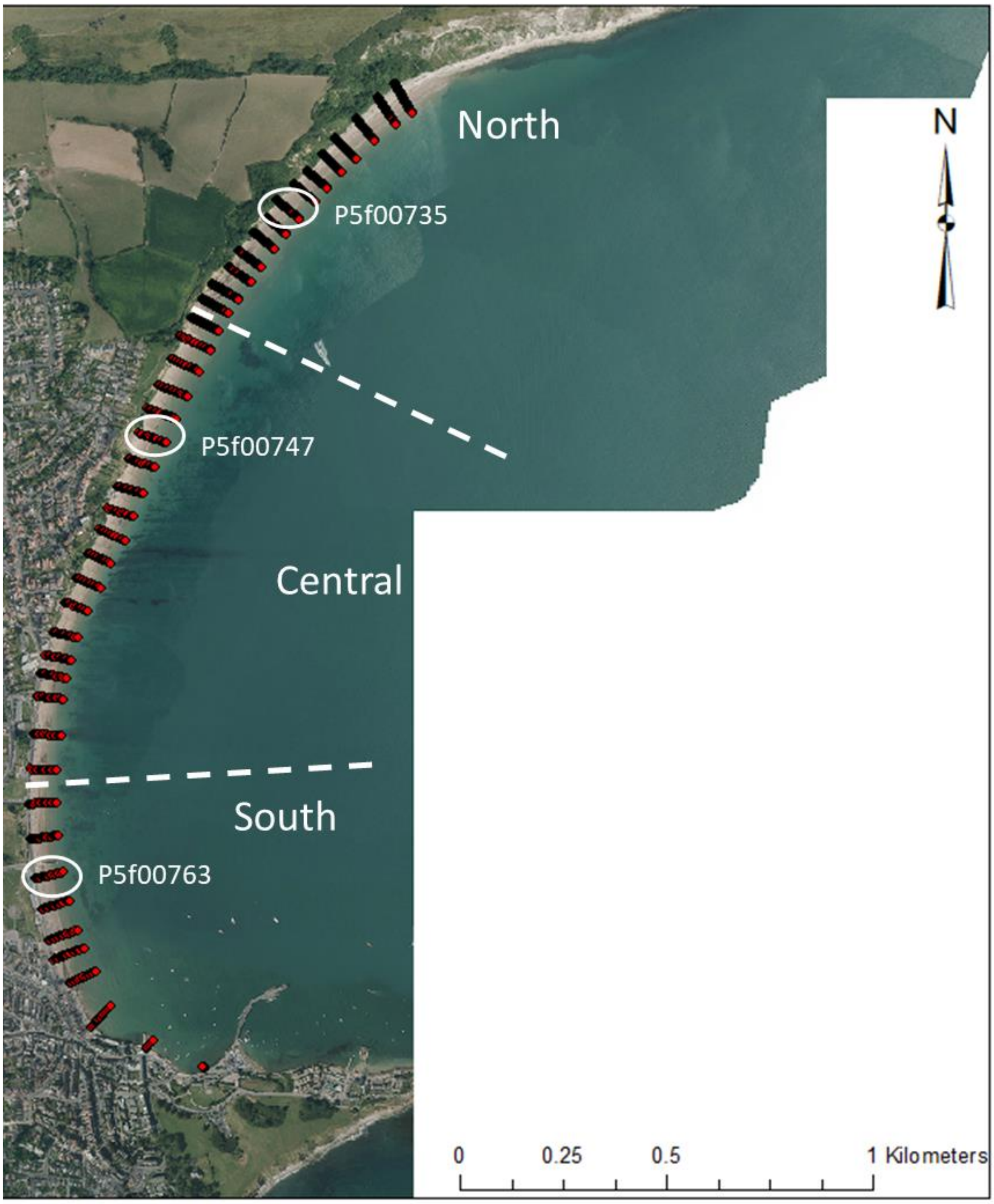


Figure 20 - A full extent of Swanage Bay split into the sections. Profiles which have further analysis have been circled and labelled.

4.2.1 Southern Section of Swanage.

Figure 21 shows the seasonal variation seen along these profiles. Figure 21a shows profiles sampled in summer compared to figure 21b which shows figures sampled in winter. Both profiles clearly show a reduction in beach area as seen by the profiles shifting back over time. Both profiles also suggest that there is a steepening occurring overtime at this location. The profile sampled in 09/03/2018 shows a significant shift in the beach profile with large sections of the upper parts of the beach being removed.

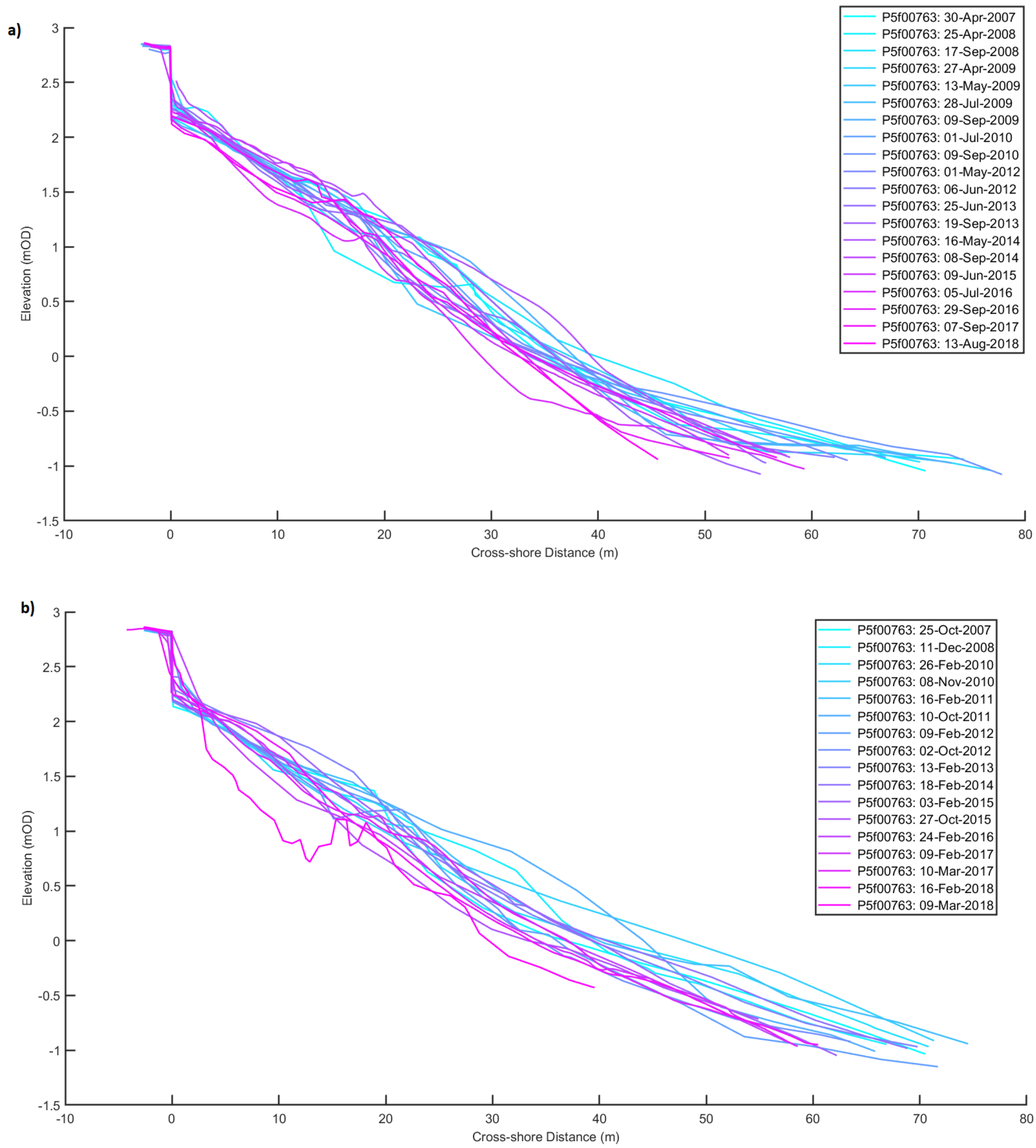


Figure 21 - Topographic surveys for profile Pff00763 located at the southern end of Swanage during a) summer conditions and b) winter conditions.

Beach volumes between 1998 and 2018 were calculated using Coastal Tools. The volumes calculated suggest that the beach was accreting from 1998 to 2004. From 2004 to 2007, the beach remained stable but since 2011, the beach has started eroding. In general, the lowest beach volumes occur during winter periods as this is when energetic waves can displace a greater volume of sediment. The lowest peak on this profile occurs during February 2018 and coincides with the "Beast from the East" where beach volume fell by almost 35m^3. The sediment is being moved offshore to a bar at depth of -5m OD which is not being captured by the topographic profiles. Post storm, the volume does seem to increase, with almost pre storm levels sampled in August 2018. This indicates that although storms can remove sediment, other hydrodynamic process are able to recover the beach. Post 2011, a trend line was fitted to the data to calculate the rate of loss of beach profile volume. The trend line showed that the beach volume was changing at a rate of -3.32m^3a^{-1}. This means that over the 7 years post the 2011 survey, the average beach volume has fallen by over 21m^3.

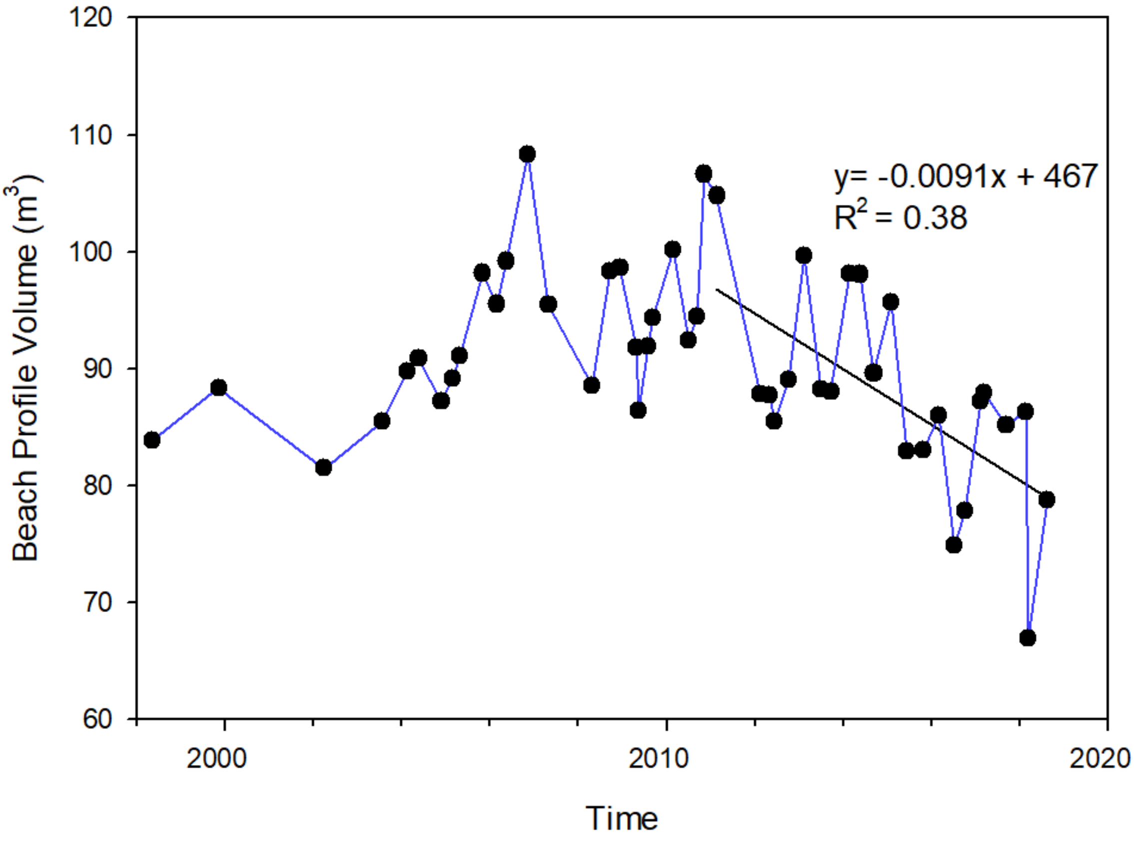


Figure 22 - Beach volume change for profile P5f00763 with trend line from 2011.

The centroid plot shows that the beach remains relatively constant pre and post nourishment. This confirms what is seen in figure 22 as there is only a beach volume change of 5m^3 between 2005 and 2006. From 1998 to 2005, an accretion and flattening of the beach can be seen. This is because the blue line is moving eastwards. However post 2005, the net trend of the centroid plot suggests that the beach profile is eroding as well as steepening. This confirms what is seen in the beach profiles in figure 23. The low point seen is due to an almost total beach removal caused by the Beast from the East.

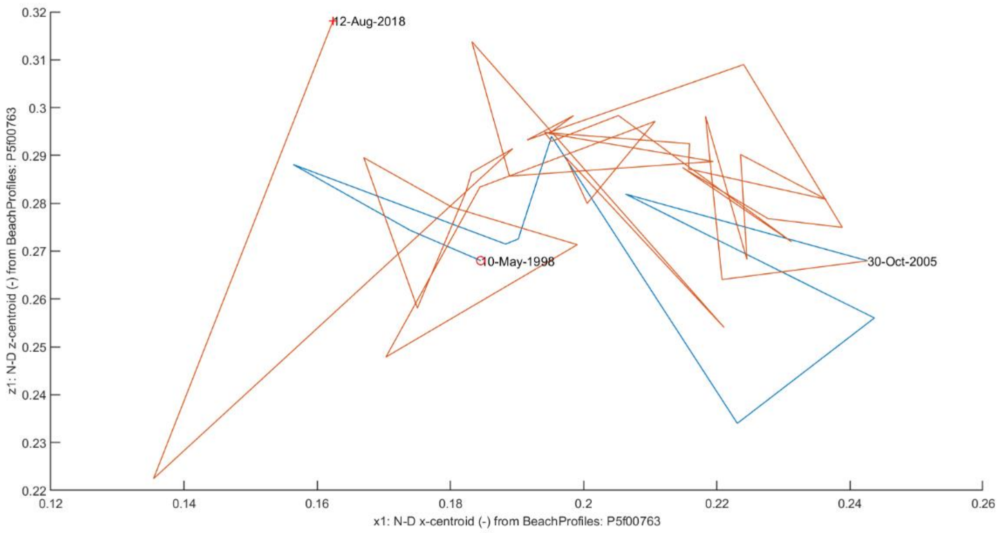


Figure 23 - Centroid plot for profile P5f00763 between 1998-2018. the blue line indicates profiles before the re-nourishment and the red line indicates profiles post re-nourishment.

4.2.2 Central Section of Swanage Beach

The central section of Swanage has experienced the most management over recent years. Not only has there been a re-nouirshment, but the whole groyne field was also restored in 2006. Although these works have taken place, sediment is still being lost. The beach profiles seen in figure 24 show the profiles from 2007. Figure 24 shows a loss of sediment over time in both the summer and winter profiles suggesting that the profile is slowly returnig to a pre-nourishment level.

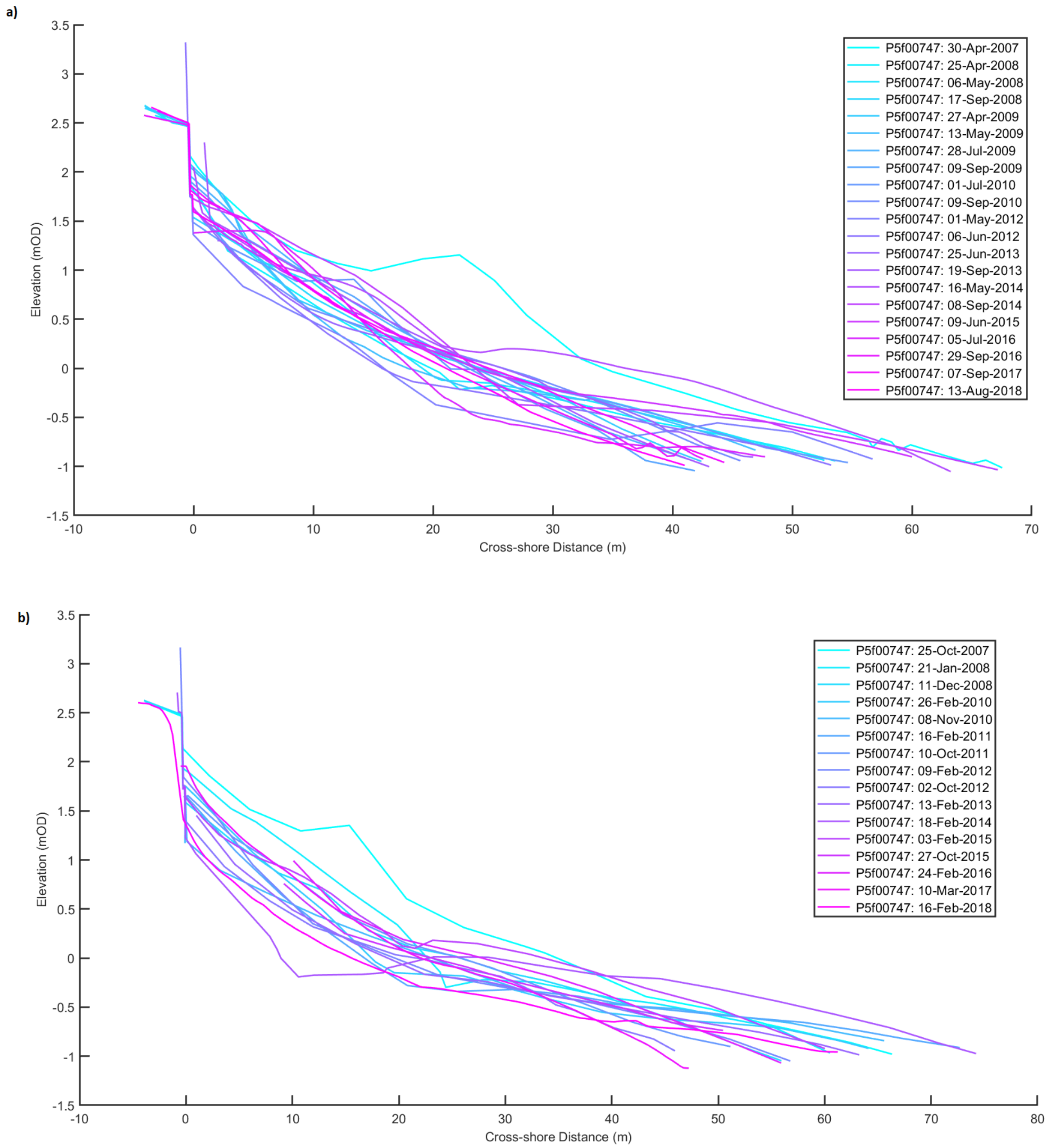


Figure 24 - Topographic surveys for profile Pff00747 located at the central part of Swanage during a) summer conditions and b) winter conditions.

Beach volumes were calculated between 1998-2018. this range was used so that pre nourishment beach volumes can be easily compared to post nourishment levels. Pre-nourishment, a typical beach volume for this profile was around 30m^3 with some seasonal variation. The re-nourishment in 2006 increased the beach volume from 40m^3 to over 95m^3 (Figure 25). Since the re-nourishment, the volume has slowly fallen. The largest fall in volume is seen shortly after the nourishmnet with the volume falling by roughly 30m^3. This is typical for many nourishment schemes, with the greatest losses occuring soon after its implementation. Other losses occur in the winter of 2012 and 2018, with recovery occuring after. The only major storm to see a reduction in beach volume is seen in 2016 when storm Angus hit. Although there is no direct proof from this figure that storms cause rapid beach volume change, there is a definate net negative trend post 2006 suggesting that there may be two factors causing sediment loss. A trend line is fitted to this data post 2006 which showed a change in volume of $-1.78m^3a^{-1}$ (Figure 25). If this rate continues, the beach will return to its pre-nourishment beach volume level by 2035.

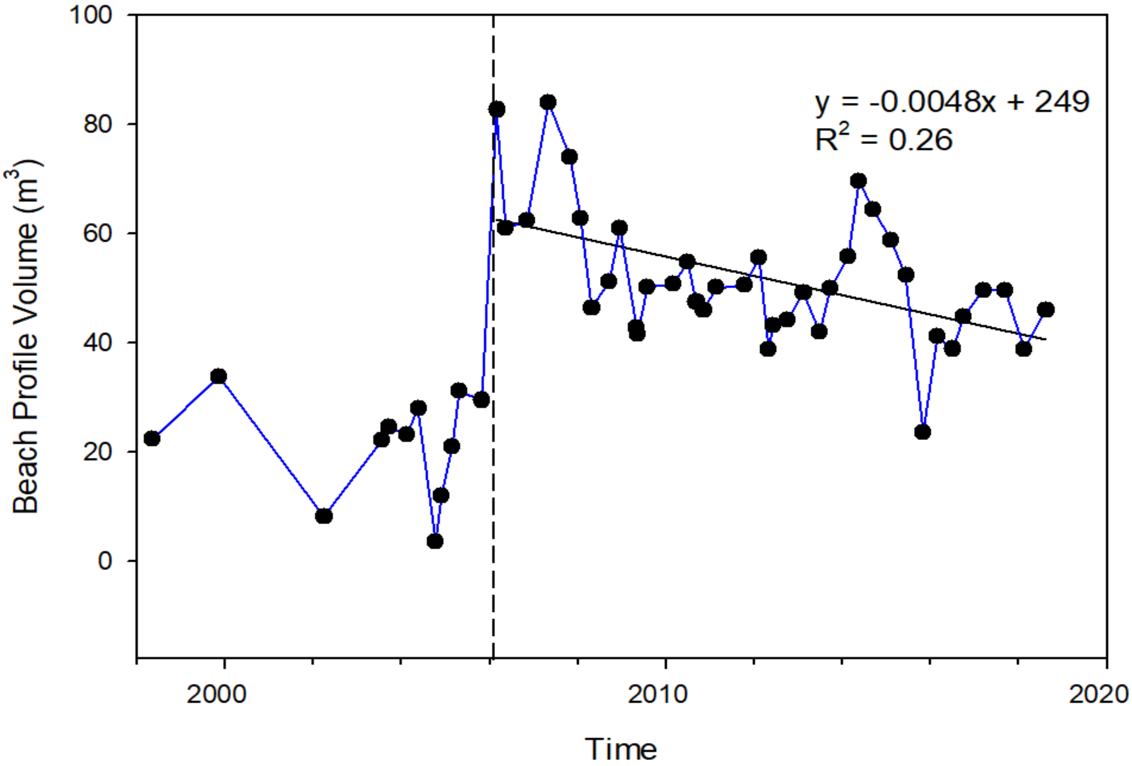


Figure 25 - Beach volume change for profile P5f00747 with a trend line from 2006 and equation. The dashed line indicated time of re-nourishment.

The beach centorid confirms the fact that the re-nourishment caused large scale accretion at the profile. There are two distinct sections. The first section shows the pre-nourishment level which shows low volumes, and the post nourishment section which is north east shows a drastic shift into accretion (Figure 26). The plot also clearly shows a shift back towards the pre-nourishment level as suggested in figure 25. Although the orange section is separate, the marked end point suggests that within the orange section, the centroid is moving south east indicating an erosion towards the blue section.

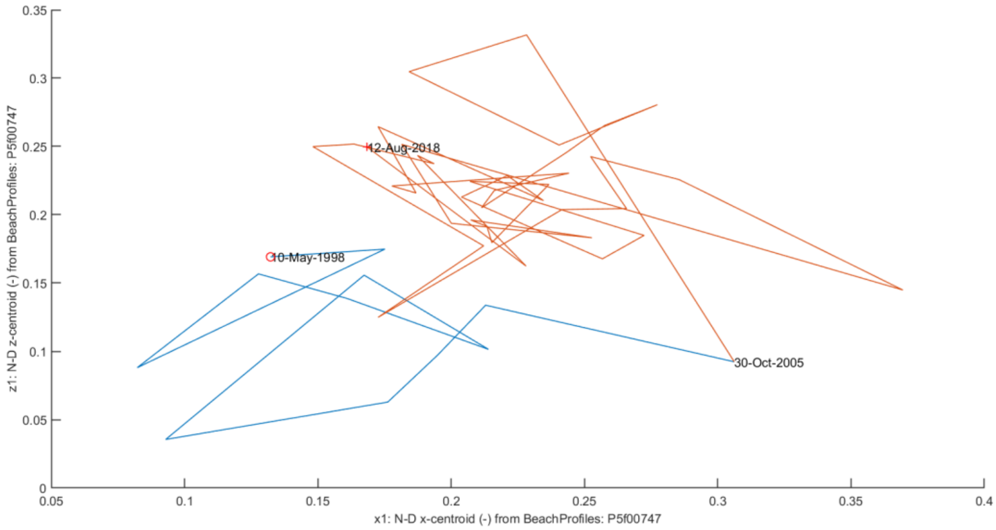


Figure 26 - Centroid plot for profile P5f00747 between 1998-2018. the blue line indicates profiles before the re-nourishment and the red line indicates profiles post re-nourishment.

4.2.3 Northern Section of Swanage

The northern section of Swanage is the only section accreting within Swanage Bay. This is because the sediment being lost from the central and southern part of the beach is being transported northwards. Another unique feature in this location is that the beach is flattening. Both summer and winter profiles show that the beach is getting larger and flatter over time (Figure 27). The winter profiles also show greater fluctuations in the profiles indicating that winter events may have a larger effect on this area.

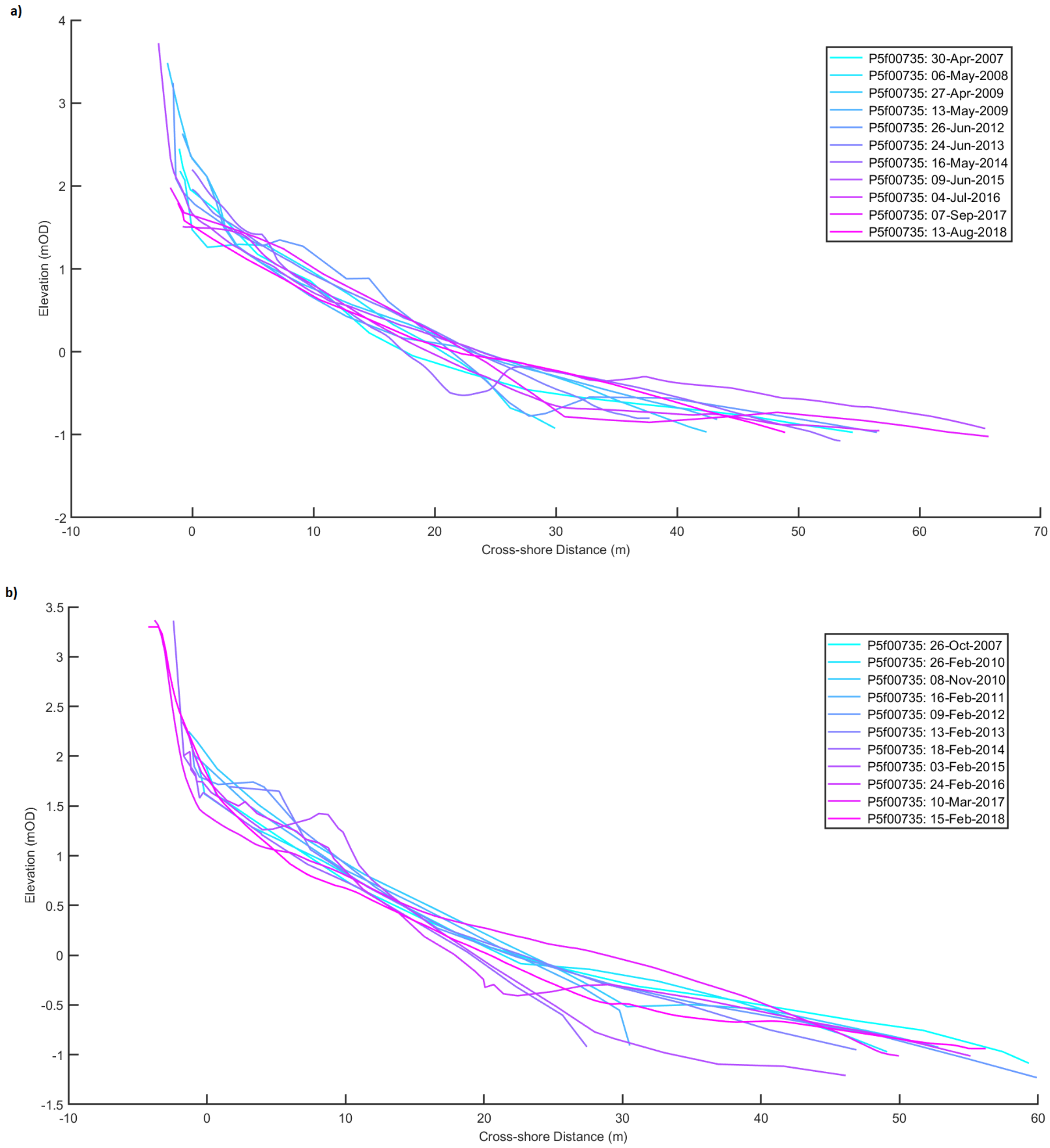


Figure 27 - Topographic surveys for profile Pff00735 located at the northern end of Swanage during a) summer conditions and b) winter conditions.

Beach volumes were plotted between 1998 and 2018 at this profile. The spike in beach volume in 2006 may be due to the re-nourishment. Although this section of the beach was not directly re-nourished, the increased volume of sediment into the system suggested that some of this may have been transported northwards. Although the nourishment saw a small spike in beach volumes, the general volume remains pretty constant indicating that this section of the beach is rather stable. The profile also sees beach volume changes seasonally suggesting that seasonality may have an effect on the beach volume north of the groyne fields (Figure 28).

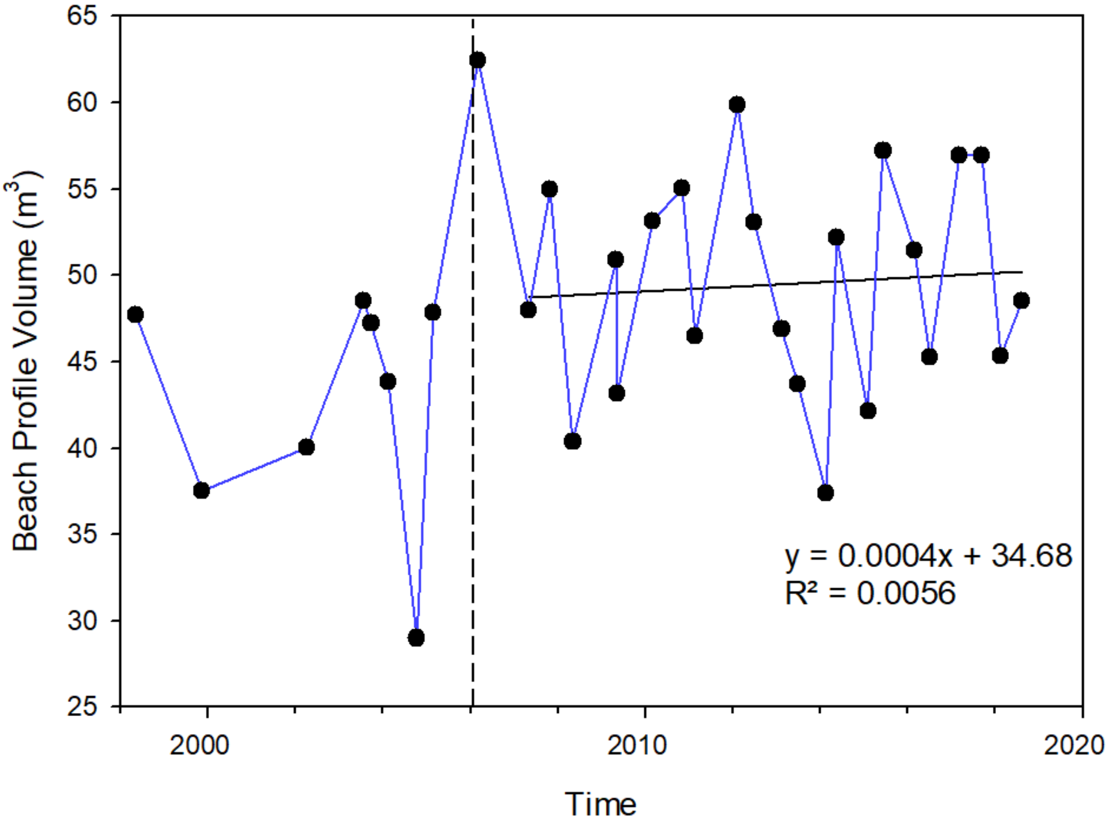


Figure 28 - Beach volume change for profile P5f00735 with a trend line fitted from 2007-2018. Dashed line shows time of re-nourishment.

Although the beach volumes do not seem to chage drastically pre and post nourishment, the centroid plot does show that the profile has flattened (Figure 29). This is seen by a shift in the beach centroid in a south eastward direction. Although this cannot be seen in the beach volume plot, it is clear to see that there has been a change since the re-nourishment occurred. Both the beach centroid and the beach volume plots suggest that this section of the beach is stable.

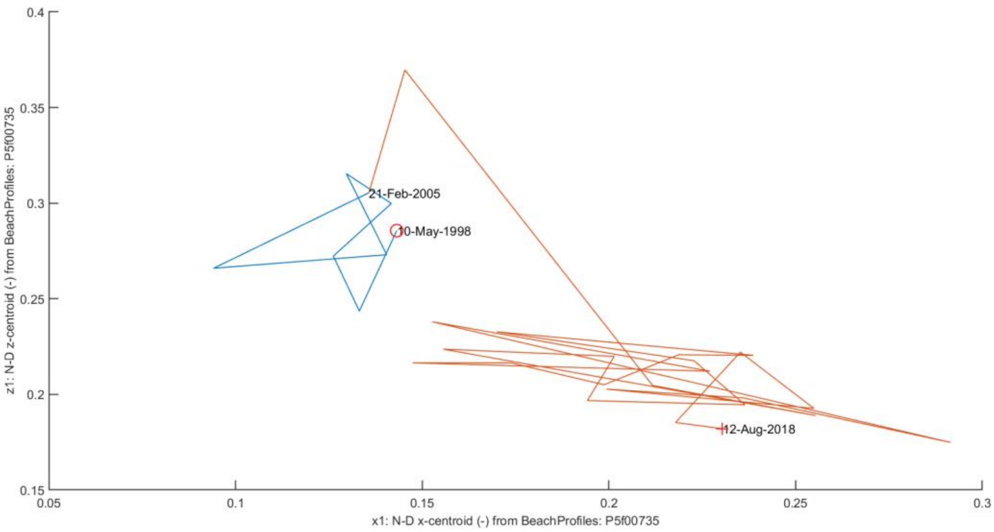


Figure 29 -Centroid plot for profile P5f00735 between 1998-2018. the blue line indicates profiles before the re-nourishment and the red line indicates profiles post re-nourishment.

4.2.4 Full extent of Swanage

Figure 30 shows a combination of all the profiles from 2007 to 2018 and how the zero moment zolume has changed for each profile. The zero moment has been chosen as it means each profile can see change, with an increase in the moment corresponding to an increase in beach volume. This gives a full extent of what is occurring across the whole of Swanage bay. Figure 30 shows that the highest beach volume and accretion occurs at the northward extent at profiles P5f00728 and P5f00729 with much greater volumes than other locations. The lowest volumes are seen along the southward profiles. There is also a large volume loss between 2008 and 2012 for profiles P5f00750-P5f00760, indicating that there was a loss of sediment post nourishment. Another loss of sediment is seen between profiles P5f00736-P50074. Although these profiles are in the northern zone of the beach which usually experiences accretion, these profiles are found directily north of the groyne field where terminal groyne syndrome may have an effect.

Overall, it is clear to see that the beach has fluctuating beach volumes across an annual time series as well as more seasonal events. In order to understand why this beach is experiencing these fluctuations, the hydrodynamic regime must be understood in order to fully understand the causes of beach volume change.

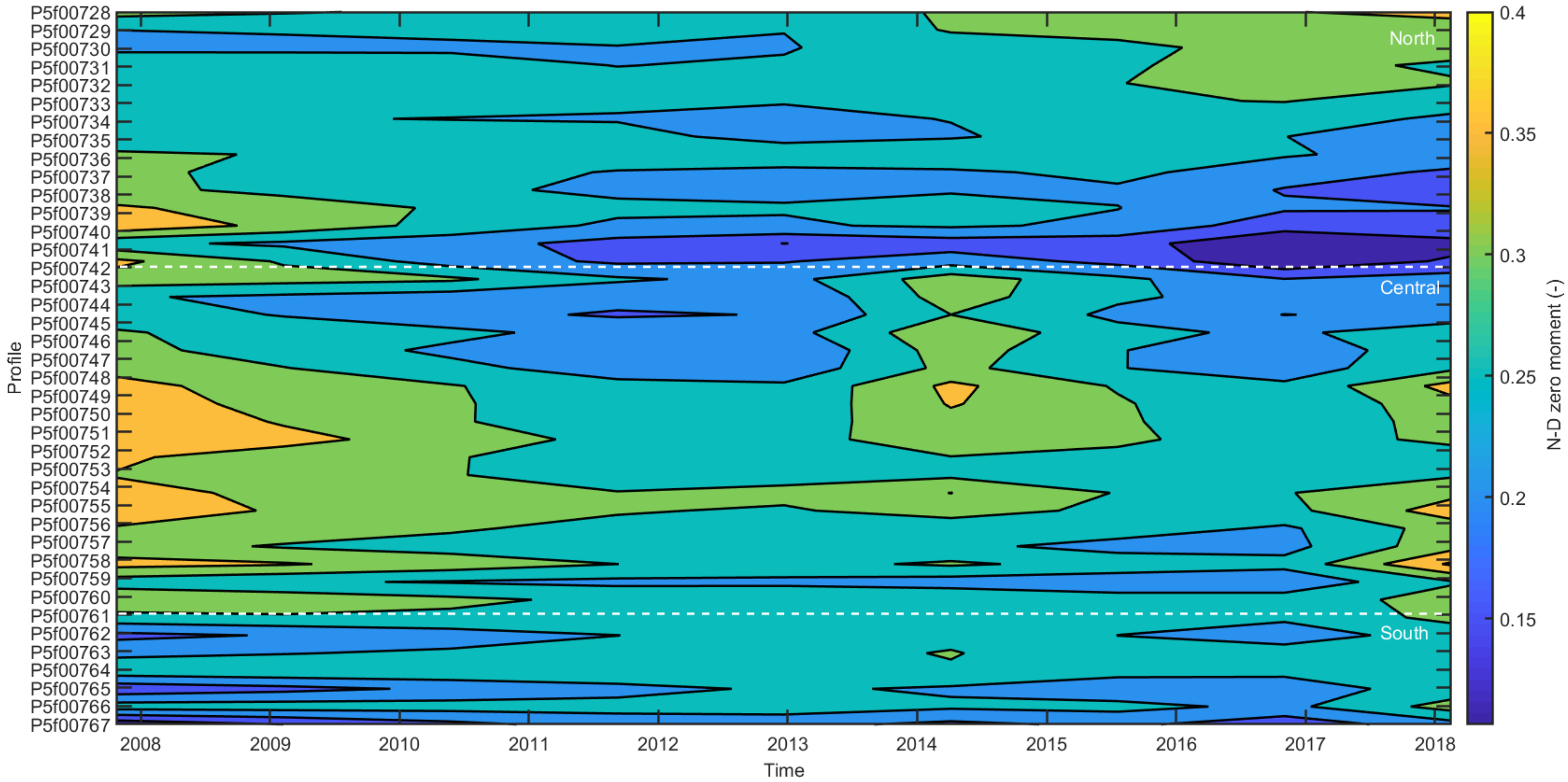


Figure 30 - Shows the full extent of Swanage Bay using all profiles listed on the y-axis. This image has used some averaging to predict the zero moment away from sample points. The white dashed lines indicate the break between each section.

4.3 Hydrodynamic Regime and its effects on beach volume.

This section will look at the typical hydrodynamic regime within Swange as well as look at extreme events which may cause rapid beach volume change. In general you will expect to see a fall in beach volumes during winter months. This is because there are high energy waves which will be more destructive to the beach. In summer, beach volumes along a given profile are expected to increase as, smaller long period waves gently move sediment onshore. However, it is not as simple as this as other factors such as wave direction and wave period may have a large affect on the rate of beach volume change.

4.3.1 Changes in Seasonal Variation

Looking at the modelled wave data, it is clear to see that during winter months, significant wave height is high, and during summer months, it is low (Figure 31). Although the validation showed that the model over predicts waves over 1.5m, post 2016, this overprediction seems to be smaller. Usually high wave heights correlate with a fall in beach volume, but this is not always the case. In order to further analyse the effects of significant wave height on beach volumes, wave energy flux was calculated which uses inshore significant wave height in the equation.

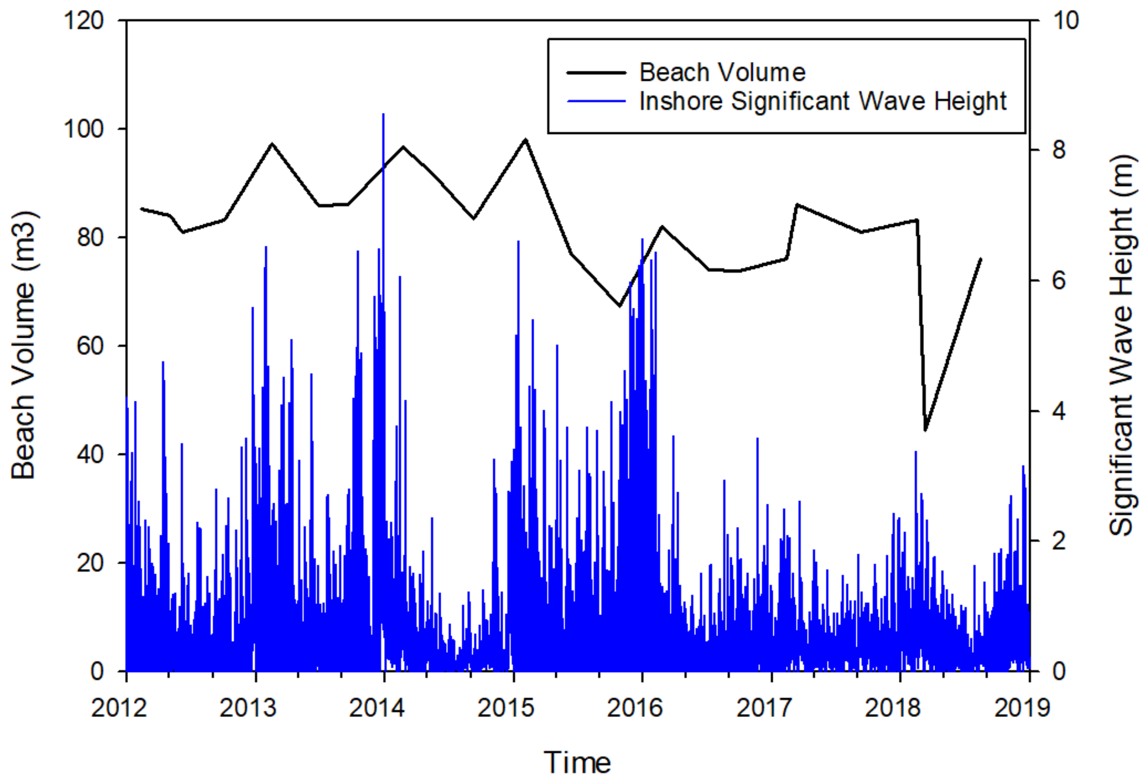


Figure 31 - Shows beach volume change for profile P5f00763 (southern section) in relation to modelled nearshore wave height.

Inshore wave energy flux was calculated using coastal tools (Townend, 2019). Inshore wave energy was chosen because in the winter, wave energy is high and in summer wave energy is low giving a seasonal variation. To compare how changes in energy flux affected beach volumes, beach volume plots were overlayed onto energy plots. The inshore wave energy was then averaged between each time stamp to get an averaged wave energy for each profile date. In general, there is expected to be a fall in beach volume whilst wave energies are high, and a rise in beach volumes when energy is low.

A rise in beach volume is expected to be met by a fall of mean energy. Figure 32 shows plots of all three analysed profiles with changes in beach volume and mean enrgy flux. Figure 32c shows how changes in beach volume occur with changing mean energy flux at profile P5f00763 (South section). In general, peaks in energy flux correlate to a rise in beach volume which is not expected. This is seen during the winters of 2013, 2014 and 2016. In some cases, rises in energy flux is met with a fall in beach volume such as during the winter of 2018. However, there is expected to be some time lag in the system meaning that beach volumes will likely change after strom conditions. Also, the plots only show times of surveys meaning the beach volume may have drastically fallen before it plateaus, which will be missed in the plot. The central section of the beach sees a similar trend to that of the southern section, but has more fluctuation (Figure 32b). The highest beach volumes are met with the lowest energy fluxes between 2014 and 2016.

Profile P5f00735 (Northern Section) shows an inverse correltation between beach volume change and mean energy flux (Figure 32a). The winters of 2014, 2016 and 2018 see spikes in mean energy flux, and also a fall in beach volume. However this pattern is not always constant which suggests that although the energy in the system plays a role in the changing of beach volumes, there must be other factors which cause changes in the volumes as seen in the profiles.

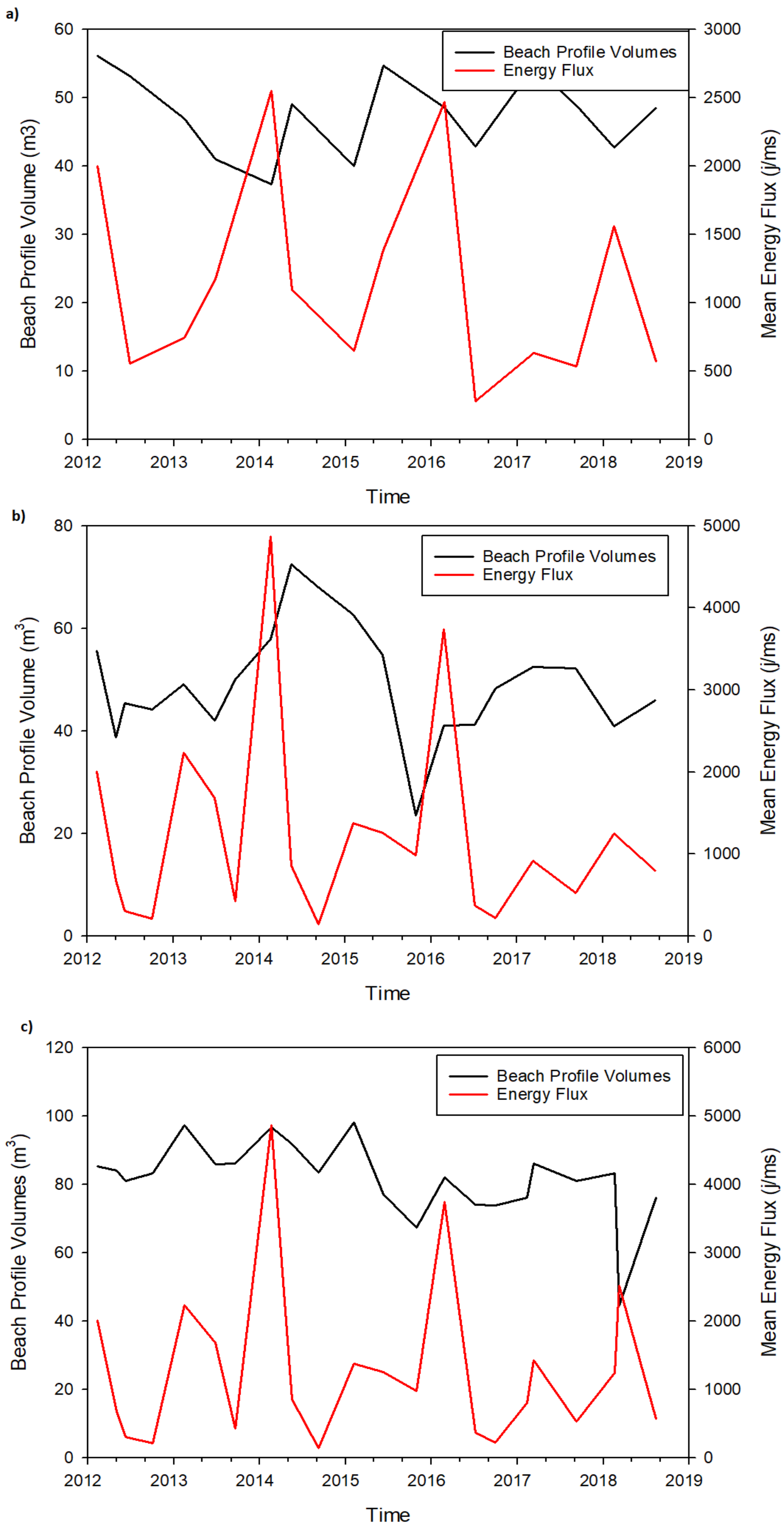


Figure 32 - Beach Volume change in correlation to mean energy flux for a) northern section b) central section c) southern section of Swanage.

4.3.2 Extreme Events

Using the model validated at the Swanage AWAC location, inshore wave directions can be modelled (Figure 33). This wave rose shows predicted directions for inshore waves between 2012 and 2018. The dominant wave direction is from the south-east with the main wave direction being more southerly. As this buoy is located at the centre of the bay, it is expected that the southern end of the beach is sheltered from these more southerly swell directions.

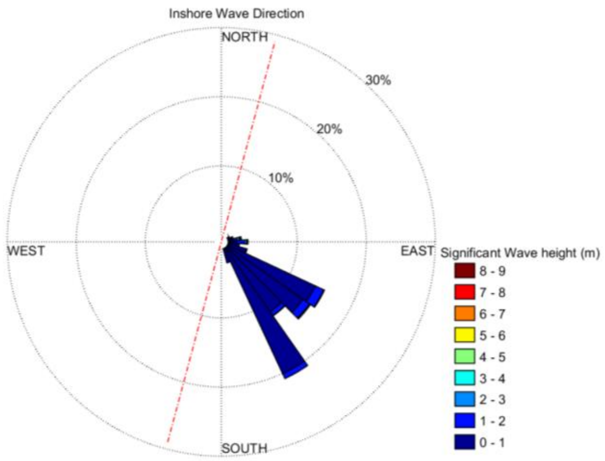


Figure 33 - A wave rose of nearshore modelled waves between 2012-2018.

As the wave cimate is important to affect rapid beach volmue changes, it is important that the combination of wave height, wave direction and wave period are all assessed during an extreme event. Since 2012, there have been three main storms which affected the south coast being the Beast from the east in 2018, Storm Angus in 2016 and the Valentines Day storm over the 2013/14 storm period.

4.3.2.1 Beast from the East

The storm known as Beast from the East hit UK coastlines between 24/02/2018-04/03/2018. During the peak of the storm, wave heights reached over 1.8m at the Pier meaning the storm threshold has been easily reached (Figure 34a). The significant wave height at the AWAC location also reaches over 2.5m indicating that the full extent of Swanage was affected by the storm. The unique part of this storm is the direction at which it entered the bay. The dominant wave direction of the storm is just south of eastward which is more easterly than the typical wave climate (Figure 34b). This means that the waves enter the bay more parallel limiting the amount of diffraction taking place. As the waves are entering the bay more parallel then usual, the southern section of the beach is more exposed giving greater potential to changing beach volumes. Another important factor of Beast from the East was the bimodal tendancy of the wave period. The wave period is measured at Boscombe due to the lack of wave period data for Swanage. The wave data shows two peaks in period at 5 seconds and 9 seconds (Figure 34c). The 5 second period period is likely to be caused by wind waves whereas the longer period waves are caused by ground swell. In total, 39.3% of the waves are swell waves. The heighest wave heights from the pier occurred 3 hours after high tide meaning that the damage caused by the storm may also have been heightened if occurred earlier.

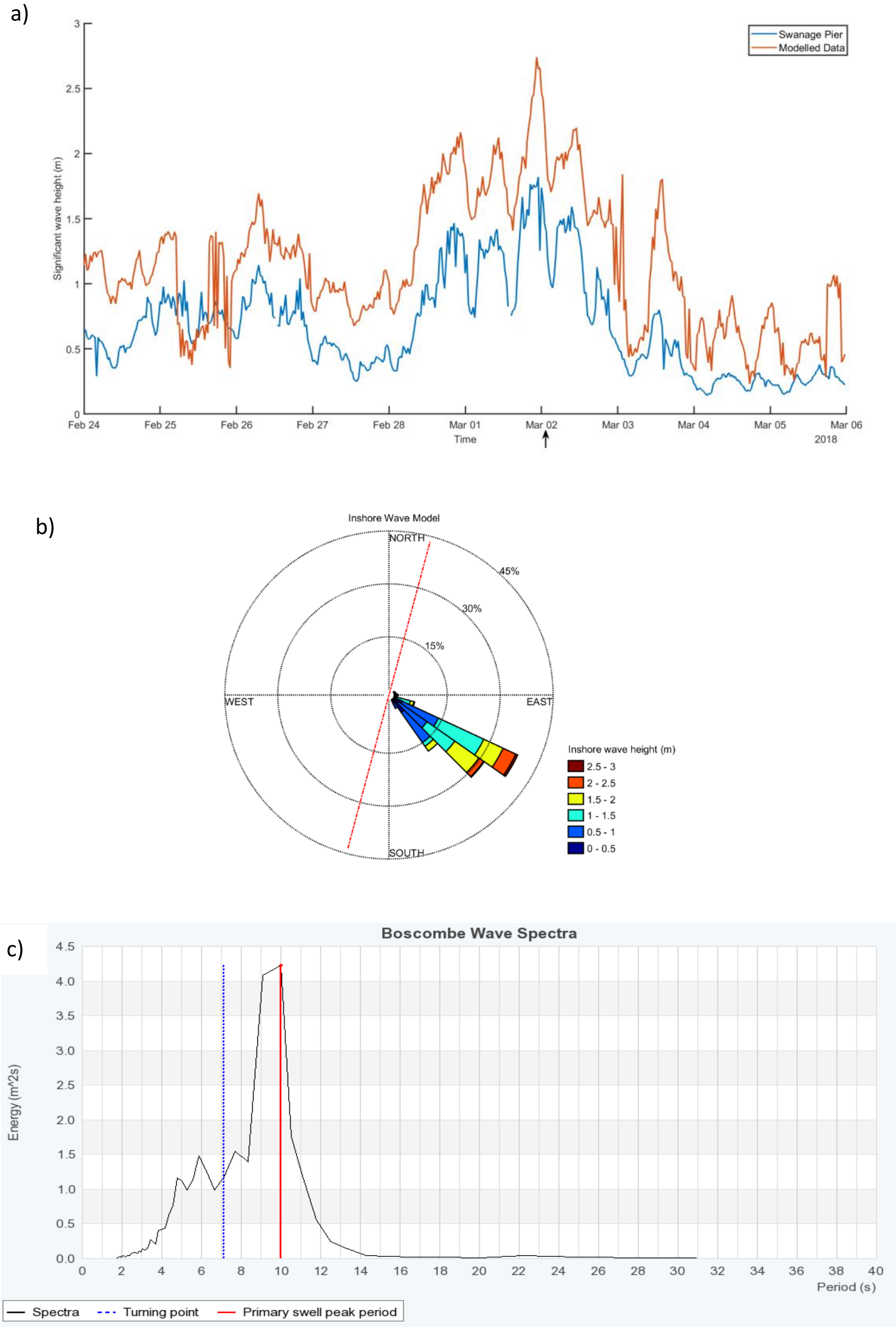


Figure 34 - wave data measured during the Beast from the East event between 24/02/2018-05/03/2018. a) significant wave height from Swanage Pier and the modelled wave height, arrow indicates storm. b) wave rose to show direction of waves during the storm with the red line indicating shoreline position, c) wave period from Boscombe buoy source: CCO (2019).

All three profiles were sampled on 16/02/2018 which was 8 days before the strom hit the coastline. All the profiles see a slight decrease in volume potentially due to the prior winter conditions but only profile P5f00763 (southern section of Swanage) shows a drastic decrease in beach profile volume directly after Beast from the East. P5f00763 was the only profile which had a post storm survey carried out on 09/03/2018. The volume drastically dropped by over 35m^3, however this is expected to be larger than expected as storm profiles aren't sampled to the same depth. All 3 profiles see a rise in beach volume post February, suggesting some form of recovery post the storm event. Figure 35 also shows that P5f00763 sees fast recovery post the storm however the total volume is not completely recovered to pre storm levels suggesting that the Beast from the East has removed sediment from the area over a longer timescale.

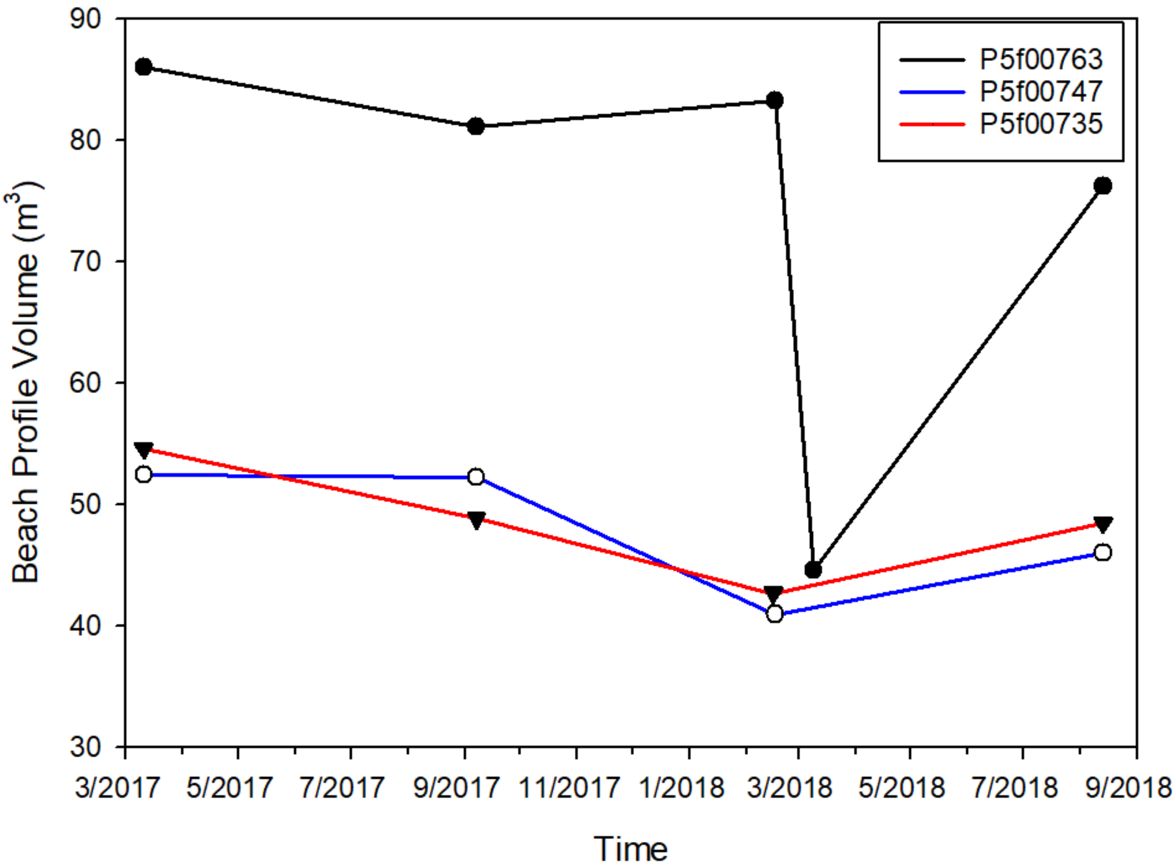


Figure 35 - beach volume change at different locations caused by Beast from the East. Black = Southern section, Blue = middle section and red = northern section.

Although the storm caused a rapid change in beach volume and localised flooding, the potential impacts of the storm may have been worse. The heighest waves recorded from the storm occurred 3 hours prior to high tide (Figure 36). Also the storm occurred on the lead up to spring tides rather than during spring tide meaning that the water level was not at its peak level. If the storm coincided with the peak spring high water, potential damage may have been even more significant.

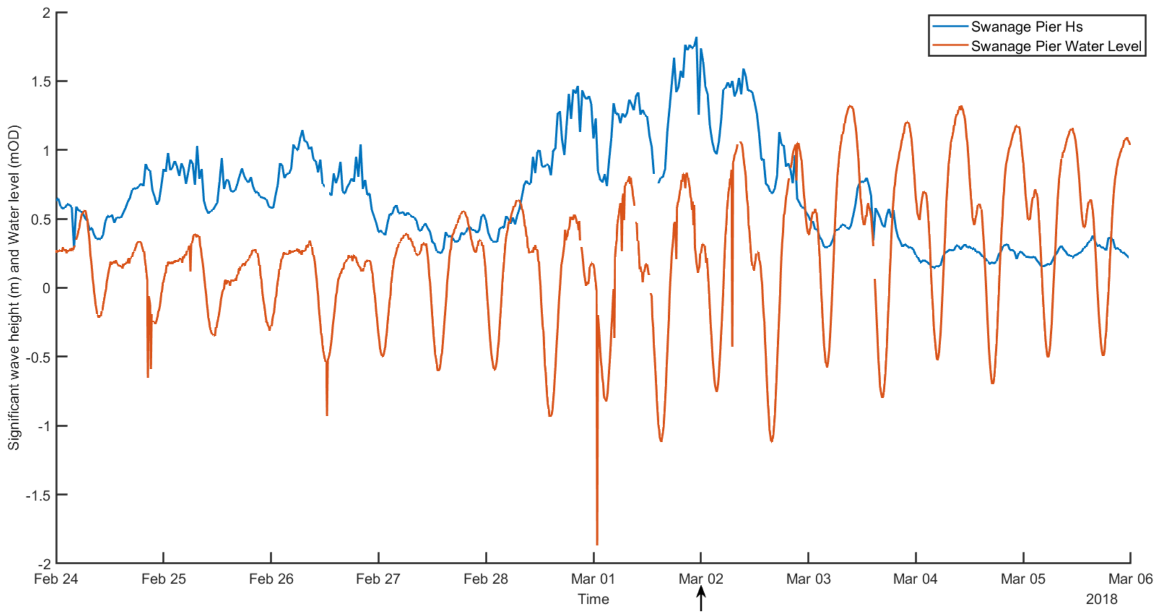


Figure 36 - Significant wave height at Swanage plotted against the water level in mOD. Arrow shows time of storm.

4.3.2.2 Storm Angus

Storm Angus affected the south coast between 19/22/2016-22/11/2016. The significant wave height during the storm event was 1.5m at the pier but over 3.5m at the AWAC location (Figure 37a). This shows that the storm threshold for the location was breached again. A modelled wave height of 0m is seen between November 20 and November 21 due to a limitation in the model. The difference between the Storm Angus and Beast from the East is that the dominant wave direction for the storm was more southerly. As the wave direction is more southerly, the wave has to diffract around Durlston Head in order to reach the southern end of the beach. This diffraction will decrease the energy of the wave meaning the significant wave height at the pier is lower during Storm Angus compared to Beast from the East (Figure 37b). The modelled wave height at the AWAC location is higher as the buoy is in deeper water and is less affected from diffraction. The wave period shows a uni-modal distribution with a peak that peaks at 9.1 seconds with a percentage swell wave of 71.5%. Although ground swell played a large role, wind waves were still recoreded giving conditions some bi-modal aspects (Figure 37c).

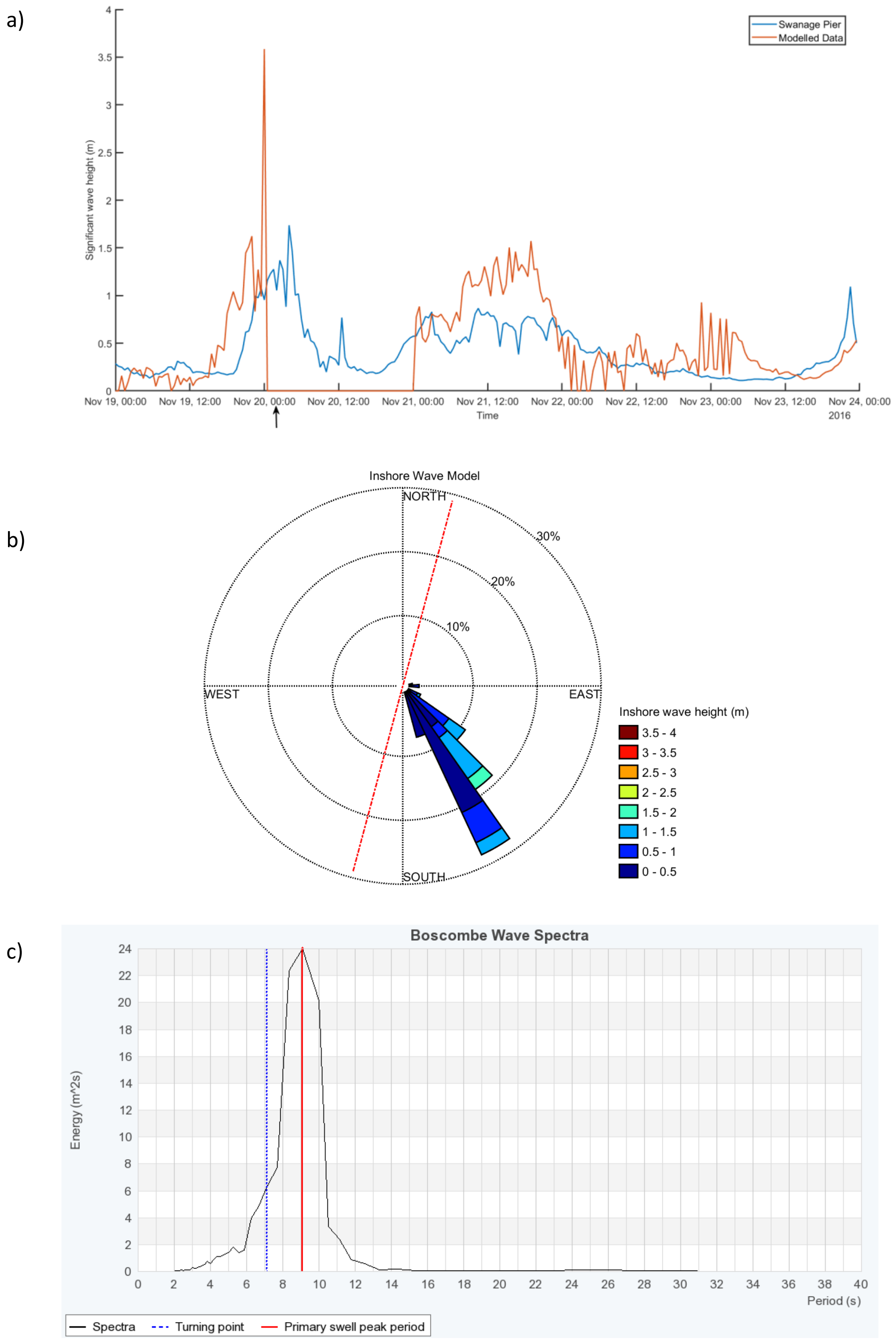


Figure 37 - wave data measured during the Storm Angus event between 19/11/2016-22/11/2016. a) significant wave height from Swanage Pier and the modelled wave height, with the arrow showing the storm. b) wave rose to show direction of waves during the storm, with red line indicating shoreline position. c) wave period from Boscombe buoy Source: CCO (2019)

According to the Environmental Agency, Storm Angus caused the seawall to be overtopped by waves, with properties being flooded (Picksley, 2018; pers comm). This is expected based on the high significant wave heights seen with a bi-modal wave period. However, according to the beach volumes measured at the three locations, Storm Angus had no significant effect on beach volume. Figure 38 shows an increase in beach volumes at 2 of the 3 profiles between 04/07/2016-10/03/2017. The storm occurred in November meaning there had been 4 months between the storm and the next topographic survey. This means that recovery was likely able to take place between the storm and the survey so the impacts of Storm Angus may have been missed.

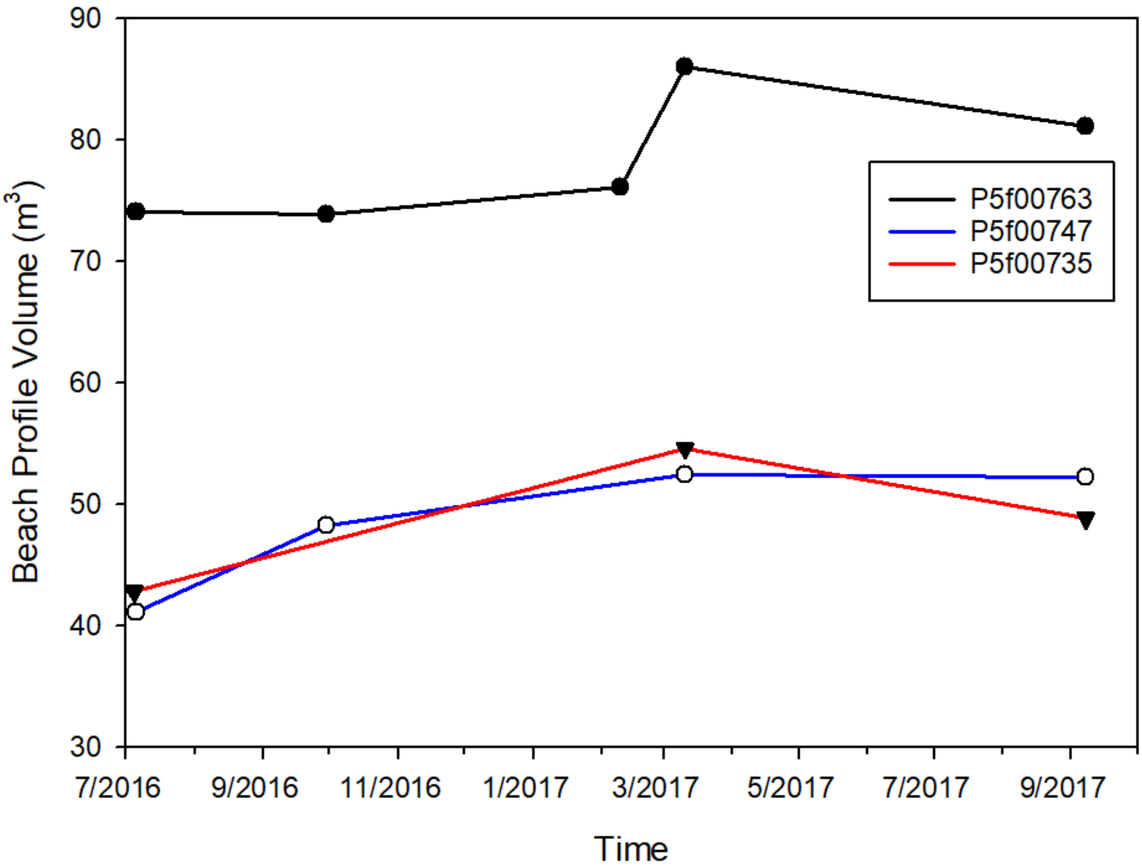


Figure 38 - beach volume change at different locations caused by Storm Angus. Black = Southern section, Blue = middle section and red = northern section.

This is similar to the cause and affects of the 2013/14 storm which also was seen to have a large affect on beach volume by the EA, but was not seen in the topographic surveys as no post storm surveys were able to be collected.

4.3.2.3 2012 Post Storm survey

In April 2012, post storm surveys were carried out in the central and southern part of the bay. The significnat wave height did not exceed the storm threshold with Hs being measured from the pier at 1.18m on the 25/04/2012 and 1.17m on the 28/04/2012. The peak of 1.18m on the 25th occurred during a spring high tide of 0.86mOD, meaning that a larger portion of the bay was affected (Figurer 39). further high waves were recorded between April 29th and May 1st, however these wave heights occurred during neap tides, which lowers the potential for beach drawdown.

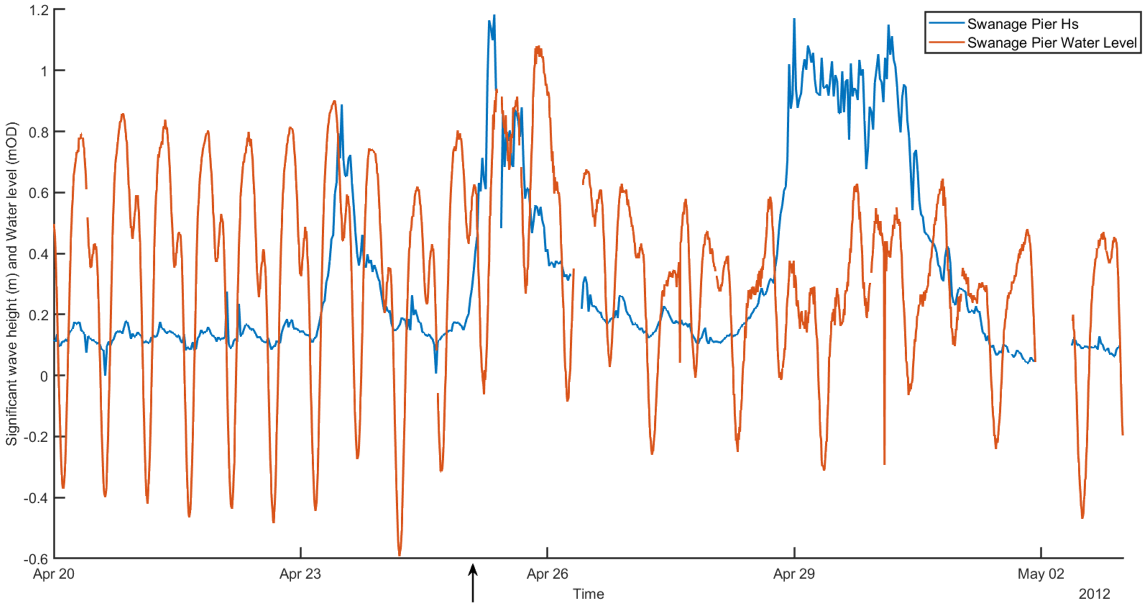


Figure 39 - significant wave height and water levels pre 01/03/2012 post storm survey. Arrow shows time of storm.

The wave direction between 22/04/2012-30/04/2012 shows a change with directions coming from east to south east with the largest waves approaching from the east (Figure 40b). The wave period is uni-modal at Boscombe buoy, with large waves as the period is 5.3 seconds. The percentage of swell waves is only 0.7% meaning mainly wind swell had an effect (Figure 40c). A tidal surge of 0.5m was seen at Swanage which would further affect the beach volume.

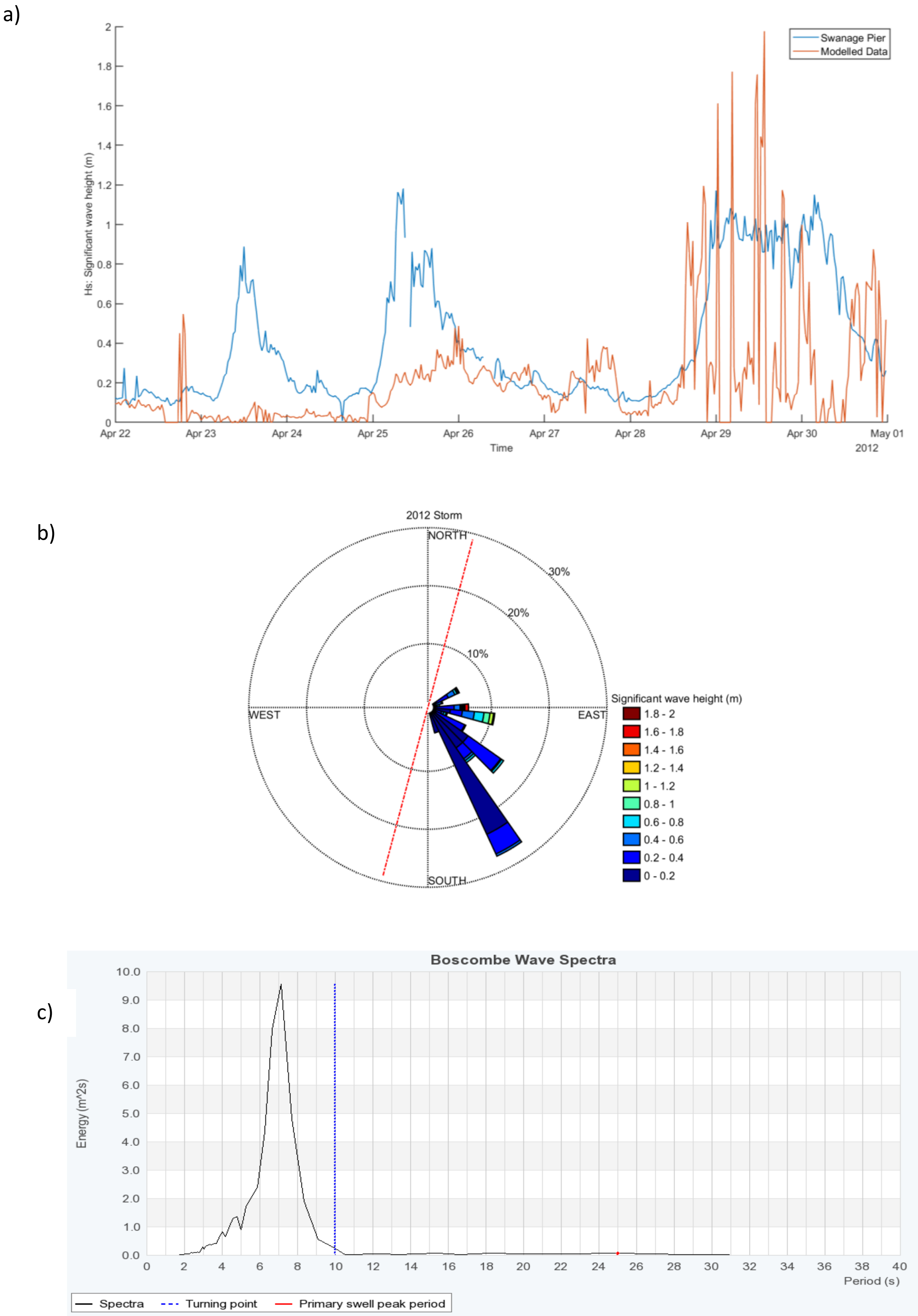


Figure 40 - wave data measured during the 2012 event between 22/04/2012-02/05/2012. a) significant wave height from Swanage Pier and the modelled wave height, b) wave rose to show direction of waves during the storm, with the red line indicating shoreline position, c) wave period from Boscombe buoy Source: CCO (2019).

Both profiles fall in beach volumes from the post storm surveys. Profile P5f00763 only has a volume drop of 1.2m^3, but drops a further 4m^3 by June (Figure 41). Profile P5f00747 has a more significant shift in beach volume, with a drop of 17m^3. This profile then saw some recovery of 5m^3, with the net loss of the storm event being over 10m^3. Due to the angles of the waves approaching from a more southerly direction, energy may have been dissipated when affecting the southern part of the beach meaning that less sediment may have been removed compared to the more exposed central part of the beach.

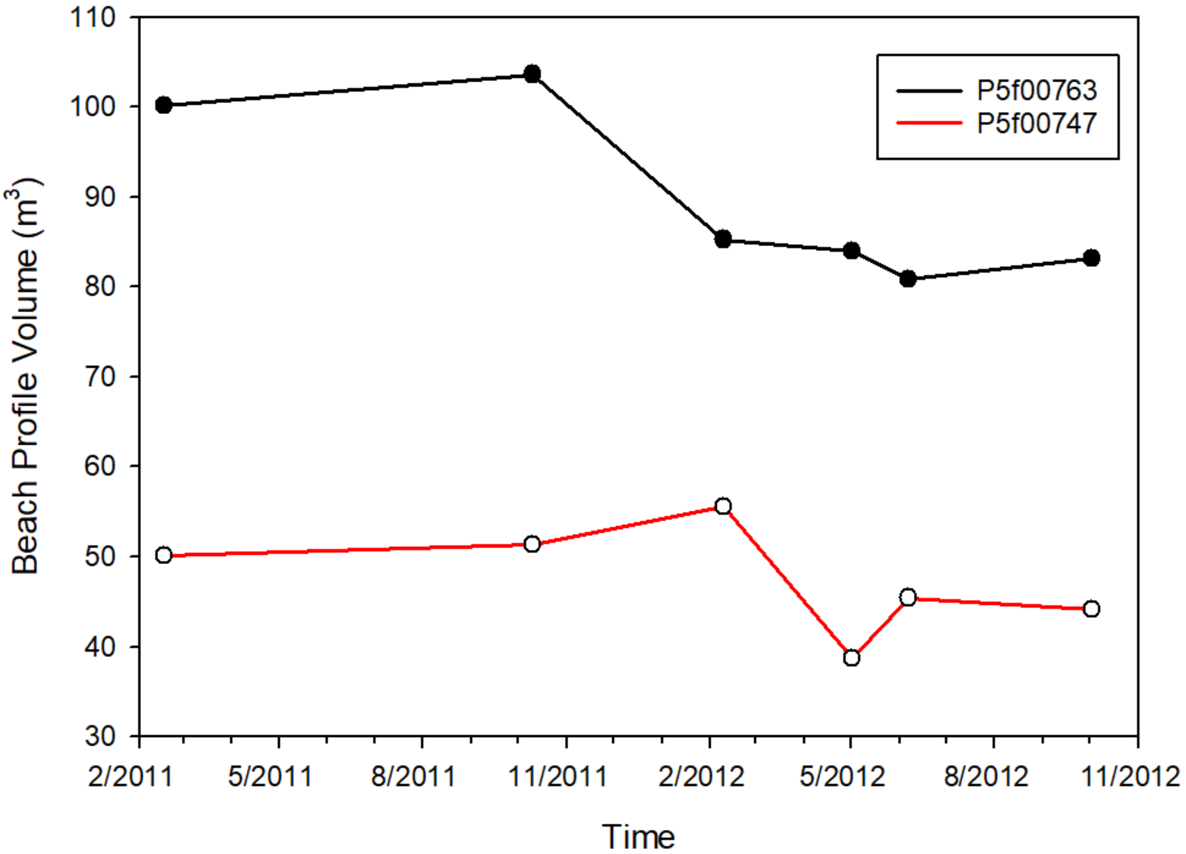


Figure 41 - beach volume change at different locations caused by the 2012 storm. Black = Southern section and red = northern section.

4.3.3 Recovery Periods

Storms such as Beast from the East and the 2012 Storm can cause rapid beach volume change either to a localised area, or across the whole extent of the beach. Although beach volumes may fall during these storm events, the beach volume tends to recover after the storm during quiescent wave periods. The most significant variance in beach volume occurred during Beast from the East in the southern side of the beach. Figure 42 shows three profiles pre storm, post storm and five months post storm for profile P5f00763 located in the southern section of Swanage. The storm caused the top 15m of the beach to be removed and be placed further off-shore. The proifle only extends to -0.5m depth as the sample date was not during a spring low tide. The profile sampled at 13/08/2018 shows that there is some recovery to the upper parts of the beach, but not to the extent of the pre storm level. However, between the cross-shore distance of 15-30m, a berm has been created with beach levels being higher than pre storm conditions. There is still a fall of total beach volume from 83m^3 to 76m^3 indicating that the beach has not been fully recovered.

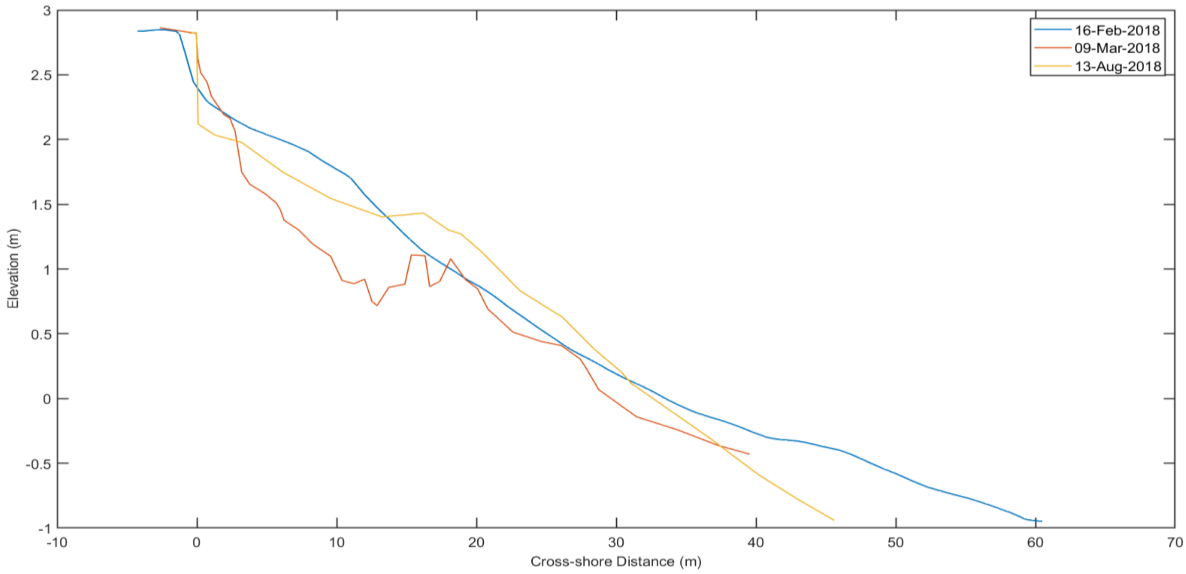


Figure 42 - shows the topographic surveys collected pre, post and 5 months post Beast from the East for profile P5f00763, at the southern end of Swanage.

The conditions post Beast from the East were relatively calm between the two profiles, with significant wave heights at the pier being recorded at only 0.2m with one spike above 1m. The modelled data shows wave heights similar to the pier with 5 peaks over 1m (Figure 43a). this implies that the energy in the system is low. The calmer conditions mean that long period waves are able to slowly bring sediment from offshore zones onto the beach which will increase the volume. This usually happens gradually due to the low energy conditions indicating that if another storm event occurred, the beach may not have fully recovered in time. The wave directions post storm show a more south-easterly direction which is expected during the calmer conditions. The wave period also only shows a uni-modal distribition showing that in general, only small wind waves are generated.

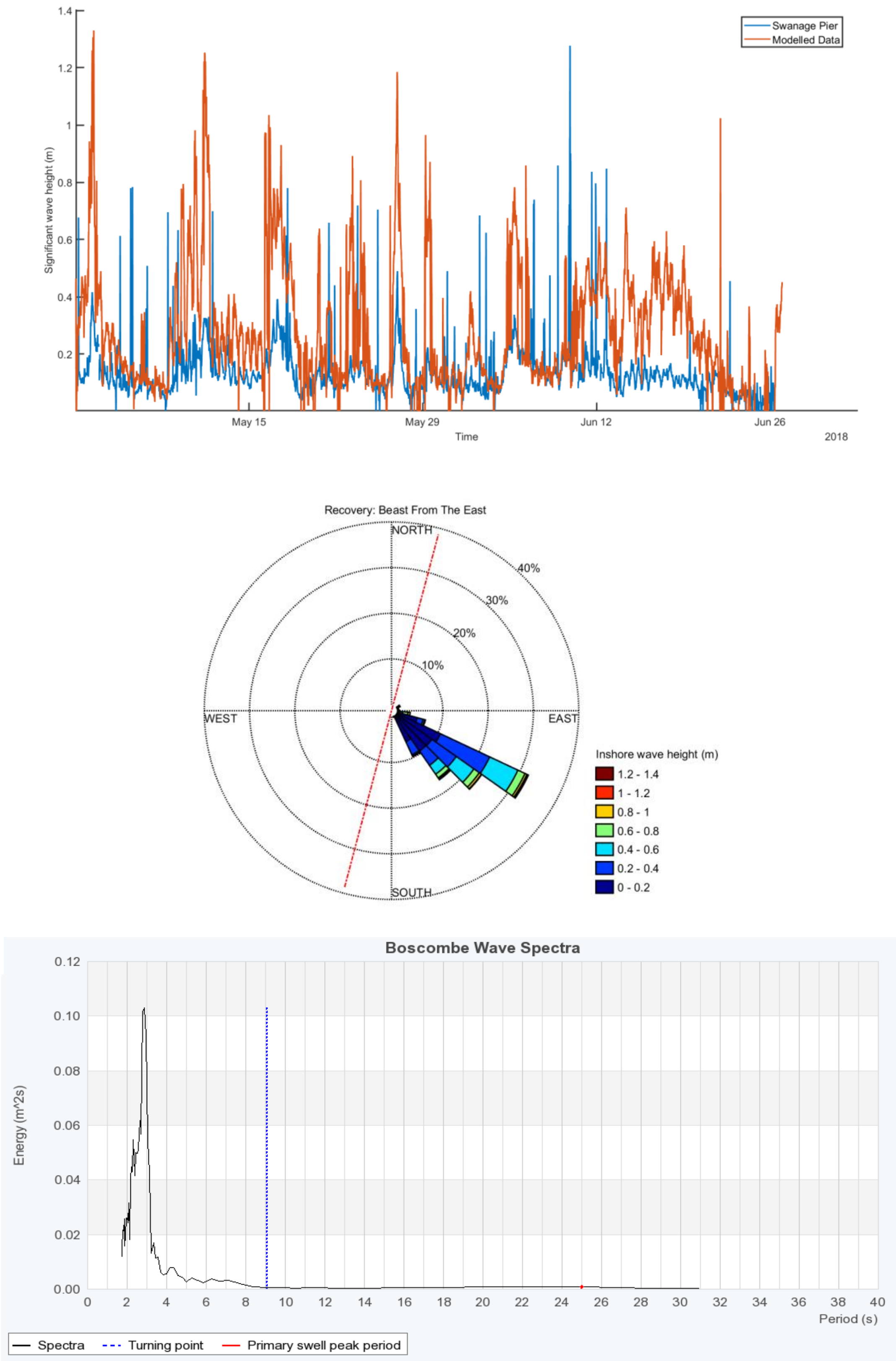
a)
b)
c)


Figure 43 - wave data measured post Beast from the East. a) significant wave height from Swanage Pier and the modelled wave height, b) wave rose to show direction of waves during the storm, with the red line indicating shoreline position, c) wave period from Boscombe buoy Source: CCO (2019).

Chapter 5: Discussion

5.1 Beach Sediment Movement

The results of this thesis show that there are two main processes which cause a movement of sediment along Swanage. Constant beach profile re-shaping is caused primarily by incident wave characteristics such as wave height, period and direction (Thomas and Lock, 2015). These parameters determine wave induced sediment transport both in cross-shore and alongshore directions (Brown et al., 1999; Rogers et al., 2010; Woodroffe, 2002). The nearshore wave model shows that the wave direction in Swanage approaches from the South East meaning that the wave usually approaches from an angle to the coastline which drives northward transport (Figure 44).

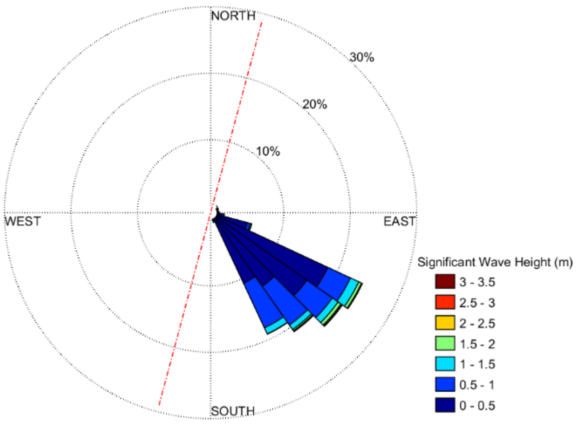


Figure 44 – A wave rose for modelled waves between 2017 and 2018. The red line indicates shoreline position.

This leads to a clockwise rotation of the bay as sediment is removed from the southern side of Swanage, and an accretion is measured on the northern parts of Swanage. Other crenulate bays situated in a similar location also experience a similar rotation. Swansea Bay is located in Wales and is eastward facing and has a dominant wave direction of 210˚. Like Swanage bay, Swansea bay is protected by a headland on the southern side meaning waves must diffract around the headland. Swansea Bay is also seeing a clockwise rotation as wave directions cannot fully align with the beach (Thomas and Lock, 2015). Beach rotation may have seasonal or short term characteristics (Klein et al., 2002; Arzaburu and Masselink, 2010), but in

Swanage, it is expected to occur over a decadal scale (Ranasinghe et al., 2004, Short and Trembanis, 2004).

Although there is a definite movement of sediment in the alongshore direction, rapid beach volume change occurs over shorter time periods. During winter, wave energy is high which should lead to a fall in beach volume. Onshore-offshore sediment transport typically occurs during storm events. Easterly storms can generate large waves which promotes sediment movement and beach drawdown. This is a frequent occurrence and can remove all but the upper backshore accumulation of gravel (Picksley, 2018; pers comm). During these periods, the clay and sandstone substrate are exposed to wave action which may cause abrasion. This contributes to a longer-term lowering of the Bay. Figure 45 shows the southern section of Swanage post Beast from the East. It is clear to see the removal of sediment leaving only the larger material and the rocky substrate remaining.

Figure 45 - the effects Beast from the East had on the southern section of the beach. Source: Dave Picksley, Environmental Agency (2019).

Beach sediment is removed during these storm periods and moved to a nearshore bar feature 200m offshore, which is too deep for topographic surveys to measure. This material is then returned to the beach during quiescent post storm conditions. There is only a thin veneer of sediment found overlaying the bed rock combined with the lack of seabed features, that suggest sediment mobility, the nearshore bar is considered as the limit of nearshore sediment movement (Picksley, 2018; pers comm). This means that the depth of closure for the bay is relatively shallow at -5mCD (Figure 46). This is supported by a study carried out by the EA which shows bathymetry change between 2007-09 and 2017-18. The bathymetry data clearly shows how the central and southern section of the beach is eroding with a clear offshore bar which is accreting, matched with accretion in the northern section of the bay. This supports that the bay may be rotating clockwise. Also, the amount of erosion and accretion is similar suggesting that there will be little loss out of the system bar at the northern extent of the bay.

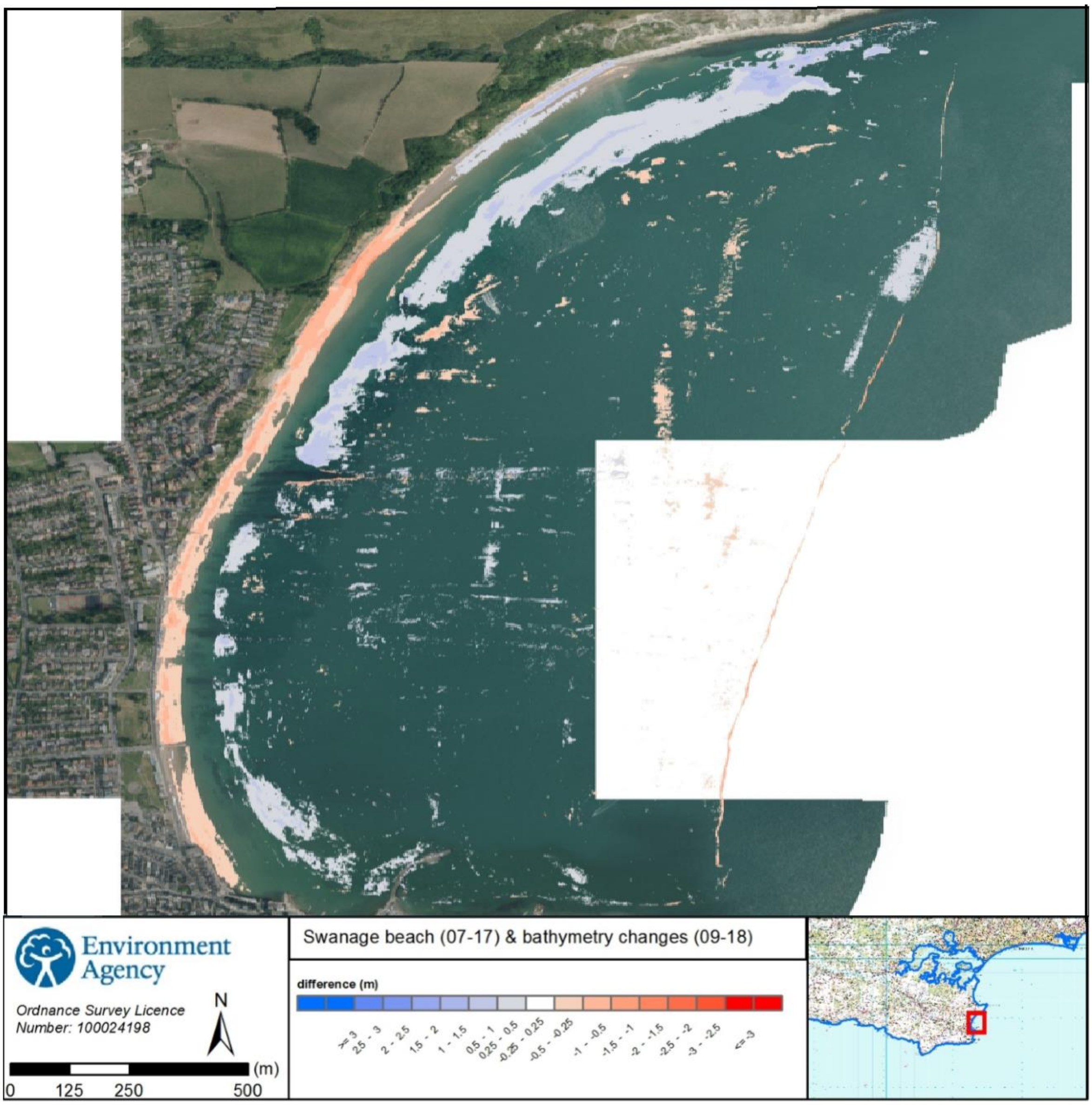


Figure 46 - Change in Swanage Beach area (2007 to 2017) and bathymetry in Swanage Bay (2009 to 2018) clearly shows accretion of a bar feature in the nearshore zone to a depth of about -5mCD Source: Dave Picksley, Environment Agency (2018).

5.2 Length and time Scales

As Swanage is a crenulate bay, it is expected that the main geology control features will be the headlands, which constrain the bay. As seen previously, the dominant waves are diffracted around Durlston Head and approach the bay from the South-east which causes northward long-shore transport. However, there is another in-bay process which is driven by storm events which causes cross-shore movement of sediment. Longshore sediment transport mainly occurs on the lower shoreface as this is where the typical wave action occurs. The upper shoreface has cross-shore length scales that are typically two or three orders of magnitude less than for the lower shoreface (Cowell et al., 2003). This scale difference means that changes in the lower shoreface are associated with disproportionately larger changes compared to the upper shoreface, due to mass continuity for sediment exchanges between the zones (Roy et al., 1994; Cowell et al., 1999). Figure 47 shows that the upper part of Swanage is eroded over the winter months indicating cross-shore dominated processes.

Figure 47 - Change in elevation between July 2016 and March 2017 for the central part of Swanage. Source: Channel Coastal Observatory (2019).

The balance between storm and seasonal variation was dependant on beach type classification (Wright and Short, 1984). For beaches at the reflective end of the spectrum, such as Swanage, sediment is focussed on the upper beach or only a short distance offshore

(Splinter and Davidson, 2013). This means that there is a rapid exchange of sediment between the beach and the offshore bar meaning that the shoreline response is dominated by storms. This is seen at Swanage Bay as the bar is seen at a depth of only -5mOD. If the offshore bar was located more offshore, the sediment transport will be more dominated by seasonal variation in wave energy. This implies that changes in beach volume are mainly governed by short time scales which can cause rapid interchange between the beach and 5mOD offshore. This also explains why profiles taken after Storm Angus and the Valentine's Day storm does not see any significant change to beach volume. As the next available samples are 3 months later than the storm events, quiescent conditions have been able to move sediment back onshore to recover the beach.

Although the wave climate causes beach change in Swanage, it is still unclear on which wave parameter causes the most significant effect on beach volume change. In order to understand this more, principal component analysis was carried out.

5.3 PCA Analysis

Although the results section shows how changes in the hydrodynamic condition has an affect on beach volume, PCA shows that its not that simple. The goals of PCA are to extract the most important information from the data and to simplify the description of the dataset (Abdi and Williams, 2010).

Table 2 - PCA analysis components with their weighting.

Component Matrix[a]

	Component	
	1	2
Beach Volume	-.398	.902
Wave Direction	.627	-.103
Hs	.762	.104
Tz	.889	.388

Extraction Method: Principal Component Analysis.

a. 2 components extracted.

Component 1 shows there is a link between all three wave parameters, with the closest correlation being between significant wave height and wave period. Component 2 no one wave paramter has a direct affect on beach volume which means that a more complex analysis is needed in order to understand the changing beach volume (Figure 48). As there is no one factor which affects beach volumes, a univariant approach cannot be applied to understanding beach volume change with a single wave parameter. However, this may be expected as a varying beach volume is a complex process which is affected by many different factors. For future studies, a multivarient approach will need to be put in place in order to see what factors affect changing beach volumes. Kriebel and Dean (1985) suggested that the greatest change in beach profile occurred during the maximum potential for erosion, such as during a spring high tide and during storm events. Water levels were not included in this analysis as all topographic surveys are carried out during a spring tide in order to measure a larger profile. The results show that the greatest effect of beach volume change occurred during times when storm periods and spring tides correlated. This approach is expected as it is still beilieved that wave direction, significant wave height and wave period play a key role in beach volume change.

Figure 48 - PCA analysis plotted to show how Wave Direction, Hs and Tz are not directly correlated to changing Beach Volume.

Another issue with the PCA is that the data used may not be frequent enough to find the true extent of what affects beach volume change. If the frequency of surveys increased, events such as storm events may be better understood as there will be a larger dataset which may lead to a better understanding of what causes beach volume change. In contrast, Short and

Trembanis (2004) carried out PCA on the Narabean Bay which is sampled monthly giving a total of 284 profiles over 26 years. Their results showed that beach rotation played a large factor on the shoreline position and was rotating in a seasonal aperiodic manner lasting between 2-10 years.

5.2 Beach Variability

As mentioned in section 3.1.1 the beach profiles are sampled bi-annually, with occasional post storm surveys being carried out. This means that changes in beach volumes may potentially be missed by the surveys. For example, the calculated beach volumes post Storm Angus and the Valentines Day storm showed no volume change between the sampling points either side of the storms. Volume change may have occurred during the storms, with photographic images showing that Swanage was affected by both of these events. This suggests that recovery has occurred between the sotrm and the next sampling points.

a)

b)

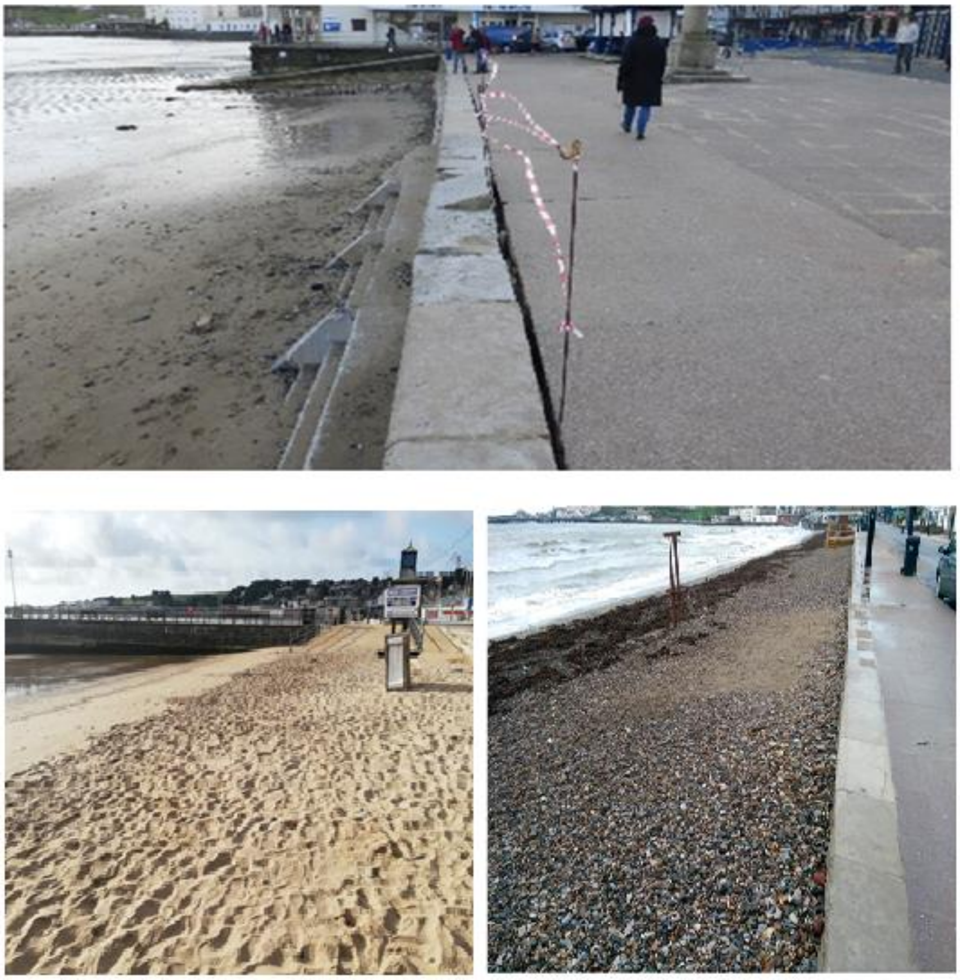


Figure 49 - a) Damage caused to the Sea Wall during the Valentine's day storm; b) Shows the effects Storm Angus had on beach drawdown with a typical beach layout on the left and the storm effect on the right. Source: Dave Picksley, Environmental Agency (2019).

Figure 49a shows the significant damage occurred to the seawall along the Swanage promenade during the Valentine's Day storm. In total, approximately 25m of the top stones of the sea wall were displaced by wave action. Figure 49a also shows how beach material was transported onto the steps, as well as there being an overall fall in beach elevation. Figure 49b shows the affects Storm Angus had the beach. Finer material is removed from the bay as finer sediment is more easily transported during high wave energy conditions, which leaves the heavier material.

In both cases, the following beach profile was surveyed over three months post storm meaning that the beach had time to recover. This means that it is un-clear as to the full extent these storms had on beach volume change. Post storm surveys were not carried out after these storms due to limited resources because both storms had country-wide affects meaning other areas became higher priority, such as at Hurst Spit. In contrast, the results show how large of an effect Beast from the East had on beach volumes meaning that it is not unlikely that these storms may have had similar effects. For the beach volume change to better predict beach change, more frequent profiles need to be sampled. However, this may not be feasible meaning that other methods to beach volume may also need to be used.

5.4 Future Beach Management Plan

As rapid beach volume change is expected to be controlled by storm events, a year of weekly or bi-weekly data or two years of monthly data is needed in order to solve the causes in beach volume change. The increased frequency of these surveys will allow greater understanding of how beach volume changes during high energy conditions during winter. It is also expected that seasonal variation will also occur. Splinter and Davidson (2013) has shown that beaches that contain both seasonal and storm-scale variability require a minimum sampling length of monthly samples over 2 years. The Narabean coastline has been sampled monthly for over 40 years and shows that both short term and longer-term beach changes are able to be measured. This allows for future predictions to be carried out with relative certainty (Short and Tremabnis, 2004). If these profiles are carried out, this will help aid the prediction in future beach volume levels. Currently, the rate of erosion at the southern end of the beach is $-2.15m^3a^{-1}$. This implies that if this rate continues, by 2040, the beach volume at this location will be $32.7m^3$ which is similar to the levels seen in the central section of the beach pre beach nourishment. The central section of the beach is also expected to be at the same pre-nourishment level by 2040. As both sections are seeing a loss of sediment, both sections should be recharged in order to maintain proper protection of the beach, rather than just the central section. However, the rate of erosion may be expected to increase with rising sea levels and stormy conditions. It is already stated that the crest height of the beach should be risen in accordance to sea level rise, meaning that a new re-nourishment scheme needs to be properly planned in order to withstand flooding events.

However, the scheme also states that the standard of protection at Swanage is 1:300 meaning that only extremely large storms will cause the defence line to fail. In the last 6 years, Swanage has been flooded 3 times during the Valentine's Day storm, Storm Angus and Beast from the East. If the standard of protection stated was correct, these storm events would not have flooded Swanage. In order to calculate this standard of protection, a joint probability analysis was carried out (Thomas Dhoop, CCO).

Although waves and water levels can be measured independently, it is thought that the combination of the two can be critical in causing beach erosion under storm conditions. However, the highest waves do not always occur at the same time as the highest water levels meaning that occasionally, large waves will have little effect on the beach volume. Unique to the site, wave directions are also important to understand in order to assess the potential risk of beach erosion. Waves directions coming from the east are more likely to cause a greater amount of erosion as less energy will be dissipated from diffraction.

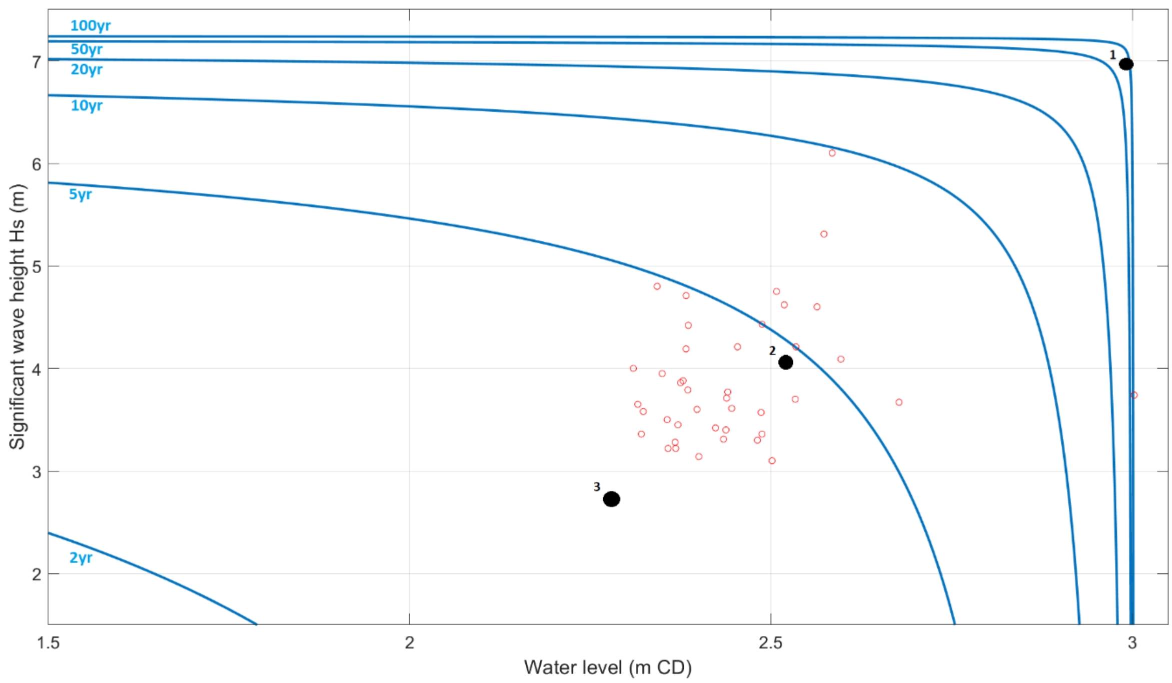


Figure 50 - Joint Probability plot for Significant wave height from Poole Wavenet and Water levels from Swanage. Points numbered below represent the 3 different storms: 1) Valentine's day; 2) Storm Angus and 3) Beast from the East. Source: Thomas Dhoop, CCO (2019)

Figure 50 shows that the three main storms which have caused damage in Swanage, all had a far more frequent re-occurrence than the standard of protection. This is because none of these storms are categorised as a 1:300 year storm event with Storm Angus and Beast from the East only having an occurrence of less than 1:5 years. However, this may be underpredicted as the Poole Buoy was used to generate wave heights due to the lack of wave data in Swanage. This means that either the height of the sea wall, or the amount of recharge to the area needs to be increased in the future in order to withstand greater storms. Also, a recent study by Hames et al, (2019) has shown that this method for joint probability analysis may be out-dated, giving potentially incorrect values.

Cowell et al (2003) explains how low-order coastal change involves morphological evolution on a geological time scale (order 10^3 years) that has significance on a coastal management scale (10^0 to 10^2 years). Cowell et al (2003) explains how the length of BMPs usually last around 50 years although the length of change in beaches may take much longer. Management plans are mainly governed by predictions of sediment gains and losses in both the longshore and cross-shore direction as well as affects caused by changes in sea level. As Swanage is a crenulate bay which assumes that the sediment is contained within the bay, a recycling scheme may also be possible in order to help manage the beach. Currently the main areas accreting are the north section and the bar at depth -5mOD, meaning that sediment may be able to be taken from these locations to help re-nourish the eroding areas. A recharge may also be needed for further stability of the beach.

5.5 Limitations

5.5.1 Beach Volume Calculations

The beach volume calculations have some limitations. This is because a standard depth for each profile is chosen for the calculation. The depth chosen for this was -1mOD for all profiles. This was chosen because most profiles stretched down to this depth. A sensitivity analysis was carried out on the samples in order to make sure that a change in selected depth did not have a huge effect on the change in beach volumes. As expected, the beach volumes decreased with a change in depth, but the difference in beach volume stayed relatively consistent meaning that the topographic profile was moderately well represented. However, for storm surveys, there was a large difference as these surveys occurred to a shallower depth. This means that the change in beach volumes between a storm event and the following typical profile will be exaggerated. This is mainly seen in the southern sections of the beach where the reduction of beach volume caused by Beast from the East is over predicted.

5.5.2 Wave Model

Although the wave model has been validated by the AWAC data collected over the winter of 2017/18, the data only shows the wave conditions at a specific point. This is because the model used to generate nearshore waves was a 1-D model within coastal tools. In order to generate wave heights and directions for the full extent of the bay, a 2-D model will need to be created. This would be useful in order to see how diffracted waves approach the different sections of the bay, rather than having to use one direction throughout the whole beach.

5.5.3 Sampling Intervals

Currently, changes in wave energy arriving at the coastline, rather than sea level rise, are expected to be the dominant processes impacting shoreline change in the coming decade (Brunel and Sabatier, 2009; Ruggiero 2013). Both cross-shore and alongshore transport cause changes in the beach volume and shoreline position, with alongshore processes generally acting over longer time frames so have less effects on the seasonal variability (Clarke and Eliot, 1988; Davidson and Turner 2009). Many empirical models have been set up to predict seasonal and multi-year variability at cross-shore dominated study sites (Miller and Dean

2004; Yates et al., 2009). These models assume that the alongshore aspect of sediment transport is small so that it can be neglected or given a constant value, with a loss to the profile being classified as noise. If the coast has a large longshore sediment characteristic, these models no longer become valid (Splinter and Davidson, 2013). Alongshore sediment transport is usually an order of magnitude larger than that of cross-shore transport. Models set to predict shoreline change at a storm dominated beach was sampled fortnightly for three consecutive years. For a seasonally dominated site, beaches are sampled every 60 days. However, it is still unclear how much data is needed and what sampling interval is required to be able to predict future shoreline change. Meaning that although Swanage Bay have been sampled bi-annually by the CCO from 2007, the frequency of the sampling is in-sufficient to be able to predict any long-term trends.

Chapter 6: Conclusions

6.1 Overall Conclusions

In conclusion this work used two open source data sets which consisted of wave height, period and direction, beach profiles and water levels resulting in 42 topographic surveys being analysed in order to understand how the hydrodynamic regime entering Swanage influences changing beach volume. Overall, the study shows that there are two main processes which cause a change in beach volume. The first process is the rotation of the bay which happens over a longer time scale which is driven by the dominant wave direction entering the bay. The other process is sediment being moved in the cross-shore direction caused by storm events which occurs over a much shorter timescale. This causes a rapid beach volume change with recovery occurring relatively soon after these events, achieving the aim of this thesis.

The PCA analysis showed that no one single wave parameter such as: wave direction, period and height has an effect on beach volume change meaning that a more in-depth multivariate analysis may be needed in order to assess further causes of beach volume change. Changes in beach volumes show that storm events have an effect on the beach volumes with storms such as Beast from the East causing rapid beach volume loss to the southern section of the beach. It is also expected that recovery periods of the beach are relatively short with the profiles missing beach volume losses caused by Storm Angus and the Valentine’s Day storm. This suggests that rapid beach volume change is caused by storm events, but there is also alongshore sediment transport which is causing a rotation in the Bay. Currently, the BMP overpredicts the defence standard for Swanage as the town has been flooded 3 times in the last 6 years. Also, the southern section of the beach has become more exposed and is eroding at a rate of over 3m^3 per profile per year. This means that a future re-nourishment may be needed in both the central and southern parts of Swanage.

To further conclude this thesis, the objectives set out in section 1.3 will be stated with a statement on each:

1. Examine wave diffraction around Durlston Point and the resulting hydrodynamics within Swanage Bay.

The dominant wave direction approaches from the South West, but as Swanage is protected from this direction by Durlston Head, waves must diffract around this point in order to enter the bay. The model set up shows that waves approach from the South East of the bay, which is a change in direction of 90˚. This causes northward alongshore transport, which in turn will causes a clockwise rotation. This happens over seasonal to annual timescales meaning that it is unlikely to cause rapid beach drawdown.

2. Assess how beach volume change varies during storm events and seasonal variation.

Beach volumes change due to annual and seasonal conditions as well as due to extreme events. It has been seen that beach volumes are likely to fall during storm events as sediment is drawn down to an offshore bar. The sediment is also expected to be travelling northwards due to the wave angle approach into Swanage meaning there is an accretion in both the offshore bar and the northern section of the beach seen.

3. Examine how the hydrodynamic regime causes a change in the beach volume.

As there is a correlation between the storm events and beach drawdown, it is understood that storm events cause a rapid loss of sediment. Although there is fast recovery in the Bay, if consecutive storms approach Swanage, one storm may cause a rapid beach volume loss with the other causing flooding to Swanage. In order to manage Swanage from future flooding events, this should be addressed in the new BMP.

6.2 Final Remarks

There are limitations in this project which may be important. The main two limitations in the methods are the frequency of the topographic surveys and the inshore wave data. The transformation from the offshore buoy into the nearshore was done using coastal tools which uses a relatively simple method. More advanced modelling techniques such as using a 2D Swan model could yield more accurate results, as wave angles can be predicted throughout all of Swanage Bay. If the frequency of the topographic surveys were also increased, a greater level of reliability could also be placed on whether Swanage is mainly controlled by extreme events, or by seasonal variation. Also, if the surveys extended further offshore, to the depth of closure, a better understanding of the beach volume change may be seen. However, this is unlikely to occur, due to budget restrictions and equipment limitations. This thesis has also ignored other properties which may influence the beach volume. A grain trend analysis could be carried out in order to see the predicted sediment movement directions.

Overall, the main driver of rapid beach volume change in Swanage occurs due to extreme events, with rapid beach drawdown occurring during high energy wave conditions. There is also northward sediment transport which is rotating the crenulate bay clockwise with the southern end of the beach eroding whilst the northern side of Swanage is accreting.

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Appendix

This appendix will show all seasonal beach profiles for Swanage. The profiles will be split into 3 sections as they have been done in the report.

North

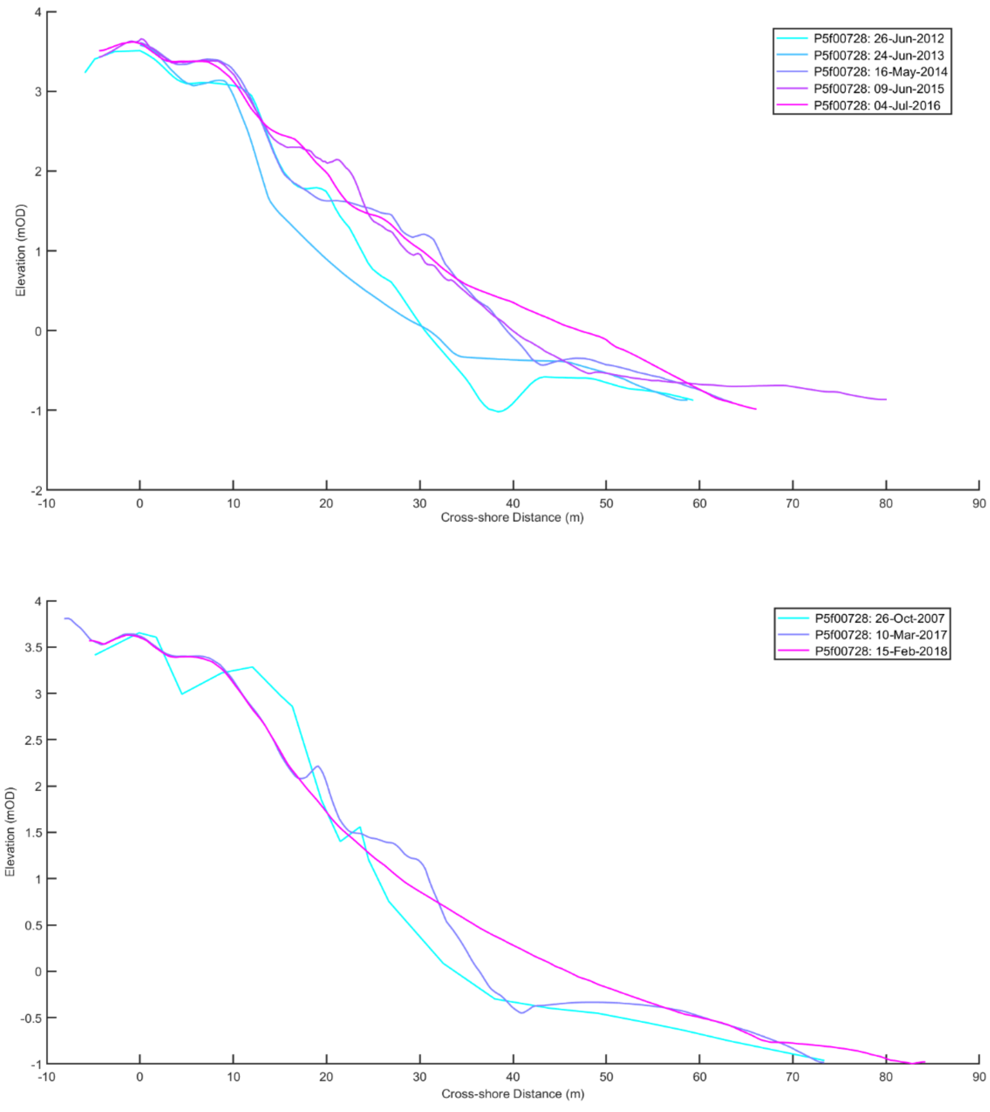

Figure 51 - Summer (top) and Winter profiles for profile P5f00728.

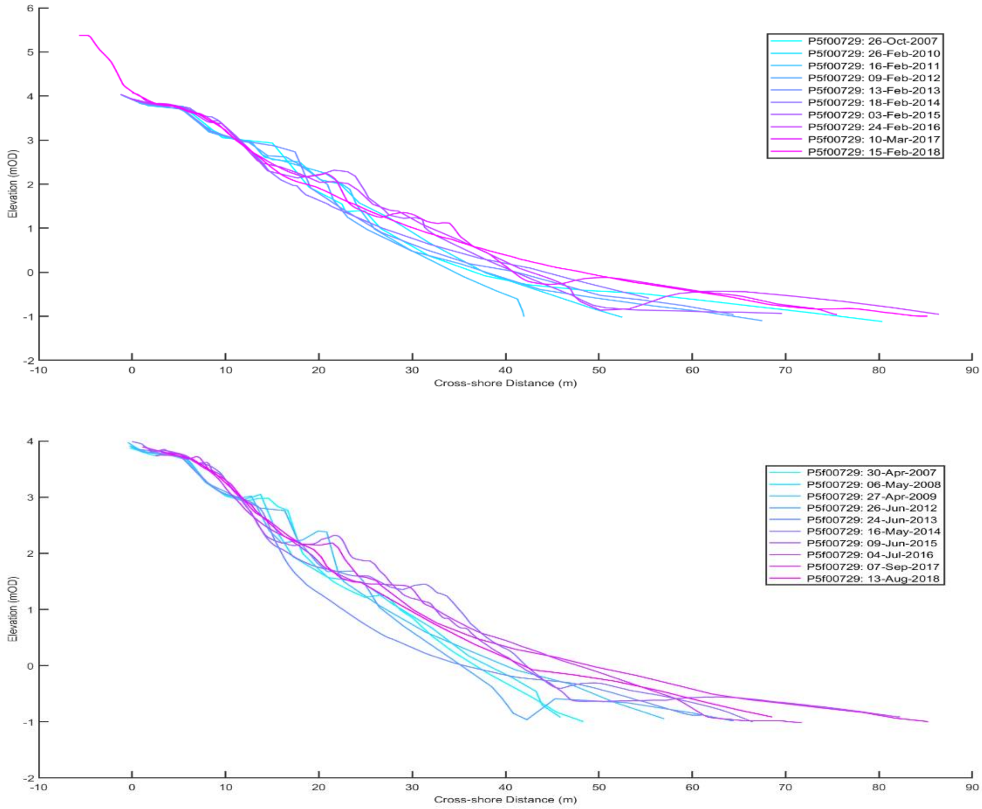

Figure 52 - Summer (top) and Winter profiles for profile P5f00729.

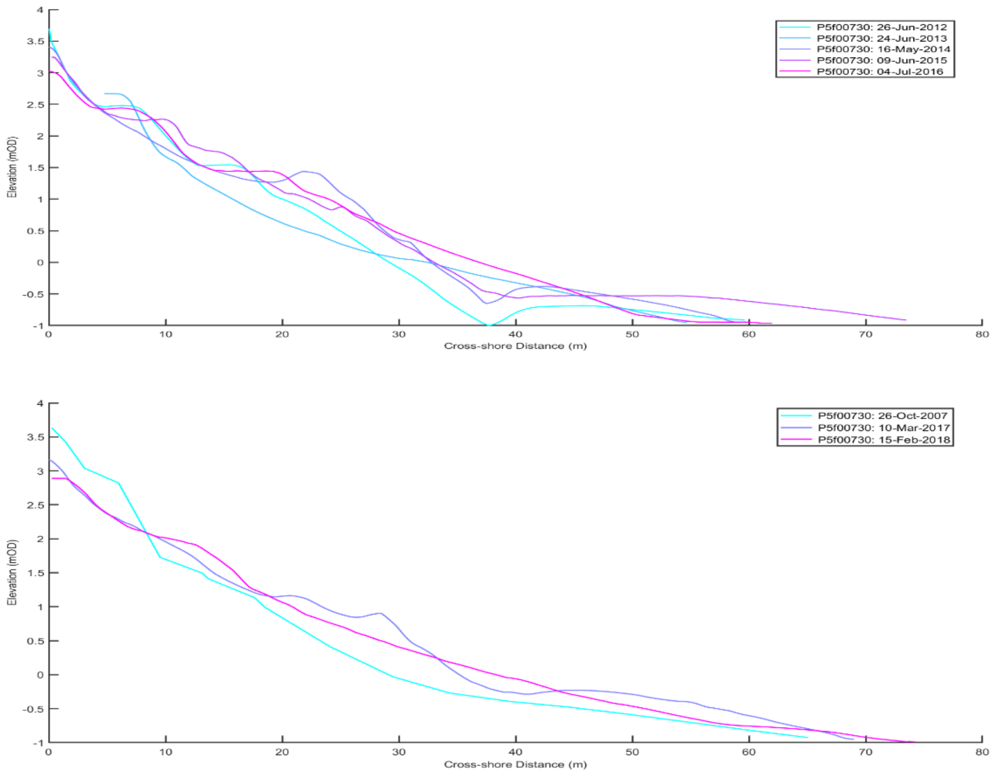

Figure 53 - Summer (top) and Winter profiles for profile P5f00730.

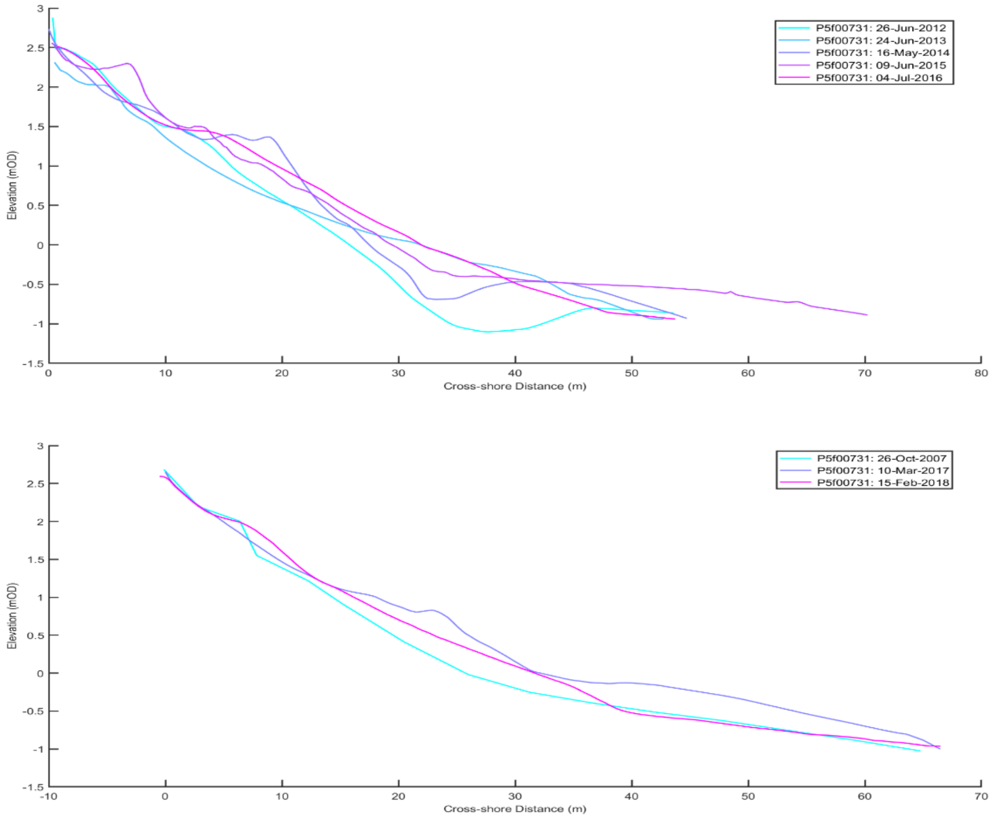

Figure 54 - Summer (top) and Winter profiles for profile P5f00731.

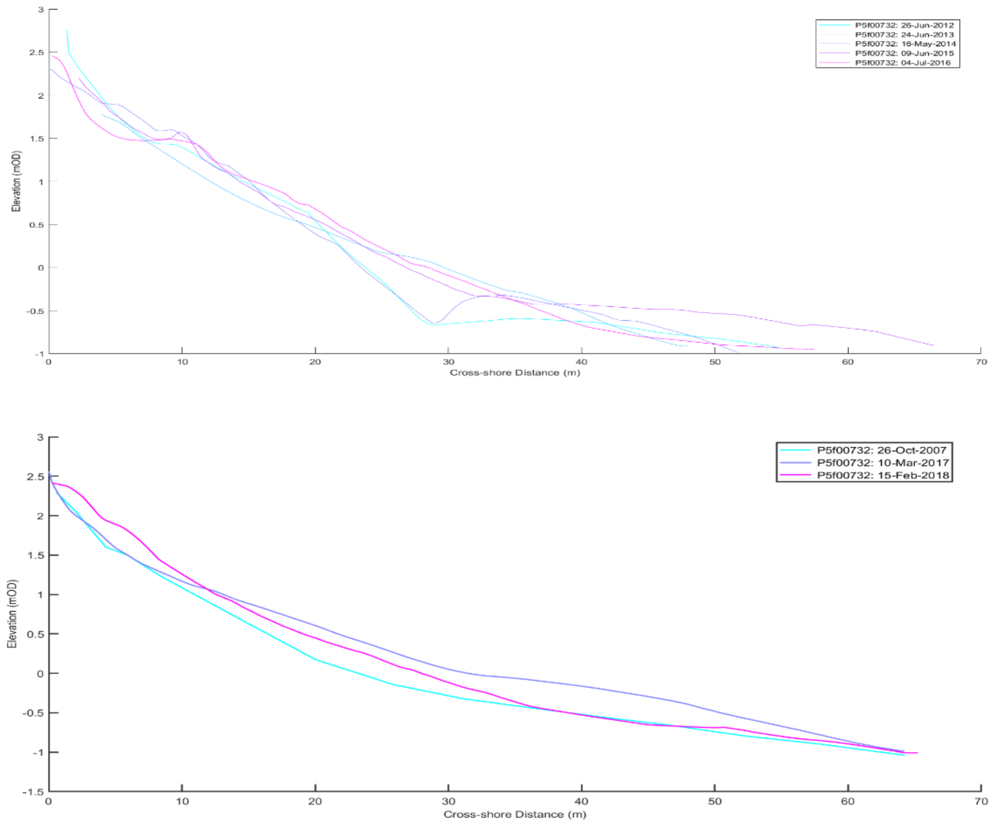

Figure 55 - Summer (top) and Winter profiles for profile P5f00732.

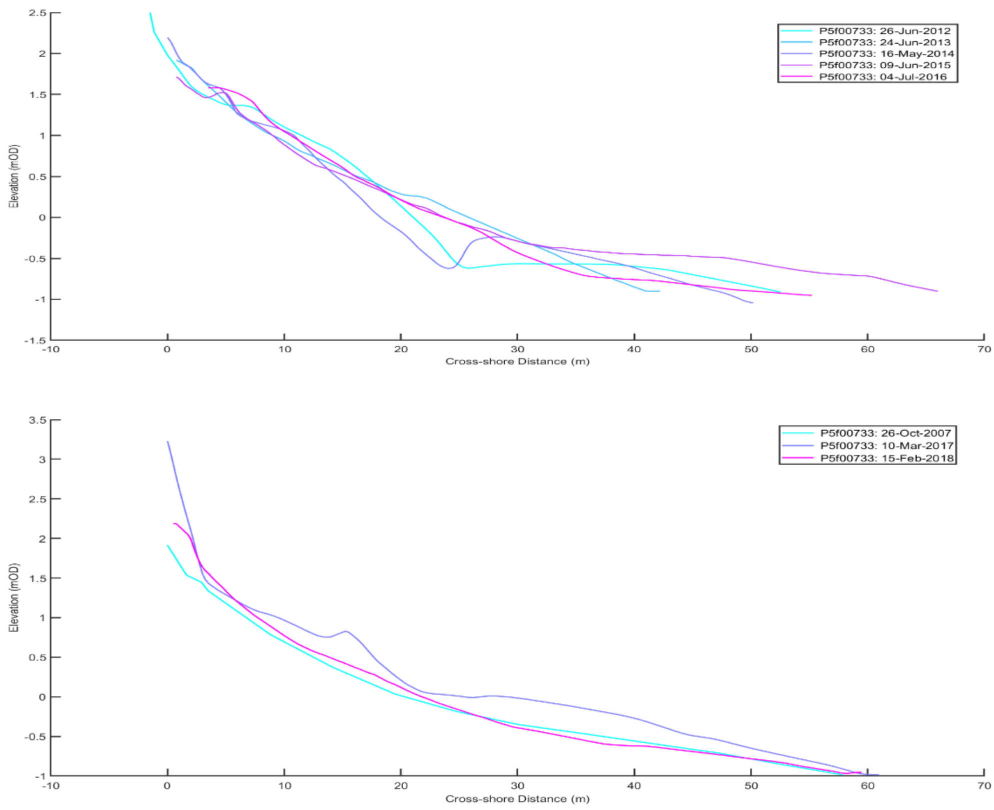

Figure 56 - Summer (top) and Winter profiles for profile P5f00733.

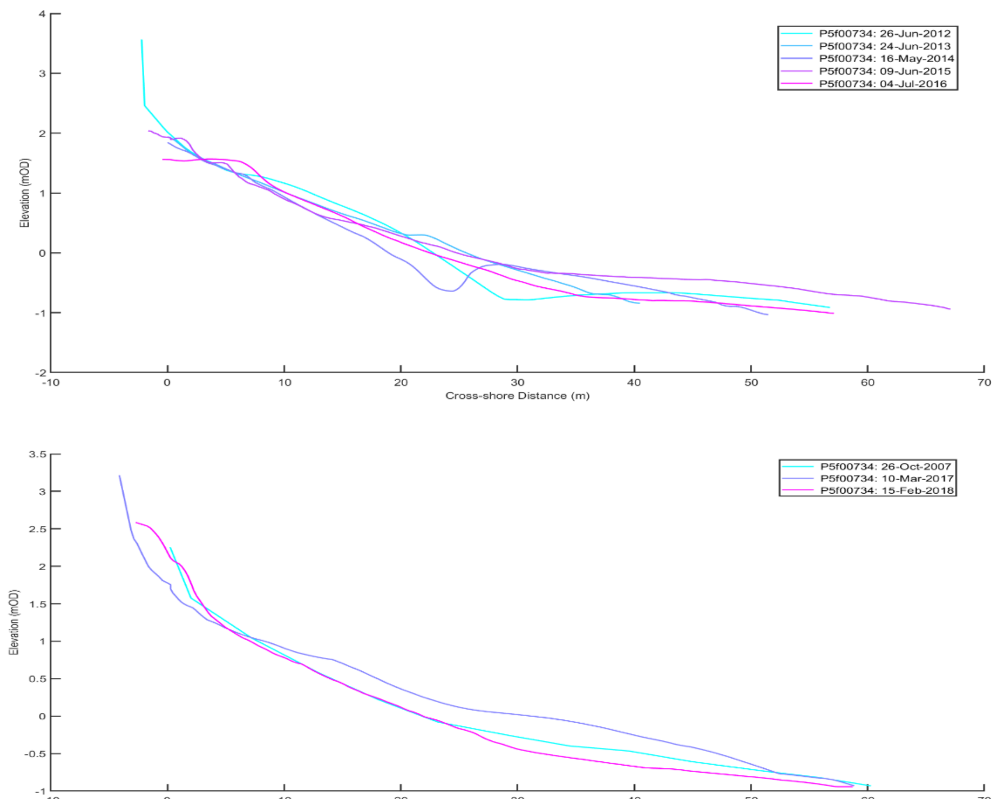

Figure 57 - Summer (top) and Winter profiles for profile P5f00734.

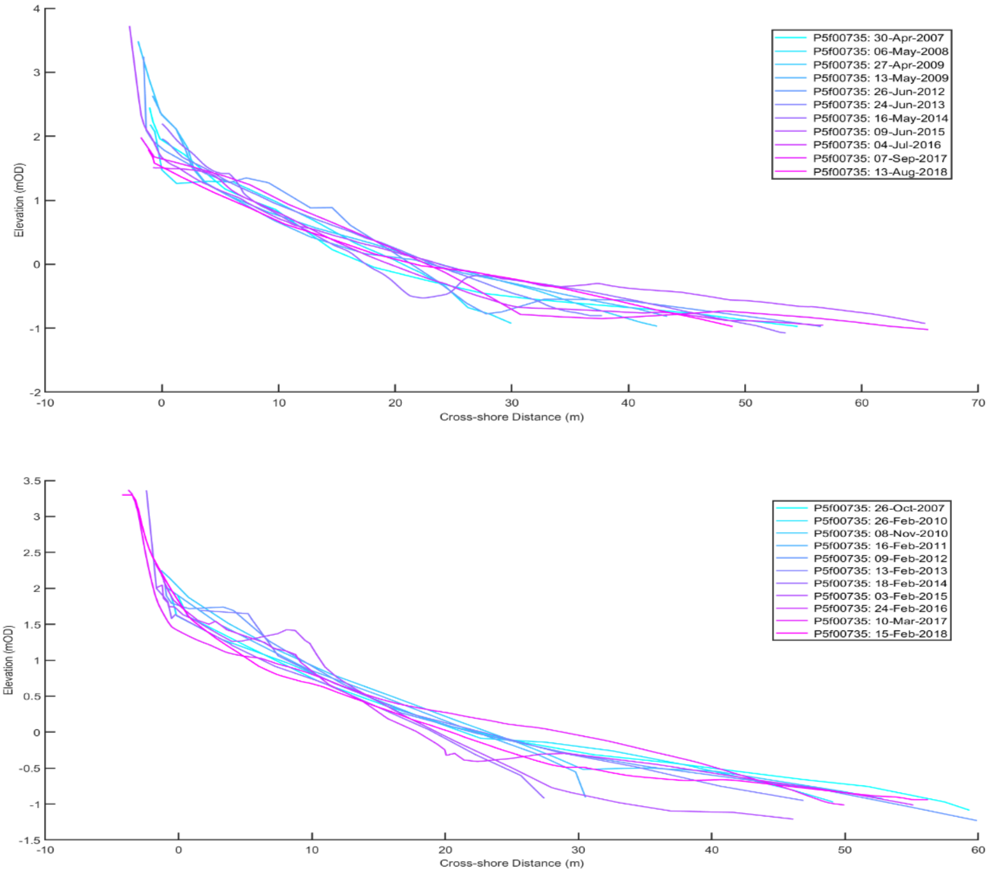

Figure 58 - Summer (top) and Winter profiles for profile P5f00735.

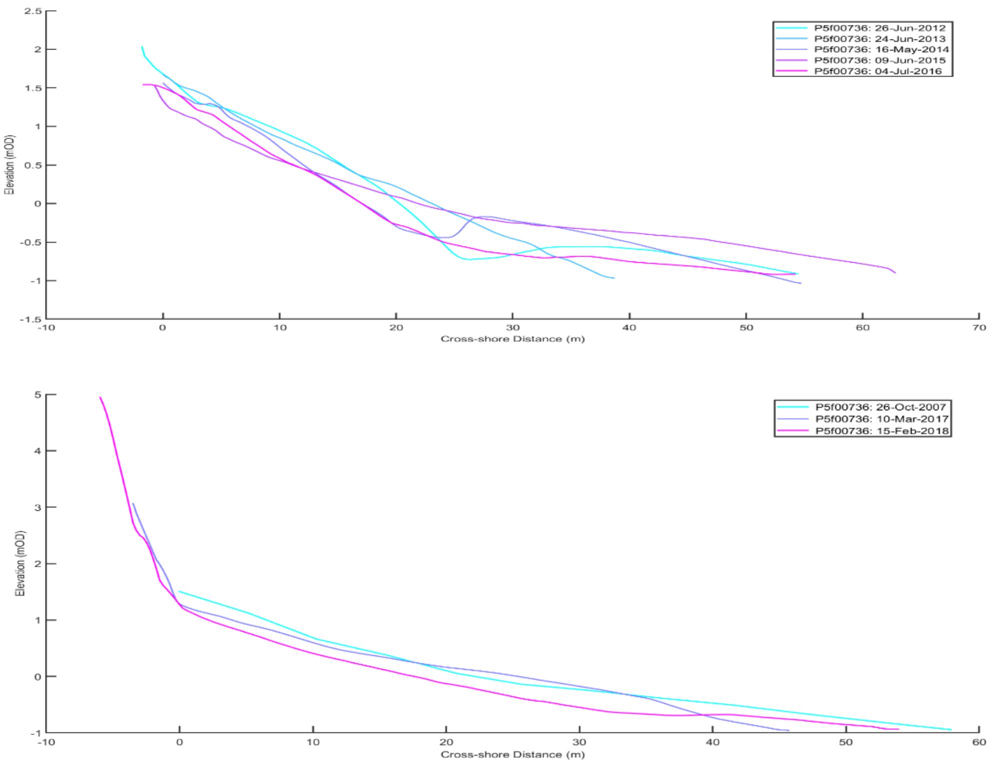

Figure 59 - Summer (top) and Winter profiles for profile P5f00736.

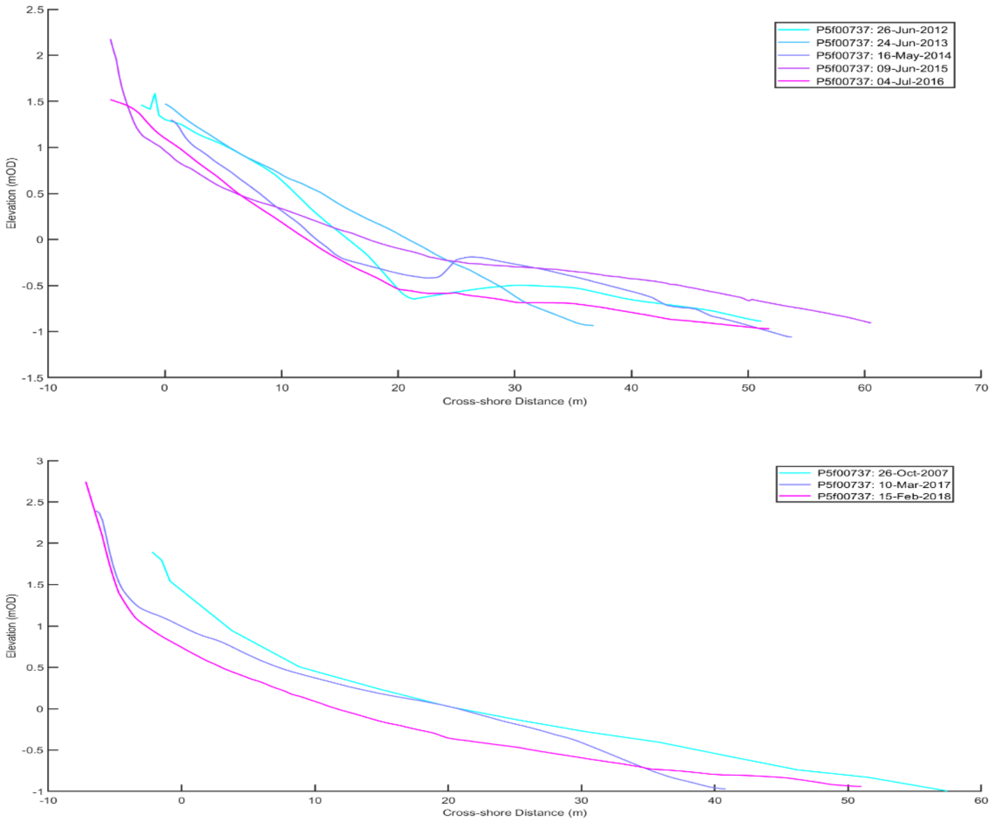

Figure 60 - Summer (top) and Winter profiles for profile P5f00737.

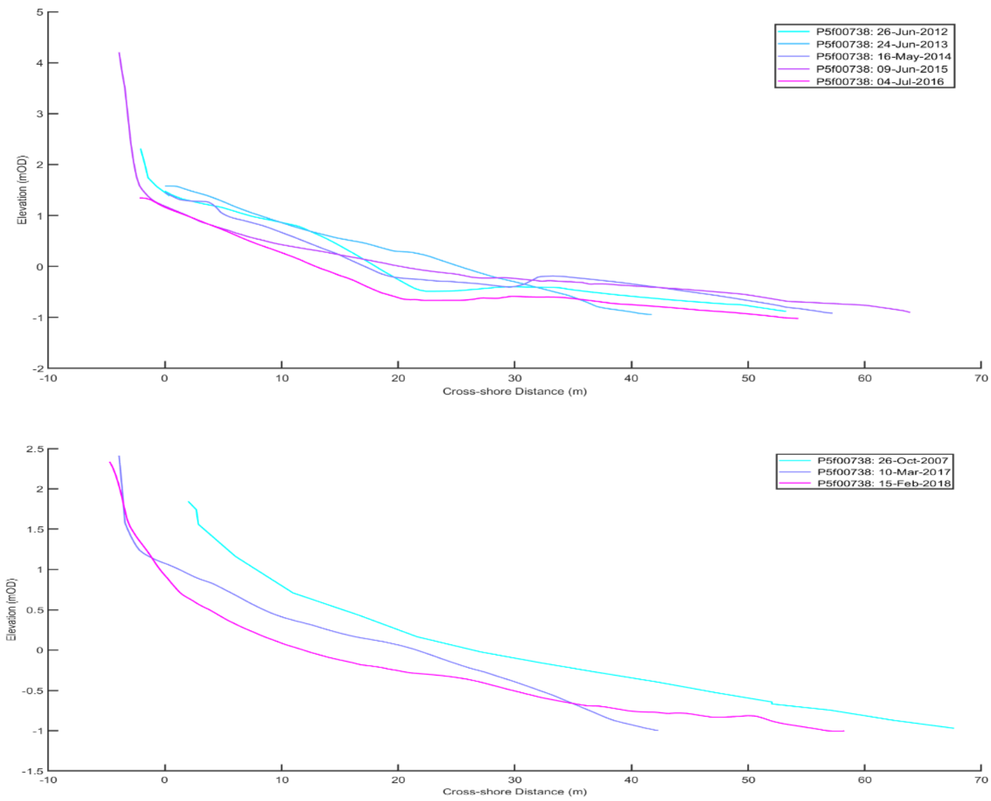

Figure 61 - Summer (top) and Winter profiles for profile P5f00738.

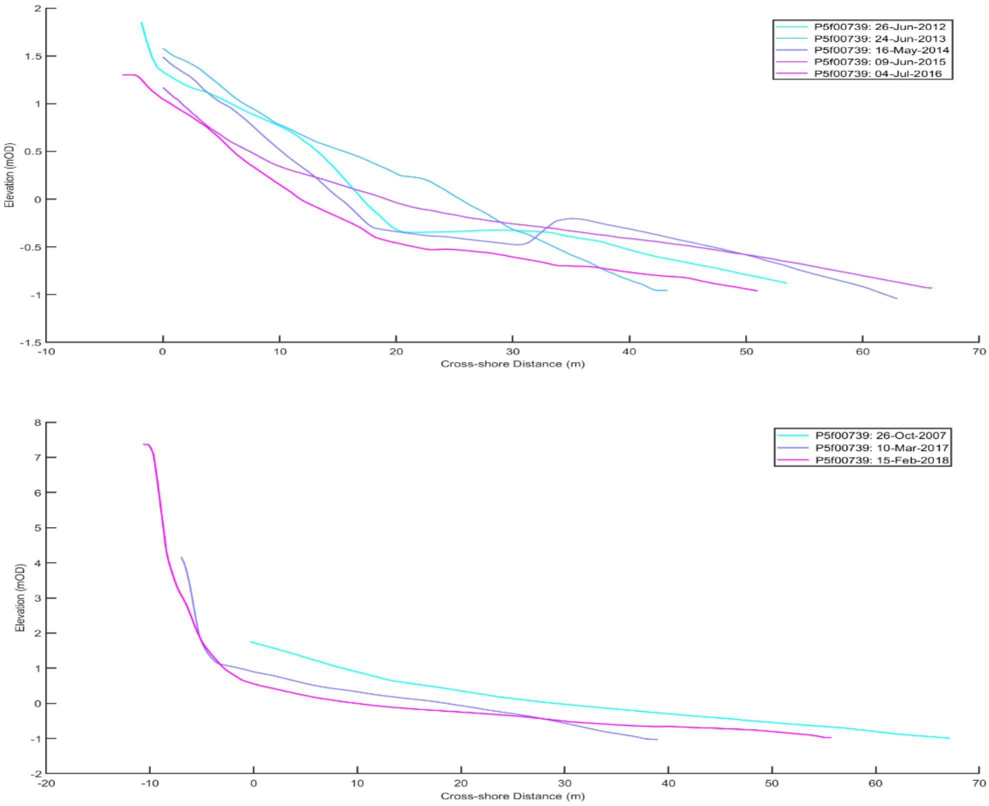

Figure 62 - Summer (top) and Winter profiles for profile P5f00739.

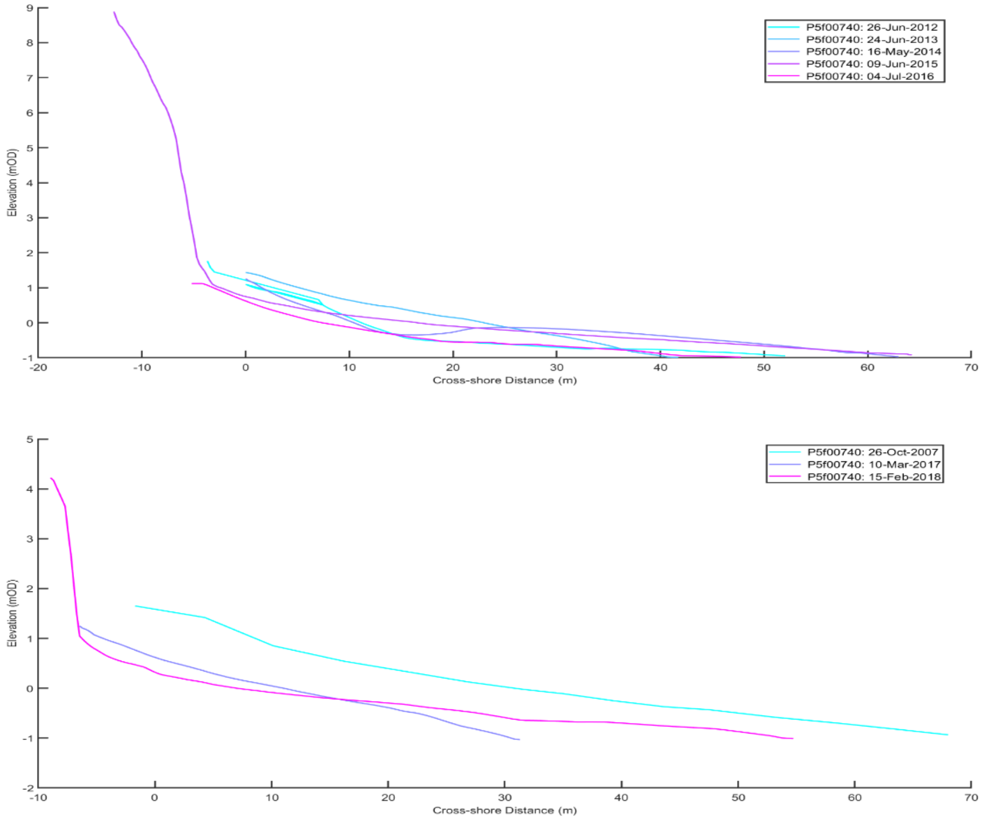

Figure 63 - Summer (top) and Winter profiles for profile P5f00740.

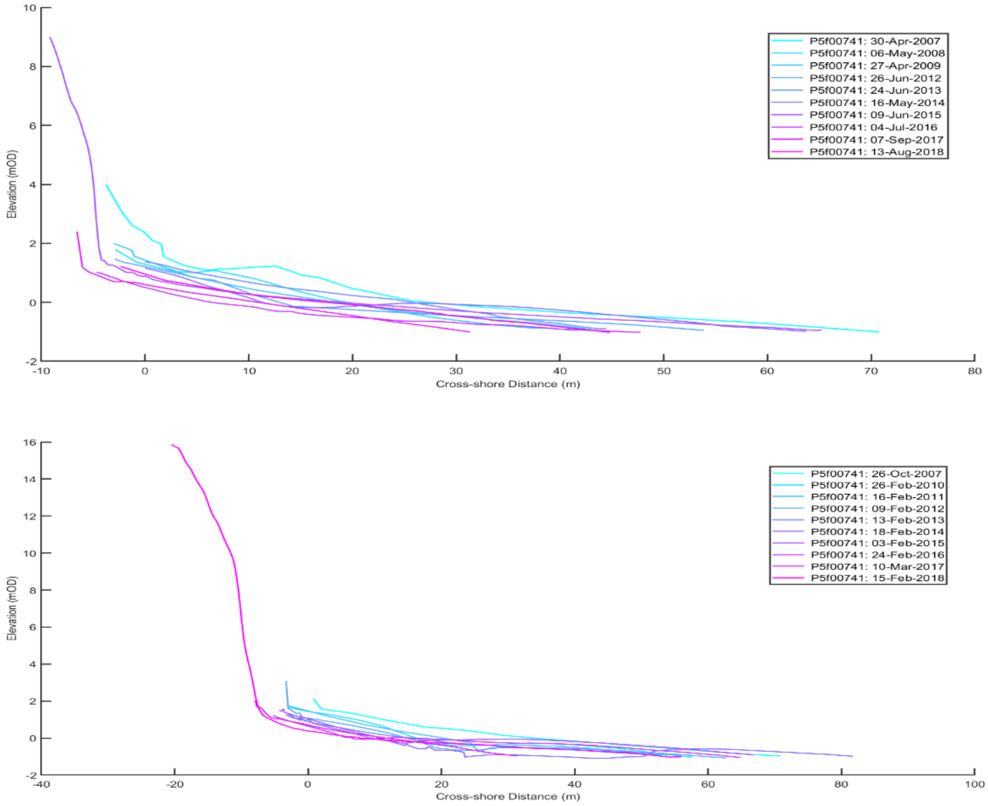

Figure 64 - Summer (top) and Winter profiles for profile P5f00741.

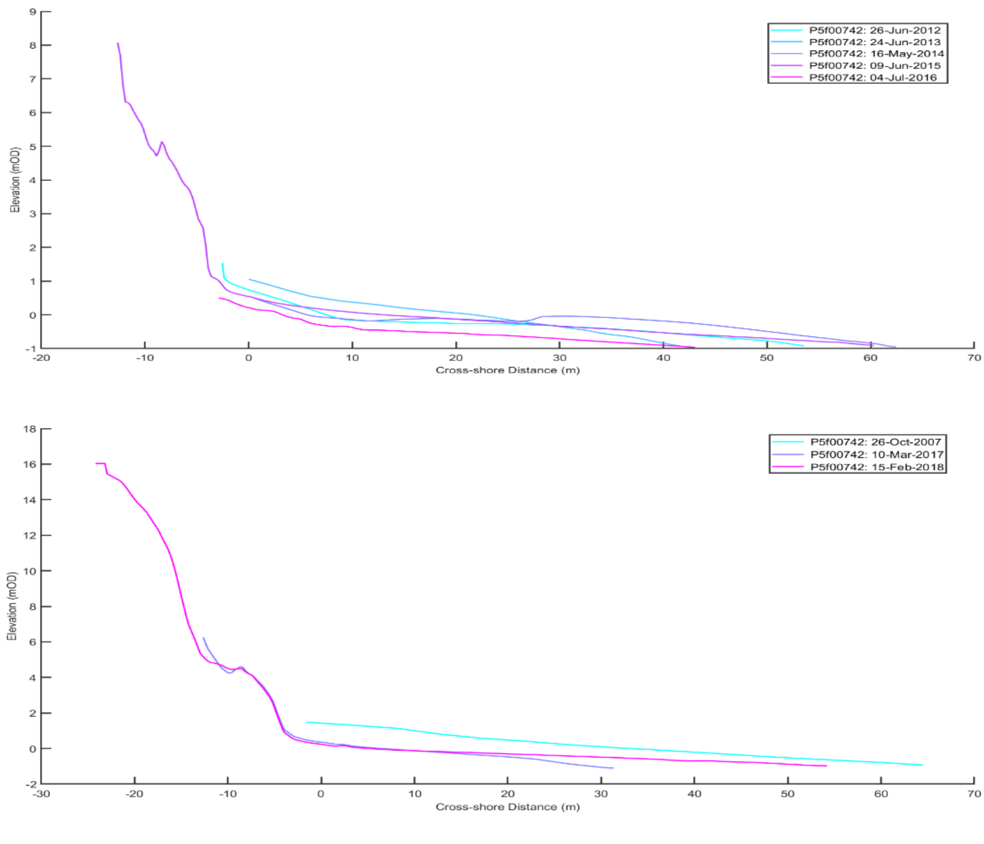

Figure 65 - Summer (top) and Winter profiles for profile P5f00742.

Central

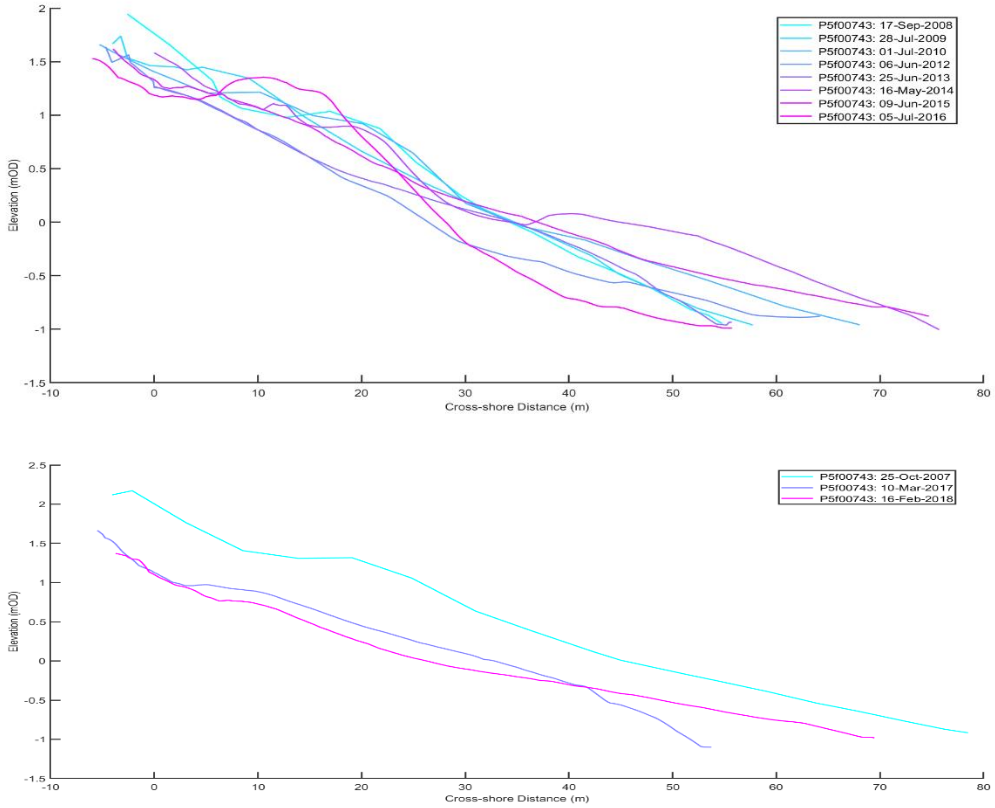

Figure 66 -Summer (top) and Winter profiles for profile P5f00743.

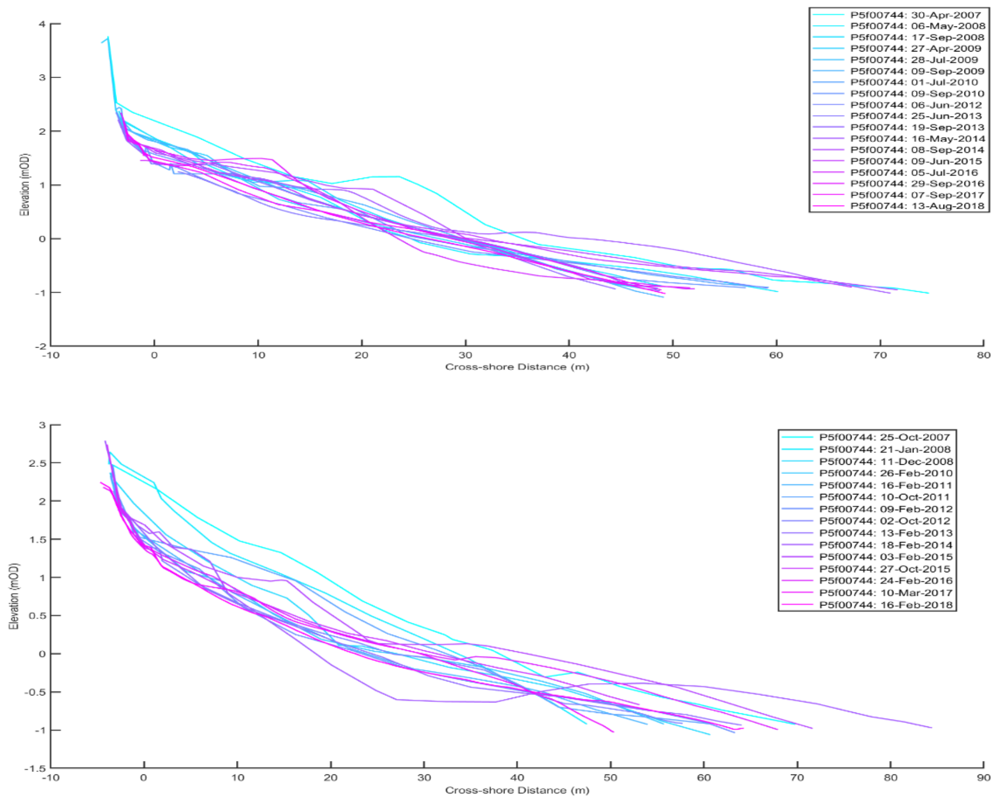

Figure 67 - Summer (top) and Winter profiles for profile P5f00744.

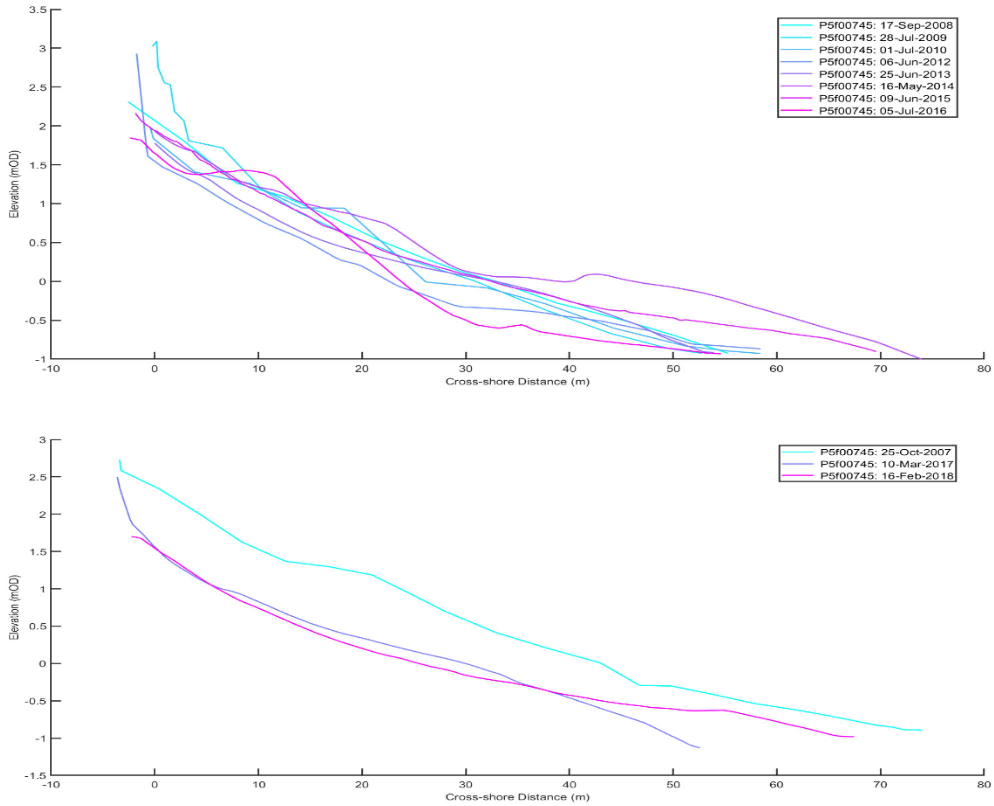

Figure 68 - Summer (top) and Winter profiles for profile P5f00745.

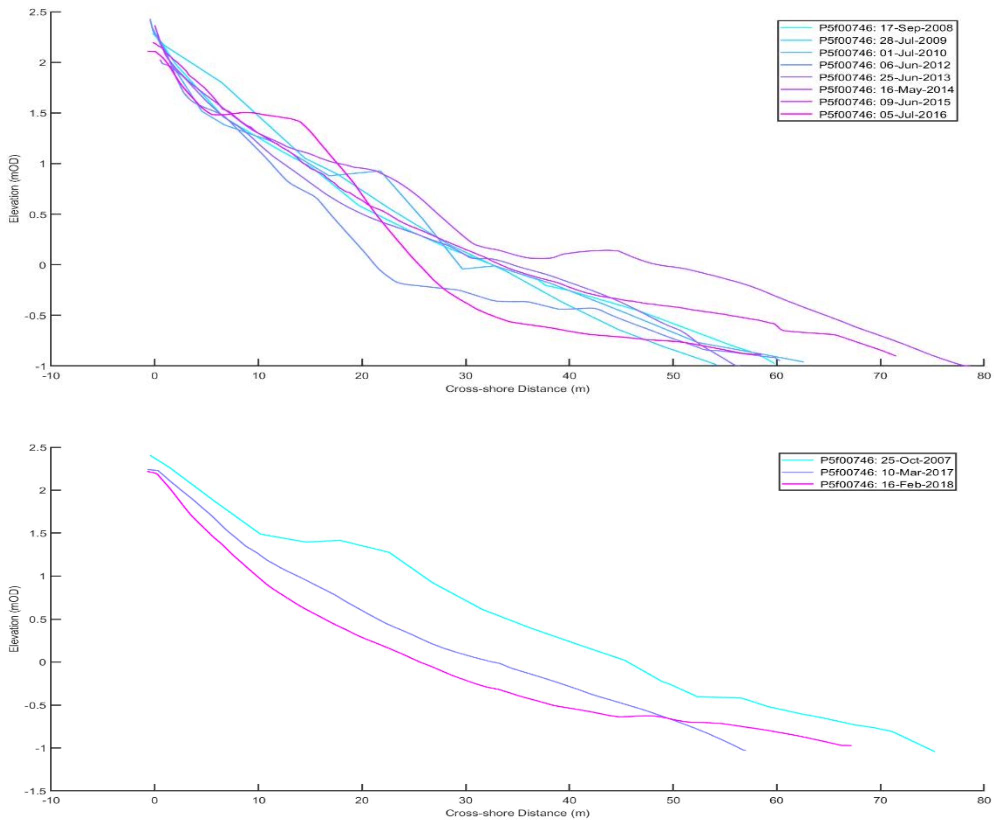

Figure 69 - Summer (top) and Winter profiles for profile P5f00746.

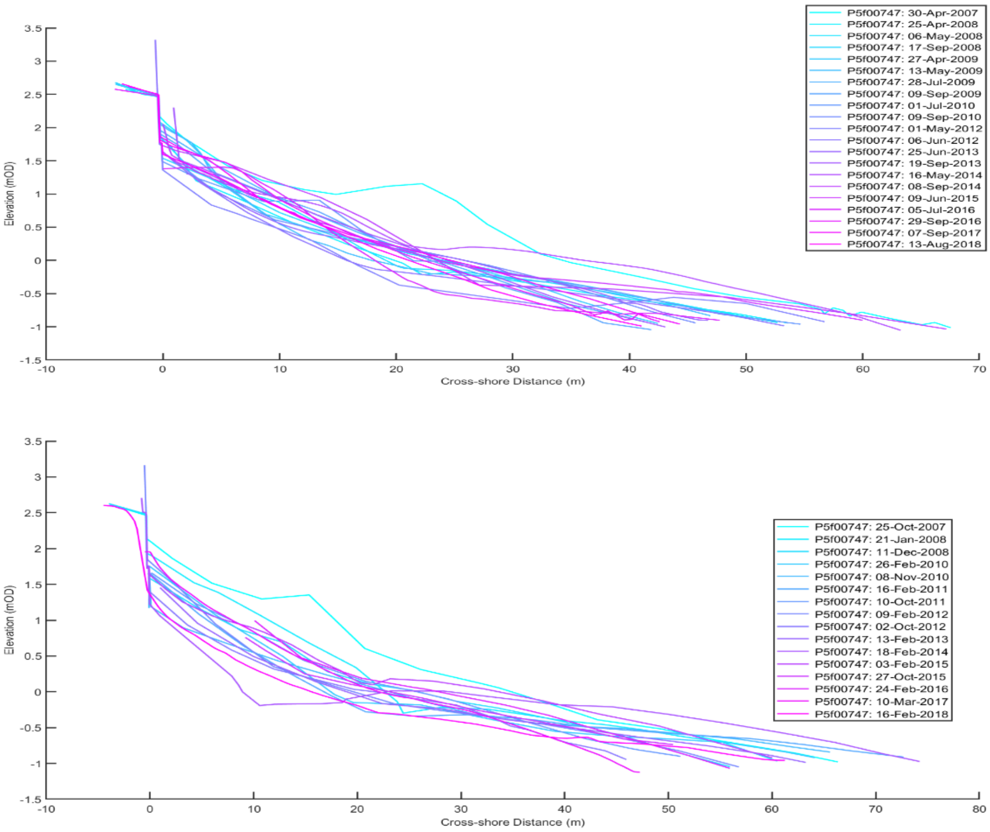

Figure 70 - Summer (top) and Winter profiles for profile P5f00747.

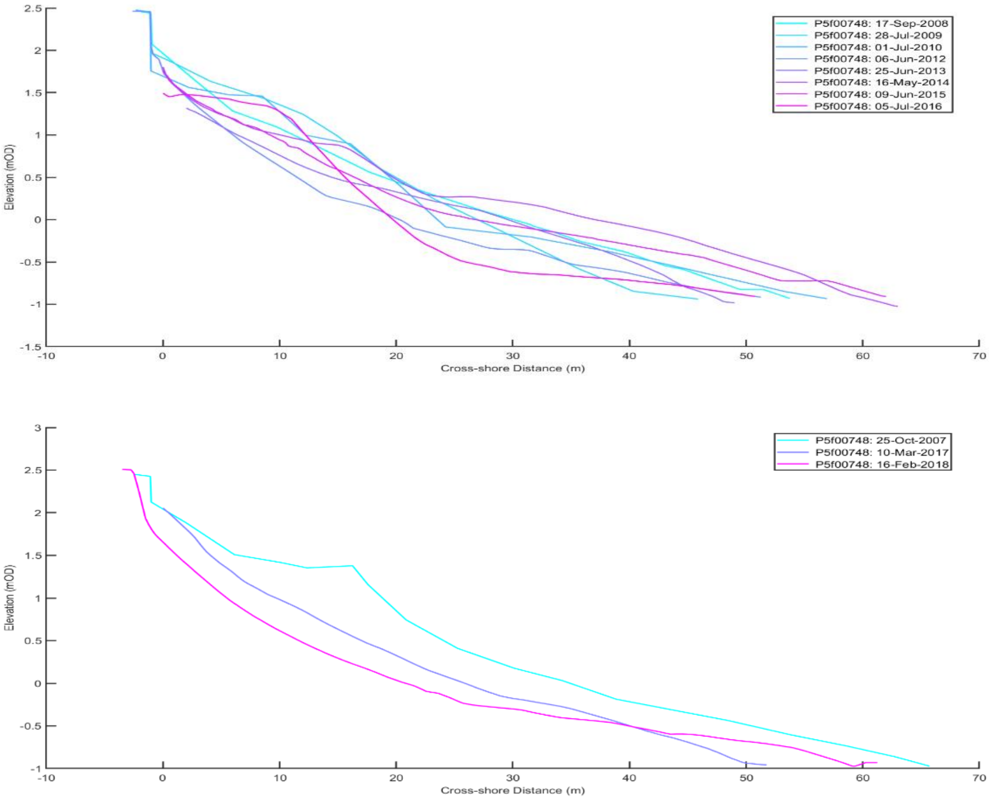

Figure 71 - Summer (top) and Winter profiles for profile P5f00748.

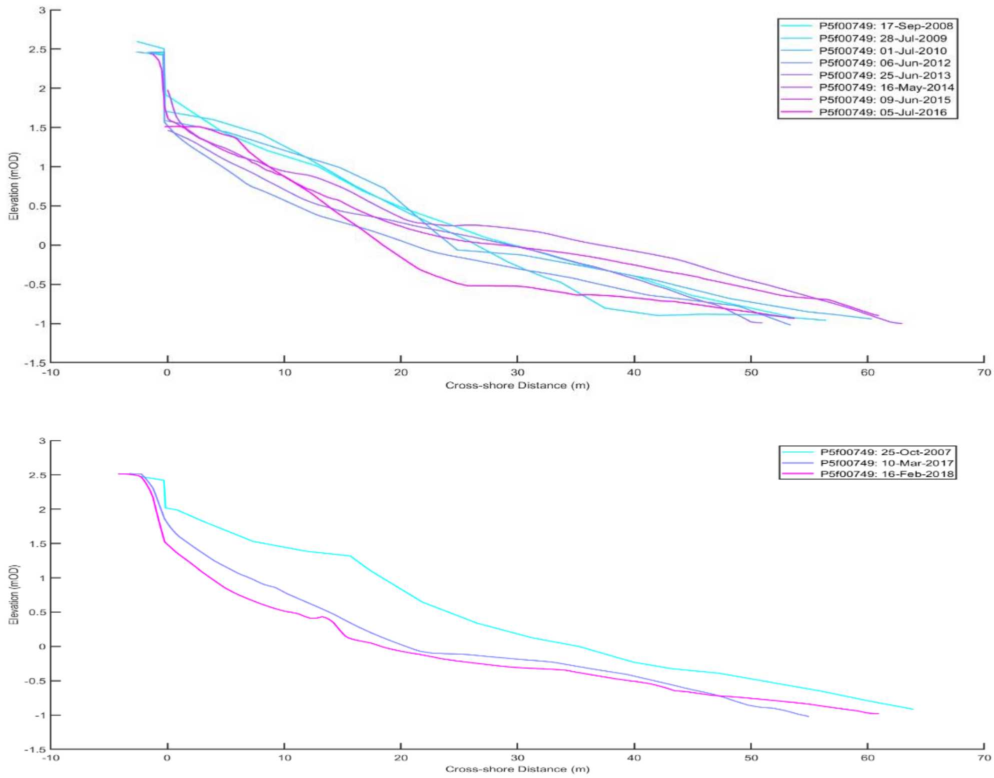

Figure 72 - Summer (top) and Winter profiles for profile P5f00749.

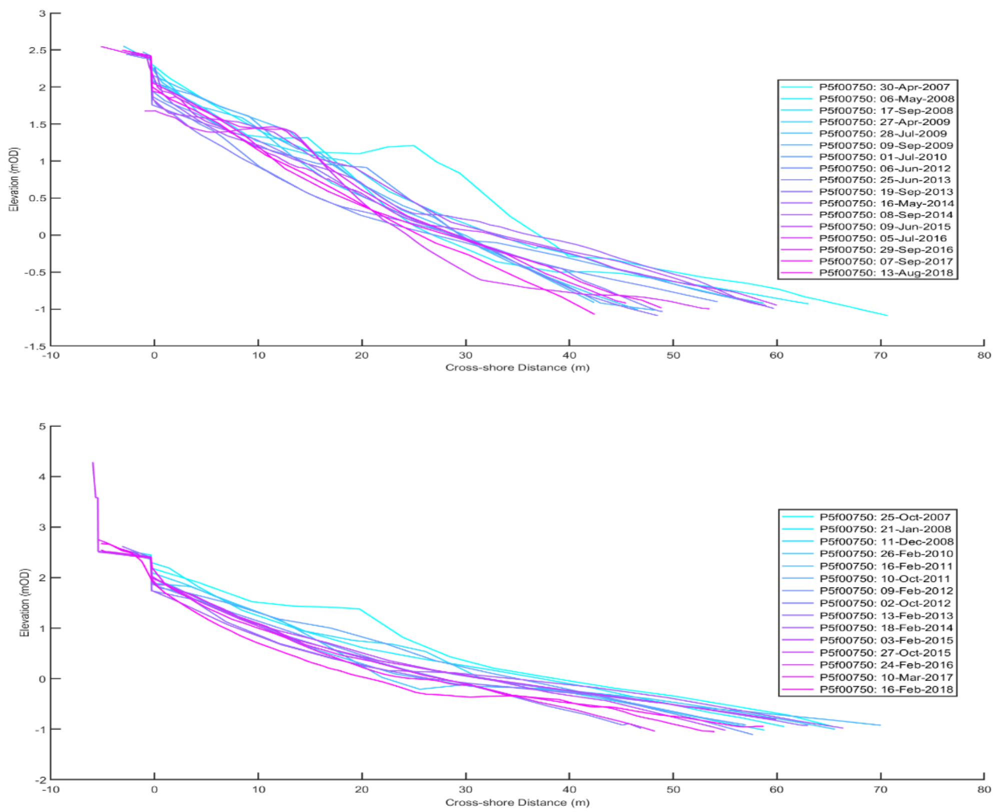

Figure 73 - Summer (top) and Winter profiles for profile P5f00750.

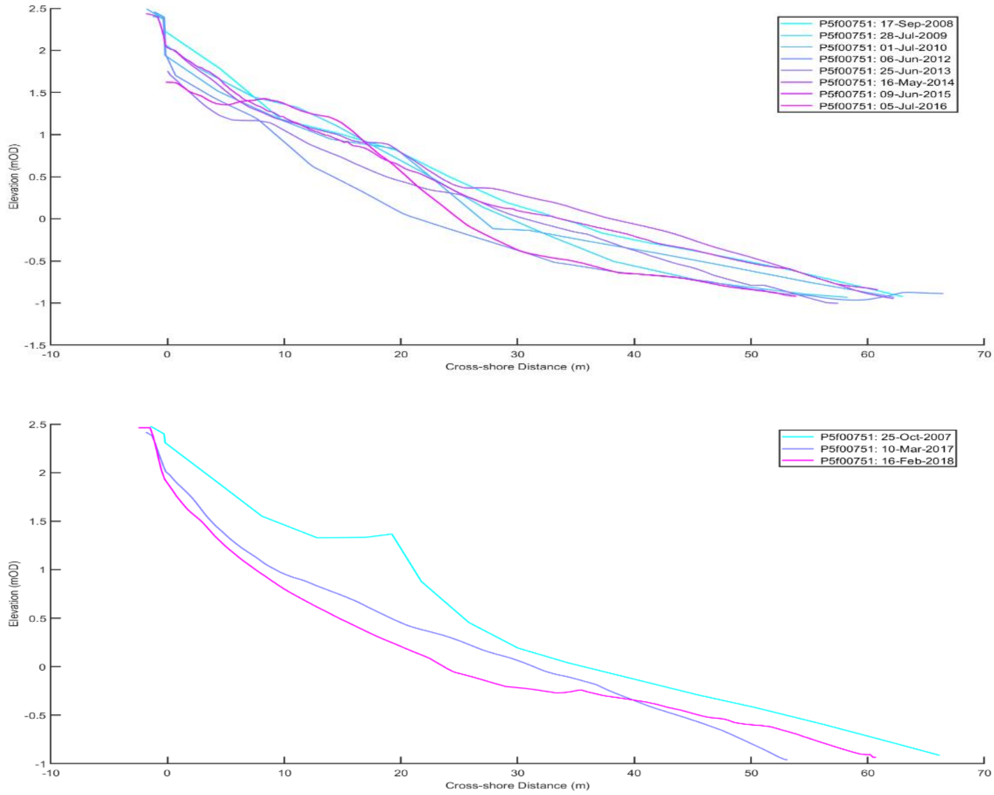

Figure 74 - Summer (top) and Winter profiles for profile P5f00751.

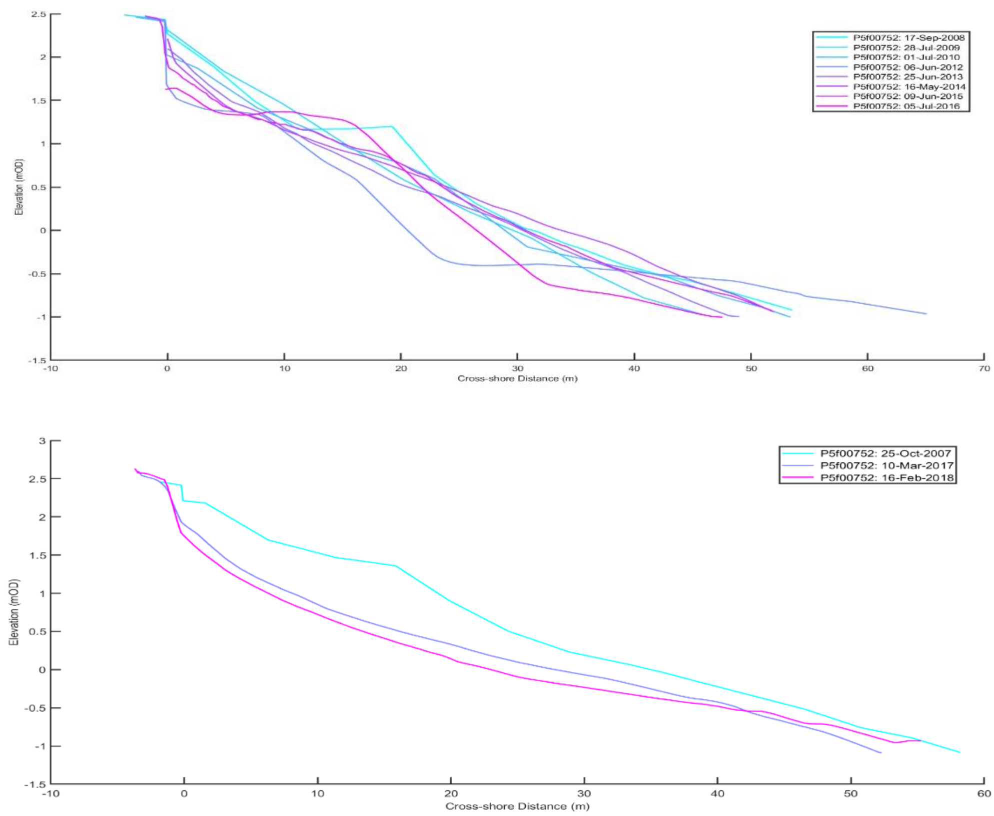

Figure 75 - Summer (top) and Winter profiles for profile P5f00752.

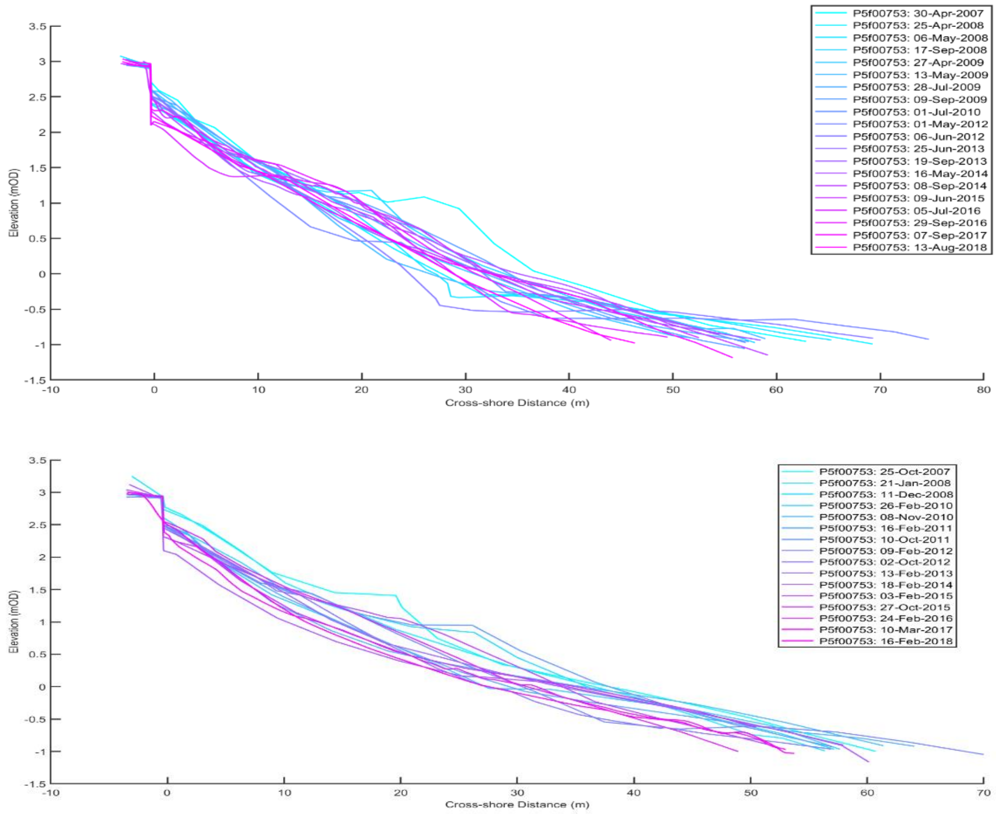

Figure 76 - Summer (top) and Winter profiles for profile P5f00753.

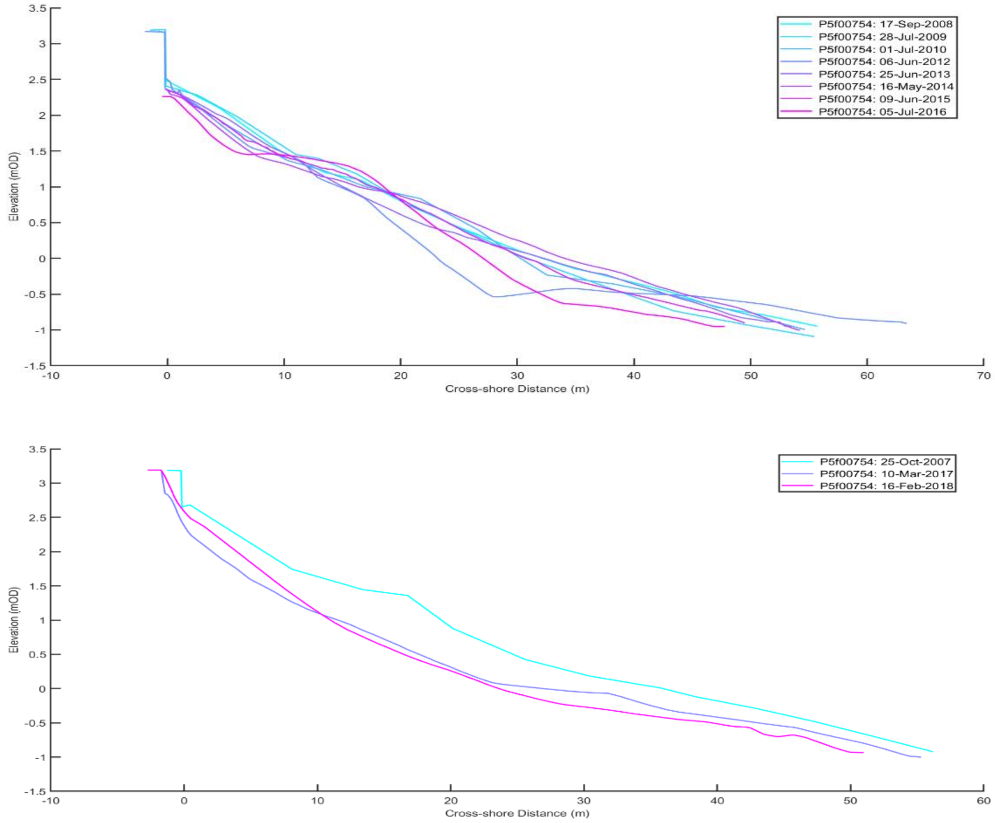

Figure 77 - Summer (top) and Winter profiles for profile P5f00754.

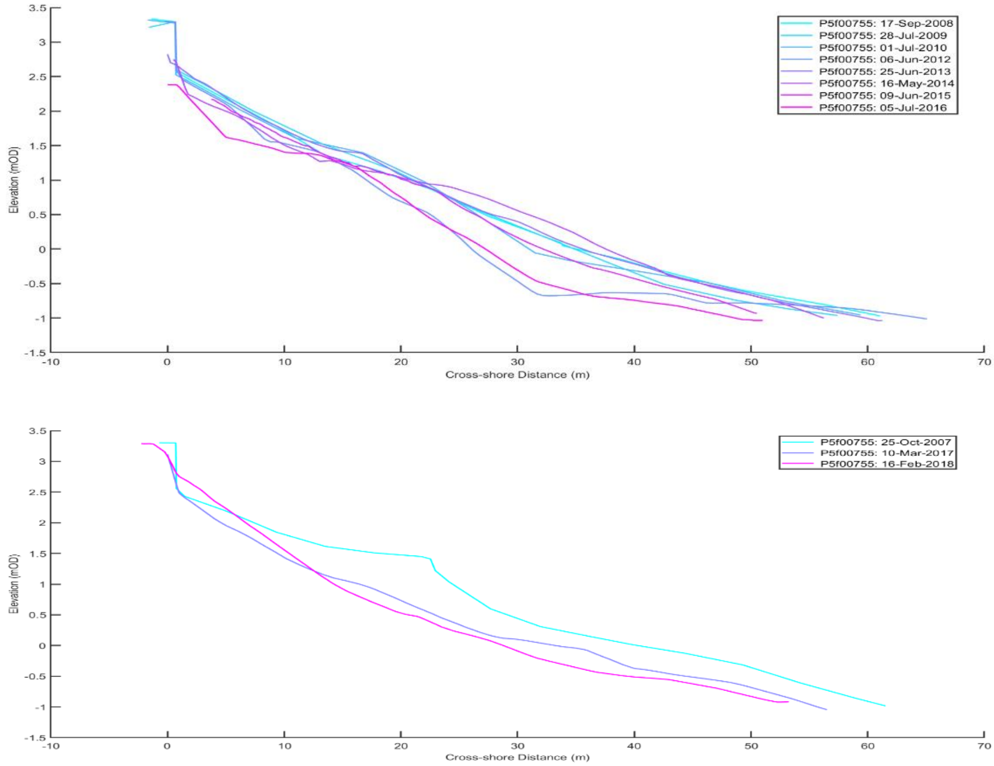

Figure 78 - Summer (top) and Winter profiles for profile P5f00755.

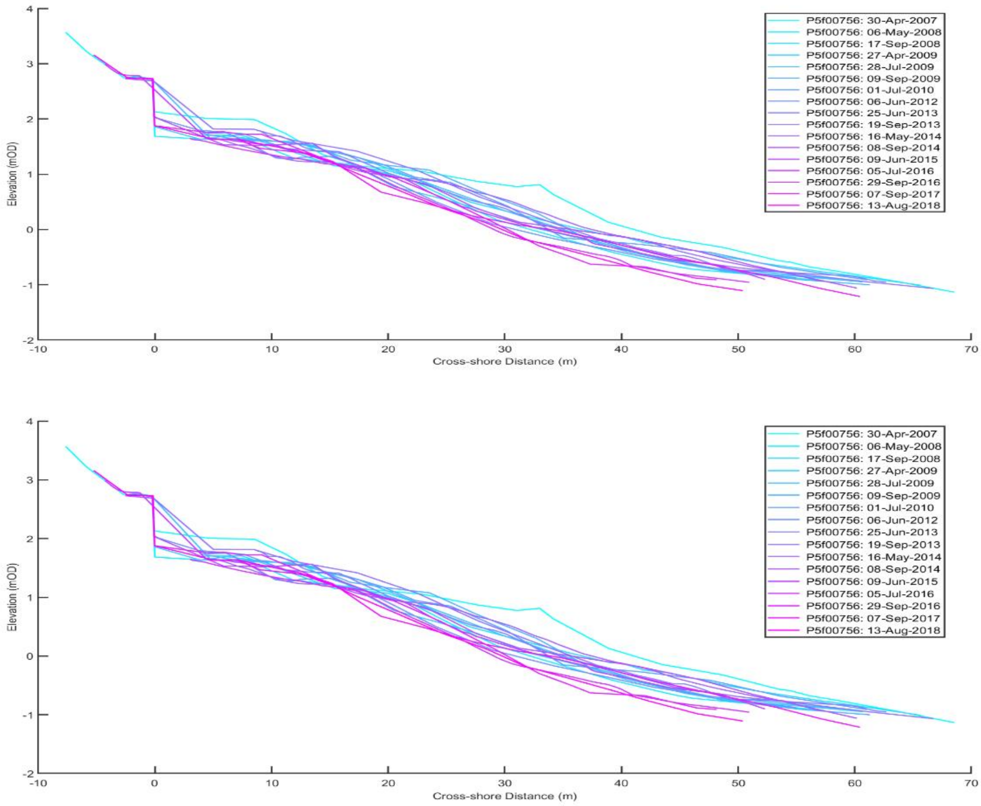

Figure 79 - Summer (top) and Winter profiles for profile P5f00756.

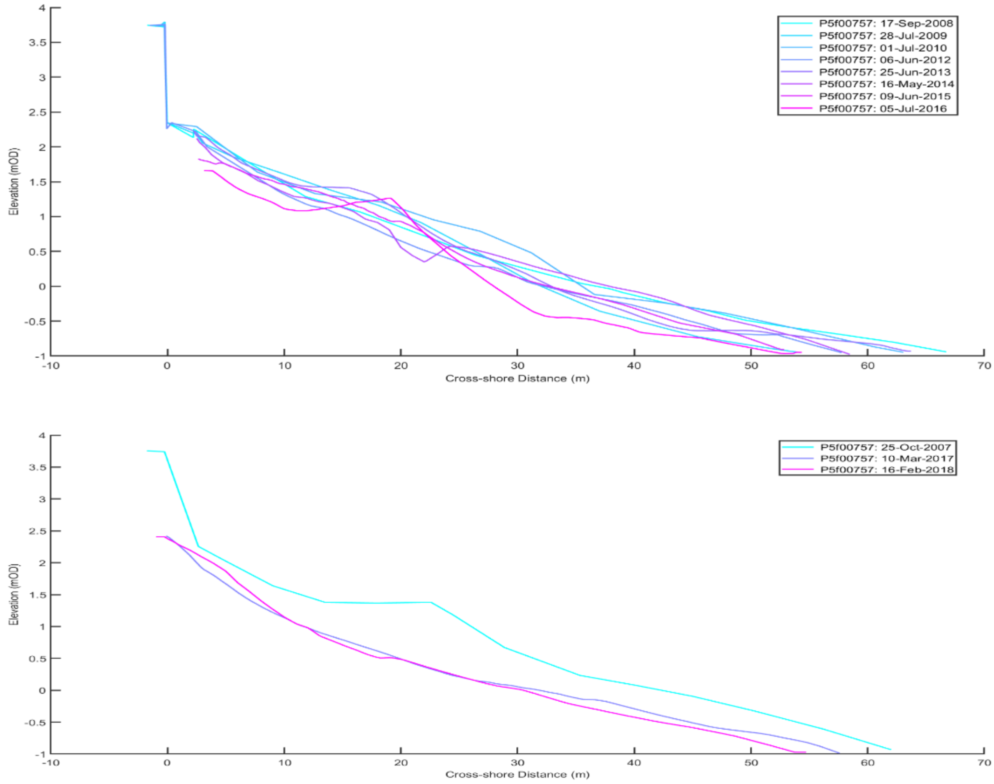

Figure 80 - Summer (top) and Winter profiles for profile P5f00757.

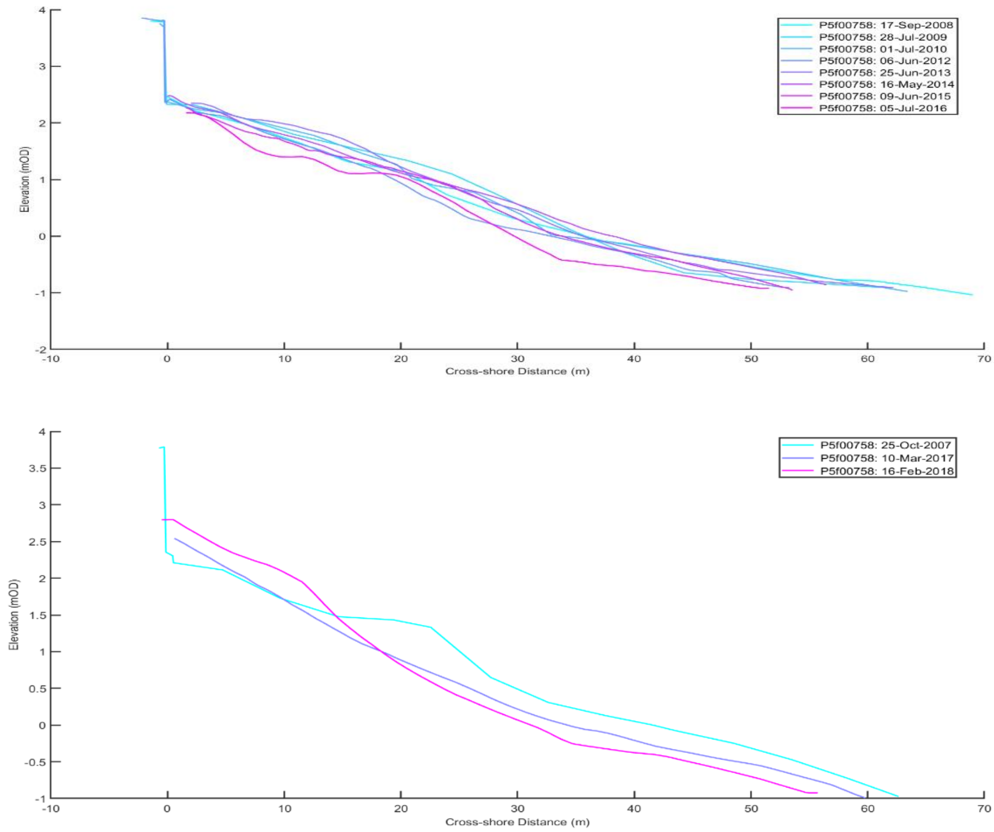

Figure 81 - Summer (top) and Winter profiles for profile P5f00758.

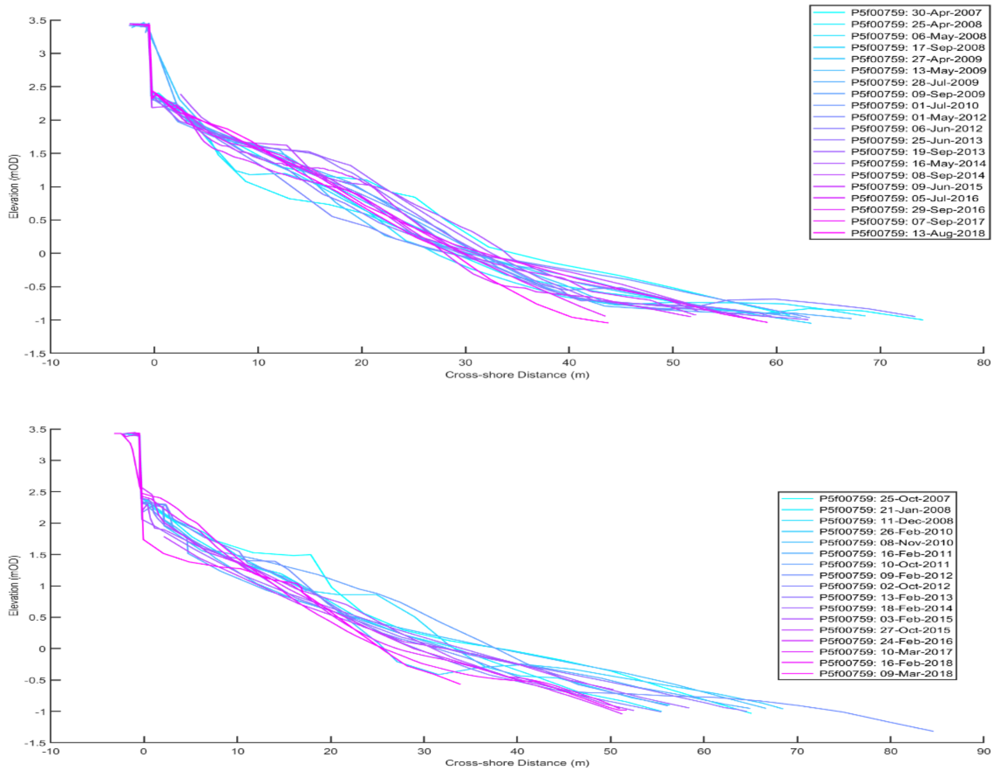

Figure 82 - Summer (top) and Winter profiles for profile P5f00759.

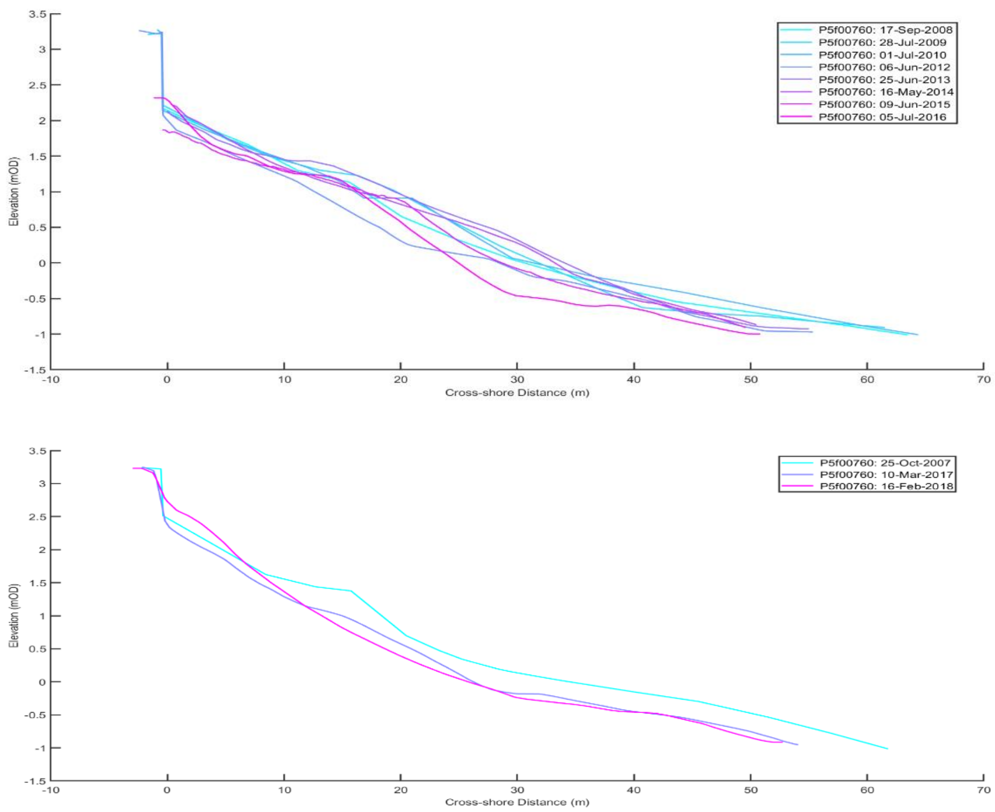

Figure 83 - Summer (top) and Winter profiles for profile P5f00760.

Southern

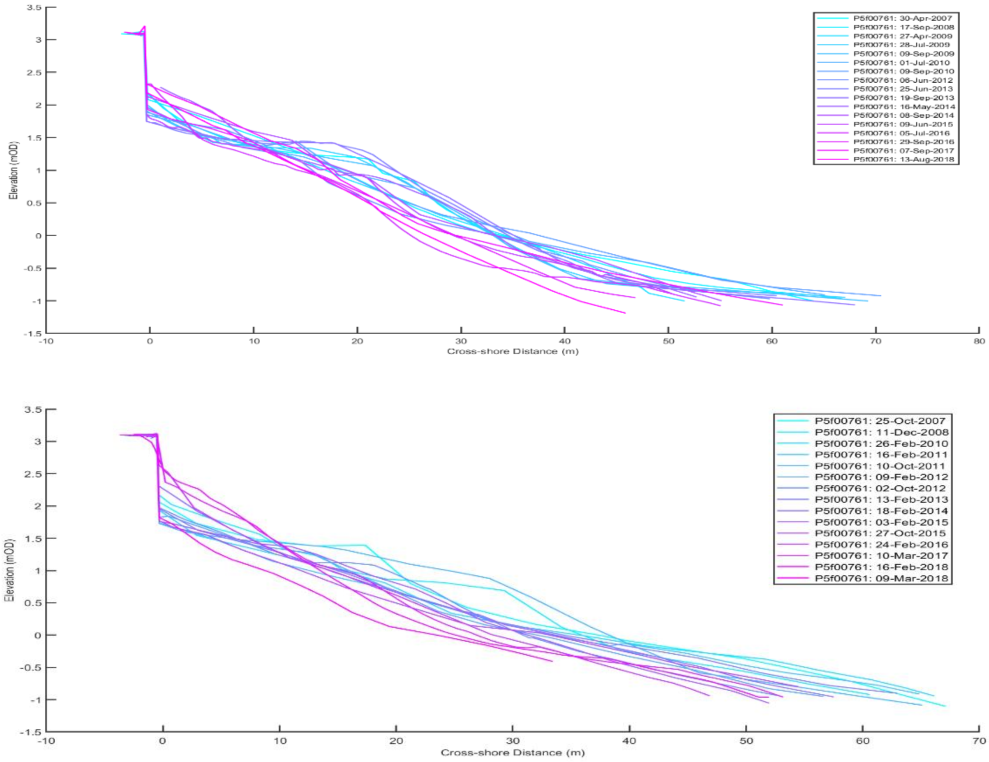

Figure 84 - Summer (top) and Winter profiles for profile P5f00761.

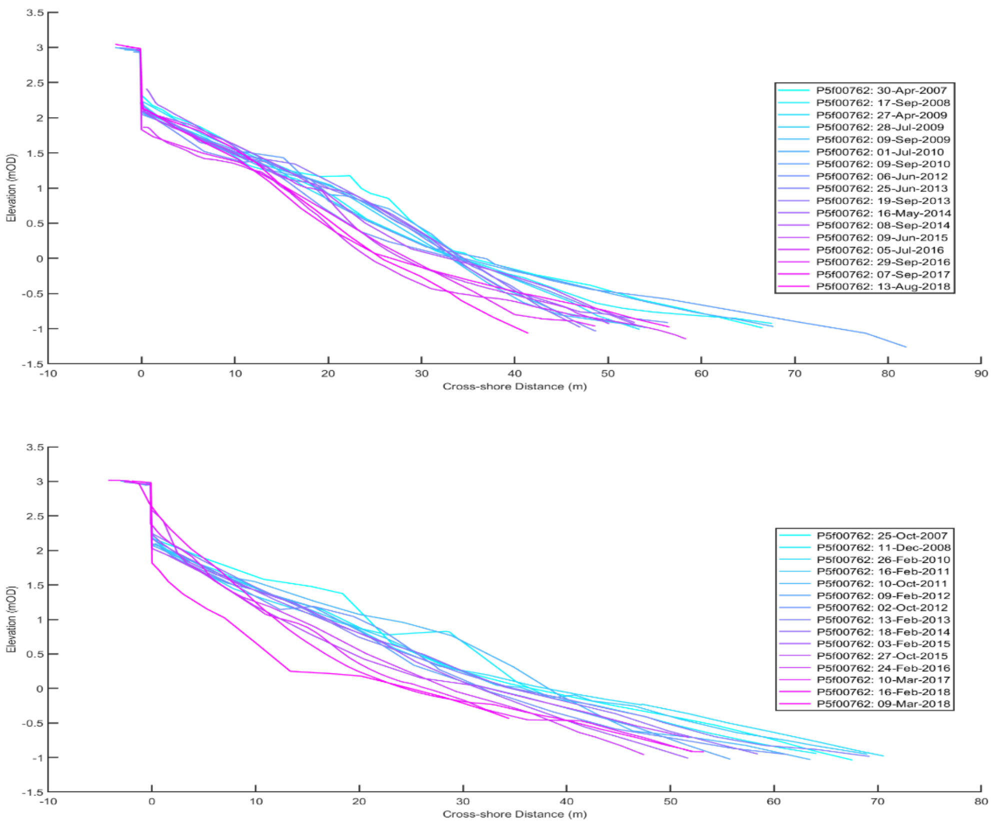

Figure 85 - Summer (top) and Winter profiles for profile P5f00762.

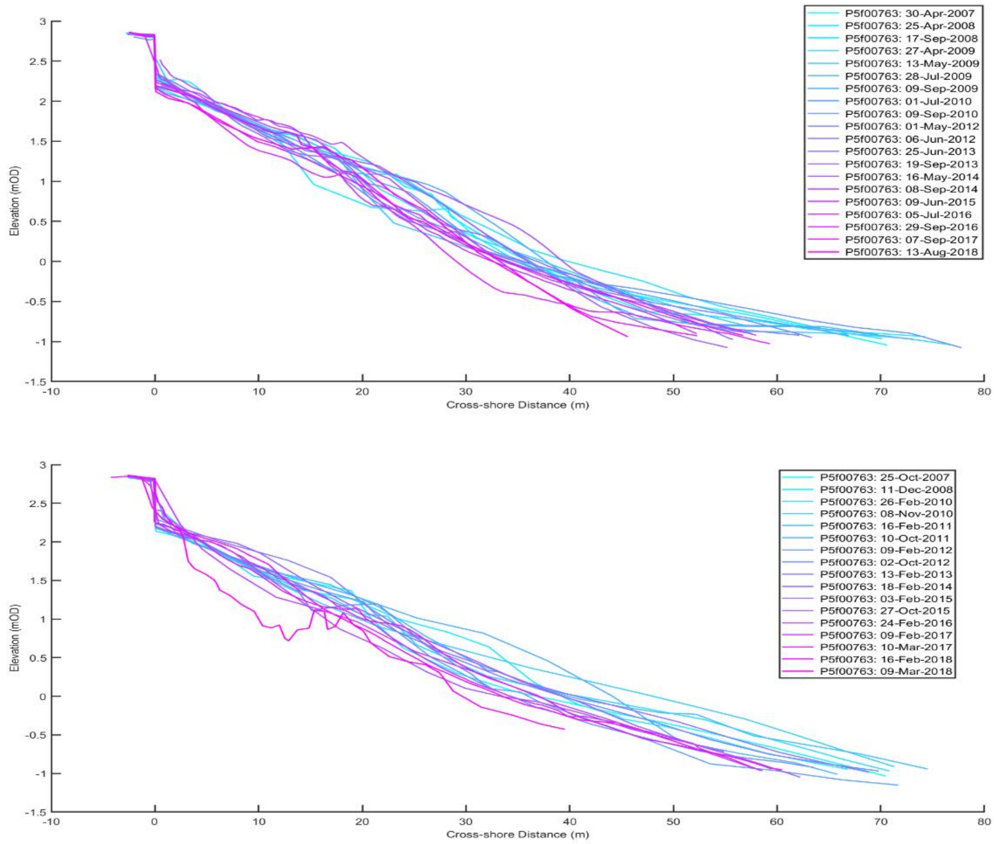

Figure 86 - Summer (top) and Winter profiles for profile P5f00763.

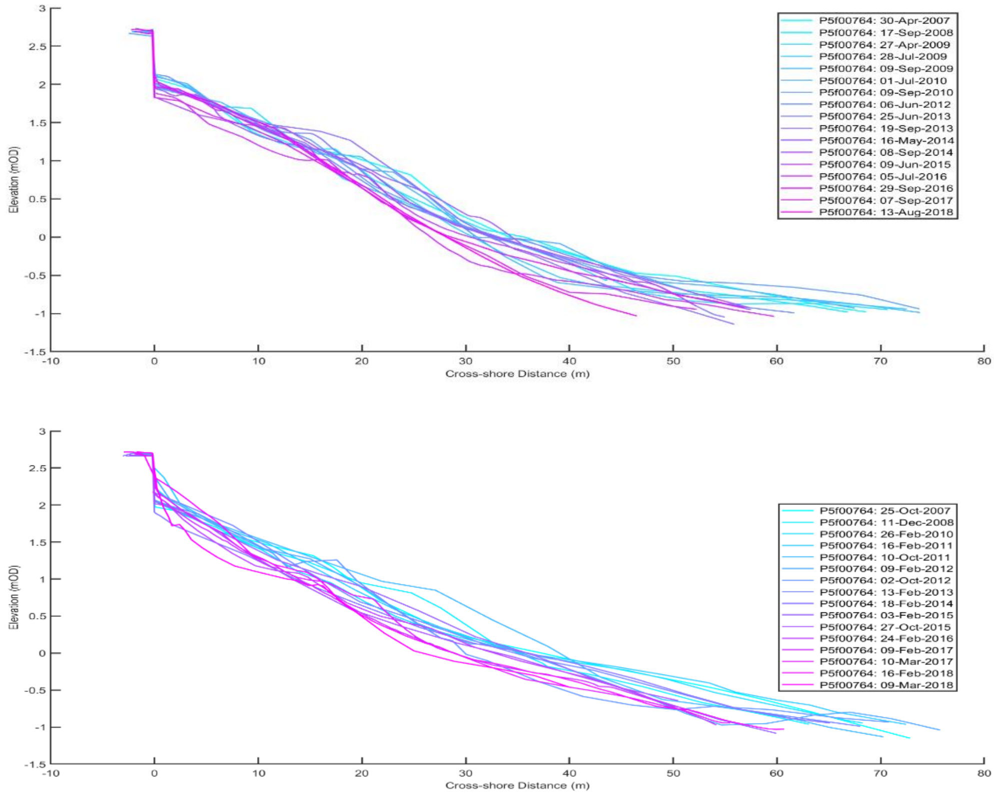

Figure 87 - Summer (top) and Winter profiles for profile P5f00764.

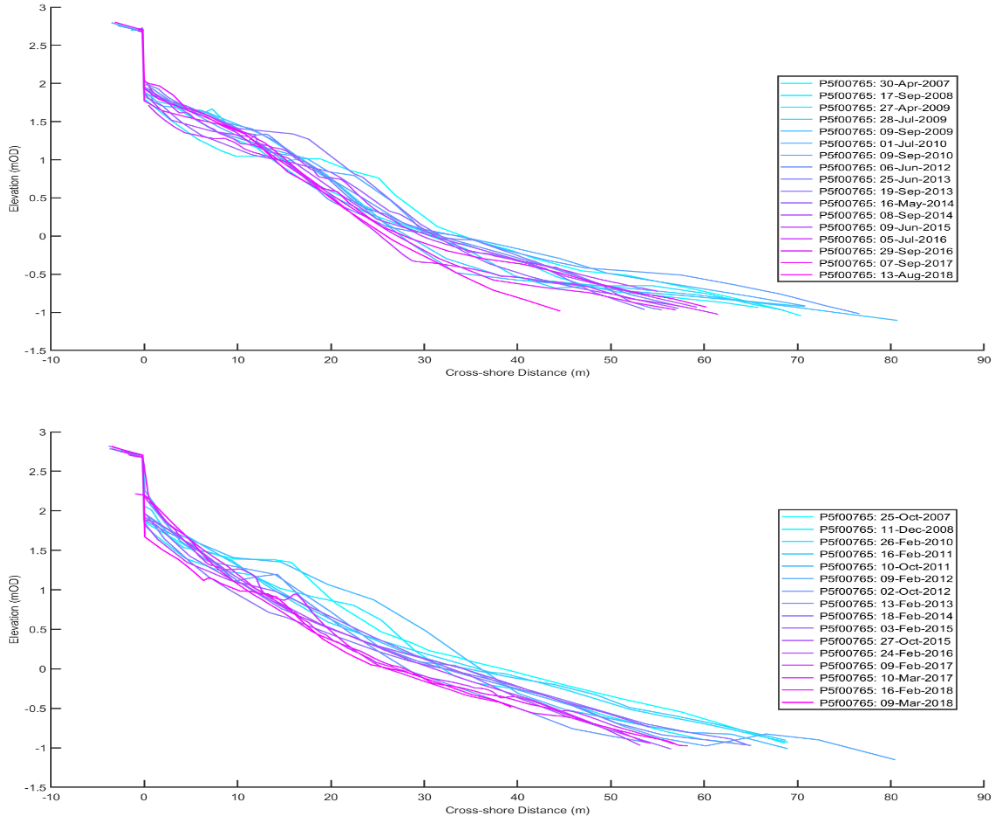

Figure 88 - Summer (top) and Winter profiles for profile P5f00765.

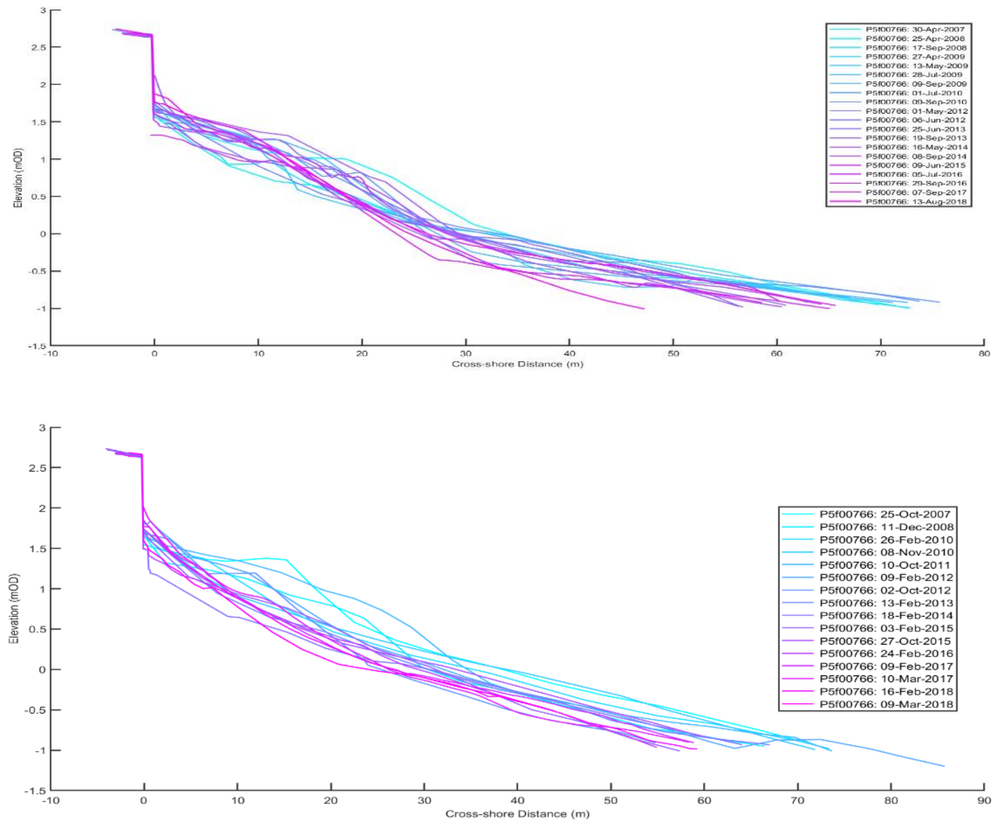

Figure 89 - Summer (top) and Winter profiles for profile P5f00766.

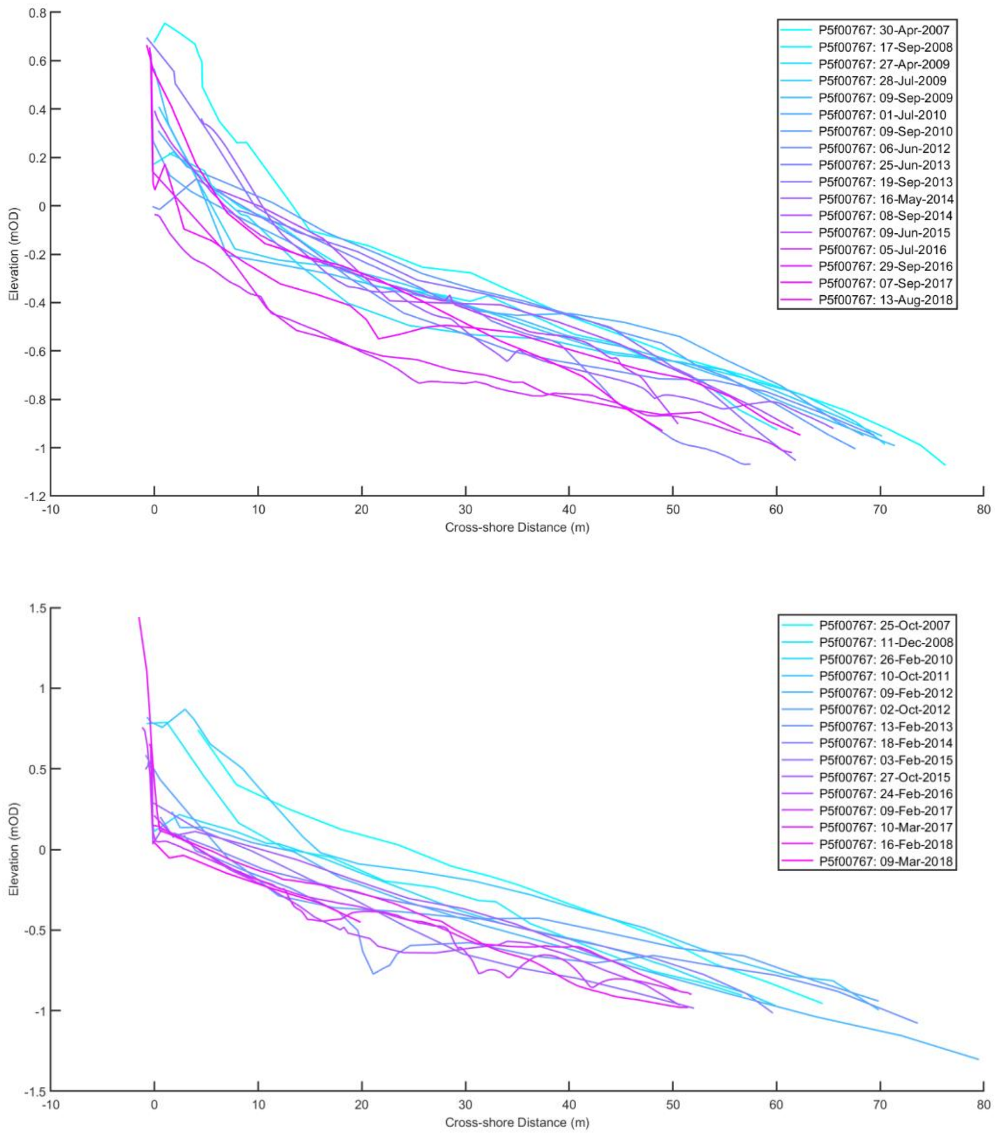

Figure 90 - Summer (top) and Winter profiles for profile P5f00767.