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Modelling Gravel Beach Profile Evolution Using Parametric and Process-Based Models

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Abstract

Understanding and predicting sediment transport processes on gravel beaches is becoming increasingly important for engineers and coastal protection schemes, as the increased frequency and severity of storm events threatens the vast infrastructure situated along many areas of the UK coastline. Gravel beaches are growing in popularity as a natural form of coastal defence due to their ability to dissipate wave energy; yet, the predictive methods of the morphodynamic response to storms are less well established than sandy beach environments. Here this study assesses the suitability of two existing gravel beach models, process-based (XBeach-G) and parametric (Shingle-B); for predicting shoreline evolution on the mixed sand-gravel barrier at Pevensey. Simulated output profiles validated for two extreme storm events (13/12/2011 and 15/2/2014), indicate that quantitively both models are able to predict the response of the entire morphological profile reasonably well. Beside this, wave run-up elevations predicted by both models are comparable to values estimated by the EurOtop 2007 formula (max variance <10%); chosen for its inclusion of a wave steepness term.

However, the prediction of morphological features on the cross-shore profile was less effective; indicating sediment transport processes were not accurately described. Significant accretion was observed in the middle of the intertidal zone in all most all measured post-storm profiles; yet, neither model was able to recreate this, with both predicting significant erosion around this elevation. Similarly, both models exhibited a distinct accretion of sediment around the upper beach in the output profiles, whereas erosion of the upper profile was most commonly measured. Model sensitivity analysis demonstrated that the effect of varying morphological input boundary conditions (grain size, hydraulic conductivity and sediment friction factor) on the prediction of the cross-shore features, was greater than that of groundwater elevation and hydrodynamic forcing (Bimodality and still water level). These findings concur with much of the literature stating that infiltration is the principal control on sediment transport on a gravel beach; with reduced infiltration promoting the seaward transport of sediment. Concluding that a significant fine fraction of sediment which is present along the MSG beach at Pevensey has inhibited the performance of both models in this study. In addition to this, considerable alongshore variability in model skill has been attributed to the human intervention at Pevensey Bay through beach nourishment, as well as the non-uniformity in wave exposure along the barrier.

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Glossary

2D	Two Dimensional
ADV	Acoustic Doppler Velocimeter
BIM	Barrier Inertia Model
BSS	Brier Skill Score
CCO	Channel Coastal Observatory
GPS	Global Positioning System
MHWS	Mean High Water Springs
MLWS	Mean Low Water Springs
MSG	Mixed Sand-Gravel
OD	Ordanance Datum
PCDL	Pevensey Coastal Defence Ltd
RMSD	Root Mean Square Difference
RTK-GPS	Real Time Kinematic Global Positioning System
SAC	Special Area of Conservation
SSSI	Site of Specific Scientific Interest
STD	Standard Deviation
SWL	Still Water Level

Chapter 1: Introduction

1.1 Background

At least 12% of the UK population are said to inhabit low elevation coastal zones (<10m) and therefore are directly exposed to the growing threat of coastal flooding (Neumann et al., 2015). The vast amounts of socio-economic infrastructure, along with areas of ecological importance are becoming increasingly vulnerable to the detrimental effects of individual and clustered storm events (Poate et al., 2015). Emphasising the demand in recent decades for coastal engineers to develop precise methods of predicting shoreline evolution; which can be used to confidently inform decision makers on the most suitable management strategy. Approximately one third of beaches in the UK are coarse grained gravel, forming a substantial proportion of this coastal management focus (Fuller and Randall, 1988). Gravel beaches are also becoming an increasingly important method of coastal defence in the UK, due to their efficiency in dissipating wave energy over narrow distances (Powell, 1990) and increased resilience to sediment transport compared to finer grained material (Austin and Masselink, 2006). Coupled with the recent insurgence from UK government strategies striving for more natural yet resilient forms of coastal defence, as the restoration of hard engineered structures is becoming increasingly unsustainable (HM Government, 2018).

Understanding the physical drivers of processes on gravel beaches is vital for effective management. Larger grain sizes create porous spaces between sediment, introducing permeability into the system, which ultimately affects the sediment transport on the beach (She et al, 2006). These factors are fundamental in controlling the behaviour of the hydrodynamics on gravel beaches and thus the occurrence of overwashing and rollback during storm conditions (Bradbury, 2000). Much of the previous research in modelling morphological evolution has focussed on sandy beach environments, exhibiting drastically different transport mechanisms and morphological response to storm events; which means there is a wide scope for improvements in the understanding of this domain (McCall et al., 2014). Many previous modelling efforts specific gravel beaches have relied on empirical formula, relating wave and sediment characteristics to predict shoreline response (Powell, 1990; Bradbury, 2000). However, these relationships are often built on site-specific validation and their applicability to the other gravel beach locations has had varied success. The current most applicable models to the gravel beach environment are Shingle-B and XBeach-G, both of which have had reasonable success in computing barrier evolution when

the boundary conditions are carefully considered (McCall, 2015; HR Wallingford, 2016). Parametric (Shingle-B) models differ in the method to process-based (XBeach-G) model, as the former are fundamental built on empirical relationships gained through data observations; whereas processes in the latter are described by a set of theoretical equations (Roelvink and Reniers, 2012). The characteristics of a gravel beach vary considerably between each location; depending on sediment properties, wave exposure and human intervention. Constructing a model to describe these dynamic processes whilst ensuring its applicability across a wide variety of gravel beach states has proved complicated in previous years; yet the demand an effective solution continues to grow.

The gravel barrier along the coast at Pevensey bay plays a major role in protecting the socio-economic and environmental value situated on the landward side of the beach. This coupled with a net loss of sediment on the beach from West to East, is exacerbated by the construction of hard engineered defences and Sovereign Harbour at Eastbourne; which facilitates the erosion of the beach face downdrift in front of Pevensey (Sutherland and Thomas, 2011). Regular nourishment of the shingle beach aims to counteract this issue by maintaining the crest elevation to between 6m and 6.5 (OD); whilst still preserving the recreational significance. With this sediment either bypassed from the Western side of the harbour on a regular basis or less frequently dredged offshore; it is argued that this is an increasingly unsustainable coastal defence technique, as much of the South Coast of England is battling with a net loss of sediment (Moses and Williams, 2008). If the models in this study prove to be suitable in predicting barrier evolution at Pevensey, then the information could be used to supplement further decision making and provide a more efficient management strategy for the region.

1.2 Aims and Objectives

The principal aim of this study is to assess the suitability of parametric and process-based models, for cross-shore barrier profile evolution in response to storm events at Pevensey Bay. In order to effectively address this aim, the following objectives have been set out:

1) Understand the current state of knowledge surrounding shoreline evolution on gravel barriers and highlight the fundamental properties which govern sediment transport and morphodynamic response to storm events.

2) Simulate previous storm events at Pevensey Bay using the parametric and process-based models and validate the predicted morphological response using accompanying beach profile

data collected by the Channel Coastal Observatory.

3) Explore the sensitivity of both models to input boundary conditions, such as morphological parameters and bimodality in the wave spectrum to assess the model's applicability to simulate shoreline evolution in response to storms at Pevensey.

Chapter 2: Literature Review

Coastal morphodynamics is a term used to describe the evolution of the shoreline as a function of hydrodynamic forcing and resultant sediment transport (Voulgaris et al., 1999). Thorough knowledge of the physical processes which define this relationship are required, to effectively determine the governing equations and boundary conditions when modelling shoreline evolution. Along sandy coastlines these processes are well understood, with transport mechanisms and morphological responses relating to two key governing factors; combined tidal-wave energy and sediment size (Short and Wright, 1983). However, the introduction of hydraulic conductivity and swash zone hydrodynamics on a gravel beach creates differing morphodynamic regimes; which have received comparatively little research focus (Pontee et al., 2004; Buscombe and Masselink, 2006). This section will go onto review the current knowledge of the processes which underpin shoreline evolution on a gravel beach; and the extent to which these principles have been applied to modelling approaches in this environment.

2.1 Gravel Beach Origins

Gravel beaches tend to occur in wave dominated, mid to upper latitude regions of glacial origin (Forbes et al., 1991). Extending approximately 1000km around the coastline and constituting approximately one third of total UK beaches (Fuller and Randall, 1988; Poate et al., 2012). Specific to the gravel beaches of East Sussex explored in this study; sediment is said to have been derived from both an offshore supply during the Pleistocene epoch, as well as the erosion of chalk cliffs due the Holocene transgression (Jennings and Smyth, 1990). The formation of these beaches is governed by the orientation of incident wave energy; subdividing gravel beaches into drift or swash aligned (Austin and Masselink, 2006; DEFRA, 2008). Grain sizes on gravel beaches can be categorised into; granular material (2mm to 4 mm), pebbles (4mm to 64mm) and cobbles (64mm to 256mm) (Carter and Orford, 1993; van Rijn and Sutherland, 2011). In the UK, the composition of gravel beach sediment varies drastically at each location; therefore, a general term 'shingle' is used to describe the range from pure gravel to a mixed composite beach (Powell, 1990).

2.2 Gravel Beach Morphodynamics

Gravel beaches typically exhibit features comparable to that of a reflective beach profile under the Wright and Short (1984) beach classification framework. In stark contrast to a

wider and flat dissipative sandy beach; an increased grain size can sustain a far steeper profile, containing a number of morphological features which include a step, cusps and a berm at the top of the beach (Austin and Masselink, 2006). The variability of sediment composition on gravel beaches coupled with differing tidal regimes generates inconsistencies in these morphological features between locations. Pure gravel beach profiles are highly reflective with typically steep slopes of tan β = 0.1 to 0.25. In contrast to this, as with most shingle beaches around the UK, the presence of a larger tidal range and addition of finer sediment acts to alter the morphology. Hydraulic sorting of sediment leads to a flatter dissipative foreshore (low-tide terrace) made up of the fine sand, with a steep gravel berm leading up to the backshore resembling a more reflective domain; known as a composite beach (Carter and Orford, 1993; Jennings and Shulmeister, 2002).

The hydrodynamics and sediment transport on gravel beaches is generally concentrated within a narrow cross shore zone (Buscombe and Masselink, 2006). With an abrupt reduction in depth, plunging or surging breakers dissipate the entirety of their peak incident wave energy at the shoreline; through a combination of swash zone run up and percolation into the unsaturated gravel profile (Stutz et al., 1998). The latter plays a key role in establishing wave asymmetry in the swash zone and a subsequent reduction in backwash volume (*cf.* Section 2.3). Which has been attributed to the onshore transport of coarse-grained material and formation of a berm in the upper beach (Turner and Masselink, 1998). Contrary to sediment transport on wide dissipative beaches being in part influenced by infragravity oscillations; steeper gravel beaches are dominated by swash motions at incident and subharmonic frequencies (Miles and Russel, 2004; McCall, 2015). On the contrary to this however, Bertin et al (2018) indicates that lower frequency infragravity waves make a significant contribution to wave run-up on gravel beaches, as incident band energy is infiltrated into the profile. The development of infragravity waves in shallow, wide nearshore zones has been associated with the offshore transport of sediment; due to the additional stresses these standing edge waves have on suspended sediment (Aagaard and Greenwood, 2008). The absence of this phenomena on gravel beaches has a profound effect, further contributing to the net onshore transport of sediment.

Sediment transport in the narrow gravel beach swash zone is almost exclusively attributed to asymmetric wave action; with insignificant effects of tidal or residual current (van Rijn and Sutherland, 2011). The mode of transport is, however, highly dependent of the composition of sand/gravel present in the sample (Buscombe and Masselink, 2006). Changes in boundary

layer flow, friction angle and protrusion of grains are directly linked to sediment heterogeneity and have been demonstrated to influence sediment transport regimes on mixed gravel beaches (Kuhnle, 1993; Mason and Coates, 2001). Wave asymmetry describes the ratio of a larger uprush to backwash velocity in the swash zone; the former reaching magnitudes of 3 m/s in more energetic wave climates. The critical threshold for motion of grain sizes in the range of 5 to 200mm, has been estimated at 1.6 m/s and is therefore often exceeded by the uprush of wave bores (Walker et al., 1991). A consequence of this being, the capability of a gravel beach to transport a large amount of sediment in the cross-shore direction during single storm events, most notably in the form of berm overtopping and rollback (Poate et al., 2012). Due to large grain sizes, high fall velocity and shallow depths in the swash zone; sediment transport is known to be bedload in the form of sliding and rolling (Carter and Orford, 1993; McCall, 2015). Intergranular collisions have also been demonstrated to have an effect the dispersion of sediment on the steep gravel beach face and have also played an important role in monitoring gravel transport (Rouse, 1997).

2.3 Hydraulic Conductivity and Groundwater Exchange

Larger grain sizes present on a gravel beach create a permeable surface allowing the vertical exchange of water (She et al., 2006). The ease at which water flows through porous spaces between grains occurs is defined as hydraulic conductivity (K); for unsaturated gravel beaches this value is in the range of 1 - 10 cm/s (Horn, 2002). As with many shingle beaches around the UK, the presence of sand (related to sorting) has a profound effect on the hydraulic conductivity; where an increase in sand content of 30-40% has been shown to reduce K to $\approx$ 0.01 cm/s (She et al, 2006). As a consequence, models which effectively describe sediment dynamics on impermeable sandy beaches perform poorly when applied to shingle environments. Therefore, as the importance of gravel beaches is becoming more apparent, research has been directed towards understanding water exchange on permeable beach surfaces; which can be used to adapt existing models. Horn and Li (2006) have demonstrated the sensitivity of gravel beach models, to an additional hydraulic conductivity term, in particular surrounding the development of the upper beach berm.

The beach ground water system is defined as a shallow, unconfined aquifer where pore water pressures below the water table are equal or greater than atmospheric (*Fig.1*). Unlike a common deep aquifer where an impermeable surface marks the upper boundary, the water table is a dynamic surface which oscillates in response to the infiltration-exfiltration of tides

and swash (Horn, 2002). The elevation of the water table has long been considered a fundamental contributor to swash zone sediment transport. Original concepts from Grant (1948) are still widely used in the subject and state that a low water table allows the infiltration of surface water into unsaturated sediment, encouraging accretion. Despite this concept, applying knowledge of groundwater dynamics to gravel beach modelling has only more recently been established (Masselink et al., 2009).
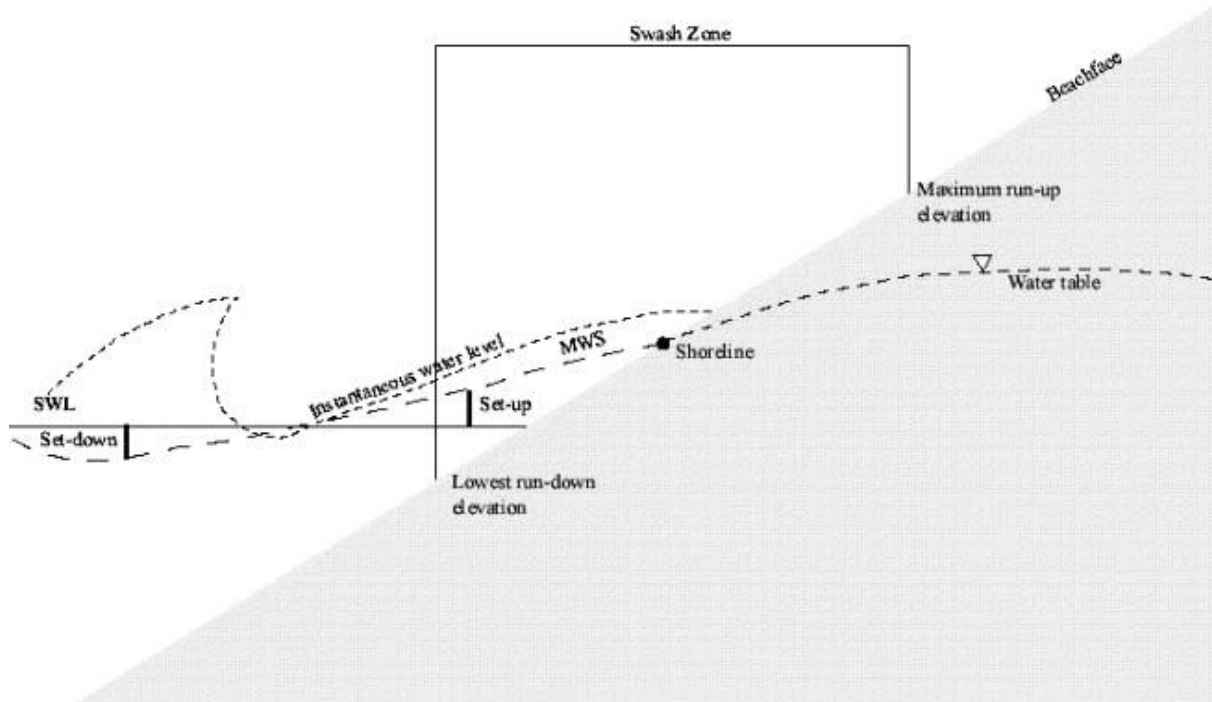
Fig.1: Sketch defining the relevant terms within the swash zone environment (Horn, 2002).

Seepage of a wave uprush into the permeable gravel surface is key in establishing wave asymmetry characteristic on a gravel beach, which as previously mentioned is attributed to onshore sediment movement and berm formation. Research in recent decades has identified two key effects of infiltration-exfiltration flow interactions on a gravel beach face. Infiltration of water into the profile reduces the thickness of the boundary layer resulting in turbulence closer to the bed, this increase in bed shear stress enhances the likeliness of sediment mobilisation. Whereas the reverse occurs during exfiltration, a thickening of the boundary layer as water seeps out of the surface; reducing near bed velocity and shear stresses. The net effect of this process is the onshore transport of sediment up the beach face (Butt et al., 2001; Masselink et al., 2009). Despite this, an upwards pressure gradient during exfiltration reduces the effective weight of the upper layer acting to increase the offshore movement of sediment.

It is however considered that enhancing bed shear stress plays a more dominant role in determining the transport regime; therefore, the primary effect of infiltration-exfiltration on gravel beaches is the onshore movement of sediment (Turner and Masselink, 1998; van Rijn and Sutherland, 2011).

2.4 Measuring Sediment Transport on Gravel Beaches

When comparing to sandy dissipative beaches, gravel beaches provide a harsh environment for data collection; with a steep beach face and energetic wave conditions breaking at the shoreline (Carter and Orford, 1993). Despite this, a range of techniques have been adopted to attempt to quantify the morphodynamics. One technique used to monitor bedload gravel transport has been the exploitation of Self-generated Noise (SGN). Collisions between grains in the swash zone can be detected by underwater hydrophones in the nearshore zone (Rouse, 1997; Priestly et al., 2008). This passive acoustic method has demonstrated the ability to gather higher resolution data for long time periods. Another method commonly adopted in the field is the use of tracer pebbles to monitor the spatial and temporal distribution of sediment (Voulgaris et al., 1999). Despite the effectiveness of this method, it is unable to capture data on the evolution of an entire beach profile. In order to do so, morphological surveys are undertaken at regular intervals to monitor the beach volume change; these can be carried out as stationary GPS surveys or moored on a quadbike for a greater spatial extent (Pontee et al., 2004). To capture the full extent of the beach on varying temporal scales, the Argus video system has also been used. Geo-referencing images captured across storm periods to identify changes in the morphological profile (de Alegria-Arzaburu et al., 2008). As well as this, the use of airborne techniques such as LiDAR and Unmanned Aerial Systems are becoming increasingly desirable as the technology becomes more easily accessible to researchers along the coastline (Elsner et al., 2018).

Despite a range of accessible field study techniques, there was still a clear demand for an extensive gravel beach dataset which could be used to reinforce knowledge and aid model validation. A large-scale experiment was carried out at the Hanover wave flume in Germany with an attempt to address this gap in knowledge. Varying wave conditions were produced over two beach scenarios; pure gravel and a mixed beach, accompanied with a selection of data collection equipment including pressure transducers, ADV's (Acoustic Doppler Velocimeter) and hydrophones. Once collected, the extensive data compilation was made publicly available with the aim of raising our understanding of gravel beaches (de San

Roman-Blanco et al., 2006). This study enabled the development of a conceptual model for gravel beaches as well as extensive validation of existing parametric models. Following this study there was a requirement to extend this analysis to varying MSG beach locations to test the significance of the model validation observed.

2.5 Storm Impacts on Gravel Beaches

The ability to dissipate energy over narrow distances as described by the mechanisms above, makes gravel beaches a desirable natural form of coastal defence (Aminti et al., 2003). Despite this, the low-lying hinterland in close proximity behind many gravel beaches are still vulnerable to inundation; as demonstrated by the 2013/2014 extreme storm events around SW England (Poate et al., 2015). Understanding the extent of damage and threshold for storm events is vital to effectively model future events and influence mitigation strategies (Burvingt et al., 2017). Elevated run-up heights enhance the onshore transport of coarse-grained gravel, resulting in a distinct storm profile; where a portion of material is lost from the active beach and deposited as a storm berm (Buscombe and Masselink, 2006). Under extreme conditions, a sequence of storm events gravel beaches may be overtopped leading to a 'rollback' of the elevated barrier crest; flattening the beach profile and flooding the land behind (Sutherland and Thomas, 2011).

The response shingle beaches to storm events has been shown to fluctuate significantly between differing locations; being attributed to sediment characteristics, hydrodynamic forcing and local geology. The fraction of sand within the sediment sample as previously discussed, has a considerable effect on the transport processes (She et al., 2006) and subsequently causes shingle beaches to act differently in response to storm events. A poorly sorted profile will likely lead to the seaward transport of fine sand generating an offshore bar (Bramato et al., 2012). Whereas under the same hydrodynamic conditions, a well sorted homogenous gravel sediment composition often leads to the onshore migration of sediment forming a storm berm around the upper beach; dependant on run-up elevations (Austin and Masselink, 2006). In addition to this, shingle beaches response to storm events has been shown to be highly dependent on the properties of the incident wave climate. Burvingt et al (2017) through a cluster analysis technique, classified beach response to storms as a factor of; wave exposure, angle of wave approach and the degree of beach embayment. Indicating that semi exposed beaches with a significant oblique incident wave attack, were likely to experience considerable variability in the alongshore erosion of sediment. Similarly, in an

analysis of beach response around the UK coastline to the 2013/2014 storms; Scott et al (2016) highlighted the concept of rotational beach response for semi exposed gravel beaches and a significantly landward retreat of the profile for many exposed coastlines.

Understanding the response of gravel profiles to storm events is key to establish the future vulnerability of a beach and has therefore gathered increased attention. It has been shown the recovery process of a gravel beach profile is longest in response to sequence of storm events as opposed to an individual period of extreme conditions (Poate et al., 2015), with some beaches taking a number of years to recover its sediment after continued wave exposure. Clustered storm events are considered to pose the largest threat to coastal regions, as gravel beaches remain vulnerable to wave run-up and continued erosion if sediment is not replenished.

2.6 Modelling Gravel Beaches

Modelling the evolution of the beach profile on gravel beaches can take two fundamental forms; an empirical/parametric or process-based model. Firstly, parametric models are built upon empirical relationships identified through data observation (Roelvink and Reniers, 2012). Input parameters which typically involve the incident wave conditions (wavelength and period) and sediment data, are related by a set of equations which estimate the output profile. Empirical equations for beach environments usually include, run up, near bed orbital velocity and critical bed shear stress (McCall, 2015).

Through extensive physical modelling at HR Wallingford, Powell (1990) developed the first major parametric modelling system for gravel beaches. 'SHINGLE' predicts the evolution of a beach profile based on three key relationships; ratio of wave height to sediment size, wave steepness and ratio of wave power to sediment size. This model has been a key tool used by the Environment Agency to model the evolution of gravel barrier crest on shingle beaches around the UK, investigating the potential for overtopping and rollback (DEFRA, 2008). Despite this, the bimodal wave spectrum characteristic of beaches in the English Channel is not within the capabilities of SHINGLE. This meant that crest erosion and flatter profile associated with larger swell waves was not well modelled (van Rijn and Sutherland, 2011). This led to the generation of Shingle-B to equate for these wave climates (HR Wallingford, 2016). Another empirical model used in much of the coastal management work around the UK is the Barrier Inertia Model (BIM); which predicts the likely of overwash on a gravel barrier (Bradbury, 2000). Extensive laboratory and field data defined an empirical

relationship between the wave steepness (S_w) and properties of the gravel barrier (freeboard and cross-sectional area). Despite its use by many coastal engineers, the suitability of the BIM to effectively predict overwash potential may be limited due to validation constrained to one site (Hurst Spit), as well as no consideration of the effect of beach slope and wave run-up elevations.

In contrast to this, a process-based model attempts to understand the underlying physical principles occurring within the beach system, to accurately recreate the processes across a range on environments. Such models tend to solve some variation of the non-linear shallow water equations to describe the hydrodynamics, the momentum equation for swash zone dynamics (Kobayashi and Wurjanto, 1992) and its subsequent effects on bed shear stress, in the form of the shield's parameter for bed load transport (Roelvink and Reniers, 2012). Attempts to model gravel beaches have been made in the past with varying success; Van Rijn and Sutherland (2011) applied the CROSMOR2008 model, which solves the wave energy equation for each individual wave in the swash zone. Additionally, 'XBeach' which was created originally for sandy coastlines (Roelvink et al., 2009) has been altered and applied to gravel beaches (Alegria-Arzaburu et al., 2011; Jamal et al., 2014). Such research has uncovered the importance of additional inclusive terms into these process-based models for gravel beaches; surrounding groundwater elevation and infiltration-exfiltration exchange (Horn and Li, 2006; McCall, 2015). To rectify this complication; McCall (2015) formulated XBeach-G, solving wave by wave flow and groundwater exchange to efficiently model gravel beaches. This model was however created for pure gravel beaches, therefore its suitability to a mixed sand-gravel composition characteristic of Pevensey is explored to a lesser extent.

Chapter 3: Methodology

3.1 Study Site

3.1.1 Overview

The gravel beach which forms the focus of this study is Pevensey Bay, East Sussex. A 9km long shingle barrier extending from the Sovereign Harbour in the West, across the frontage of Pevensey, to Cooden at the eastern end of the beach (*Fig. 2*). The natural shingle barrier is the primary mechanism for coastal defence in the area; with key socio-economic and environmental assets situated behind it. The Pevensey Levels is a low-lying section of marshland inland of the gravel beach; containing an abundant community of birds and plant life which are extremely vulnerable to inundation of saltwater water. Under Natura 2000, Pevensey Levels are designated as a Site of Special Scientific Interest (SSSI) and Special Area of Conservation (SAC); therefore, must be protected against any potential threat of flooding (Environment Agency, 2010). The heavily developed coastline across Pevensey Bay means in excess of 18600 properties (Welch, 2019), an array campsites and key railway line would all be exposed to flooding if the barrier were to be breached (East Sussex County Council, 2014).

Fig. 2: Spatial extent for morphological field data collection at Pevensey (brown line). Wave buoy off the coast of Pevensey (Yellow point - 50°46.91'N 000°25.10'E).

The composition of sediment along Pevensey bay resembles that of a classic mixed sand-gravel composite beach profile. A low tide terrace consisting of finer grain sediment (d50 < 2mm) fronted by a steeper high tide beach face made up of gravel and cobbles (d50 > 5mm) (van Rijn and Sutherland, 2011). For the purpose of this study, a single grain size d50 = 14mm is assumed constant across the entirety of the beach profile at Pevensey Bay (HR Wallingford, 2016). Despite this, the heterogeneity of sediment across the gravel barrier varies considerably; with the fraction of fine sediment in the surface layer being a function of hydrodynamic forcing and beach recharge events (Dornbusch et al., 2005).

The tidal range in the area is typically between -2.8m and 3.8m OD and crest elevation of the Pevensey barrier is +6.5m OD. This results in flooding events being highly dependent on the constructive interference of wave run-up, storm surge and high tides. The incident wave climate at Pevensey (*Fig. 3*) consists of longer period swell events arriving from the southwest direction up the English Channel, or shorter period wind waves from the east originating from a limited fetch length (Sutherland and Thomas, 2009). Despite the wave spectrum at Pevensey Bay experiencing less bimodality than other locations at the Western end of the English Channel. It has been observed that significant Atlantic swell events have the potential to propagate to the Eastern end of the channel resulting in long period storm waves arriving at Pevensey amongst short period storms (Polidoro et al., 2018).
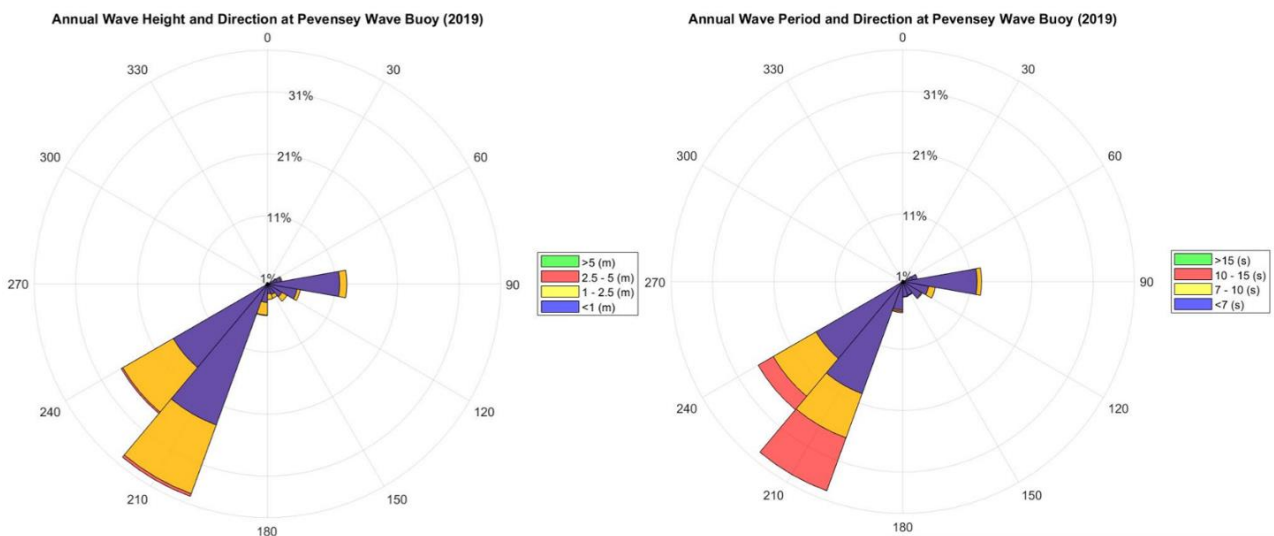
Fig. 3: Annual wave data for 2019 at Pevensey wave buoy. Occurrence of wave height (left) and wave period (right) for each direction.

3.1.2 Current Beach Management

Beginning in the mid-20th century, the coastline along Pevensey Bay has been engineered using a variety of techniques. 150 wooden groynes have been constructed along the beach in an attempt to mitigate against the longshore drift of sediment from west to east, however these have reached the end of their design life. Along with this, a series of seawalls and rubble mound structures fronting Pevensey to protect the most vulnerable sections from overtopping events (Sutherland and Thomas, 2011). Current management of the gravel beach at Pevensey Bay has been contracted by the Environment Agency to Pevensey Coastal Defence Ltd (PCDL) as part of a 25-year agreement. A more adaptive management approach has been adopted; aiming to sustainably protect the value along the coastline against flooding whilst carefully considering social, economic and environmental concerns (HM Government, 2018).

The primary issue at Pevensey is the associated risks of a 30,000 m^3 net loss sediment budget west to east; as the equilibrium of the breach has been unbalanced (Harvey, 2016). This problem is exacerbated by the presence of a rubble mound breakwater constructed at the Sovereign Harbour, trapping the natural movement of sediment and promoting downdrift erosion in the lee of the structure (Sutherland and Thomas, 2011). The primary mitigation aims for the PCDL is to maintain the gravel barrier to a 1 in 400-year flood protection standard; accomplished through a combination of beach nourishment from offshore dredging and manual bypassing of sediment around the Sovereign harbour (crest elevation +6.5m OD). An annual average of 21,000 m^3 of dredged material is deposited and 9,000 m^3 is bypassed along the coast at Pevensey (Harvey, 2016).

3.1.3 Management Profiles

The Channel Coastal Observatory (CCO) topographic survey programme for the south coast of England, aims to gather a long-term archive of shoreline elevation data by taking bi-annual beach profiles. The Pevensey Bay management unit '4cSU23' extends from Sovereign Harbour in the west to Bexhill in the east. Unit 4cSU23 extending around 9km across the frontage of Pevensey Bay, is split into profiles at 150m intervals for monitoring by the CCO. The limits of these profiles are '4c01672' in the east (Bexhill) to '4c01729' in the West (Sovereign Harbour). CCO beach surveys are carried out using either Real Time Kinematic Global Positioning System (RTK-GPS) or the higher resolution laser scanning technique. In an attempt to understand and predict the morphological evolution across the full spatial extent

at Pevensey, 4 management profiles have been chosen as the focus of this study (*Fig. 4*). These profiles were identified in order to take into account the spatial variability in sediment composition documented at Pevensey (Dornbusch et al., 2005), along with any changes in the incident wave climate along the coast, due to refraction of waves around Beachy Head to the west.

Fig. 4: Management profiles chosen as the focus of the model validation in this study. '4c01704', '4c01710', '4c01716' and '4c01722' (East to West).

3.2 Previous Research at Pevensey Bay

The MSG beach at Pevensey ensures the morphodynamic processes will vary to that of pure gravel (McCall et al., 2012; McCall 2015). The presence of fine sand in a gravel barrier has been shown to, limit the infiltration of surface water into the sediment (Horn, 2002) and also promote an offshore erosion of finer sediment during storm events (Stephane et al., 2008). Despite this, there is still the potential for the barrier crest to be overtopped by wave action. Demonstrated by the 1999 flooding of 50 homes along the frontage of Pevensey, where the

barrier crest was flattened and overwash onto the backshore occurred (Sutherland and Thomas, 2011).

As Pevensey Bay is currently one of the primary concerns for the Environment Agency's coastal management sector, it is clear there has been a variety of ongoing research into the processes along the barrier. Sutherland and Thomas, 2011 provide a detailed summary of the key management strategies which take place along the barrier and how the decision-making process will evolve into the future to take a more adaptive approach. Additionally, field study-based research has been undertaken using a variety of techniques such as pole mounted volumetric surveys (Welch, 2019), remote sensing and aerial imaging (Stephane, 2018) to make observations of barrier evolution. Efforts have also been taken to understand the effect which beach nourishment at Pevensey has had on the sediment composition and the potentially detrimental effects for beach erosion. Horn and Walton (2007) have identified the sediment grading can change from a predominantly fine and coarse gravel upper beach, to containing a significant fine sand fraction in response to nourishment of the profile.

Also, a modelling approach has been used to outline morphodynamic response to storms; yet the ability to predict potential overwash and beach threshold is limited (van Rijn and Sutherland, 2011). The process-based model 'CROSMOR2008' was found to be most effective at predicting shoreline evolution under the largest storm waves; whereas the parametric model 'SHINGLE' significantly overpredicted the build-up of sediment on top of the crest. Both models used in this study were of limited suitability to storm events at Pevensey, with CROSMOR originally developed for observing bar migration on sandy beaches (van Rijn et al., 2003) and the SHINGLE model giving no consideration to the potential for a bimodal wave spectrum at Pevensey (HR Wallingford, 2016). Therefore, there is an obvious void in the knowledge of barrier evolution at Pevensey Bay and a demand for the application of gravel beach specific models is present.

3.3 Data Observations

Hydrodynamic and morphological data acquired from the CCO is used to set up and validate both XBeach-G and Shingle-B models, to assess their suitability to predict gravel beach profile evolution. The storm events summarised in this section, which will be used to validate the models, have been selected due to the energetic wave climate and subsequent sediment loss which has occurred. The response of a gravel beach due to wave events which exceed the storm alert threshold for prolonged periods, is of a key interest for coastal engineers looking

to protect coastal regions and is thus the focus of this modelling exercise. Two significant wave events; in 2011 and 2014, have been identified from a time series of wave data, which have complimentary pre-storm and post-storm beach profiles for model validation.

3.3.1 2011 Storm Event

On the 12th - 13th of December 2011, the gravel barrier at Pevensey Bay was exposed to a considerable storm event (*Fig. 5*). Incident wave heights (H_s) in excess of 4.4m coupled with the occurrence on a high tide (3.26m OD) led to significant erosion of the shingle profile, with local reports of water levels reaching the crest elevation of +6.5m OD during high tide. *Fig.5* demonstrates the severity of this individual wave event, with the storm alert threshold for significant wave height being exceeded for a duration of around 7 hours. Despite the peak swell wave period (T_p) of 10.1s occurring after the peak of the storm; the wave run up due to tidal and storm surge levels, coupled with H_s was significant enough to cause considerable erosion of the upper gravel profile. Analysis of wave spectra data indicated that there was significant bimodality in the wave climate, with a 60-70% swell component throughout the storm event.
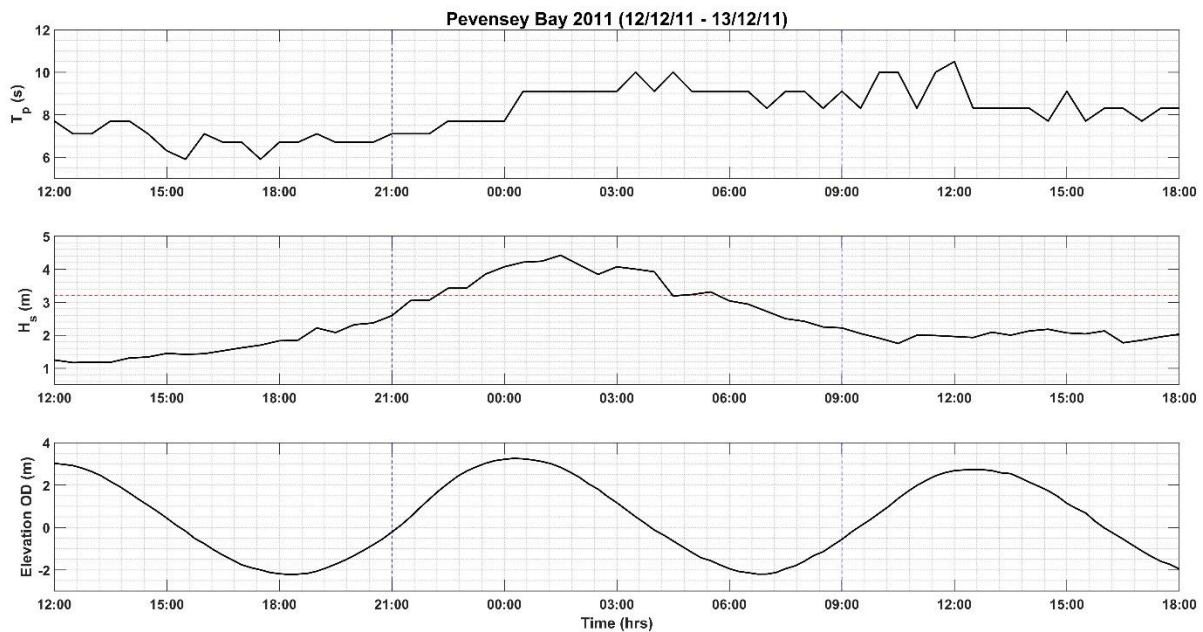
Fig. 5: Summary of the incident wave climate and tidal regime across the 2011 storm event. Dashed vertical blue lines indicate the model simulation period (21:00 12/12/11 to 09:00 13/12/11) and the dashed horizontal red line indicates the storm alert threshold at the Pevensey Bay wave buoy of 3.21m

The CCO completed a post-storm survey of Pevensey Bay on the 23/12/11 (10 days after the storm event), which is compared with the closest pre-storm survey of the 16/08/11. The morphological response of Pevensey Bay as a result of the 2011 storm event is summarised in *Fig. 6.* In all 4 profiles across the spatial extent of Pevensey (Profiles 1704 to 1722) it is clear that erosion of the upper gravel profile occurs. This is exacerbated in profiles 1710 and 1722 where this erosion leads to retreat of the crest by 2m and 2.5m respectively. In both the cases the shoreline elevation immediately seaward of the crest in reduced by approximately 0.8m, substantially reducing the volume of sediment in the upper profile. *Fig. 6* also demonstrates the significant accretion of sediment which occurs in the intertidal zone at Pevensey, which is present across 4 profiles explored. This deposition of sediment results in the formation a bar, with a step like feature in profiles 1704, 1710 and 1716 and a less pronounced berm in profile 1722.
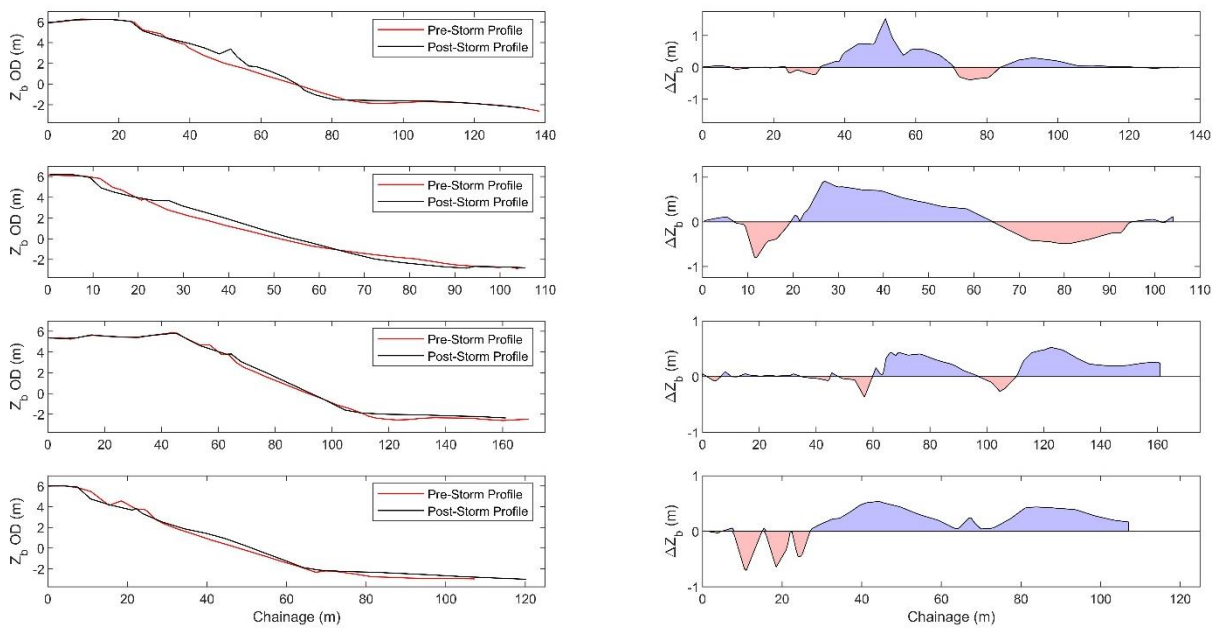
Fig. 6: Morphological response of the gravel barrier at Pevensey Bay due to the 2011 storm event. Left-hand panels indicate pre-storm and post-storm profiles, while right-hand panels demonstrate respective bed level change of each profile. The 4 rows of panels represent the spatial distribution of profiles across Pevensey Bay, from 1704 in the east (top row) down to 1722 in the west (bottom row).

3.3.2 2014 Storm Event

The second storm event used for model validation in this study occurred between the 14th - 15th of February 2014. This individual storm event was among a cluster of events occurring

across the winter of 2013/2014, which were some of the most devastating ever recorded across the south coast of England (Poate et al., 2015). The location of Pevensey Bay at the eastern end of the English Channel meant the extreme wave heights and long period swells which were recorded in the SW of England did not propagate the full extent of the channel. That being said, *Fig. 7* shows that wave heights did exceed the storm threshold and similarly to the 2011 storm event, this peak of the storm was coincided with a high tide phase. Analysis of wave data shows H_s exceeded the storm alert threshold of 3.21m for a duration of around 7.5 hours, with a max H_s of 4.22m recorded for the modelled simulation period. Similarly, to the 2011 event, a significant 60-70% swell component was observed in the dataset, indicating bimodality in the wave time series.
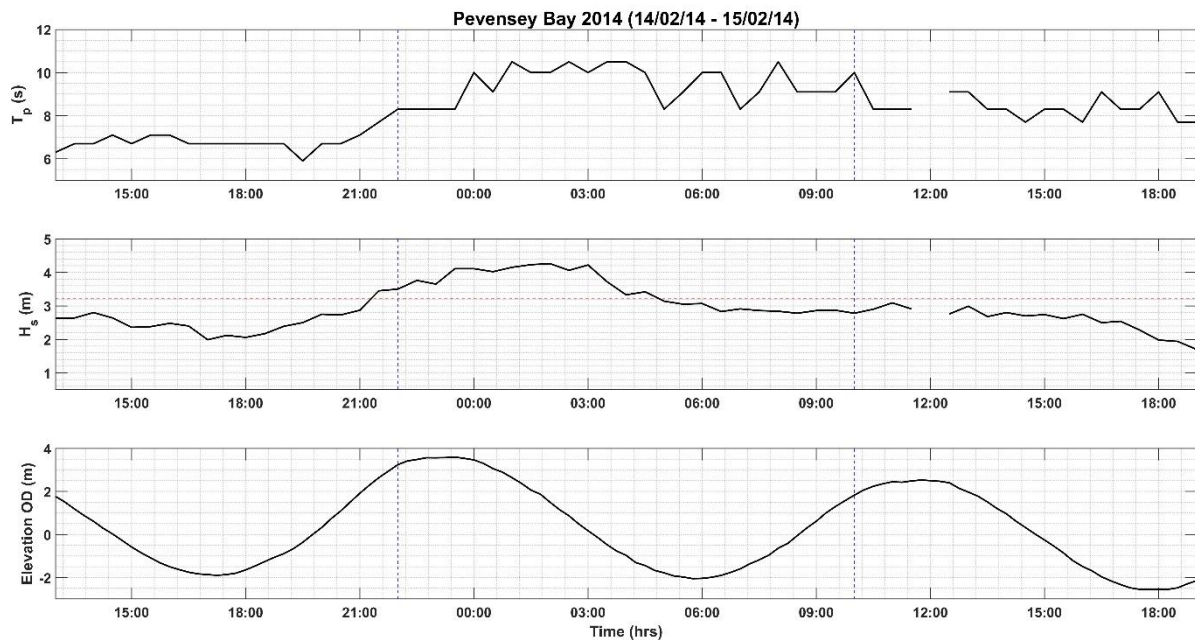
Fig. 7: Summary of the incident wave climate and tidal regime across the 2014 storm event. Dashed vertical blue lines indicate the model simulation period (22:00 14/02/14 to 10:00 15/02/14). The dashed horizontal red line indicates the storm alert threshold at the Pevensey Bay wave buoy of 3.21m. The missing wave data outside of the simulation period indicates flagged data in the CCO time series.

The morphodynamic response of the shoreline was captured by a post-storm survey carried out by the CCO on the 19/03/14, just over a month after the storm described above. This was in response to a sequence of storms which occurred in February 2014. The most suitable pre-storm survey available was collected on the 09/01/14; it is therefore worth noting that significant storm events did precede this survey date in December 2013 which could have affected the morphological profile.

The response of the shoreline to the individual storm event between the 14/02/14 and 15/02/14 can be visualised in *Fig. 8* by comparing the pre-storm and post-storm surveys. A retreat of the barrier crest can be observed in profiles 1704 and 1722, with a subsequent erosion of the upper section of the shingle profile; in both cases the maximum bed level reduction is 0.5m. This is contrasted by the berm formation observed in profile 1710, with an accretion of sediment increasing the crest edge elevation by 0.2m. A subsequent reduction in bed level of the back barrier by 0.25m indicates some overtopping occurred during the storm period. Comparable to the accretion of sediment observed as a result of the 2011 storm, the upper three rows in *Fig. 8* indicate the same bar formation in the intertidal zone occurred as a result of the 2014 event. In contrast to this, profile 1722 experiences a significant volumetric loss of sediment across the entire shingle barrier and foreshore, something which would be of considerable concern to coastal engineers and managers.
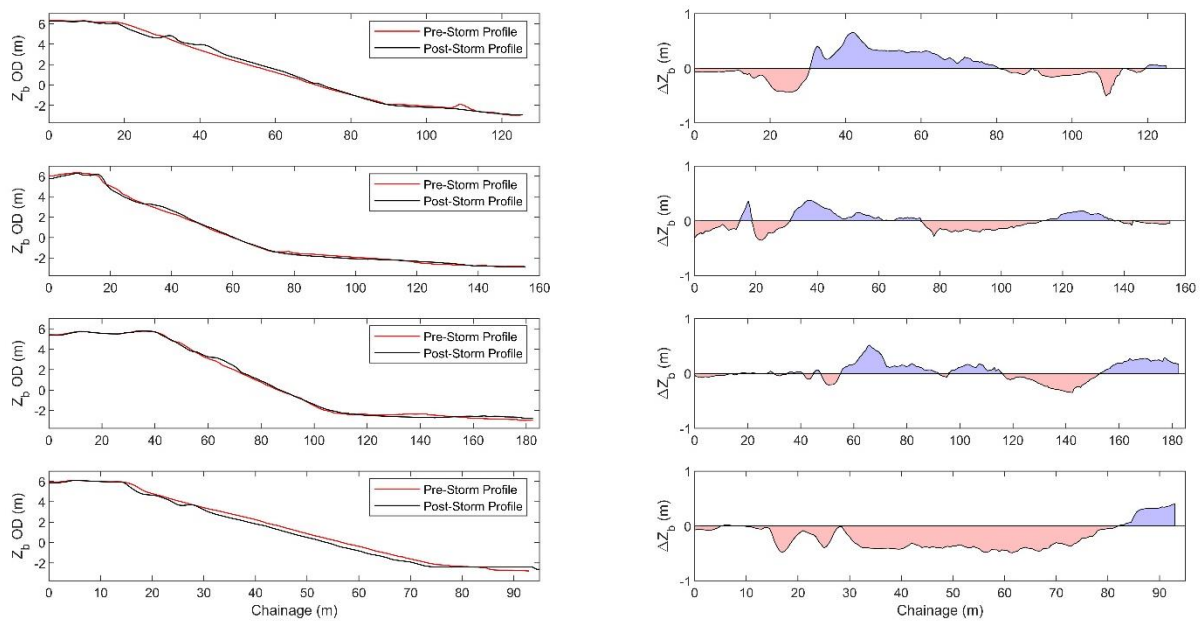
Fig. 8: Morphological response of the gravel barrier at Pevensey Bay due to the 2014 storm event. Left-hand panels indicate pre-storm and post-storm profiles and right-hand panels demonstrate respective bed level change of each profile. The 4 rows of panels represent the spatial distribution of profiles across Pevensey Bay, from 1704 in the east (top row) down to 1722 in the west (bottom row). All elevations are converted to ordnance datum (OD).

Chapter 4: Model Overview and Setup

4.1 Model Description

The evolution of the gravel beach profile at Pevensey will be investigated with the application of two hydrodynamic models. One parametric model 'Shingle-B' and one process-based model 'XBeach-G'. This section provides a brief introduction to each model and how they will be validated in this study.

4.1.1 XBeach-G

XBeach-G is a depth-averaged, non-hydrostatic extension of the XBeach model which was originally developed for sandy beach environments. The version of the model used in this study is one-dimensional (cross-shore transect) where the computational x-axis is positive in the seaward direction (McCall, 2015). XBeach-G solves wave-by-wave flow and surface elevations to better encompass the swash zone dynamics of steep reflective beaches. To correctly account for the infiltration-exfiltration processes discussed in Section 2.3; XBeach-G computes groundwater dynamics with an additional groundwater model using, Darcy's law for flow through a porous medium (McCall et al., 2014). The key governing equations of the XBeach-G model are outlined below; however, a full description of the hydrodynamics, groundwater and sediment transport equations (and terms) is listed in McCall (2015). An introduction to the graphical interface on the XBeach-G software is also available in McCall et al (2014) which will aid the data validation and analysis for this study.

Depth-averaged flow is computed using the non-linear shallow water equations, a non-hydrostatic pressure term and an additional groundwater exchange term (*Eq. 1* and *Eq. 2*):

$$\frac{\delta\zeta}{\delta t} + \frac{\delta hu}{\delta x} + S = 0 \qquad\qquad (Eq.1)$$

$$\frac{\delta u}{\delta t} + u\frac{\delta u}{\delta x} - \frac{\delta}{\delta x}\left(v_h \frac{\delta u}{\delta x}\right) = -\frac{1}{\rho}\frac{\delta(\rho\bar{q}+\rho g\zeta)}{\delta x} - \frac{\tau_b}{\rho h} \qquad\qquad (Eq.2)$$

In *Eq.1*, ζ is the free surface elevation, x and t are spatial and temporal scales, h is water depth, u is depth averaged cross-shore velocity and S is groundwater exchange. For *Eq.2*, v_h is the horizontal viscosity , ρ is the density of water, $\bar{q}$ is the dynamic pressure, g is acceleration due to gravity and τ_b is the bed shear stress.

Infiltration-exfiltration exchange is computed through an additional groundwater model (McCall et al., 2012) (*Eq.3* and *Eq.4*):

$$\frac{\delta h_{gw} u_{gw}}{\delta x} + w_{gw,s} = 0 \qquad (Eq.3)$$

$$u_{gw} = -K \frac{\delta \overline{H}}{\delta x} \qquad (Eq.4)$$

Where u_{gw} is the horizontal groundwater velocity, h_{gw} is the groundwater surface elevation, $w_{gw,s}$ is the vertical groundwater flux at surface, K is the hydraulic conductivity and $\overline{H}$ is the hydraulic head.

The mode of sediment transport on gravel beaches and thus for XBeach-G is assumed to be bed load; therefore, an equation for volumetric bed load transport (q_b) derived by van Rijn (2007) is adopted (*Eq.5* and *Eq.6*):

$$q_b = \gamma D_{50} D_*^{-0.3} \sqrt{\frac{\tau_b}{\rho}} \frac{\theta' - \theta_{cr}}{\theta_{cr}} \frac{\tau_b}{|\tau_b|} \qquad (Eq.5)$$

$$\theta = \frac{\tau_b}{\rho g \Delta_i D_{50}} \qquad (Eq.6)$$

Where γ is a calibration coefficient (0.4) (van Rijn 2007), D_* is the non-dimensional grain diameter, θ is the shields parameter, θ_{cr} is the critical shields parameter for sediment motion and θ' is a modified shields parameter accounting for steep bed slope (*Eq.7*).

$$\theta' = \theta \cos\beta (1 \pm \frac{\tan\beta}{\tan\phi}) \qquad (Eq.7)$$

Where β is the angle of the bed and ϕ is the angle of repose ($\approx 40°$ for gravel) (McCall, 2015).

4.1.2 Shingle-B

The fundamental driving factor for the development of Shingle-B was underestimation of the crest erosion due to the effect of bimodality in the wave spectrum (HR Wallingford, 2018). Shingle-B is a beach profile prediction model developed at HR Wallingford, available as an online tool open to the public for use. Input data required to predict beach curves, are wave climate, water level, existing profile and sediment size. A series of physical laboratory tests at the HR Wallingford wave flume facility are used to derive the equations which predict the output profile. The output curve is broken down into four sections as shown in *Fig. 9*. By using the observed curves from laboratory tests; parameters can be identified with corresponding wave characteristics and a regression model can be applied to describe the curve as a function of multiple wave variables (*Eq.8*):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \dots \qquad (Eq.8)$$

Where x_i and β_i are output covariates (wave height, wave period, swell percentage *etc.,*) and regression coefficients which are estimated to determine profile shape. A full review of the governing empirical equations of the model can be observed in Powell (1990) and a technical report produced by HR Wallingford (2018), which outline regression formulae for profile characteristics.
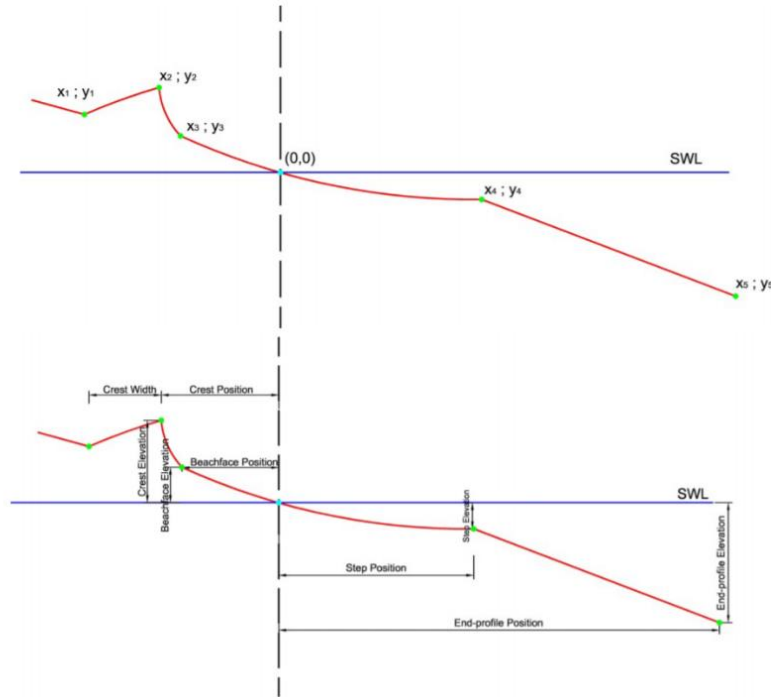
Fig. 9: Framework for output profile of Shingle-B model (HR Wallingford, 2018).

4.2 Model Setup

Input parameters and boundary conditions for both models used in this study are acquired from a selection of secondary data archives and sourced data from relevant literature. This section will outline how both XBeach-G and Shingle-B were set up, for predicting gravel beach profile evolution at Pevensey.

4.2.1 XBeach-G

The hydrodynamics of XBeach-G are derived from a combination of input wave and tidal conditions forcing the offshore boundary; which is defined by the Channel Coastal Observatory (CCO) Pevensey Bay wave buoy situated at around 15.5m depth (OD). Firstly, a time series of tidal elevations at 15-minute intervals, sourced from the British Oceanographic Data Centre (BODC) were input into the 'Tide' section of the XBeach-G GUI. This data was

gathered from a tide gauge at Newhaven, around 20 miles west of Pevensey Bay. Thus, deemed a reasonable assumption of combined tide and surge water level at the boundary. Secondly, wave conditions at the offshore boundary were derived from an input wave spectrum in the 'Waves' section of the GUI. Values of significant wave height (H_s) and peak period (T_p) were gained from the wave spectra time series collected at the CCO Pevensey Bay wave buoy. From the input spectrum the XBeach-G model creates a random time series of incident wave conditions to force the offshore boundary. A bimodal wave spectrum was chosen for the validation of the model during the storm events, yet the sensitivity of the output profile to this spectral characteristic was explored in the analysis. The water depth at which the wave buoy is situated is sufficiently deep to ensure wave breaking does not occur at the boundary, but also not too deep that it exceeds the limits of the non-hydrostatic pressure assumption within the model.

The morphodynamics of XBeach-G are computed through an initial profile input, along with various parameters which govern the swash zone dynamics within the model. Bi-annual beach profile data collected by the CCO at a resolution of 0.5m chainage is used as an input pre-storm profile of the gravel barrier. To ensure wave shoaling between the offshore boundary and the shoreline is accurately recreated by XBeach-G, it is necessary to extend the input profile from MLWS out to the wave buoy. Bathymetry data collected at a 0.25m resolution, supplied by the Environment Agency; was used to obtain transects of the bottom profile extending around 5km offshore depending on the transect chosen. A combined shoreline profile and bathymetry transect is then input into the 'Profile' section of the XBeach-G GUI. In addition to this, XBeach-G requires a selection of input parameters to be defined, which remain constant throughout both the spatial and temporal domain of the model. These parameters which govern the physical processes on the gravel barrier have been obtained through a selection of relevant literature describing Pevensey Bay and other shingle beaches along the south coast of the UK. For the purpose of sensitivity analysis in this study, values of grain size (d50), hydraulic conductivity (K) and sediment friction factor (f) are all adjusted to explore the effect they have on the predicted gravel profile. Grain size estimates used to input into XBeach-G were gathered from HR Wallingford (2018) and Dornbusch (2005). Estimations of hydraulic conductivity for given grain sizes have been obtained through McCall (2015) and She et al (2006) for varying fine sand fractions. These parameters along with all over variables are summarised in *Tab. 1*.

Generation of the computational grid focussed around the balance of computational expense and capturing subscale processes in the swash zone of the gravel barrier. A gradually increasing cross-shore resolution of 0.15m at the barrier crest, up to $\frac{\lambda}{15}$ or 7-8m at the offshore boundary effectively (where λ = wavelength), captures all wave shoaling, breaking and run up processes (McCall, 2015). Both 2011 and 2014 storms were simulated for a duration of 12 hours in XBeach-G, to capture the peak of the storm along with a full tidal cycle.

4.2.2 Shingle-B

In contrast to XBeach-G, the hydrodynamics of Shingle-B is derived from an input wave spectrum and a still water level (SWL), rather than a time series of tidal elevation. For the validation of Shingle-B this SWL is set to 1.5m and for the purpose of exploring the sensitivity of this value to the output profile, this value is adjusted to 0m and 3m (OD). The input wave spectrum again acquired from the CCO Pevensey wave buoy, forms the basis of the empirical relationships which are used to estimate the elevation of the output profile. An additional swell percentage term describes the bimodality of the wave spectrum and again is altered to explore the sensitivity of this parameter. The use of a breaking wave height term in Shingle-B requires the input profile to be the CCO profile alone with no additional bathymetry data required.

Input parameters relating to the morphodynamic response of the shoreline in Shingle-B are almost entirely predetermined and cannot be changed for the user. Extensive validation of the model was carried out with a grain size (d50) of 12.5mm (HR Wallingford, 2016).

4.3 Model Output Analysis

To assess the skill of model outputs and ultimately their suitability to predict morphological change on a gravel barrier; the measured post-storm profile obtained through data collection, is compared to the output shoreline profile from either XBeach-G or Shingle-B. Aside from a visual comparison between the measured and output profiles, a number of statistical techniques discussed in this section can be applied. Quantitively assessing the error associated with the predicted profile and also estimating the performance of the model in recreating nearshore processes and morphological change during a storm event. The distribution of sediment at Pevensey is generally described as a coarser gravel crest with a predominantly sandy foreshore slope, therefore providing potential limitations to the processes described by equations and boundary conditions of either models. Beside this, for

both the 2011 and 2014 events, there is a significant time delay between the peak of the storm and the post-storm survey date (10 days and 5 weeks); leading to the possibility for further morphological change in the intertidal zone. In an attempt to assess the model skill while considering both of these factors, the analysis in the model validation section will follow two paths; comparing the full measured and output profile as well as statistically comparing the measured crest and modelled crest formation. The limits of this crest formation analysis will be between the back barrier and MHWS (3.88m OD).

The statistical techniques used to assess the skill of the model to recreate the measured output are i) the normalised Standard Deviation (σ_{norm}) (*Eq. 10*), ii) the normalised centered Root Mean Square Difference (cRMSD$_{norm}$) (*Eq. 12*) and iii) the Pearson Correlation Coefficient (ρ) (*Eq. 13*). All three parameters described above are subsequently plotted on a Taylor diagram to provide a concise statistical summary of the proximity of the modelled output to measured bed level change (Taylor, 2001). These statistical parameters are calculated using bed elevations interpolated to a regularly spaced chainage grid at 0.5m resolution and are defined below:

$$\sigma = \sqrt{\frac{\Sigma(Z - \overline{Z})^2}{N}} \qquad (Eq.\ 9)$$

where Z = bed elevation (m), $\overline{Z}$ = mean bed elevation (m) and N = number of data points, which compute modelled (σ_{mod}) and measured (σ_{meas}) standard deviation.

$$\sigma_{norm} = \frac{\sigma}{\sigma_{meas}} \qquad (Eq.\ 10)$$

$$cRMSD = \{\frac{1}{N}\Sigma_{n=1}^{N}[(Z_{mod} - \overline{Z}_{mod}) - (Z_{meas} - \overline{Z}_{meas})]^2\}^{\frac{1}{2}} \qquad (Eq.\ 11)$$

$$cRMSD_{norm} = \frac{cRMSD}{\sigma_{meas}} \qquad (Eq.\ 12)$$

$$\rho = \frac{\frac{1}{N}\Sigma_{n=1}^{N}(Z_{mod} - \overline{Z}_{mod})\,(Z_{meas} - \overline{Z}_{meas})}{\sigma_{mod}\sigma_{meas}} \qquad (Eq.\ 13)$$

Additionally, it is also necessary to quantify the performance of the model in predicting shoreline evolution in response to a storm event. Here the Brier Skill Score (BSS) (*Eq. 14*) is used to assess the accuracy of the output profile with reference to the measured profile. Complete agreement between the two profiles leads to a BSS score of 1, if the output assumes no change closer than the initial profile leads to a score of 0 and an estimate worse than the initial profile leads to a negative BSS score. The magnitude of the negative skill

score gives no real indication of the magnitude of difference between the output and measured profiles (Sutherland et al., 2004). For the purpose of estimating the BSS, only differences between the output or measured and initial profile greater than that of the measurement error or 3 times the d50 are used (McCall, 2015). Measurement error for the laser scanner techniques used in the surveys carried out by the CCO is 0.015m.

$$BSS = 1 - \frac{\sum_{n=1}^{N}(Z_{mod} - Z_{initial})^2}{\sum_{n=1}^{N}(Z_{meas} - Z_{initial})^2} \qquad (Eq.\ 14)$$

Chapter 5: Model Results and Validation

This following section will outline the results of model simulations and compare these to the observed storm data from 2011 and 2014, discussed in Section 3.3. The validation of both XBeach-G and Shingle-B in this study was confined by the availability of data for the storm periods at Pevensey Bay. Therefore, the method of model validation in this section will look at morphological response during both storms, volumetric changes in surface sediment and crest evolution due to wave run up. The model input parameters and boundary forcing characteristics discussed throughout Chapter's 5 and 6 are summarised in *Tab. 1* below.

Tab. 1: Overview of model input hydrodynamic and morphological parameters for Pevensey Bay.

Hydrodynamic Forcing			Input Parameters		
2011	H_s (m)	4.42	**XBeach-G**	d50 (m)	0.014 (0.007 - 0.021)
	$T_{p\ swell}$ (s)	10.10		K (m/s)	0.13 (0.06 - 0.2)
	$T_{p\ wind}$ (s)	7.10		Gw Lvl (m)	0
2014	H_s (m)	4.22		Duration (s)	43200
	$T_{p\ swell}$ (s)	10.50	**Shingle-B**	Swell (%)	70
	$T_{p\ wind}$ (s)	7.10		tan β	0.167
				Mass Lost	0
				SWL (m)	1.5 (0 - 3)

5.1 2011 Storm Event Validation

The morphological response of the shingle barrier across Pevensey Bay due to the 2011 storm event is demonstrated in *Fig. 10*, through a comparison of post-storm data observations and outputs from XBeach-G and Shingle-B model simulations. Firstly, it can be observed the back barrier and crest elevation are simulated well by XBeach-G indicating the modelled run up elevations are comparable to that of the storm event. Despite this, in all profiles across Pevensey, XBeach-G has simulated the formation of a berm between the barrier crest and the MHWS elevation; whereas the berm formed in all observed post-storm profiles was below the MHWS mark. Respective accretion values immediately below the barrier crest of 4.8 m^3m^{-1}, 2.4 m^3m^{-1}, 5.2 m^3m^{-1} and 5.8 m^3m^{-1} for profiles 1704, 1710, 1716 and 1722. This disparity between the observed and modelled location of berm formation has led to XBeach-G simulating an erosion of the foreshore slope across all 4 profiles due to the energetic conditions; contrasting the accretion observed in the post-storm data *(cf.* Section

3.3.1). This is most notable in profile 1716, where a 7m retreat of the shoreline is simulated 0.5m above the still water level. Despite the lowest RMSD value computed for this output profile (0.398) (*Tab. 2*), the substantial over prediction of erosion around 0.5m elevation is a fundamental factor for the reduction of the BSS predicted for this profile (-0.14). Although analysis of the beach step has limited significance towards the objectives of this study, it is worth noting that XBeach-G in all cases across Pevensey Bay over predicts the accretion of sediment at this location. Which ultimately has an adverse effect to some degree on the statistical performance of the model when analysing the entire output profiles. Despite the obvious differences in berm formation down the foreshore slope between XBeach-G simulations and observed data; profiles 1704 and 1710 at the eastern end of Pevensey performed reasonably well (0.535) and well (0.624) in recreating morphological response to storm events.
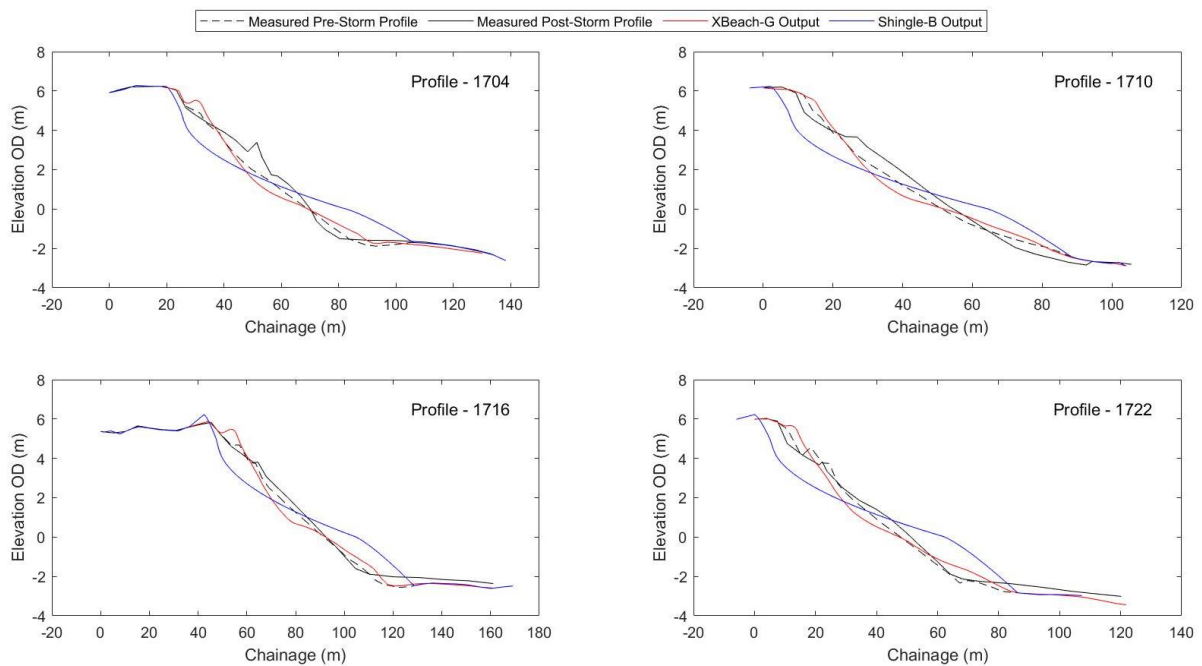
Fig. 10: Beach profiles at 4 locations across the frontage of Pevensey Bay, 1704 (top left), 1710 (top right), 1716 (bottom left) and 1722 (bottom right). Measured pre-storm profile, measured post-storm profile, XBeach-G output profile and Shingle-B output profile for each location. In each scenario the back barrier marks the 0m chainage point. MHWS mark is 3.88m (OD) and the MLWS mark is -2.82m (OD).

Observing the profiles from the Shingle-B model simulation (*Fig. 10*), it can be seen that the magnitude of erosion and accretion across the entire profile is greater than that of the XBeach-G output. Firstly, extensive erosion of the upper beach face and barrier crest is

predicted in all profiles across Pevensey; with a landward retreat of 9.5 and 9m in profiles 1710 and 1722. Comparing this to the loss of sediment observed around the barrier in the post-storm profiles, Shingle-B is able to reproduce these processes relatively well; despite overpredicting the magnitude of this erosion. The simulated increase in crest elevation in profile 1716 of 0.62m along with the barrier rollback observed in the other output profiles, indicates water level and run up elevations have been also overpredicted by the Shingle-B model. Similar to XBeach-G, Shingle-B simulates extensive deposition of sediment below the still water level which disagrees with the observed post-storm data. Using profile 1704 as an example, the Shingle-B model simulates an accretion of 40.1 $m^3 m^{-1}$ below the still water elevation specified for the simulation (0m OD); whereas the observed profile exhibits a net erosion of 2.2 $m^3 m^{-1}$ for the same elevation. These discrepancies are manifested in the statistical comparison of the two profiles at all locations across the beach at Pevensey.

Tab. 2: Summary of computed statistical parameters for all profile simulations ran for the 2011 storm event. Standard Deviation (STD), Root Mean Square Difference (RMSD), Pearson Correlation Coefficient (ρ) and Brier Skill Score (BSS). Score ratings for Brier Skill Score include: $0.6 < BSS < 0.8$ (good), $0.3 < BSS < 0.6$ (reasonable), $0 < BSS < 0.3$ (poor) and $BSS < 0$ (bad).

Profile	STD	RMSD	ρ	BSS
XBeach-G: 1704	3.17	0.54	0.97	0.54
XBeach-G: 1710	2.91	0.63	0.98	0.62
XBeach-G: 1716	3.35	0.40	0.99	-0.14
XBeach-G: 1722	3.00	0.47	0.99	-0.37
Shingle-B: 1704	2.81	0.84	0.97	-3.02
Shingle-B: 1710	2.42	0.91	0.96	-2.80
Shingle-B: 1716	3.08	0.71	0.98	-7.80
Shingle-B: 1722	4.41	0.92	0.96	-2.80

Fig. 11 gives a qualitative indication that XBeach-G performed more effectively in predicting morphological evolution across Pevensey Bay than Shingle-B; denoted by the proximity of both model simulation points to the observed data point on the Taylor plot. Normalised standard deviation values in *Fig. 11* show that the variance in the Shingle-B output profile differs significantly to that of the XBeach-G model output and the observed profile. Which

Fig. 11: Summarising the skill of XBeach-G and Shingle-B to predict morphological evolution across the frontage of Pevensey Bay using a Taylor Diagram. For the purpose of the Taylor Diagram, Standard Deviation (STD) and Root Mean Square Difference (RMSD) have been normalised.

could be attributed to the extensive erosion and accretion magnitudes observed in the Shingle-B output profiles. Apart from profile 1722, the correlation between both models and the observed values does not seem to differ significantly; confirming the variance in the Shingle-B dataset is responsible for the reduced model skill in predicting morphological change.

5.2 2014 Storm Event Validation

The measured and modelled evolution of the shingle barrier at Pevensey Bay in response to the 2014 storm event, can be visualised in *Fig. 12*. As previously discussed (*cf*. Section 3.3.2), the response of the shoreline to the 2014 individual storm event was

uncharacteristically moderate, considering the highly energetic wave climate. Any clear discrepancies in this results section will be discussed later in the study to aid the model validation process.

In contrast to the 2011 storm event, XBeach-G has simulated an increase in crest elevation in all but one of the profiles across Pevensey (1704). The 0.08m increase in crest elevation observed in the post-storm profile '1710' is modelled relatively well by XBeach-G, with a slight overestimate of a 0.15m predicted by the model simulation. Subsequent accretion of sediment on top of the barrier in the measured and modelled profiles is 1.9 m^3m^{-1} and 3.4 m^3m^{-1} respectively, showing the effectiveness of XBeach-G in this instance. Despite this, observed data for profiles 1716 and 1722 show no crest build up occurred, yet the XBeach-G outputs simulate a substantial increase in crest elevation of 0.75m and 0.25m respectively.
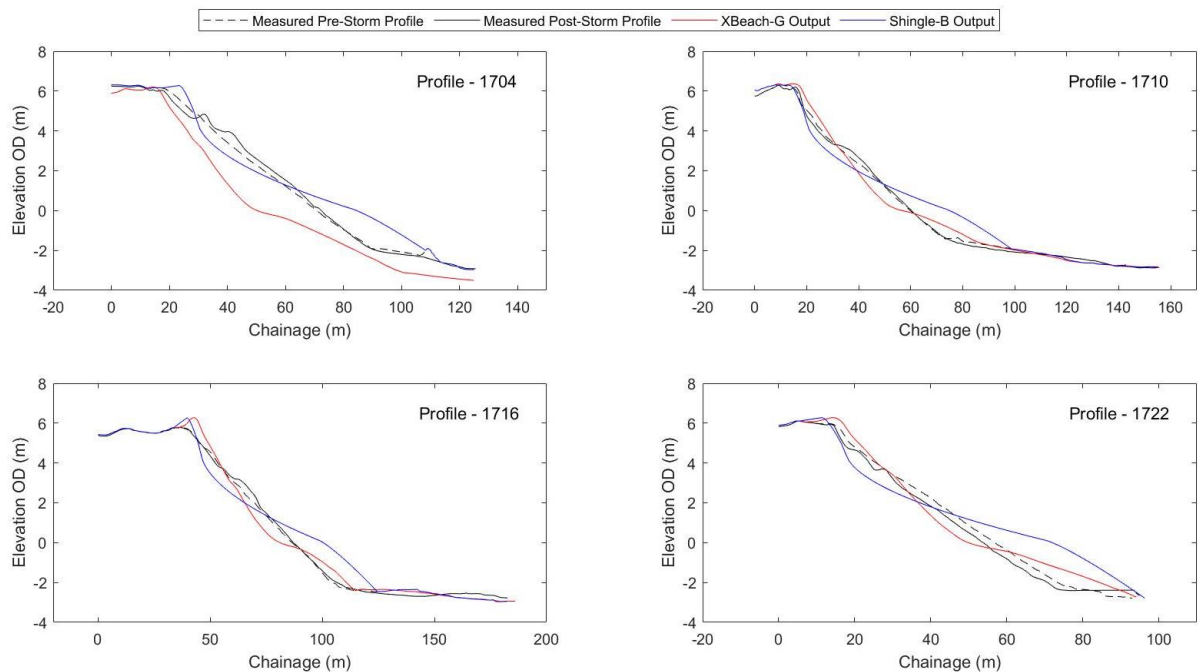
Fig. 12: Beach profiles at 4 locations across the frontage of Pevensey Bay in response to the 2014 storm event, 1704 (top left), 1710 (top right), 1716 (bottom left) and 1722 (bottom right). Measured pre-storm profile, measured post-storm profile, XBeach-G output profile and Shingle-B output profile for each location. In each scenario the back barrier marks the 0m chainage point. MHWS mark is 3.88m (OD) and the MLWS mark is - 2.82m (OD).

In all four profiles, XBeach-G again predicts an erosion of sediment down the foreshore slope between the MHWS mark (3.88m) and the still water level at 0m; not recreating the intertidal berm which was observed in all measured post-storm profiles. The overpredicted accretion volumes above MHWS along with overpredicted erosion below MHWS has led to a BSS for

model performance of negative for all of the sites across Pevensey (*Tab. 3*). Besides profile 1704 where extensive erosion occurred across the entire shingle barrier, RMSD values for profiles 1710, 1716 and 1720 (0.40, 0.42 and 0.47) show the model still predicted the morphological evolution with a reasonable magnitude of error. All XBeach-G output profiles in *Fig.12* indicate an overprediction of shingle accretion volumes at the beach step, similar to the 2011 storm event.

The Shingle-B model output profiles plotted in *Fig. 12* exhibits a comparable morphodynamic response to the 2011 storm event simulation. Extensive accretion of shingle occurs below the still water level which has been eroded from the upper beach face. The minimum predicted volume of accretion below 0m (OD) occurred at profile 1710, with a value of 38 $m^3 m^{-1}$; which subsequently obtained the smallest RMSD (0.59). Prediction of the barrier crest was simulated reasonably well, depending on the location across Pevensey Bay. Output profiles 1710 and 1722 down to MHWS were in particular agreement with the measured post-storm profiles from both a qualitative sense and the minimal crest formation they exhibited (0.75 $m^3 m^{-1}$ and 1.9 $m^3 m^{-1}$). In contrast to this, profile 1704 simulated a seaward migration of the crest of 7m, predicting considerable accretion of shingle in front of the barrier crest.

Tab. 3: Summary of computed statistical parameters for all profile simulations ran for the 2014 storm event. Standard Deviation (STD), Root Mean Square Difference (RMSD), Pearson Correlation Coefficient (ρ) and Brier Skill Score (BSS).

Profile	STD	RMSD	ρ	BSS
XBeach-G: 1704	3.30	0.81	0.92	-21.14
XBeach-G: 1710	3.10	0.40	0.99	-3.30
XBeach-G: 1716	3.47	0.42	0.99	-2.81
XBeach-G: 1722	3.01	0.47	0.99	-1.83
Shingle-B: 1704	3.01	0.76	0.98	-6.63
Shingle-B: 1710	2.91	0.59	0.99	-13.10
Shingle-B: 1716	3.29	0.61	0.98	-11.93
Shingle-B: 1722	2.46	0.93	0.98	-8.96

Fig. 13 provides a concise summary of the model skill parameters for both XBeach-G and Shingle-B, simulating the 2014 storm event at Pevensey. The extensive erosion of the beach face predicted by XBeach-G at profile 1704 is demonstrated by the Shingle-B data point lying closer to the observed point, despite the differing variance of the Shingle-B model output. At all other profiles across Pevensey it is clear that XBeach-G is more effective at predicting morphological change than Shingle-B.
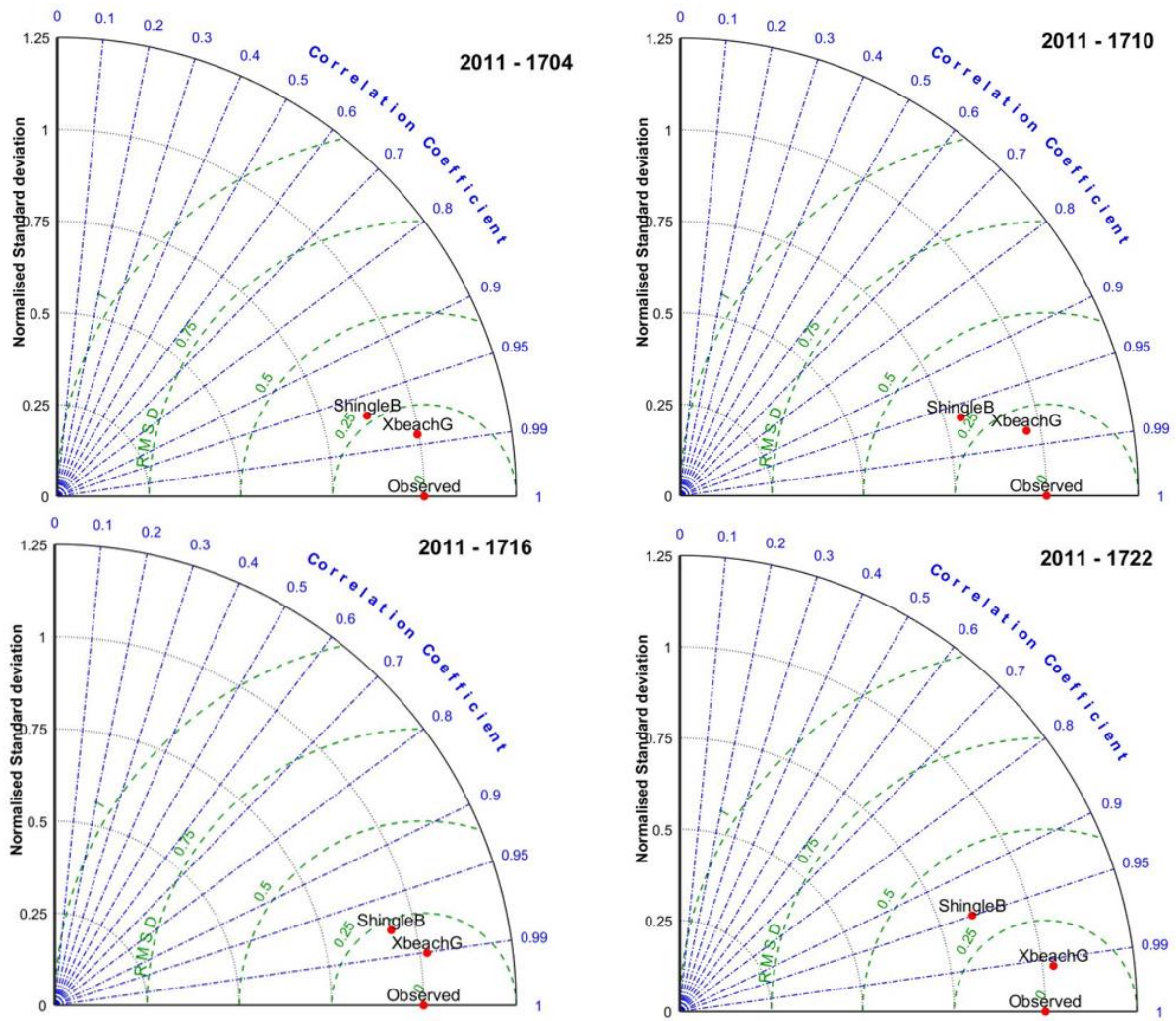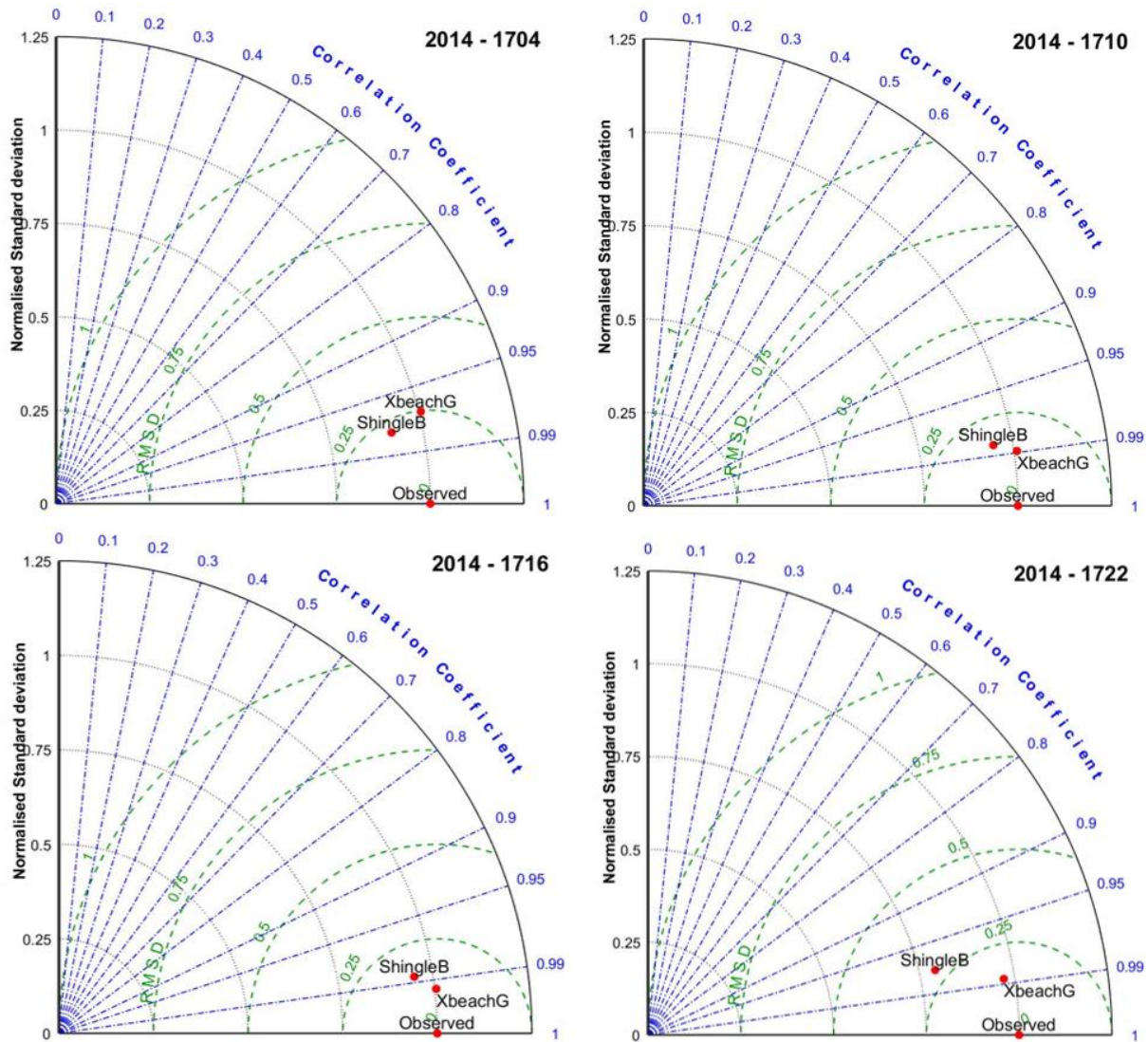

Fig. 13: Taylor Diagram summarising the skill of XBeach-G and Shingle-B to predict morphological evolution across the frontage of Pevensey Bay. For the purpose of the Taylor Diagram, Standard Deviation (STD) and Root Mean Square Difference (RMSD) have been normalised.

5.3 Volumetric Transport

As discussed in the section above, predicting the evolution of a shingle barrier in response to storm events is vitally important for the protection of vulnerable coastal regions. However, arguably just as important for Pevensey Bay due to the regular beach nourishment activities which take place, is the understanding of beach volume changes due to storm events. It is therefore necessary as part of the model validation process for XBeach-G and Shingle-B at Pevensey, to assess the model's capability to predict beach erosion and accretion volumes.

Fig. 14 provides a concise summary of the changes in sediment volume of the beach profile for both the measured and simulated storm events for both models. The black line represents a region where measured erosion or accretion volumes equals that of the predicted volume change from the model. Above the black line modelled > measured and below the black line modelled < measured. This provides a concise summary of whether the model has under or overpredicted the change in beach volume across the entire profile.

In almost all instances Shingle-B overpredicts the magnitude of beach erosion and accretion across Pevensey Bay; illustrated by the cluster of red dots above the 'Measured = Modelled' line in *Fig. 14*. The one exception being the output profile 1722 from the 2014 simulated
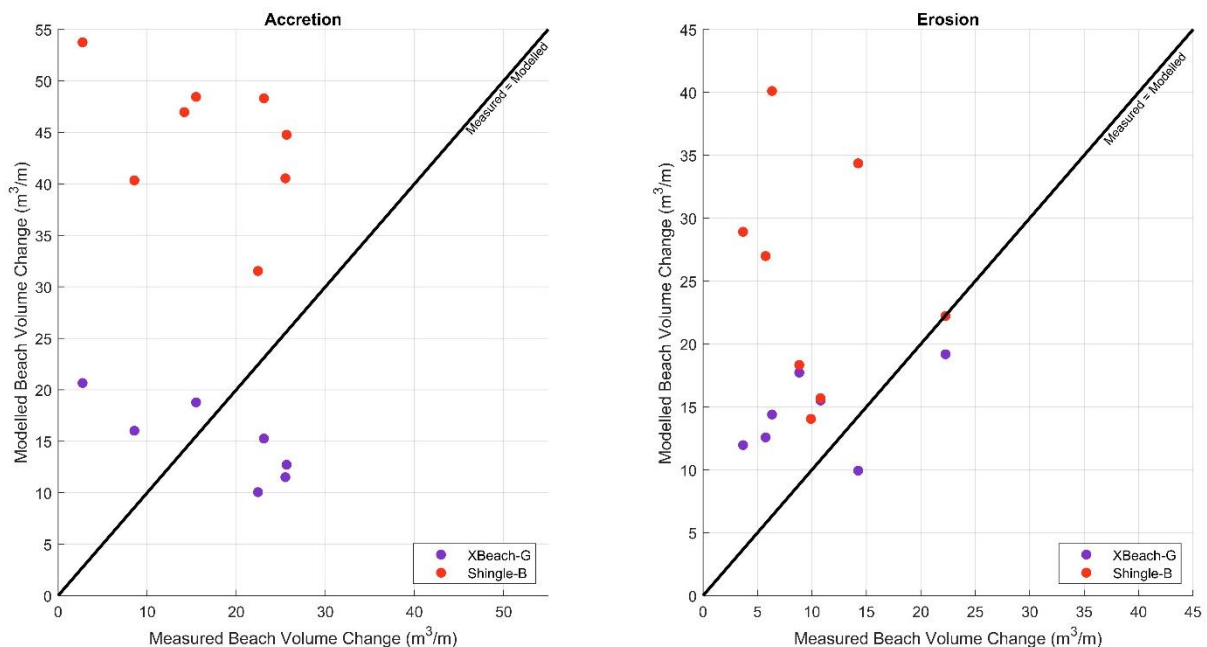
Fig. 14: Comparison of accretion and erosion volumes for measured and simulated storm events for both XBeach-G (purple) and Shingle-B (red). Black line indicates measured erosion/accretion is equal to modelled. XBeach-G output profile 1704 for the 2014 storm event is not contained in the figure.

storm event, where Shingle-B predicts an erosion volume of 22.23 m^3m^{-1} and the post storm profile erosion almost equal at 22.27 m^3m^{-1}. These overestimates of beach accretion by Shingle-B, can be attributed to the extensive deposition of shingle around the beach step.

On the other hand, XBeach-G appears far more capable of predicting changes in sediment volume, demonstrated by the proximity of purple dots to the black diagonal line in *Fig. 14*. Interestingly, the XBeach-G model output with the highest statistical skills parameters and performance values (2011 - 1710) occurred where both erosion and accretion volumes were underpredicted. Measured accretion and erosion values of 22.44 m^3m^{-1} and 14.25 m^3m^{-1} compared to the model output predictions of 10.06 m^3m^{-1} and 9.94 m^3m^{-1} respectively. Comparisons between measured and modelled beach volume change appear to be more scattered on the left-hand plot, indicating erosion volumes due to storm events are better predicted by both models.

5.4 Run Up Elevation and Maximum Water Level

Vitally important for the protection of coastal regions is understanding the potential for overtopping during a storm event due to combined tide-surge levels and wave run-up. Not only is immediate damage caused to properties in the lee of the barrier, but erosion of the crest lowers the barrier elevation making the region more vulnerable to clustered storm events. Specific to Pevensey Bay, a crest elevation of between 6m to 6.5m (OD) is maintained to protect infrastructure behind the shingle barrier. It was therefore deemed necessary as part of this study to assess the capability of both XBeach-G and Shingle-B to simulate run-up elevations for the 2011 and 2014 storm events.

In the absence of measured water level data at Pevensey Bay, the validation of modelled run-up elevations will use the original EurOtop 2007 approximation for run-up elevations on shingle beaches (EurOtop, 2016). This formula presumes the largest waves will reshape the beach profile and subsequently cause overtopping; so, in this case the calculated crest elevation (h_c) can be assumed equal to the run-up exceedance height of 2% ($R_{u2\%}$).

$$\frac{h_c}{H_{m0}} = 0.3s_{om}^{-0.5} \qquad\qquad (Eq.15)$$

$$s_{om} = \frac{H_{m0}}{L} \qquad\qquad (Eq.\ 16)$$

Where h_c is the crest elevation, H_{m0} is the spectral significant wave height, s_{om} is the wave steepness, calculated using the mean wave period (T_p) to acquire wavelength (L) at the

intermediate depth of 15.47m at the offshore boundary (EurOtop, 2016). A similar empirical relationship is used to estimate run-up elevations in Shingle-B, developed by extensive fields tests by Polidoro et al (2013).

Fig. 15 shows the results of the validation, with estimated water levels from the three calculation methods for both of the 2011 and 2014 storm periods. Model output water level estimates have been broken down in the individual components of SWL (tide and surge) as well as wave run-up. It can be seen that both models have performed reasonably well in recreating maximum water elevations at the shingle barrier, when compared to the EurOtop (2007) formula. Despite this, there is significant variance in the relative run-up estimations from both models. In all scenarios for both storm events, Shingle-B predicts the largest wave run-up, with maximum water elevations of 6.38m and 6.59m for respective 2011 and 2014
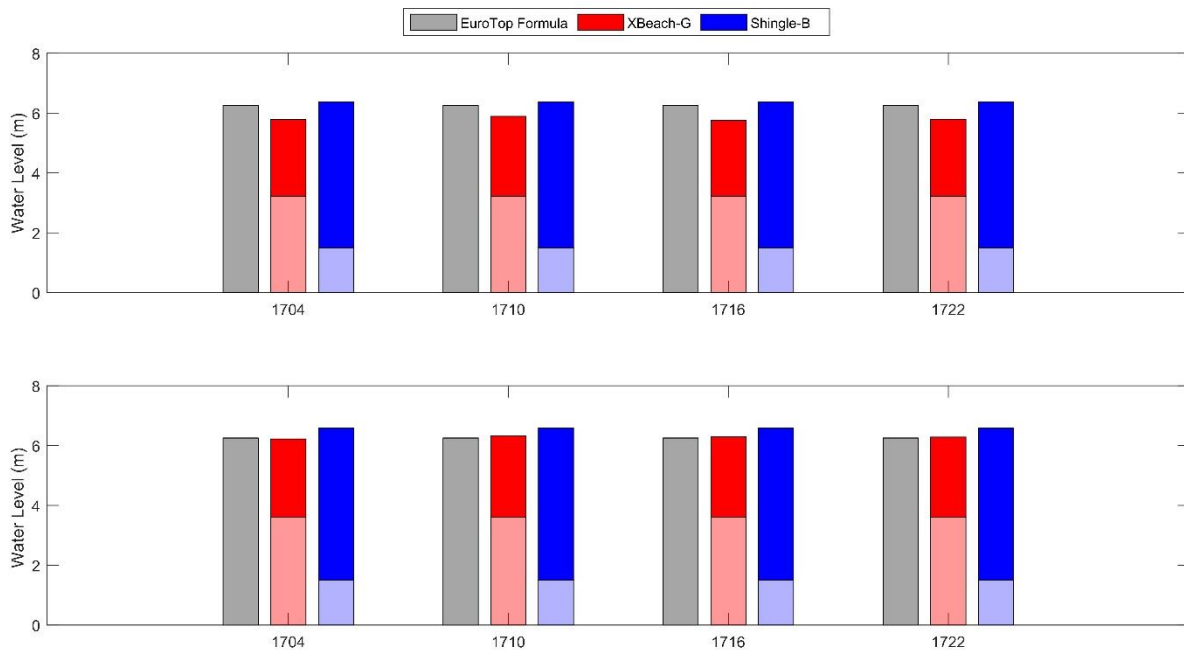
Fig. 15: Run-up elevations using the EurOtop (2007) formula (grey bar) for model comparison, along with model approximations from XBeach-G (red bar) and Shingle-B (blue bar) for validation. The top plot represents the 2011 storm event and the bottom plot represents the 2014 storm event. Transparent sections of the XBeach-G and Shingle-B bars indicate the input water level in the model, to identify relative wave run-up elevations. For XBeach-G the maximum tide and surge level was defined at 3.23m for 2011 and 3.6m for the 2014 storm event. For Shingle-B a still water level (SWL) of 1.5m was used.

storm events. The effects of these over-predicted run-up levels have been observed previously (*cf* Section 5.1; Section 5.2), with a subsequent over estimation of crest build up in almost all Shingle-B simulations compared to the EurOtop (2007) formula.

In contrast to this, the 2011 storm simulation from XBeach-G is shown to underestimate the maximum water level when compared with the EurOtop (2007) method. The largest variance in this estimation occurring at profile 1716, with a 0.49m difference between the two computation techniques. The effects of XBeach-G underestimating the run-up can be observed in Section 5.1, with the significant accretion of sediment being simulated below the barrier crest (*Fig. 10*). Whereas in the 2014 storm simulation, the run-up elevations are extremely similar to that of the EurOtop formula.

Chapter 6: Model Sensitivity

To investigate the effect which varying boundary conditions have on the output morphological profile from both XBeach-G and Shingle-B; a selection of input parameters and forcing conditions are explored through a number of sensitivity simulations, covering the storm events described above (*cf.* Section 3.3). The profiles presented in this sensitivity analysis are 1710 and 1716 from the 2011 simulated storm event; selected on account of the model skill parameters calculated for the output profiles. The aim of this analysis is to further explore the model's suitability after the validation process, as well as calibrating the model to achieve optimal performance for the complex hydrodynamic and morphodynamic climate at Pevensey. Though it was not feasible to explore the entire range of input parameters for both the models used in this study, it can be assumed that the subheadings outlined below adequately describe the range of processes in the nearshore. Specific to Pevensey Bay, three influential factors have been identified as being crucial to governing the morphological processes when modelling shoreline evolution, through both literature and an investigation of the study site. The presence of fine-grained sediment across the beach profile (*cf.* Section 6.1.), the exchange of swash with groundwater on the shingle barrier (*cf.* Section 6.2) and the characteristics of the input hydrodynamic boundary conditions (*cf.* Section 6.3).

6.1 Morphological Parameters

The mixed sand-gravel composition of the beach profile at Pevensey Bay leads to a considerable cross-shore and along-shore spatial variability in grain size and other associated parameters. These boundary conditions in the model equations are in part responsible for the magnitude of bed shear stress and subsequently sediment transport in the swash zone. Therefore, to effectively recreate processes affecting the morphological evolution of the beach profile, it is important these input parameters closely resemble the observed characteristics. This section of the sensitivity analysis focusses on the XBeach-G simulation, as the morphological parameters in Shingle-B are pre-set in the model (12.6mm - d50). Sensitivity analysis is of particular importance with the morphological parameters in XBeach-G, as these are single values which represent the entire cross shore profile are constant for the duration of the simulated storm.

6.1.1 Grain Size (d50)

For the sensitivity analysis of grain size in XBeach-G, three d50 values have been chosen. Beside 0.014m as used in the model validation section, 0.007m and 0.021m have been selected as upper and lower d50 limits to explore. For all simulations in the grain size sensitivity analysis, hydraulic conductivity and sediment friction factor are kept to the values used in the validation. Despite D_{50} and K being inherently linked and therefore being a potential limitation, this aspect of the sensitivity analysis is to attempt to explore changes in sediment grading in XBeach-G.

Fig. 16 demonstrates the effect which a varying grain size has on the modelled evolution of the profile in response to the 2011 storm event. At profile 1710 (top panel), the effect on the vast majority of the intertidal zone is relatively insignificant, with all three grain sizes predicting very similar erosion of the profile between elevations 0m to 2m (OD). However, elsewhere down the beach face there are disparities between the output profiles. Around MLWS (-2.82m) it is clear that reducing the grain size increases the volume of accretion at the bottom of the foreshore slope. Between a cross shore distance of 80m and 90m, the 0.007m simulation accreted 4.1 m^3m^{-1} of sediment, whereas the output profiles from grain

Fig. 16: XBeach-G output profiles from the 2011 storm event simulation at two profile locations at Pevensey Bay (1710 and 1716) along with pre-storm and post-storm measured profiles. Top panel represents profile 1710 and the bottom panel represents 1716. Different output profiles indicate varying grain size (d50 - m) used to run each model simulation as part of the sensitivity analysis.

sizes 0.014m and 0.02m experienced erosion volumes of 0.9 m^{3}m^{-1} and 1.3 m^{3}m^{-1}. In addition to this, above MHWS it is clear that decreasing the grain size reduces the level of accretion predicted by the model, with the 0.021m output simulating slight erosion of the front of the barrier crest and the formation of a berm at the upper beach face. At profile 1716 (bottom panel) a similar reducing in accretion of the upper beach face is predicted by reducing the grain size. In this case a larger grain size (0.021m) leads to a seaward migration of the berm crest by 4.5m, signifying greater volumes of accretion. Despite this, across all grain sizes no erosion of the of the upper beach face occurs at these profile locations. Alongside this, a similar pattern to the erosion of the foreshore in profile 1710, is predicted at 1716. A reduction in grain size from 0.021m to 0.007m increases the erosion volume of this region (0m to MHWS) from 9.8 m^{3}m^{-1} to 12.5 m^{3}m^{-1}. Both panels in *Fig. 16* demonstrate a greater onshore transport of sediment under the largest grain size (0.021m), with the offshore transport of material to the MLWS mark under the smallest d50 (0.007m).

To understand the significance of these observations made from *Fig. 16*, a Taylor Diagram comparing model skill parameters for each grain size simulation is shown in *Fig. 17*. At both locations 1710 (left panel) and 1716 (right panel), the largest grain size of 0.021m was most effective at predicting the morphological evolution; with respective RMSD values of 0.59 and 0.38. Despite a small variance in data points on the right and left panels, the smallest
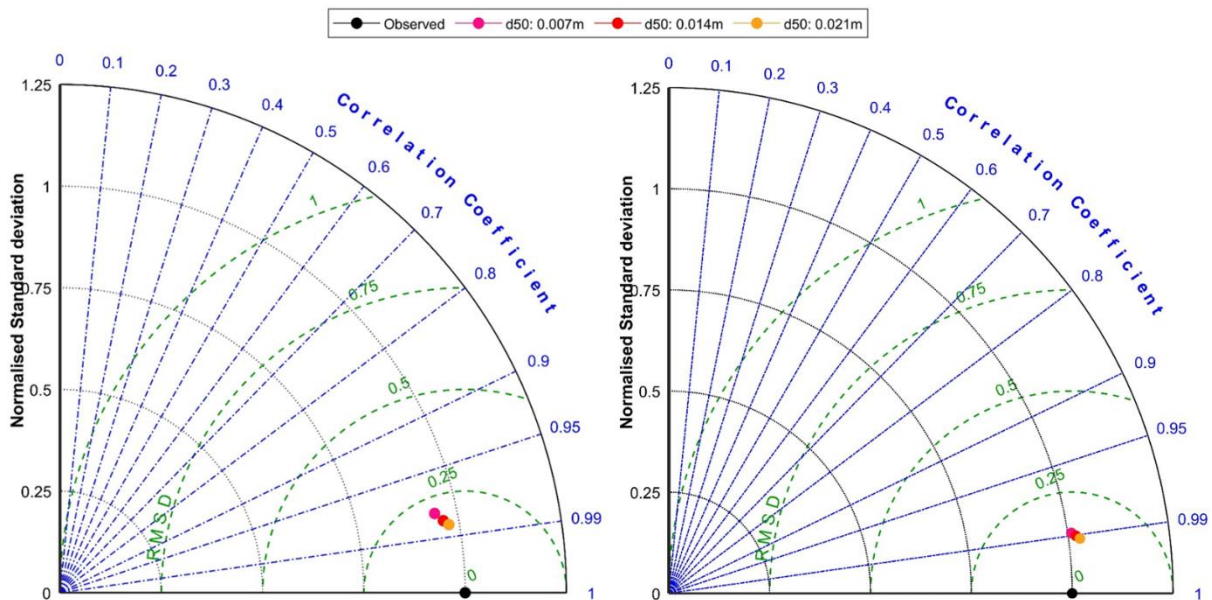
Fig. 17: Summary of statistical skill parameters for model simulations in the grain size (d50 - m) sensitivity analysis. Left panel represents profile 1710 and right panel represents profile 1716. For the purpose of the Taylor Diagram, Standard Deviation (STD) and Root Mean Square Difference (RMSD) have been normalised.

grain size (0.007m) can be said to be the least effective at predicting profile evolution, with the pink dots in *Fig. 17* placed furthest away from the observed point at both locations.

6.1.2 Hydraulic Conductivity (K)

The extent of infiltration and exfiltration through the surface layer of the beach profile in XBeach-G is governed by the hydraulic conductivity (K) input parameter. Varying K value alters the permeability of the structure and the vertical exchange of water through the surface of the beach profile; thus, a controlling factor on sediment transport in the swash zone (*cf.* Section 2.3). The composition of the shingle barrier at Pevensey is medium gravel with a fine sand fraction which varies considerably in the cross-shore direction. Small deviations in the fine sand fraction of a sediment sample can be attributed to large changes in the permeability of the structure and subsequently the hydraulic conductivity of the surface layer. Therefore, a sensitivity analysis of the hydraulic conductivity term in XBeach-G was deemed an essential as part of this study. As used in the model validation, a constant grain size of 0.014m will be adopted for this section. The range of K values explored in this sensitivity study, is a lower limit of 0.06 ms^{-1}, a middle value as used in the validation of 0.13 ms^{-1} and an upper limit of 0.2 ms^{-1}. These K values have been obtained through relevant literature (She et al., 2006; McCall 2015) and correspond to the respective hydraulic conductivity of the three grain sizes described above (0.007m, 0.014m and 0.021m; *cf.* Section 6.1.1).

The results of the K value sensitivity analysis (*Fig. 18*), shows the significant effect which a varying hydraulic conductivity has on the predicted morphological response from XBeach-G. In the top panel (1710) much of the middle and lower foreshore slope remains relatively unchanged when the K value increased to 0.02 ms^{-1}. Whereas a reduction to 0.06 ms^{-1} results in; an accretion of $3.9 \text{ m}^3\text{m}^{-1}$ in the region above MLWS and a reduced erosion volume of $4.7 \text{ m}^3\text{m}^{-1}$ in the middle of the intertidal zone. Much of the disparity between profiles in the top panel occurs above MHWS. Increasing the K value to 0.2 ms^{-1} results in the predicted formation of a berm in the upper beach around 5m seaward of the max crest elevation. Yet similar to a K value of 0.13 ms^{-1}, still predicts an accretion of sediment in front of the barrier crest. In contrast to this, a small hydraulic conductivity (0.06 ms^{-1}) simulates considerable erosion of the upper beach face between 2m and 4m (OD) elevation and slight erosion in front of the crest. A 3.5m retreat of the predicted crest edge is observed when reducing K from 0.13 ms^{-1} to 0.06 ms^{-1}.
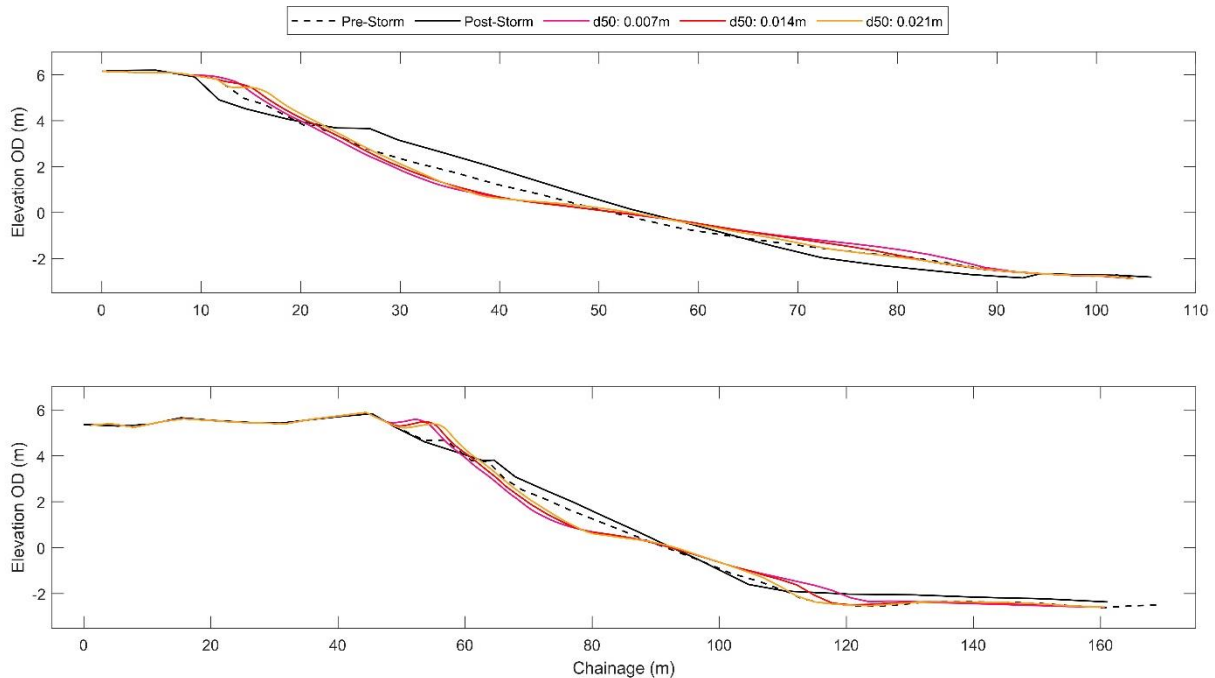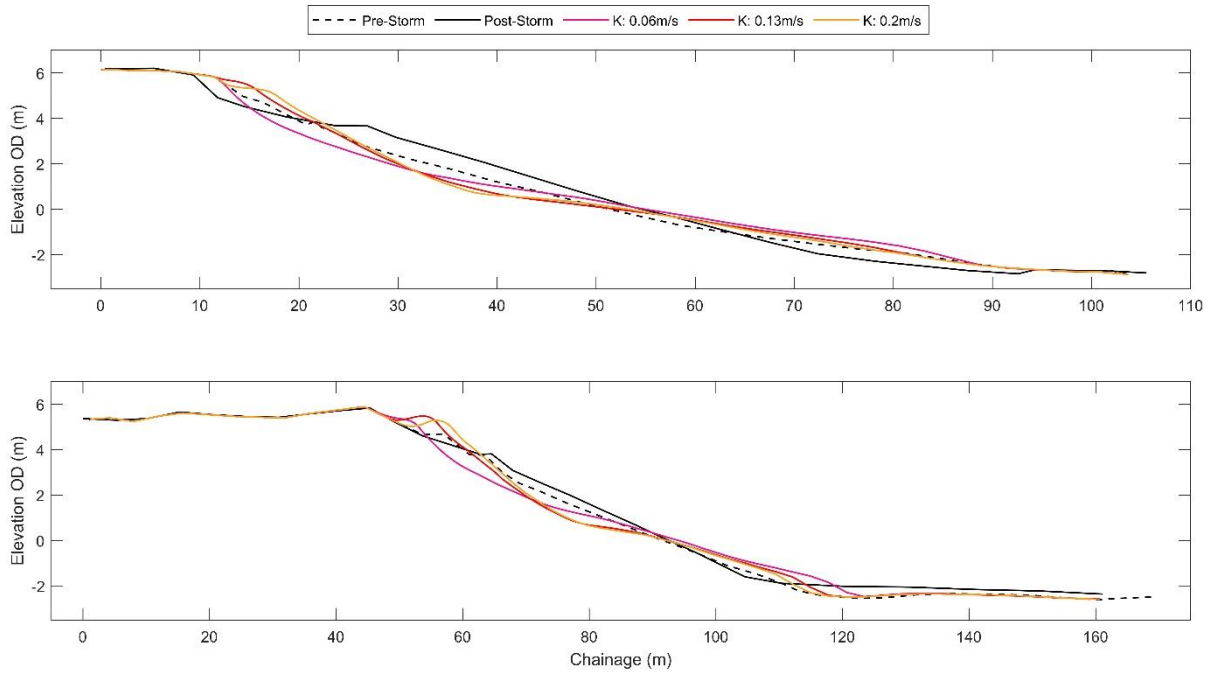
Fig. 18: XBeach-G output profiles from the 2011 storm event simulation at two profile locations at Pevensey Bay (1710 and 1716) along with pre-storm and post-storm measured profiles. Top panel represents profile 1710 and the bottom panel represents 1716. Different output profiles indicate varying hydraulic conductivity (K - ms^{-1}) used to run each model simulation as part of the sensitivity analysis.

The bottom panel in *Fig. 18* shows the similar sensitivity to changing the hydraulic conductivity term in XBeach-G. Again, an additional accretion of sediment is observed at the toe of the foreshore and in the middle of the intertidal zone when the hydraulic conductivity is set to the minimum (0.06 ms^{-1}). In all three sensitivity simulations for the 2011 storm at profile 1716, XBeach-G predicts the formation of a berm just above MHWS. The smallest and least pronounced berm occurs under the smallest value of K. Whereas the largest hydraulic conductivity simulation results in the most pronounced accretion of sediment. This increased permeability of the surface layer of sediment as K is increased, is enabling more infiltration of uprush into the profile, encouraging onshore directed accretion of sediment as observed in *Fig. 18*. Therefore, it may be assumed that a lower value of K more suitably describes the sediment characteristics at Pevensey, as an overprediction of accretion does not occur in this simulation (K = 0.06 ms^{-1}). However, at this stage of the sensitivity analysis it is not certain that changes to the hydraulic conductivity is the only factor contributing to the discrepancies between the measured and modelled profiles.

The significance of these simulations exploring the sensitivity of the hydraulic conductivity term in XBeach-G, can be visualised in the Taylor Diagram in *Fig. 19*. Interestingly, at both

locations along Pevensey Bay, the main separating factor for the three K value simulations in terms of statistical skill, is the differing variance (STD) of the model output compared to the measured profile. Yet despite the visible disparity between profiles in both panels of *Fig. 18*, the RMSD and correlation coefficient do not vary substantially with changes to K.
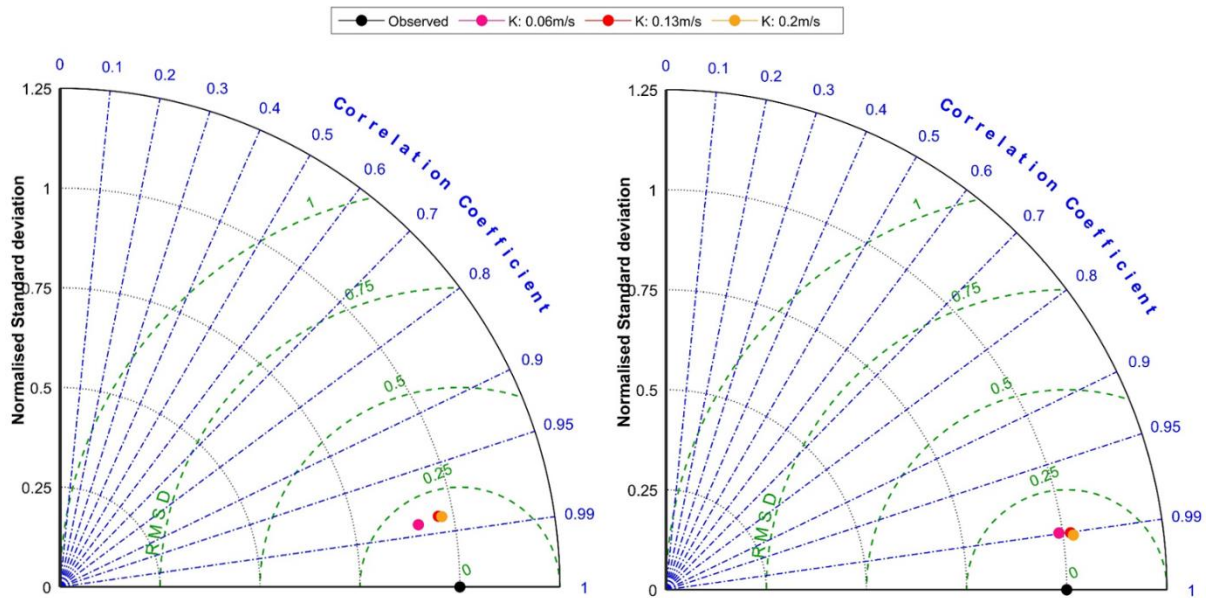
Fig. 19: Summary of statistical skill parameters for model simulations in the sensitivity study of hydraulic conductivity (K - ms^{-1}). Left panel represents profile 1710 and right panel represents profile 1716. For the purpose of the Taylor Diagram, Standard Deviation (STD) and Root Mean Square Difference (RMSD) have been normalised.

6.1.3 Spatial Variability in Model Performance

To further the sensitivity analysis of grain size and hydraulic conductivity, it was necessary to investigate the performance of XBeach-G across the full frontage of Pevensey Bay using the input parameters outlined above. As previously discussed, the spatial variability in sediment composition at Pevensey may ultimately hinder the performance of model's simulating morphological change, which could present uncertainties in reports produced by coastal engineers. In an attempt to resolve this issue, XBeach-G simulated the 2011 storm event across all four profiles (1704, 1710, 1716 and 1722), each exploring the sensitivity of all d50 and K scenarios.

Fig. 20 shows the model sensitivity to grain size and hydraulic conductivity across the full spatial extent of the shingle barrier at Pevensey Bay, by exploring the changes in model performance (BSS). A normalised scale on the z-axis enables a clear representation of skill

scores ranging from 1 to below zero, giving relative rather than absolute performance of the model across the barrier. At all profile locations it is clear from *Fig. 20* that model simulations with the lowest input d50 (0.007m) and K (0.06ms^{-1}) performed worst in predicting morphological response. With a 'bad' BSS' emerging from all four model simulations, it is clear a fine gravel size of 0.007m and low hydraulic conductivity does not
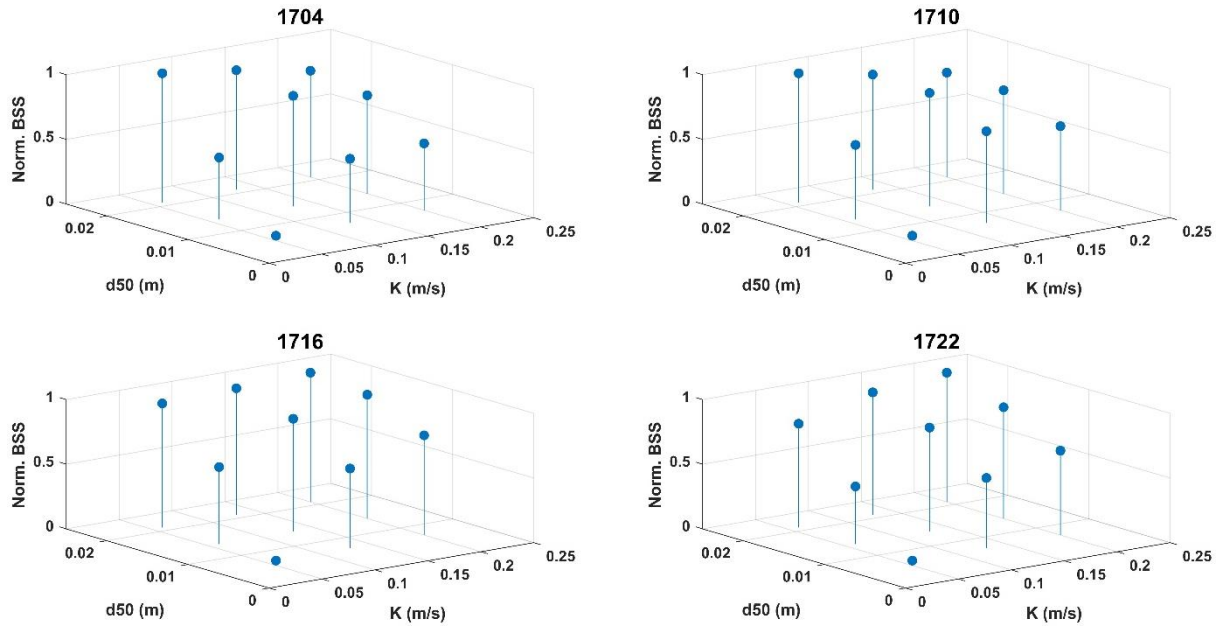
Fig. 20: Summary of full XBeach-G sensitivity analysis for both grain size (d50) and hydraulic conductivity (K) at four profile locations across Pevensey Bay for the 2011 storm event. The model performance scale is a BSS plotted on the z-axis for each of the scenarios ran; skill scores are normalised for the purpose of this figure. BSS' for these simulations ranged from -2.57 to 0.71.

represent the sediment characteristics and swash zone processes at any location across Pevensey. The best model performance was observed at profile 1710, with a d50 of 0.021m and a K value of 0.06 ms^{-1}; generating a BSS for this simulation of 0.71. These input parameters also produced the best performance at profile 1704, demonstrated by the highest spikes in the top two panels of *Fig. 20*. In contrast to this, at profiles 1716 and 1722 the best model performance occurred with the largest d50 (0.021m) and highest K value (0.2 ms^{-1}). Comparing the sensitivity of both terms in the model outputs at all four profiles, verifies the presence of an alongshore variability in sediment composition across the barrier.

6.1.4 Sediment Friction Factor

The sediment friction factor (f_s) is contained within the XBeach-G model equations for sediment transport and can be defined by the user in the setup phase. It is used to compute the

friction velocity which in-turn computes the Shields parameter; to describe the initiation for motion of sediment in the model. The extent of sediment transport predicted in the output profile is highly dependent on shear stresses in the swash zone and therefore particularly sensitive to a varying f_s. As documented in McCall (2015), the values of f_s used in this sensitivity analysis range from a lower limit of 0.005 and an upper limit of 0.05; where 0.025 is the default value used in the model validation section.

The results from the analysis can be visualised in *Fig. 21*, comparing model output profiles at 1710 and 1716. At both locations the sediment transport is shown to be strongly affected by the sediment friction factor, with a low f_s value (0.005) simulating the minimum erosion and accretion across the profile. Whereas, the middle (0.025) and high (0.05) input f_s predicts considerably more erosion of the foreshore slope and berm formation above MHWS.
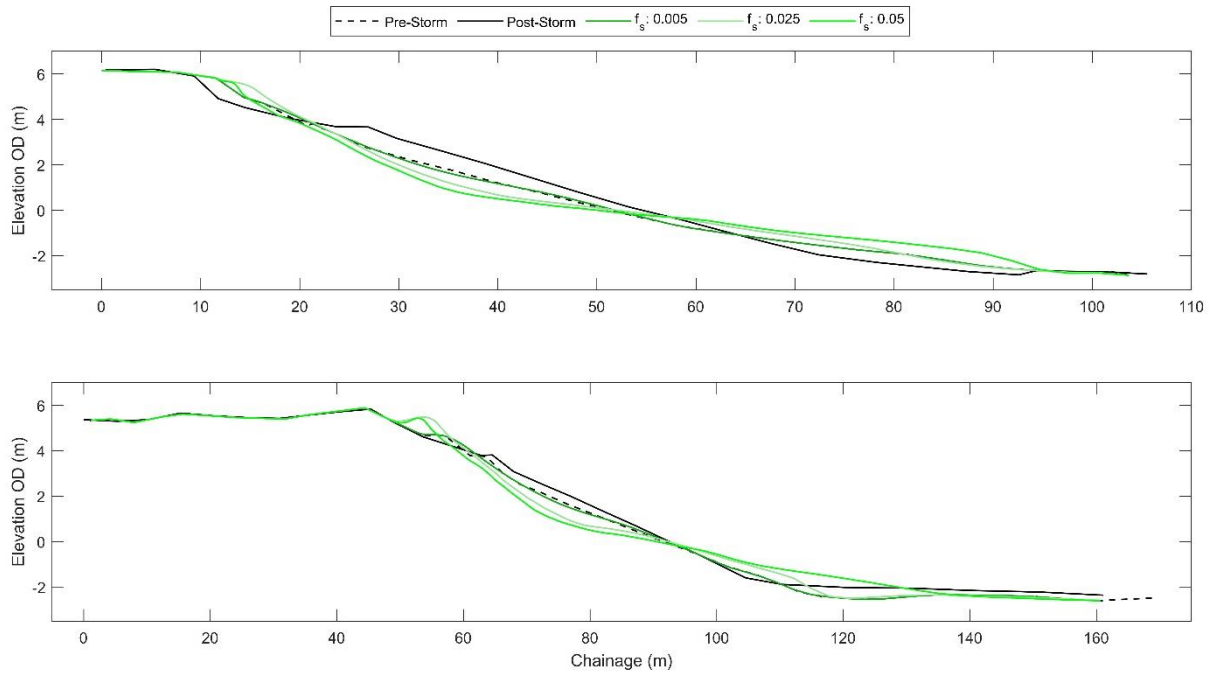
Fig. 21: Comparison of model output profiles from the sediment friction factor sensitivity analysis for locations 1710 (top panel) and 1716 (bottom panel). All other input parameters remain the same as the validation section.

Interestingly, a substantial increase of sediment accretion below the crest occurs for the middle f_s simulation. To identify the swash zone processes responsible for these changes in sediment transport, *Fig. 22* presents the maximum velocity at each point down the profile calculated by XBeach-G for all f_s inputs. At profiles 1710 and 1716, a reduction in the sediment friction factor (0.005) results in the in the lowest computed velocity at the MHWS

elevation. This can be visualised in *Fig. 21* with a substantial reduction in the onshore transport of sediment leading to little berm formation in the upper beach. In contrast to this, an increase in the swash zone velocity as f_s is increased results in a greater volume of accreted sediment at MHWS; shown by a pronounced berm predicted at profile 1716. It is worth noting that the greatest velocity estimated by XBeach-G occurred under the middle sediment friction factor input (6.89 ms^{-1} and 7.07 ms^{-1} for 1710 and 1716).
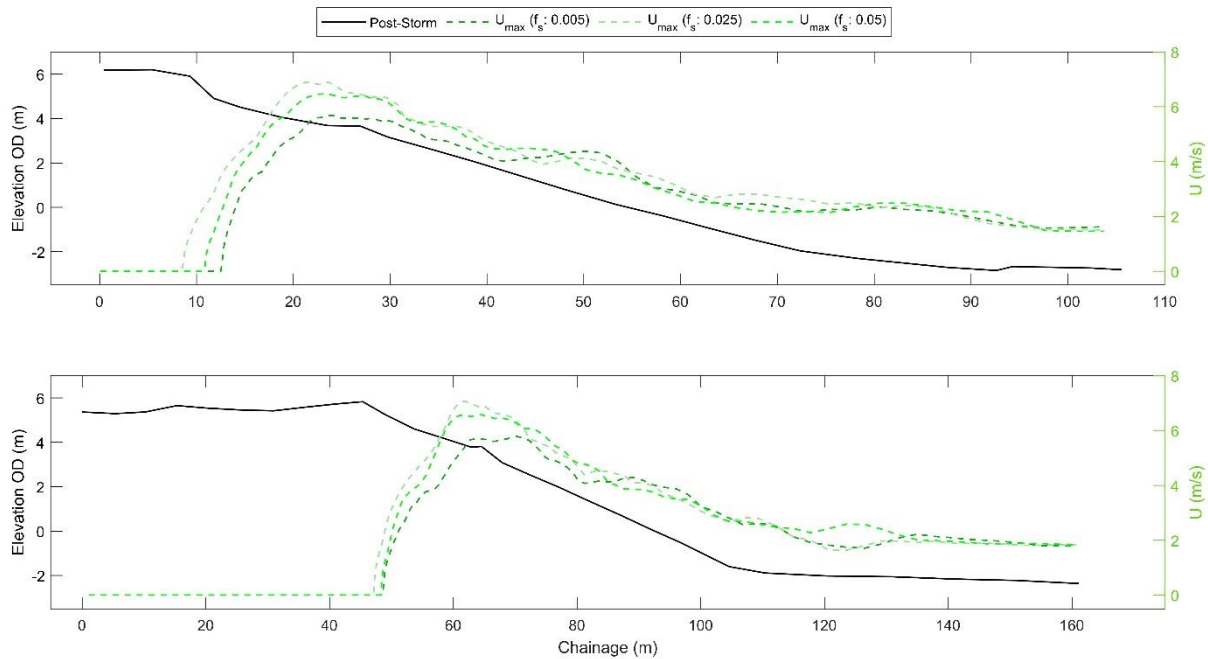
Fig. 22: Maximum velocity profiles for each f_s input, computed by XBeach-G. Top panel represents profile 1710 and bottom profile represents profile 1716. Black line (left y-axis) is the measured post-storm profile and three dashed green lines (right y-axis) show velocity for each output chainage.

6.2 Groundwater Elevation

The adaptation of the original XBeach model to predict morphodynamic response on gravel beaches, led to the inclusion of an additional groundwater model to incorporate the vertical exchange of water through the permeable upper surface layer of sediment. The XBeach-G setup contains a user defined groundwater level, where the sensitivity of this term is explored in this section. The level of the groundwater head compared to the bed level and surface water level is a controlling factor on the infiltration and exfiltration processes in the upper surface layer (Masselink et al., 2009).

For the purpose of this sensitivity study the 2011 storm was simulated again at profiles 1710 and 1716, for four varying groundwater levels covering the majority of the shingle barrier

depth. The default elevation used in the model validation was 0m (OD) and for this section; -2m, 2m and 4m were also simulated. *Fig. 23* demonstrates the results of the groundwater elevation sensitivity analysis, with the observed pre-storm and post-storm profiles along with the four output profiles predicted by XBeach-G. At location 1710 almost no change in morphological response is simulated by XBeach-G with a change in groundwater elevation. A slight increase in accretion around 12m chainage is observed with an input of 0m and aswell around MHWS under the 4m input value. At profile 1716 the difference in output profiles was again negligible; besides a small disparity in the predicted response of the shoreline between the berm and crest. The highest input groundwater elevation (4m) predicts 0.2m less accretion of sediment behind the berm.

This sensitivity study indicates that the input groundwater elevation is relatively insignificant compared to a varying input hydraulic conductivity (*cf.* Section 6.1.2) for the modelled infiltration-exfiltration processes and their subsequent effect on sediment transport.
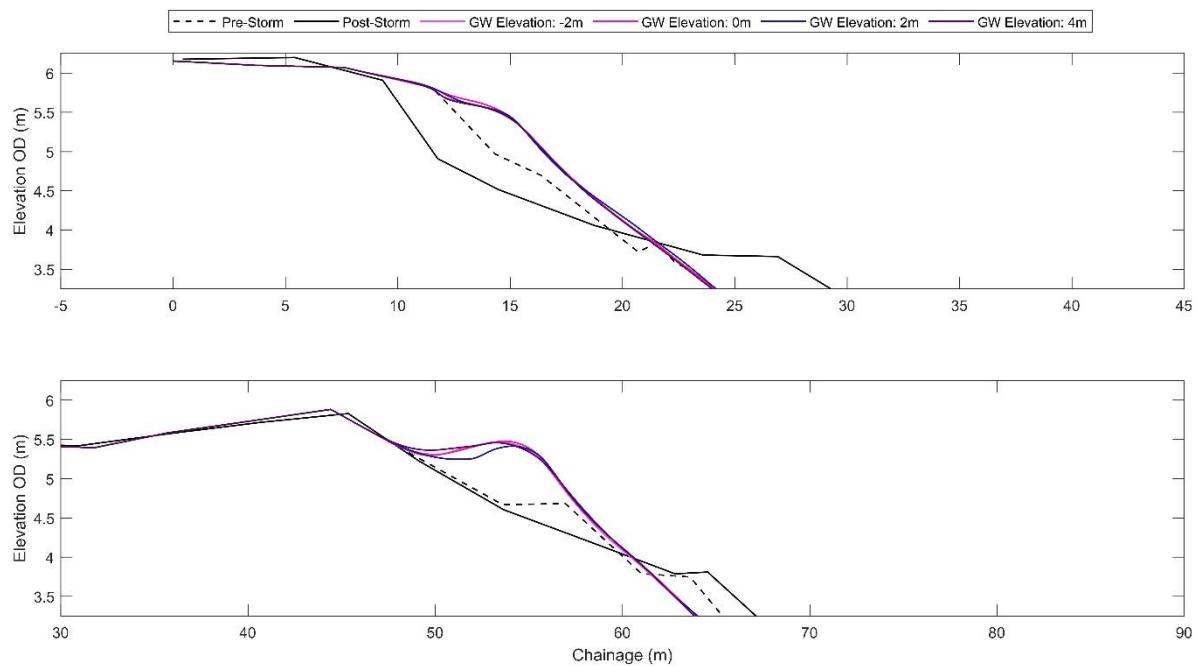
Fig. 23: 2011 simulated storm event at profiles 1710 (top panel) and 1716 (bottom panel) with a variety of input groundwater elevations for sensitivity analysis (-2m, 0m, 2m and 4m). Only the upper section of the profile (> 3.25m elevation (OD)) is displayed in the plot due to the small variance between model output profiles.

6.3 Hydrodynamic Forcing

Accurately recreating the wave climate observed at the shoreline is a fundamental factor in effectively modelling morphodynamic evolution. Hydrodynamic forcing at the model boundary is responsible for estimating bed shear stress in the swash zone, the extent of sediment transport and run up elevations on the gravel barrier. Therefore, a key focus for coastal engineers is to understand the effect of varying hydrodynamic input parameters on model performance.

6.3.1 Wave Spectrum

The location of Pevensey Bay creates differing hydrodynamic forcing conditions to previous studies which have modelled similar shingle barriers (McCall et al., 2014; HR Wallingford). The reduced potential for long period swell events from the Atlantic to propagate up to the Eastern extremity of the English Channel creates a more unimodal wave spectrum for the majority of the year; with wave energy often focussed around one frequency. Yet as previously discussed, the occurrence of bimodal spectrum has been observed under significant storm events such as explored in this study (Polidoro et al., 2018). It was therefore necessary to explore the sensitivity of the predicted model output to a varying input wave spectrum. In this section of the sensitivity analysis both XBeach-G and Shingle-B are explored; where for the unimodal conditions a mean peak period (T_p) of 9.1s was used as an average for the model duration, taken from the CCO wave time series. For the XBeach-G setup either a unimodal or bimodal option can be specified, whereas in Shingle-B only a swell percentage can be input into the model. Therefore, for this section of the analysis the unimodal wave spectrum for Shingle-B is defined by a 0 swell percentage and the bimodal input is 70% as used in the validation of the model.

Fig. 24 demonstrates the results of this sensitivity analysis section. At both locations (1710 and 1716) XBeach-G exhibits no change in the predicted response of the shoreline under a varying wave spectrum; showing the insignificant effect which energy at higher frequencies ($T_{p\,wind}$) has on the output profile. In contrast to this, a more substantial change is predicted by Shingle-B at both locations. At profile 1710 the extent of erosion simulated between MHWS and the crest, is reduced under a unimodal wave spectrum. This is shown by the respective retreat of the barrier crest under unimodal and bimodal conditions of 4.5m and 9.5m. Similarly, in the bottom panel of *Fig. 24* (1716) the over-predicted increase in crest elevation observed under bimodal conditions is less substantial with a unimodal input spectrum.

Qualitatively assessing the Shingle-B output profiles indicates this unimodal wave spectrum is more effective at simulating the crest migration.
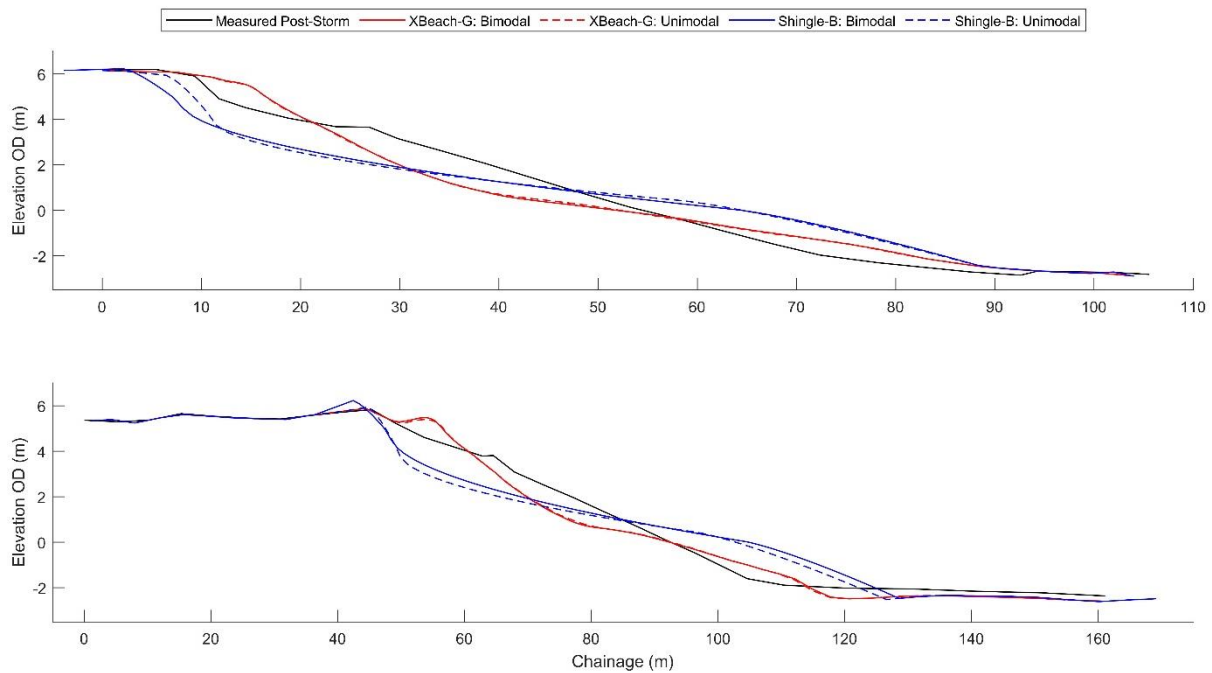
Fig. 24: Predicted morphological response of the shingle barrier at Pevensey to unimodal (dashed line) and bimodal (solid line) storm conditions. Top panel represents profile 1710 and the bottom panel represents profile 1716.

Where varying the wave spectrum is shown to have little effect on the simulated XBeach-G profile, the Shingle-B model was more skilful in recreating the measured conditions under unimodal conditions. This is summarized in *Fig. 25*, where model skill parameters for the Shingle-B output profiles above an elevation of 3.88m (MHWS), have been calculated. Run up elevations on gravel beaches have been closely linked to the shape of the wave spectrum and the proportion of swell energy (McCall et al., 2014); therefore, extracting the upper section of the output profiles (> MHWS) was deemed necessary for this sensitivity study. Interestingly at both profiles (1710 and 1716), Shingle-B under a unimodal input wave spectrum was more effective at recreating the crest position than under bimodal conditions.

The most substantial variation was observed at profile 1710; where respective correlation coefficients for bimodal and unimodal spectrums were 0.91 and 0.96. These discrepancies in model skill scores at 1710 could be attributed to the overpredicting of erosion in the upper section of the beach profile under a bimodal spectrum. It is worth noting that the swell waves reaching the Eastern extremity of the English Channel and which are used in this study do not

exceed 10.5s. Whereas, in other locations more exposed to longer period swell waves (increased energy at lower frequencies); the models may perform differently and therefore this part of the sensitivity study is only applicable to Pevensey Bay.
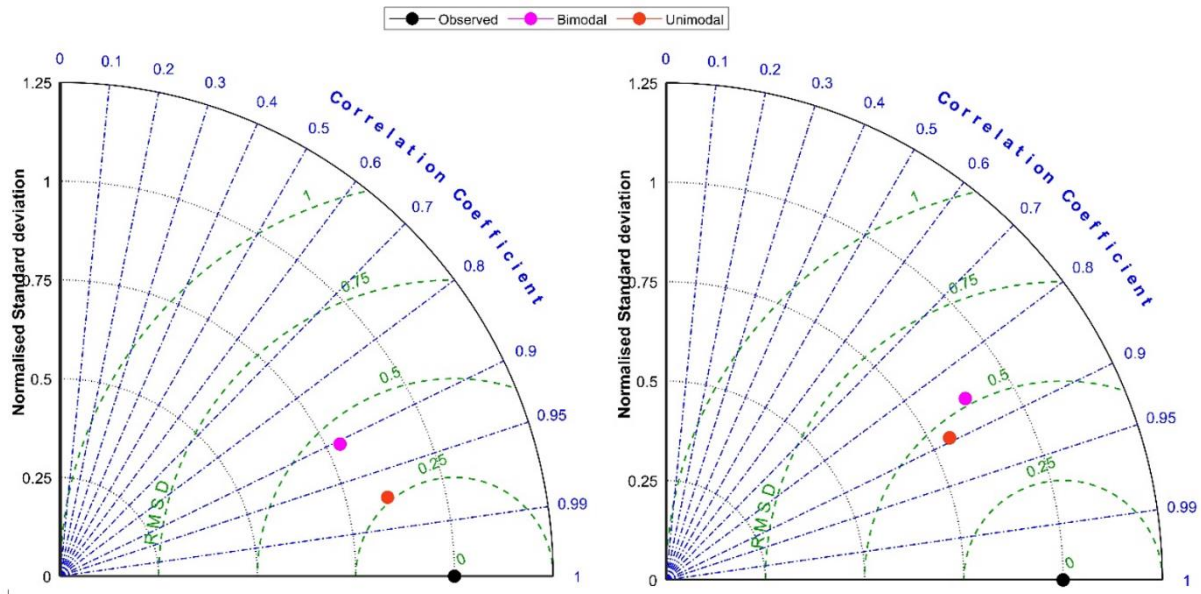
Fig. 25: Shingle-B simulation of the 2011 storm event at profiles 1710 (left panel) and 1716 (right panel), under a bimodal (pink dot) and unimodal (red dot) wave spectrum. Data points summarise the calculated statistical skill parameters for the upper section of the beach (MHWS to back barrier). Parameters on the plot include; normalised root mean square difference, normalised standard deviation and the correlation coefficient.

6.3.2 Still Water Level

In the absence of a time series of tidal elevation such as in the XBeach-G model setup; Shingle-B instead requires a single input still water level (SWL) to be defined. The elevation of swash zone processes, wave run-up and sediment transport described by the empirical relationships of Shingle-B are focussed around this elevation; thus, the output profile is extremely sensitive to this value. This is deemed a necessary step in the sensitivity analysis as the extent of crest erosion and overwash potential is linked to this parameter.

Fig. 26 shows the results of this section of the sensitivity analysis. Considerable changes in the predicted morphological response are observed between the differing SWL input values. Under the 0m SWL, there is almost no change between the measured pre-storm and output Shingle-B profile above MHWS. Whereas considerable erosion of the profile occurs down the intertidal zone. Conversely, the highest input SWL (3m) predicts extensive erosion and

retreat of the upper beach. Resulting in a landward crest migration of 19m and increase in crest elevation of 1.78m. It is clear from the figure that the 3m SWL is unable to recreate the processes in the upper beach well, with a substantial over prediction in crest retreat. However, accretion of sediment around the lower foreshore is shown to be best represented by the highest SWL input, with the 0m SWL predicting the accretion to occur around MLWS.
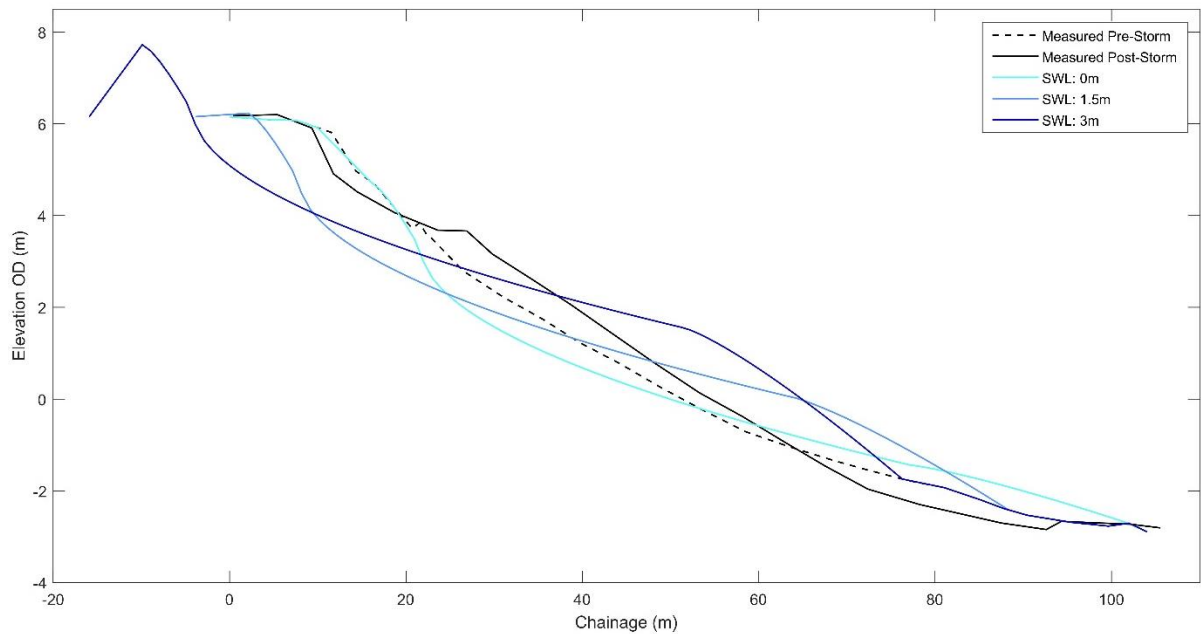
Fig. 26: Predicted morphological response of the shingle barrier with a varying input still water level (SWL). Model is run at profile 1710 for the 2011 storm event.

Chapter 7: Discussion

In order to gain a full understanding of the suitability of both models to predict morphological evolution, this chapter will discuss the significance of the model simulation results observed in Chapter's 5 and 6. As well as this, review the potential limiting factors affecting the performance of models explored in the study; introducing the effects of recommended model assumptions and the human intervention at Pevensey. While it is possible to identify similarities in model performance for studies at other locations; modelling of the shingle barrier at Pevensey has been relatively undocumented in the literature, besides an investigation into CROSMOR2008 by Van Rijn (2011). Therefore, site specific comparisons of model validation and sensitivity of XBeach-G and Shingle-B will not be possible for this discussion. This section will aim to provide an indication of the suitability of both models to be used as an effective coastal engineering tool in the future at Pevensey.

7.1 Assessing Model Performance

The results detailed in Chapter's 5 and 6 provide an indication that both models in certain scenarios have the ability to predict morphological evolution at Pevensey reasonably well (max XBeach-G BSS, 0.62). However, the extent of this model performance has been shown to be highly sensitive to both, the input parameters and the modelled profile location along the frontage of the shingle barrier (mean BSS for 2011; 0.16 for XBeach-G and -4.1 for Shingle-B). In general, XBeach-G has been seen to quantitively outperform Shingle-B in the prediction of the entire profile response, yet, in almost all cases the cross-shore features observed in the measured profile were not simulated well by either model.

Seemingly a key focal point for coastal engineers modelling storm effects on a shingle barrier, is the predicted response of the upper beach and crest (Polidoro et al., 2018). The ability of both models to accurately simulate the change in crest position and upper beach volume in this study, was varied across both storm events. The 2011 XBeach-G storm simulation predicted either no volume change or an accretion of sediment below the crest, whereas the 2011 Shingle-B storm generally predicted considerable erosion and retreat of the top of the barrier. In contrast to this, all simulations of the 2014 storm for both models predicted either little change or, an increase in crest volume and elevation with a build-up of sediment at the top of the barrier. Analysis of the predicted water levels (*Fig. 15*), indicates these discrepancies in sediment volume change at the top of the profile, could be attributed to the error in the estimations of wave run-up elevations predicted by both models (Orford et al.,

2003; Bergillos et al., 2016). With underestimated run-up elevations typical leading to a build-up of sediment below the crest and an over estimation leading to a build-up on top of the crest or in some cases erosion and retreat if substantial overwash occurs (Buscombe and Masselink, 2006). The overestimation of run-up predicted by Shingle-B across all simulations in the validation section, is concurrent with the results of the modelling exercise at Pevensey Bay documented by Van Rijn (2011). Where 'SHINGLE'; the predecessor to the parametric model used in this study, was found to over predict crest build up by 1m compared to the process-based model output (CROSMOR2008). It is important to note however, the empirical EurOtop formula used in the absence of measured run-up data at Pevensey, contains its own level of uncertainty which should be considered when comparing it to modelled estimates (Diwedar, 2016). Despite this, a study by Poate et al (2016), highlighted the increased accuracy of empirical formula containing a wave steepness term (EurOtop) to encompass wave period into run-up estimations.

The motivation to carry out an analysis of run-up elevations in this study, was to identify any possible exaggerated effects on the morphological response of the shoreline due to a bimodal wave spectrum at Pevensey. Bimodality has been previously shown to have significant effects on wave run-up elevations during storm events, often resulting in unexpected magnitudes of erosion along the coastline (Bradbury et al., 2007). For locations exposed to a wave climate containing a distinct double peaked spectrum, with substantial energy at low frequencies; the modelled morphodynamic response under unimodal and bimodal conditions has been profoundly different (Coates et al., 1998; HR Wallingford, 2016). Whereas, the limited difference between measured and modelled profiles observed in this study through the sensitivity analysis of wave spectrum (*cf* Section 6.3.1), can be attributed to the lack of long period swell wave energy propagating up the English Channel to Pevensey (Polidoro et al., 2018). A peak swell period ($T_{p\ swell}$) of 15 to 20 seconds has been observed in some previous studies (Bradbury et al., 2007; HR Wallingford, 2016), compared to a $T_{p\ swell}$ of 10.1 and 10.5 seconds for the two storms modelled in this study (2011 and 2014 respectively).

The differing morphological principles which underpin the processes in both models used in the study, may go some way to explaining the variance in predicted shoreline response observed in Chapter's 5 and 6. XBeach-G has been designed principally for pure gravel beaches, with much of its validation focussed on relatively homogenous fine and coarse gravel profiles (McCall, 2015). Yet, despite an increasing number of studies applying XBeach-G to MSG beaches (Bergillos et al., 2016; Brown et al., 2019); the model contains

little consideration for a fine sand fraction in the sediment composition. With the morphological processes across the entire cross-shore profile being represented by one single grain size (D_{50}) and hydraulic conductivity (K) value. In contrast to this, Shingle-B developed at HR Wallingford, is designed with the aim of representing the majority of shingle beaches around the UK coastline (HR Wallingford, 2016). As a default in the model setup, Shingle-B describes a sediment grading curve using grain size values of, D_{50} (0.0125m) and D_{10} (0.0028m). The grading of sediment in the profile defined by the input parameters above, is therefore the governing factor on the permeability of the shingle profile in the model.

It is well understood that sediment transport processes on MSG beaches differ to that of pure gravel, most notably through the presence of fine sand in the profile and its effect on permeability (Costa et al., 2008; Almeida et al., 2014). This was apparent in many of the predicted XBeach-G profiles, as individual morphodynamic features down the cross-shore profile were often poorly recreated. The increase in elevation between the simulated and measured berm formation in the upper beach, indicates the model was overpredicting the onshore transport of sediment; which is associated with the infiltration of uprush velocities through a well sorted gravel surface (Horn, 2002). In addition to this, in almost all post-storm profiles an accretion of sediment occurred in the middle of the foreshore slope. Despite this, both models predicted varying magnitudes of erosion around this elevation, greatly reducing model performance for the whole profile. It may be the case that on the MSG beach at Pevensey, fine sand is filtered out of the upper barrier during storms and deposited by the backwash to the intertidal zone. Wave asymmetry due to infiltration losses; means the larger grain sizes moved onshore by a strong uprush bores are not kept in suspension by a relatively weak backwash (Mason and Coates, 2001; Buscombe and Masselink, 2006). With no consideration of fine material, these key processes are absent from the swash zone dynamics in both models. The study by She et al (2006) highlights this issue, concluding that small increases in the fine sand fraction drastically reduce the hydraulic conductivity; with a fine fraction of 30% or more is said to exhibit the same K properties as a homogenous sand sample. That being said, a post storm survey of sediment samples down the cross-shore profile would be required to reach an accurate conclusion on this issue (Roberts et al., 2013). These findings are concurrent with the study by Brown et al (2019), modelling the morphodynamic response of relative sea-level change and storm events. Where a high model performance was achieved through calibration, yet the recreation of MSG transport processes and individual cross-shore features was less accurate.

However, in some cases within the literature, the influence of fine sand amongst the upper surface gravel layer has been shown to have insignificant effects on morphological change; with the coarse gravel fraction dominating the swash zone processes (Bergillos et al., 2016). And that MSG beaches respond very similar to that of pure gravel beaches in the event of a significant storm period (Pontee et al., 2004). This is reflected in the XBeach-G model outputs to a certain extent; through the sensitivity analysis of grain size and hydraulic conductivity (*cf* Sections 6.1.1 - 6.1.2). Calculated model skill and performance parameters for the entire output profile, indicate that the largest input grain size ($D_{50} = 0.021$m) was quantitively the most effective at predicting shoreline response for most scenarios in the sensitivity study. Despite this, for the application of the model as an engineering tool; the predicted erosion or accretion of features such as the barrier crest, may be of more importance than that of the overall response of the profile.

There is considerable variability in both the spatial extent of measured erosion and accretion, as well as discrepancies between measured and modelled volumetric changes in beach sediment; both of which could be attributed to the varying magnitude of wave expose along the frontage of the barrier at Pevensey Bay (Burvingt et al., 2017). Pevensey Bay like many beaches along the South coast of England is partially exposed to significant swell events which propagate from the SW up the English Channel. A greater of exposure at the Eastern extremity of Pevensey Bay results in an increased wave energy at the shoreline, which could promote differing transport processes to the Western end. Despite this, both models exhibit an alongshore uniformity in hydrodynamic conditions and subsequent morphodynamic processes, therefore predicted volume changes are similar much the same across the barrier (McCall et al., 2014).

7.2 Limitations

Despite the results detailed in Chapter's 5 and 6 demonstrating both models are able to recreate morphological response to storms at Pevensey reasonably well, it is important to consider what assumptions are being made and the subsequent limiting factors on model performance. Some of which are limitations relevant to the application of both XBeach-G and Shingle-B to all gravel barriers, whereas others are specific to the environment at Pevensey Bay.

7.2.1 Secondary Data

The data used in this study to force the model boundaries and validate model outputs was acquired from a secondary source, so the first limiting factor would be the error associated with the data collection methods. As previously mentioned, the CCO surveys used for model validation were collected via RTK-GPS for the 2011 storm and the laser scanning technique for the 2014 storm event, with respective instrumental errors of 0.03m and 0.015m. However, this magnitude of error is shown to be insignificant compared to the assumptions made in model equations (McCall, 2015). A second and potentially more significant limiting factor is the time lag between the storm event and the collected pre-storm and post-storm surveys. In an idealistic sense, post-storm profiles used for model validation would be collected immediately after the storm has occurred, in order to best represent the morphodynamic response of the shingle barrier to the wave climate. Yet, a bi-annual schedule for beach surveys carried out by the CCO, meant a respective time delay between the storm and post-storm profile for the 2011 and 2014 events, of 10 days and 5 weeks. It is therefore assumed for the model validation process, that these profiles represent the morphodynamic response of both storms at Pevensey; where in reality, further transport of sediment could have occurred due to hydrodynamic forcing in this time period.

Poate et al (2015) carried out a study analysing the effects of the 2013/2014 storms on gravel coastlines around the Southwest of England. Results from the study demonstrated the ability of beaches to partially recover the volume of sediment lost, at timescales as short as two days in response to individual storm events. The recovery of the beach was shown to be generally limited to accretion of the lower profile under less energetic conditions. A similar study of MSG beaches by Ciavola and Castigilone (2009); showed that the initial recovery of the profile on the timescales outlined above, was principally made up of fine sand deposition forming a berm in the intertidal zone. Both of these studies highlight the limitation of the time lag between the storm event and the collected post-storm profile. As well as possibly providing an explanation for the substantial volume of sediment observed in the middle of the intertidal zone after the storms at Pevensey.

7.2.2 Model Assumptions and Boundary Conditions

The first significant assumption which this study has made for the application of both models at Pevensey, is that sediment transport during storm periods is entirely restricted to cross-shore movement; with no longshore component (McCall, 2015; HR Wallingford, 2016).

Assuming that the incident wave energy arrives parallel to the shore, resulting in zero net transport of sediment alongshore. The presence of Beachy Head to the West of Pevensey Bay, causes the refraction of wave energy travelling predominantly from the SW up the English Channel. This slight oblique nature of wave attack creates a net longshore transport of sediment from West to East along the frontage of the shingle barrier, in addition to the cross-shore movement of sediment during storm events (Sutherland and Thomas, 2011). The important factor is therefore the timescale of the longshore transport regime and whether this could have an effect on the cross-shore assumption made by both models.

Burvingt et al (2017) has demonstrated that along large embayed beaches with an oblique wave approach, there is often a rotational erosion of sediment which occurs across a storm event. With this effect most common on semi-exposed beaches along the South coast of the UK. Aside from the angle of incident waves, Harley et al (2015) highlighted that a variability in wave exposure along the frontage of semi-exposed coastlines can create an alongshore gradient in incident wave energy; controlling the magnitude of cross-shore transport on the beach. To further explore this potential limitation at Pevensey, the laser scanned beach survey data (Resolution: 0.5m) collected from the 2014 storm event, was used to create an interpolated surface of bed level change; estimated from pre-storm and post-storm surveys (*Fig. 27*). The bed level data demonstrates a considerable alongshore variability in the magnitude of erosion and accretion of the shingle barrier in response to the 2014 storm. In general the Eastern extremity of Pevensey bay experiences more accretion of the profile, whereas considerable erosion of the bed level is exhibited at the Western end. Episodic patterns in accretion and erosion can be observed across the frontage of Pevensey Bay around the swash zone section of the profile, where 50-70% of the longshore transport is said to occur on gravel beaches (Buscombe and Masselink, 2007).

However, in the absence of a sediment budget for this region across the timescale of the storm event, it is difficult to conclude whether the alongshore variability in bed level observed in *Fig. 27,* can be attributed to a longshore movement of sediment or variances in wave forcing; due to changes in exposure and local bathymetry, varying the extent of cross-shore sediment transport (Weaver and Slinn, 2010; Harley et al., 2015). Where the offshore bathymetry is taken into consideration by XBeach-G; Shingle-B requires no such input data other than a beach profile and offshore wave conditions. Therefore the predicted wave energy would be entirely uniform across the frontage of Pevensey Bay (Polidoro et al., 2018). The importance of longshore sediment transport on cross-shore dominated beaches has been
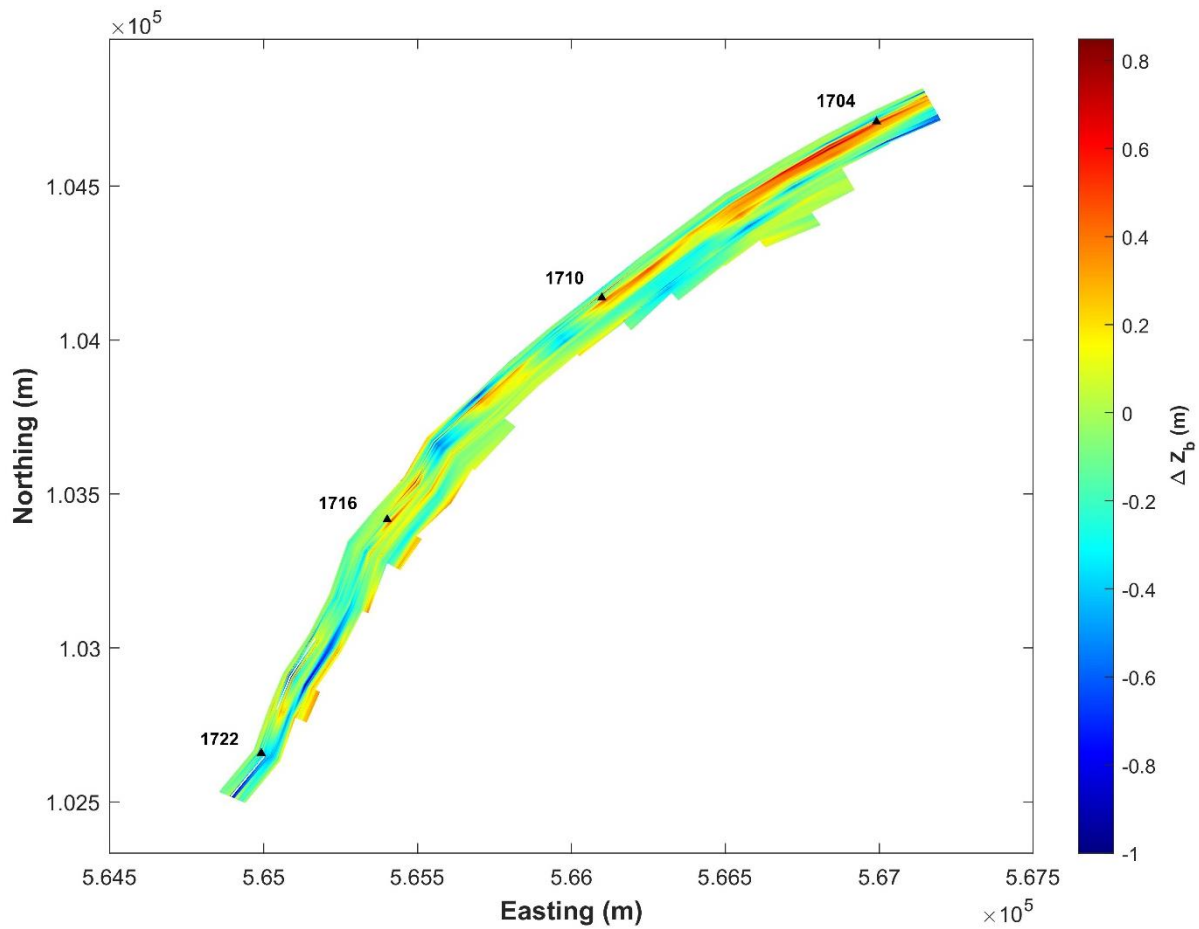
Fig. 27: Longshore variability in measured bed level change at Pevensey Bay, in response to the 2014 storm event. The extent of the bed level surface is between profile 1723 in the West and 1703 in the East, with the profiles explored in the model validation illustrated by the black triangles. Areas of red indicate an increase in bed level (accretion) and areas of blue indicate a decrease in bed level (erosion).

highlighted in the past, with Chadwick et al (2005) attributing the extensive erosion of Slapton Sands to a combination of prolonged exposure to wave energy and differential longshore transport rates.

Another limiting factor as previously touched on in Section 7.1, is the application of XBeach-G to MSG beaches such as Pevensey Bay. Concurring with the results of this study; McCall (2015) highlighted the model's ability to predict the processes associated with storm events such as wave run-up, yet the prediction of morphodynamic features in response to these forcing conditions is less effective. In addition to this, the characteristics of sediment used for this study have been obtained from a secondary data source (HR Wallingford), where one grain size value was used to a represent a shingle barrier with a distinctly variable sediment composition in both the cross-shore and alongshore direction (Watt et al., 2008).

Another consideration is the compromise made in the model setup to reduce computational power. Solving the theoretical equations which determine the processes in XBeach-G is far more computationally expensive that the empirical relationships which underpin the parametric model used in the study (Shingle-B). A total of 92 XBeach-G simulations were run for this study, emphasising the need to set-up the model to run as efficiently as possible, whilst maintaining sufficient resolution to accurately recreate the hydrodynamic and morphological processes at Pevensey.

Wave asymmetry and boundary layer streaming are processes which are computed through the interaction of the incident wave conditions and the profile at each grid point (Roelvink and Reniers, 2012). Grid resolution must therefore be reduced enough to correctly capture these processes and accurately describe how they evolve over the spatial extent of the profile. A varying grid resolution is automatically generated by the XBeach-G GUI (Deltares, 2014), from a pre-selected 0.15m at the back barrier increasing to 7-8m at the offshore boundary. The minimum recommended offshore grid resolution is $\frac{\lambda_o}{15}$ (where λ_o is offshore wavelength), to capture the hydrodynamic processes from the model boundary to the shoreline. For the wave climate in this study a peak spectral period (T_p) of 9.1s equates to an offshore wavelength of 129m; which is greater than the recommended minimum λ_o from the offshore grid size described above (λ_o = 120m). Therefore sufficient to accurately recreate the wave shoaling processes. However, the increase in resolution from the back barrier to offshore boundary, resulted in a cross-shore resolution at the lower section of the foreshore and beach step, of around 2m for the longer profiles. This could subsequently be a limiting factor in the prediction sediment transport processes at this elevation (McCall, 2015); which could in turn effect modelled erosion and accretion volumes at the top of the beach (Masselink et al., 2010).

The last consideration to be made in this section is the model limits for input wave conditions. The equations used in the model hold true for wave characteristics within certain model bounds through extensive validation; outside these limits the model assumptions may no longer be correct. For XBeach-G, this most notably concerns the required depth at the offshore boundary to ensure wave breaking does not occur. Graphical representation of this can be observed in the user manual (Deltares 2014), yet for this study a depth of 15.47m was sufficient for wave conditions during both of the simulated storm events. In contrast to this, the empirical relationships of Shingle-B are defined within much more constrained model

bounds, as the model was validated principally in laboratory flume experiments. Described by *Fig. 28*, all input wave conditions for this study were focussed in the orange section, 'Within input range but far from training dataset', illustrated by the orange thumbnail. This indicates the empirical relationships may not hold totally true for the input conditions, which ultimately affects the output profile. However, the scale is purely arbitrary and provides no quantitative description of the distance from the validated conditions.
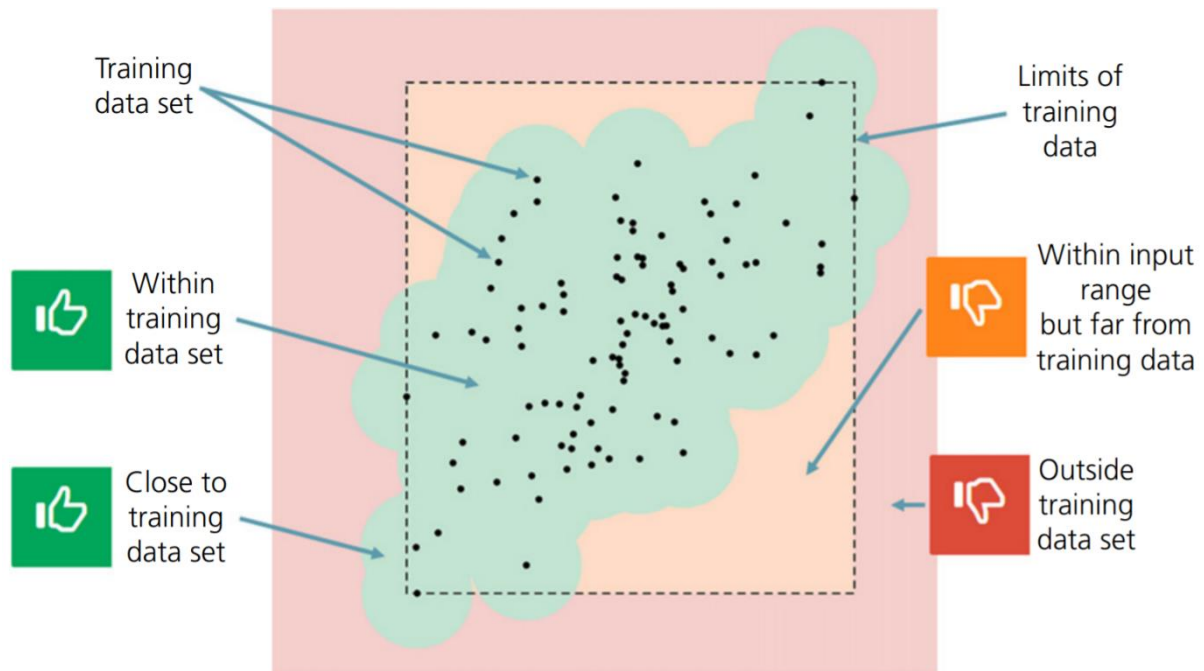
Fig. 28: Shingle-B model bounds for input wave conditions (Hr Wallingford, 2016).

7.2.3 Human Intervention at Pevensey Bay

The final and potential most influential factor which is limiting the performance of both models in this study is the human intervention, which is occurring at Pevensey Bay, through the engineering of hard structures along the coastline and the regular beach nourishment which takes place. Although not maintained Pevensey contains a series of wooden groyne structures along with a seawall and harbour at the Western end (Sutherland and Thomas, 2011). All of which act to disturb the natural equilibrium of sediment transport in the area and cannot be incorporated into the models in this study (Polidoro et al., 2018).

Regular nourishment activities take place on the frontage of Pevensey Bay, in order to maintain the crest elevation at between 6m and 6.5m (OD). This involves either bypassing of

sediment which is accumulated West of the Sovereign Harbour, or the addition of dredged shingle from an offshore bank (Sutherland and Thomas, 2011). Daily movement of sediment along parts of the shingle barrier during the winter months, creates the possibility that the measured profiles used for model validation in this study do not truly represent the shoreline response to the two storm events. Analysis of beach recharge data indicates that many of the activities tend to focus around areas of economic importance, for example the Western end of Pevensey around profile 1722 which is heavily nourished during the winter months, in part due to the downdrift erosion caused by Sovereign Harbour (Sutherland and Thomas, 2011). No recharge at any of the four modelled profiles was reported to take place during the winter of 2011, which may go some way to explaining the increased model performance (BSS) for this storm simulation. Whereas for 2014, beach nourishment occurred at profiles 1704 and 1722, with the former having a removal of 684m^3 of sediment, to the Western end of the beach. At profile 1722, extensive recharge occurred with a cumulative total of 1493m^3 being deposited at five intervals between 1/02/14 and 17/02/13. It is worth noting that this profile experienced the greatest magnitude of erosion observed across all the profiles in the 2014 validation.

Horn and Walton (2007) have highlighted the effects of beach nourishment on the on the sediment composition, with a study of Cooden Beach just East of Pevensey. Nourishment was shown to increase the fraction of fine sediment in the upper beach compared to before the recharge; where this effect is said to be far more pronounced in response to the dredging method, over simple bypassing of shingle. Reduced critical bed shear stresses due to the addition of fine material, has been shown to increase sediment transport rates for both the gravel and sand fractions; therefore an increased potential for erosion (Horn and Walton, 2007). In relation to the effect it has on the model validation phase of this study, the addition of fine sediment through nourishment would act to significantly reduce the hydraulic conductivity of sediment (She et al., 2006); which was not considered in the model setup.

7.3 Scope for Future Study

Through the validation and sensitivity analysis of both models used in this study, it is clear there are certain limiting factors which have affected model performance and should be addressed in order to successfully apply these models to shingle barriers in the future. These factors can be broken down into two primary categories; firstly, the fundamental principles of the models used and secondly, the limitations of their specific application to Pevensey.

Further development of both models has been well discussed in previous literature. For XBeach-G, McCall (2015) identifies the demand for a 2D model including longshore transport processes, as well as multiple inputs for morphological parameters, to better describe the spatial variability in MSG beach dynamics. For Shingle-B, Polidoro et al (2018) highlights the need for the validation of the model beyond the current limits of the hydrodynamic conditions, to increase the applicability of the Shingle-B to extreme storm conditions.

Specific to future work at Pevensey in response to this study, is firstly the acquisition of data to aid the model validation process. As discussed in Section 7.2.1, pre-storm and post-storm data which more accurately represents beach profile response to storm events, is required to effectively validate both models. Along with this, it may be necessary to collect primary data on the sediment composition of the profile at Pevensey, in order to better describe the properties of the beach profile in XBeach-G. Despite this study completing a model calibration to a certain extent; accurate description of sediment characteristics from primary data could be used to find the optimal model setup for the shingle barrier at Pevensey.

This study focussed on the validation of XBeach-G and Shingle-B for previous storm events based on the extreme wave climate they exhibited; with reasonable a model performance in certain scenarios. It therefore maybe necessary from an coastal management standpoint, for future studies to predict the shoreline evolution for a variety of return periods. Sutherland and Thomas (2011) outlines extreme wave heights and return periods for Pevensey, indicating the storms modelled in this study were at a return period of 1 in 10 years. However, considering the long-term (>50 years) management of Pevensey Bay and the uncertainty surrounding sea level rise and the increased frequency of storms (Neumann et al., 2015); it is advisable that greater return periods are explored. It is stated under the current management contract that a protection standard provided by the barrier crest (6m - 6.5m) is up to a return period of 1 in 400 years. However, the run-up elevations modelled in response to the storm simulations in this study, indicate that this barrier elevation may not be sufficient if increased wave heights were coupled with the occurrence of a spring tide levels.

Conclusions

The research carried out in this study has explored the application of process-based (XBeach-G) and parametric (Shingle-B) models, for predicting gravel beach profile evolution in response to storm events at Pevensey Bay. The simulated morphodynamic response of both models was validated using post-storm beach profile data, collected by the CCO for two extreme wave events; the 12th - 13th of December 2011 and the 14th - 15th of February 2014 (Chapter 5). In addition to this, a sensitivity analysis of morphological and hydrodynamic parameters in both XBeach-G and Shingle-B was conducted, to assess the effect of varying boundary conditions on model performance (Chapter 6). Chapter's 5 and 6 demonstrate the reasonable ability of both the process-based and parametric models to predict morphodynamic response under certain scenarios and with careful consideration of the input boundary conditions. Despite this, some morphodynamic features and the volume of sediment transport; often considered by coastal engineers as the most important factor in profile response, was simulated with less success. Through the validation of both models however, it was clear that XBeach-G was more effective in almost all aspects of predicting morphodynamic response than its counterpart in this study, Shingle-B. The response of the entire profile was simulated with the greatest skill by the process-based model in the study (max validation BSS: 0.62). Shown by the Taylor diagrams used for a quantitative summary of calculated model output skill parameters (STD, ρ and RMSD); placing XBeach-G in closer proximity to the observed point for almost all simulations. Despite this, individually observing the computed correlation coefficients (validation mean: 0.97) and RMSD (validation mean: 0.78), demonstrate that Shingle-B was still quantitively effective at predicting the response of the entire profile.

Considering the potential application of both models for an engineering purpose, it was necessary to further assess aspects of the simulated storm events; such as wave run-up elevations and the migration of cross-shore morphodynamic features. In the absence of water level measurements for Pevensey Bay, the EurOtop (2007) formula was used as a comparison to simulated wave run-up elevations. Despite a small variance between the three methods ($<$ 10%), it was clear that processes described by both models were able to recreate run-up reasonably well. Shingle-B however, slightly overpredicted this estimate for all simulations, which was shown to be an influencing factor on the overprediction of crest build-up/retreat by the model. Whereas XBeach-G was qualitatively more effective at recreating the elevation of the crest in response to the storm events. This research explores the fundamental principles

of hydrodynamic forcing on gravel beaches, from previous studies around the UK and its effect on modelling storm response. Bimodality in the wave spectrum had the greatest impact on the Shingle-B output profile, with a substantial increase in crest erosion predicted under these conditions. Despite this, the effect on the XBeach-G model was limited; which for this study was linked to the lack of long period swell waves propagating the full extent of the English Channel ($T_{p\ swell}$: 10.5s). Beside this, the alongshore uniformity in the wave forcing assumed by both models, could in part explain the overprediction of sediment transport observed in most model outputs. The embayment coastline at Pevensey Bay leads to varying levels of wave exposure along the frontage of the barrier.

Model sensitivity analysis of morphodynamic parameters in Chapter 6, highlighted both the, dependency on an accurate description of input boundary conditions for maximum model performance and also the complications when applying both of these models to a MSG environment, such as Pevensey Bay. This section was concurrent with much of the literature stating the importance of infiltration/exfiltration processes on gravel beaches, for the extent of sediment transport and the formation of cross-shore morphodynamic features. The vast overestimation of erosion volumes in the middle of the intertidal zone in all simulations has been attributed to the single D_{50} described by both models, promoting the onshore transport of sediment to the upper beach. Whereas the sediment grading at Pevensey containing a considerable fine fraction, has resulted in the seaward transport of this material in response to the storm event; which cannot be represented by the models.

This study has demonstrated the suitability for both models to be used as an engineering tool; however its use on MSG beaches has highlighted some key limitations. An adapted model which accurately describes the spatial variability in sediment characteristics is required to more effectively recreate the sediment transport processes during a storm event. In addition to this and specific to semi-exposed beaches such as Pevensey Bay, a 2D model coupling cross-shore and longshore transport components may more effectively recreate the alongshore variability in beach response; which is vital for the protection of many shingle coastlines around the UK. Aside from this, any future modelling exercises which are carried out at Pevensey would need to carefully consider the beach nourishment activities along the barrier and the effect this has on shoreline evolution.

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