COASTAL IMPACTS IN THE LEE OF A WAVE ENERGY SITE: WAVES, BEACH MORPHOLOGY AND WATER-USERS (WAVE HUB, CORNWALL, UK)

by

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Christopher Stokes

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Abstract

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The Wave Hub facility in Cornwall (South West UK) is a marine renewables test site, predominantly designed for the purpose of trialling wave energy converters prior to commercialisation. Beach water-users such as bathers and surfers are of economic importance to tourism in Cornwall, and during the Wave Hub consultation there were concerns among stakeholders that wave energy extraction would reduce the height and quality of coastal waves for surfing, as well as affecting sediment transport and beach morphology. This thesis investigates the interaction between wave conditions, beach morphology, and beach water-users, and proposes how a wave climate altered by wave energy extraction is likely to alter these interactions. A multidisciplinary research approach is adopted, involving the collection of qualitative and quantitative social data, the collection of over 5 years of physical wave and beach morphology data, and predictive modelling of the effects of an attenuated wave climate.

Quantitative, structured interview data from 403 water-users, collected at two beaches (Perranporth and Porthtowan) in the lee of Wave Hub, indicate that the population of water-users in the area is predominantly made up of surfers (53%), but bodyboarding and swimming/bathing are also popular activities (29% and 11%, respectively). In-depth semi-structured interviews reveal that water-user perceptions of wave energy extraction and its potential coastal impacts are constructed using intuitive risk perceptions, rather than technical understanding. These risk perceptions are constructed through a weighing of their perception of wave energy devices ('technology') and their perception of the coastal environment ('nature'). To investigate how waves are perceived, nearshore wave buoy measurements collected in 14 m water depth and transformed to breaking height, are compared to concurrent visual observations of mean breaker height and period. On average water-users underestimated significant wave height and period by 48% and 17%, respectively. Accounting for variations in wave perception, the wave preferences of different water-user groups are determined. Water-users are found to share a common preference towards wave
periods of 9 - 20 s, but different water-user groups are found to have different ranges of preferred wave height, which is found to govern whether wave energy extraction will decrease or increase the occurrence of preferred waves.

Previous research indicates that three-dimensional (3D) beach morphology with crescentic bar and rip features is the primary controller of surf-zone hazard, and also strongly influences the quality of surfing waves at the coast. A dataset of 5.5 years of quasi-weekly bar measurements, and quasi-monthly intertidal surveys from Perranporth beach is used to quantify seasonal to inter-annual changes in three-dimensionality. Integrated, cumulative fluctuations in wave steepness, wave power, and relative tide range that occur over seasonal time scales are shown to be well correlated to seasonal fluctuations in beach three-dimensionality. 3D morphology is well related to a disequilibrium term that predicts increases or decreases in three-dimensionality by examining the difference between instantaneous wave conditions and a temporally varying equilibrium condition, based on a weighted average of antecedent waves. This indicates that periods of wave regime change between erosive winter conditions with high steepness waves and accretive summer conditions with low steepness waves are related to the growth of 3D features, and vice versa, while extended periods with similar wave conditions drive the beach towards equilibrium.

Using a range of realistic and extreme coastal wave height attenuation scenarios determined from previous Wave Hub modelling studies, it is predicted that none of the scenarios will have a universally positive or negative effect on the occurrence of wave conditions preferred by water-users. When used to predict beach three-dimensionality at Perranporth beach, the attenuated wave climates are found to reduce the variability in three-dimensionality. Even an extreme and unrealistic level of wave energy extraction (100% energy capture) was shown to have an insignificant effect on the occurrence of preferred waves, and only under an extraction scenario where the impact was not varied with wave frequency did this level of attenuation have a significant effect on the predicted beach three-dimensionality. The inshore wave attenuation from Wave Hub is therefore likely to have an insignificant effect on wave conditions and beach morphology of relevance to beach water-users. A number of observations and recommendations are discussed for the development of a sound and robust methodological approach, which can be used to investigate the effects of wave energy extraction on beach water-users at future wave farm sites.
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\( \alpha \)  
the standard deviation (alongshore) of a contour or sandbar crests position about the cross-shore mean position

\( \dot{W}_s \)  
mean sediment fall velocity

\( \Delta x \)  
estimated data measurement error

\( \delta \)  
peak level of wave height attenuation (\% attenuation of \( H_s \) at \( T_PTF \))

\( \Delta \Omega \)  
Disequilibrium stress term

\( \epsilon \)  
surf-similarity parameter of Bauer and Greenwood (1988)

\( \gamma_b \)  
breaker depth ratio

\( \infty \)  
infinity, used to describe a flat (infinite width) WEC PTF

\( \lambda_{xy} \)  
smoothing scales used for quadratic loess interpolation scheme

\( \mu \)  
the central frequency of the Gaussian distribution used to model wave attenuation at different frequencies

\( \Omega \)  
dimensionless fall velocity parameter of Gourlay (1968) and Dean (1973)

\( \Omega_{eq} \)  
equilibrium dimensionless fall velocity

\( \phi \)  
decline parameter that controls wave parameter weighting

\( \sigma \)  
standard deviation

\( E_f \)  
water-user experience factor

\( P_{r,H} \)  
wave height perception ratio

\( P_{r,T} \)  
wave period perception ratio

\( \theta \)  
wave direction

\( \theta_p \)  
wave direction associated with peak spectral energy
\( b \) 
subscript denoting wave height at breaking

\( m \) 
subscript denoting wave height at an arbitrary depth

\( o \) 
subscript denoting wave conditions in deep water

\( CI \) 
subscript denoting a cumulative-integral wave parameter

\( LP \) 
subscript denoting a low-pass filtered wave parameter

\( WA \) 
subscript denoting a weighted average wave parameter

\( a \) 
regression parameter (y axis intercept)

\( b \) 
regression parameter (linear trend)

\( C \) 
wave phase speed

\( c \) 
regression parameter used to determine the rate of change in the DST13 beach three-dimensionality model

\( C_g \) 
wave group speed

\( D_{50} \) 
median sediment grain size

\( d_{\text{min}} \) 
the level above Lowest Astronomical Tide of the lowest water level experienced during a tidal cycle

\( E \) 
wave energy density

\( F \) 
forcing term used in the DST13 beach three-dimensionality model

\( f \) 
wave frequency

\( g \) 
acceleration of gravity

\( H \) 
wave height

\( h \) 
water depth

\( H_b \) 
breaking wave height

\( H_s \) or \( H_{1/3} \) 
significant wave height (mean height of the highest 1/3\(^\text{rd}\) of waves)

\( H_{\text{rms}} \) 
wave height calculated from the Root-Mean-Square sea surface elevation

\( H_{s,n\%} \) 
significant wave height that is exceeded \( n\% \) of the time

\( H_{\text{vis}} \) 
visual estimation of the average breaking wave height

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\( i \) the number of days prior to the present time-step

\( k \) used as a generic description of a daily-averaged wave parameter

\( m \) number of model free parameters

\( m_n \) \( n \)th wave spectral moment

\( N \) population size or length of time series

\( n \) sample size or time step number

\( P \) wave power

\( P_y \) alongshore oriented component of wave power

\( r \) regression parameter used to determine the ratio of positive to negative forcing in the DST13 beach three-dimensionality model

\( s \) wave spectral energy density

\( t \) time step

\( T_e \) mean period in the spectral distribution of energy

\( T_m \) mean wave period of the sea state

\( T_p \) wave period associated with peak spectral energy

\( T_s \) or \( T_{1/3} \) significant wave period (mean period of the highest \( 1/3^{rd} \) of waves)

\( T_{PTF} \) peak period of a Wave Energy Converter Power Transfer Function. This is the period at which energy extraction is most efficient

\( T_{vis} \) visual estimation of the average breaking wave period

\( \tan \beta \) beach gradient

\( X \) cross-shore position of a contour or sandbar crest

\( x \) used to denote measured data

\( X_b \) cross-shore bar crest location from residual bathymetry surveys

\( x_b \) used to denote predictions from a benchmark model

\( X_c \) the (corrected) alongshore averaged cross-shore position of a contour or sandbar crest
$X_i$ cross-shore pixel intensity maxima, used to detect bar position from Argus images

$x_m$ used to denote model predictions

$y$ relative attenuation of $H_s$ for a given peak wave period

AIC the Akaike’s information criterion (Akaike, 1974)

BSS the Brier Skill Score (Brier, 1950)

FDE Frequency Dependent Extraction

HFI Hydrodynamic Forcing Index parameter of Almar et al. (2010)

ICZM Integrated Coastal Zone Management

MHWN mean high-water neap tide elevation

MHWS mean high-water spring tide elevation

MLWN mean low-water neap tide elevation

MLWS mean low-water spring tide elevation

MRE Marine renewable energy

MSL mean sea level elevation

MSR mean spring tide range

ODN vertical Ordnance datum at Newlyn

PTF Power Transfer Function

$R$ Pierson correlation coefficient

$R^2$ squared Pierson correlation coefficient

RE Renewable energy

RMS the Root-Mean-Squared difference between two data sets

RMSE the Root-Mean-Squared error

RTR relative tide range parameter of Masselink and Short (1993)

TR tide range

$u,v$ cross-shore and alongshore pixel coordinates, respectively
WEC  Wave Energy Converter

x,y  cross-shore and alongshore local grid coordinates, respectively
I would like to thank my PhD supervisors, Paul Russell, Emily Beaumont, Deborah Greaves, and Daniel Conley for their endless encouragement, support, and critical feedback of my work. I met Paul back as undergraduate when I was studying the infamous Surf Science and Technology degree at Plymouth University; even then he was relentless in pointing out what was significant and interesting about the work we were doing, much to my surprise. This continued as he became my thesis supervisor (along with the equally encouraging Gerd Masselink) on the Applied Marine Science MSc degree, and now during my PhD. He inspires me and others in our department by being an accomplished academic, and also (secretly) one of the most successful competitive surfers to have come from the UK. Emily has provided the perfect ying to Paul's yang, and has shown me the value and rigor in qualitative research. She also braved the wind and rain when helping me collect many interview responses on the beaches of Cornwall, and reminded me that it was not so ridiculous to be asking people what they thought of the waves that day. This PhD would never have existed without your combined scientific interests, and it would have been infinitely less fun without your light-hearted chats about surfing and knitting.

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Authors Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee. Work submitted for this research degree at Plymouth University has not formed part of any other degree either at Plymouth University or at another establishment.

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Relevant scientific conferences and symposiums were regularly attended at which work was presented; external institutions were visited for consultation purposes and papers were prepared for publication.

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Christopher Stokes

Date .................................
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Chapter 1

Introduction

1.1 Preamble

1.1.1 UK Marine Renewables

In the United Kingdom and across the world, there is an ever increasing demand for energy. To help meet this demand the UK government plans to install sufficient renewable energy capacity to supply 15% of the UK’s gross energy consumption by 2020 (H.M. Government, 2009). This has been incentivised by EU targets to help mitigate climate change and improve energy security (Commission of the European Communities, 2008). Marine renewable energy (MRE) is abundant in the UK (Fig. 1.1); the exploitable wave and tidal energy capacity is calculated at 50 TWh/y and 21 TWh/y respectively, equating to approximately 20% of the UK’s electricity needs in 2011 (Carbon Trust, 2011). The South West region of the UK has a particularly large potential for marine energy capture. Its abundant and mixed marine energy resources (Fig. 1.2) resulted in its designation as the UK’s first marine energy park in 2012 - the South West Marine Energy Park (SW MEP). The SW MEP aims to enhance collaborative partnerships between government, industry and academia, and comprises a geographic region encompassing Bristol, Cornwall and the Isles of Scilly, in which a variety of MRE technologies can be developed in favourable conditions.

Despite the governments intentions, the uptake of all forms of renewable energy has been slower than was hoped, and it has been widely observed that local opposition from stakeholders and the general public has created a considerable barrier to terrestrial projects in the UK (Walker, 1995, Bell et al., 2005, Devine-Wright, 2005, Wolsink, 2006, Wustenhagen et al., 2007, Haggett, 2008, McLachlan, 2009). Additionally, the physical separation of offshore installations from communities has not allayed concerns or opposition, as might have been expected (Wustenhagen
Figure (1.1). Annual mean wave power (kW/m of wave crest, left panel) and tidal power (kW/m², right panel) around the UK (adapted from Department for Business Enterprise & Regulatory Reform (2008)). Wave data was derived from 7 years of model output from a second generation spectral wave model with a 12 km resolution. Tide data was modelled using the POL HRCS model, with a resolution of 1/60° latitude by 1/40° longitude. The white line indicates the model extents. The dashed rectangle indicates the geographic region of the South West Marine Energy Park shown in Fig. 1.2.

It seems that visual, audible and other proximity-dependent impacts that are often associated with terrestrial renewable energy installations are far from the only issues that can rouse opposition to offshore renewables. With the optimistic EU and UK targets for MRE installation, the occurrence of public and stakeholder oppositions to projects is likely to be an on-going issue that will need to be dealt with case by case. In particular, interactions with coastal stakeholders are likely to increase if the relatively new MRE sector expands at the target rate.

1.1.2 Potential Effects of Wave Energy Extraction

The broad range of possible impacts of extracting energy from ocean waves have been discussed for a number of decades. Early texts on marine renewables proposed that impacts from wave farms could include hazards for navigation, an eyesore on the horizon, possible effects on oxygenation, mixing, and thermal stratigraphy, not to mention “severe and unacceptable” consequences to littoral transport (Brin, 1981,
Figure (1.2). Map of the UK’s South West Marine Energy Park (adapted from Regen SW (2014)), showing the mixture of wave, tide and wind resources and Local Enterprise Partnerships (LEPs) in the region. Geographic location of this figure is indicated in fig. 1.1. The dashed circle indicates the location of Wave Hub, just offshore of Hayle in Cornwall. The wave energy converter pre-deployment test site ‘FaB test’ is also indicated.

Wick and Clarke, 1981). It was suggested that a Wave Energy Converter (WEC) would act in a similar way to a breakwater, and in addition to the possible negative impacts, potential benefits could therefore result from a reduced wave climate in their lee. These include providing shelter for shipping and a reduction in coastal erosion. These initial propositions were well founded on the assumption that generating electrical energy from ocean waves will cause an energy deficit in the shadow region in the lee of WECs. Linear wave theory states that the mean energy density carried by ocean surface gravity waves is proportional to the wave height squared (Phillips, 1977). As such, extracting energy from a wave field will lead to a reduction in the height of the waves that are transmitted through the wave farm. In addition there are likely to be effects on wave frequency (Alexandre et al., 2009, Smith et al., 2012, O’Dea and Haller, 2014) and direction (Monk et al., 2012, 2013), which are less well understood.

Naturally this has raised some concern with regards to physical coastal impacts, as altering the deep water wave climate will change nearshore conditions as waves propagate to the coast. An altered inshore wave climate could elicit knock-on effects to beach morphology and sedimentation as wave height, wave period and wave
Figure (1.3). Location of Wave Hub off the coast of North Cornwall (adapted from www.wavelhub.com). The filled red circle indicates the position of Wave Hub, while the white filled box indicates the exclusion zone within which wave energy converters will be moored. The dashed line indicates the sub-sea cable joining Wave Hub to the national electricity grid at Hayle.

direction are the key parameters that control longshore sediment transport (US Army Corps Of Engineers, 1984), and modal beach state (Wright and Short, 1984). Altering coastal waves and beach morphology will have an effect on the surf-zone’s amenity (quality of surfing waves) and safety (presence of rip currents) for coastal water-users. As visual and noise impacts are likely to be alleviated by the distance of an offshore wave farm from the coast, any effect on waves and beach morphology are likely to be the physical impacts that are most apparent and relevant to people at the coast.

1.1.3 Wave Hub Controversy

The Wave Hub facility in Cornwall (Figs. 1.2-1.4) is a marine renewables test site, predominantly designed for the purpose of trialling wave energy converters (WECs) prior to commercialisation. The infrastructure was installed in 2010 (Wave Hub, 2010) and a number of device developers plan to install full scale prototypes in 2015 (Wave Hub, 2013a, 2014). These include point absorber (http://www.seatricity.net/) and rotating mass (http://www.wello.eu/) type WECs, and there is also a possibility of floating offshore wind devices being trialled there (Wave Hub, 2013b). During the proposal stages the Wave Hub project met objections from commercial fishing, shipping and tourism stakeholders, but the greatest objections came from the UK surfing community. The North coast of Cornwall is a popular area for coastal recreation, and during the Wave Hub consultation there was an outcry from a collective of UK surfers who were concerned about wave energy extraction reducing wave height
and wave quality, as well as affecting sediment transport (Baxendale, 2006, Farwagi, 2006). This group rallied over 500 emails of objection (McLachlan, 2009) via a surf forecasting website, arguing that the project would be better sited elsewhere, as the value of the electricity generated would be far less than the value of the surfing industry in Cornwall considered to be threatened by the project (Baxendale, 2006, 2007). It is unclear whether these concerns were only limited to Wave Hub as a test site, or extended to full commercial deployments that may occur in the future.

Although not all surfers and coastal water-users shared this objection (for example environmental group ‘Surfers Against Sewage’ supported Wave Hub following wave modelling results (Surfers Against Sewage, 2009)), it nonetheless raised concern among many of the Wave Hub stakeholders. West et al. (2009) point out that this was not a trivial objection by what appears to be a self-concerned recreational group; there are many coastal communities in the South West that are dependent on the economic income from surfing. Coastal water-users will have both shared and individual concerns about coastal impacts from MRE installations, and despite a disjointed opposition from water-users over Wave Hub, there is a possibility that future proposals could meet a far more collective opposition from this stakeholder group (West et al., 2009).

The concerns of water-users with regards to Wave Hub as a test facility therefore need to be fully understood, including the processes through which concerns have come about and have been altered. This will better inform consultation and avoid opposition from this group if larger commercial MRE deployments are proposed in the future. The potential for wave energy extraction to alter the specific wave conditions and beach morphology that this stakeholder group interacts with during visits to the coast also needs to examined. Only then can the impact to water-users be properly assessed, and future consultation with this stakeholder group be optimised. In the context of the present research, water-users include surfers, bathers, bodyboarders, swimmers, kayakers, rowers, sailors, kitesurfers, paddleboarders, windsurfers and other participants in recreational or commercial activities that use the nearshore or surf-zone environments at beaches, and will therefore often be referred to as beach water-users.

1.2 Aims and Structure of Thesis

1.2.1 Aims

The overarching aims of this thesis are to investigate the interaction between wave conditions, beach morphology, and beach water-users, and to propose how a wave
Figure (1.4). Schematic of the installed Wave Hub infrastructure, and proposed renewables devices (from www.wavehub.co.uk). The schematic is not to scale; in reality the Wave Hub is situated some 15 km offshore of the substation at Hayle, and 10 km from the nearest coast at St Ives. Each of the four births at the site will be able to accommodate an array of WECs, rather than a single device as depicted above.

Climate altered by wave energy extraction is likely to alter these interactions. A conceptual model linking these key themes is presented in Fig. 1.5. The Wave Hub provides a case study for this research, but as WECs are yet to be deployed at Wave Hub, it has not been possible to measure their physical effects during this project. Instead, a variety of data have been collected to increase our understanding of the natural coastal system, and the interaction that coastal water-users have with it. Of equal importance to investigating the physical and social impacts of Wave Hub, is developing a sound and robust methodology that can be used to investigate such effects at future wave energy sites. Where possible the findings and methods from this work are therefore generalised, with the aim being to provide insight into the point at which future, larger-scale deployments will begin to have a significant effect on the coastal zone and the people that use it.

A review of literature relevant to the social and physical factors involved in wave energy extraction is provided in Chapter 2, and is briefly summarised in Section 1.4 of this chapter. Following this review four main thesis objectives were defined:
1. Investigate the concerns of beach water-users with regards to potential coastal impacts from wave energy extraction.

2. Determine how different beach water-user groups perceive and use the surf-zone environment.

3. Investigate how beach morphology of relevance to water-users varies in response to changes in wave climate.

4. Predict changes to waves and beach morphology of relevance to water-users under different wave energy extraction scenarios.

### 1.2.2 Structure

As the research aims encompass both physical and sociological lines of enquiry, this thesis is multidisciplinary by necessity. A mixed methodology is therefore used, including qualitative interviews, quantitative interviews, and the collection of a multi-year beach morphology and wave condition data set. Given the diversity in the methods used, a single methodology chapter is not provided. Instead, each chapter will outline the specific methods employed for that chapter. The structure, objectives, key data collection, and research outputs from the eight thesis chapters are depicted in Fig. 1.6. Section 1.2.3 further summarises the chapters.

![Conceptual model of the key themes studied in this thesis.](image-url)
Figure (1.6). Thesis structure.
1.2.3 Chapters

- **This chapter** introduces the themes and research questions underpinning the thesis. Overarching aims are identified, and used to inform four key research objectives.

- **Chapter 2** provides a review of the literature relevant to the aims and objectives of the thesis. Gaps in the relevant literature that may be filled by this research are identified.

- **Chapter 3** explores the physical coastal impacts that are anticipated by beach water-users in the lee of Wave Hub using interview data and a qualitative research approach. The reasoning process used by the participants is used to develop a conceptual model that explains when a negative impact to the coastal environment is likely to be anticipated.

- **Chapter 4** presents the results of a quantitative interview survey conducted at two study sites in the lee of Wave Hub. The questioning is developed from themes that emerged in chapter 2 and examines the perception of wave conditions and the wave resource in the region. Wave conditions preferred by different water-user groups are identified.

- **In Chapter 5** the collection of a multi-year data set of beach morphology is described. This data is used to examine the temporal signature of changes in beach three-dimensionality, a parameter that is used as a proxy for the safety and amenity of the surf zone for water-users. The morphological time series are compared to a variety of wave and tide parameters to establish which conditions are conducive of high and low beach three-dimensionality.

- **In Chapter 6** the morphodynamic relationships identified in chapter 5 are used to develop a predictive model that can explain changes in beach three-dimensionality from wave and tide data, over seasonal and inter-annual time scales.

- **Chapter 7** integrates the findings of Chapters 4 - 6 by predicting how the preferred wave conditions identified in chapter 4, and the three-dimensional morphology measured in chapter 5, may be altered by wave energy extraction. Realistic and extreme wave extraction scenarios are developed and used to assess the inshore wave climate and drive the model developed in Chapter 6. The likely magnitude and significance of the predicted impacts are discussed.
• **Chapter 8** provides a synthesis of the previously outlined work, and ties together the various themes that are explored in the thesis. New insights and findings from the research are described. Recommendations for research and consultation at future wave energy sites are discussed.

• **In Chapter 9** Conclusions from the thesis are made.

### 1.3 Study Region

The selected region for this research encompasses a 13 km stretch of coastline in North Cornwall (UK), between Perranporth and Porthtowan. These beaches are heavily used by coastal water-users such as surfers and bathers year round, and have particularly large beach and in-water populations in the summer. This region was selected because worst-case-scenario wave modelling has indicated that the wave shadow from Wave Hub will potentially be most acute over that stretch of coast (Millar *et al.*, 2007, Li and Phillips, 2010), as demonstrated in Fig. 1.7. Perranporth and Porthtowan were chosen for monitoring of beach morphology at the onset of the Wave Hub project, and an almost unbroken series of monthly surveys have been conducted at each site since February 2008. Previous observations from the data set are described by Poate *et al.* (2009), Poate (2011), and Poate *et al.* (2014), and the morphological data collected for this thesis is a continuation of that data set. Both beaches are W-NW facing and are fully exposed to the dominant Westerly wave approach, receiving an energetic wave climate of Atlantic swell and locally generated wind seas (Davidson *et al.*, 1997). The directional wave rider buoy, maintained by the Channel Coastal Observatory (www.channelcoast.org) and located just offshore of Perranporth beach (Fig. 1.8) in approximately 14 m depth, measured mean and maximum significant wave height ($H_s$) of 1.6 m and 7.2 m respectively, and mean peak period ($T_p$) and direction ($\theta_p$) of 10.6 s and 283° respectively, between January 2007 and May 2014. The North Cornwall coast is macrotidal, with mean neap and spring tide ranges of 3.1 m and 6.1 m respectively.

At spring low tide Perranporth beach has a cross-shore extent (dune foot to water’s edge) of approximately 0.5 km and an alongshore extent (headland to headland) of 3.4 km, while at high tide the upper beach is constrained in the small southern portion of the beach (Fig. 1.8). The beach is composed of medium quartz sand with a median grain size, $D_{50}$, (mean fall velocity, $\bar{W}_s$) of 0.35 mm (0.04 m/s) at the mid tide region (Poate *et al.*, 2014). Devonian hard rock cliffs surround the beach, but the southern and northern ends of the beach are backed by a steep vegetated dune system. Perranporth has a shallow lower beach gradient ($\tan \beta \approx 0.012$), but com-
Figure (1.7). Geographical location of the study sites, and a worst-case-scenario modelling prediction of wave shadowing from the Wave Hub facility, adapted from Millar et al. (2007). Contour lines show the predicted change in significant wave height under a 0% energy transmission scenario at Wave Hub. Reference state: $H_s$ 3.3 m, mean wave period ($T_m$) 11 s, from direction 269° from North, using a JONSWAP spectrum with a directional standard deviation (spreading) of 30°.

pared to the subdued (< 1 m vertical range) and alongshore-uniform changes that characterise the upper beach morphology, the region below mean-low-water-spring (MLWS) is highly dynamic (2 m vertical range), and regularly exhibits pronounced crescentic bar and rip features (Poate, 2011, Austin et al., 2013, Masselink et al., 2014). It is categorised as a low tide bar and rip beach (Scott et al., 2011), and features a double bar system (Poate, 2011, Masselink et al., 2014).

Porthtowan beach extends from a valley of Devonian rock, and features a highly embayed, geologically-constrained upper beach. The cross-shore extent of the beach is approximately 0.4 km at spring low tide and the lower beach is much more expansive (1.1 km alongshore) than the upper, and connects at the north to another partially embayed beach (Chapel Porth). The sediment is medium quartz sand with gravel at the upper beach, and has a $D_{50}$ ($W_s$) of 0.38 mm (0.05 m/s) at the mid tide region (Poate et al., 2014). Boulders are often exposed at the upper beach following erosion of the sand layers. As with Perranporth, the lower beach has a shallow gradient ($\tan \beta \approx 0.015$) with a double bar system that can feature well developed rips.
that are often located in proximity with the headlands of the embayment (Poate, 2011).

In addition to the morphological data collected at these beaches (described in chapter 4), Perranporth and Porthtowan were also used for collection of social data, namely in depth semi-structured interviews (described in chapter 2) and a quantitative interview survey (described in chapter 3). Two additional semi-structured interviews were conducted in the village of St Agnes, in the centre of the study region. A map indicating the location of the study sites, and the data types collected at each site, is presented in Fig. 1.8. The location of Wave Hub is also indicated, along with the Sevenstones lightship which provided deep-water wave measurements, and the Perranporth wave buoy which provided inshore (\(\sim 14\) m depth) coastal wave measurements. Low tide images of Perranporth and Porthtowan are presented in Fig. 1.9, demonstrating the spatial extents of the two main study sites and the surrounding geology.

1.4 Potential Effects of Wave Energy Extraction on Water Users – A Brief Introduction

The degree to which existing marine uses will clash with wave energy extraction depends on whether the uses are mutually exclusive, or whether they can co-exist to some extent (Kim et al., 2012). Local stakeholders in wind farm installations have historically been most concerned about visual and audible impacts from wind turbines (Pedersen and Persson Wave, 2003, Devine-Wright, 2005, Pedersen et al., 2007), but at this early stage in the development of wave energy, beach water-users are already voicing a completely unique set of concerns over the potential physical impact to waves (Baxendale, 2006, Farwagi, 2006, Baxendale, 2007, McLachlan, 2009, West et al., 2009, Bailey et al., 2011). The Wave Hub controversy may have only involved a vocal minority from the water-using community, but it demonstrates that even a relatively small-scale wave farm can instigate significant opposition at distant surfing beaches. Considering the ambitious targets that the UK and other governments have set for marine renewables installation (H.M. Government, 2009), and the relatively low energy density that these technologies can presently provide (Wustenhanagen et al., 2007), there is likely to be a widespread increase in the number of projects proposed around the world's coastlines in the coming decades. As Wave Hub demonstrated, regions with an optimal wave resource for energy extraction can also be highly valued by beach water-users who have a shared interest in the wave resource. As a result, future interactions between wave energy projects and beach
Figure (1.8). Map of the three sites used for data collection, Porthtowan, St Agnes, and Perranporth. Shaded grey areas depict the beach extents. Data types collected at each site are indicated by the following symbols: ▲ = inshore wave data, ⊕ = morphological surveys, ◆ = remote video imagery, ◎ = quantitative interviews, ⚫ = semi-structured interviews. The ▼, ○, and red square in the inset map indicate the location of the Sevenstones deep-water wave measurements, Wave Hub site, and extents of the main map, respectively.
water-users are inevitable.

The Wave Hub provides an ideal case study with which to examine the variety of physical impacts that concern beach water-users. While a number of articles have sought to explore the opinions and attitudes of the general public towards wave energy extraction (McLachlan, 2009, West et al., 2009, Bailey et al., 2011), at present only a few interviews with members of the surfing community (Black, 2007, McLachlan, 2009, West et al., 2009, Li and Phillips, 2010), and one questionnaire survey of 400 coastal visitors (Voce et al., 2013) make up our entire understanding of the opinions of coastal water-users. To predict the effects of wave energy extraction on beach water-users and tailor effective consultation with them as a stakeholder, a more detailed understanding is needed of the wave and beach conditions that are of key interest to them. However, at present their use and perception of the marine environment is poorly understood (West et al., 2009). In studies which have modelled wave impacts from WECs there has been a recent shift away from the assumption of a frequency independent attenuation of waves, towards an attenuation which varies with wave frequency (Alexandre et al., 2009, Smith et al., 2012, Rhinefrank et al., 2013, O’Dea and Haller, 2014). The relative effect that wave energy extraction will have on surfing waves can therefore no longer be assumed to depend solely on the

Figure (1.9). Low tide images from Perranporth (left panel) and Porthtowan (right panel). Note the different spatial scales in the two images.
peak efficiency of the WECs, or their distance from the coast. Consideration must also be given to the degree of overlap between a given WECs power transfer function (which describes its frequency-absorption characteristics) and the range of wave frequencies preferred by beach water-users.

The coastal effects of wave energy extraction on water-users are not limited to changes in coastal waves however; knock on effects to beach morphology could also influence water-use. Previous research indicates that three-dimensional (3D) beach morphology, with bar and rip features, significantly increases the bathing hazard for water-users by enhancing rip current circulation (Scott et al., 2008, MacMahan et al., 2011, Scott et al., 2011, Brighton et al., 2013). Interestingly, these beach types also enhance the quality of surfing conditions by increasing the angle of breaking waves to within limits suitable for wave riding (Hutt et al., 2001, Mead and Black, 2001b,a, Scarfe et al., 2003, 2009). A number of beaches in the lee of Wave Hub sit at a classification boundary, regularly transitioning from a planar two-dimensional (2D) state to a 3D state featuring crescentic bars and rip channels, due to relatively small changes in hydrodynamic forcing (Scott et al., 2008, Austin et al., 2010, Scott et al., 2011, Poate, 2011). As wave height and period are key parameters governing beach state (Wright and Short, 1984), changes in either parameter caused by wave energy extraction could alter the morphological state, bathing hazard, and quality of surfing waves at these beaches considerably.

Sitting at the dissipative-intermediate end of the Wright and Short (1984) beach state model, reductions in wave height are usually associated with increases in beach three-dimensionality at these sites (Poate, 2011, Poate et al., 2014). Wave energy extraction could therefore increase bathing hazards, while also potentially improving beach morphology for surfing at these types of beaches, contrary to the original concerns that wave quality may be degraded. Although the effects of wave energy extraction on beach sedimentation have now been modelled in a number of studies, the potential for wave farms to affect beach morphodynamic state has only been studied in two peer-reviewed publications (Poate, 2011, Abanades et al., 2015). In addition, validated predictions of short and long term changes in beach three-dimensionality have not yet been achieved. The likely effect of wave energy extraction on wave conditions and beach morphology of relevance to water-users will therefore be examined in the present research.
Chapter 2

Review

2.1 Public Perception of Marine Renewable Energy

2.1.1 Attitudes to Renewable Energy Technology

The first research into public attitudes and perception of renewable energy (RE) was conducted in the 1970’s and 1980’s when terrestrial renewable energy from wind turbines became increasingly common. As wind technology is now one of the most mature forms of RE, it also has the greatest volume of social research associated with it. With recent increasing interest in marine renewables, existing terrestrial and offshore wind farm projects have been looked upon to provide guidance with respect to public perception, attitudes and acceptance of marine renewables. Initially wind farm developers were unconcerned about the potential for public opposition, as high general levels of support had previously been shown for the technology. However early research conducted by Carlman (1982, 1984) quickly showed that despite this broad acceptance of wind farms, public and stakeholder support for specific projects could not be assumed. From these early findings, three key areas of social acceptance of RE have been identified, namely: broad socio-political acceptance, local community and stakeholder acceptance, and market acceptance of the technology (Wustenhagen et al., 2007). Each of these can individually affect whether a renewable technology or renewables siting is able to progress to fruition, and acceptance in one area does not guarantee acceptance in another.

As one of the primary purposes of renewable energy technology is to mitigate climate change, the socio-political and community perception of renewables is undeniably linked to the perception of climate change. West et al. (2010) examined three cultural attitudes towards climate change that have been identified in the literature, and used them to categorise interviewee discourses about renewable energy. Those whose discourse exhibited ‘Individualist’ attitudes had little concern about climate
change, seeing climate as naturally fluctuating, and therefore did not see an envi-
ronmental need for RE technology. Those with a ‘Hierarchist’ attitude saw climate
change as a pending issue, but viewed the installation of RE as a government con-
cern, that they had little responsibility towards. Lastly, those with an ‘Egalitarian’
attitude viewed climate change as an apocalyptic issue that would affect society in
coming generations, and therefore felt a strong moral obligation towards installing
RE. Clearly public perception of renewables is not therefore homogeneous, although
Devine-Wright (2005) suggests that this may have been mistakenly perceived in
the past, resulting in ‘one-size-fits-all’ public engagement that was poorly received
(West et al., 2010). Furthermore, such cultural attitudes (‘world views’) are subject
to change (West et al., 2010), and attitudes towards RE in a broad sense can vary
from attitudes to individual RE proposals. A ‘U’ shaped curve has been used to
describe a common pattern observed in stakeholder opinions of wind farm technol-
y: initially high general levels of support for a wind technology are shown, then
once a project is proposed at a specific location attitudes toward the technology
become more critical. Sometime after the technology has been installed, attitudes
are seen to be more positive again, as the installation is increasingly accepted by
the community (Wolsink, 1994, 2007).

The term ‘Not In My Back Yard’ (NIMBY) is a concept that has often been
used to explain such opposition to local industrial development. This claims that
people might support a technology until a local installation is proposed, at which
time they oppose the project for selfish reasons (O’hare, 1977). This concept has
been widely criticised in RE research however, for being a blanket explanation used
to discredit sometimes quite valid and varied arguments against a project (Wolsink,
proximity to an installation does have a strong influence on public attitudes, but
argues that the nature, strength and spatial extent of the attitudes are dependent
on localised factors such as how the land is valued by the community. Land that
is already industrialised for example may not be so heavily defended by the local
community, and green technology may even be welcomed if it is perceived to increase
the innate value of the area (Wustenhagen et al., 2007). Renewable energy projects
however are often likely to invoke social opposition, as despite their green credentials
they are often harnessing energy in natural areas that are highly regarded by the
public for their scenic quality, or other natural resource coexisting with the renewable
energy. In addition to this, even modern renewables have a low energy density
when compared to fossil fuel or nuclear power plants, and their visual impact is
therefore wider-spread in comparison. Equally, more siting decisions and stakeholder
interaction will be required to generate a significant amount of energy (Wustenhagen
Alternative A

Distance: 8 km, No. Turbines: 144, Number of wind farms: 5 and Cost: 40 euro/year

Alternative B

Distance: 18 km, No. Turbines: 49, Number of wind farms: 15 and Cost: 80 euro/year

I choose  A  B

Figure (2.1). Example of a choice set from Ladenburg and Dubgaard (2009), used to explore coastal users preferences to offshore wind farm siting by means of a willingness to pay methodology.

et al., 2007).

2.1.2 Attitudes to Marine Renewable Energy and Wave Hub

Compared to the vast number of studies regarding attitudes to terrestrial RE projects, there has been considerably less research into the attitudes of coastal users towards offshore renewables (Landry et al., 2012), and in particular marine (wave and tide) renewables (West et al., 2009). Offshore wind farms have been observed to invoke similar concerns about visual impacts to their terrestrial counterparts, such as the strong opposition shown by locals in Llandudno, North Wales (UK) to an offshore wind farm proposal, who perceived that it would industrialise the seascape and lessen the restorative quality of the view (Devine-Wright, 2009a). Marine renewables however present an interesting scenario, as projects can be far removed from areas of population, such as offshore wave farms, or completely submerged, such as
tidal stream turbines. They therefore have greatly reduced visual or noise impacts associated with them, which along with ecological impacts are usually the effects that most concern local stakeholders in terrestrial and offshore wind farm deployments (Pedersen and Persson Waye, 2003, Devine-Wright, 2005, Pedersen et al., 2007, Haggett, 2008, Devine-Wright, 2009a). Perhaps because of this, a majority support has been shown for wave and tide energy at this early stage of its development. One government poll in 2003 found that 60% of respondents supported local wave and tide energy development (McGowan and Sauter, 2005), while a questionnaire survey in 2008 found that residents in three Cornish towns showed 64% and 89% support for local tide and wave development, respectively (Bailey et al., 2011). Despite this, the Wave Hub proposal instigated opposition from around 500 individuals from the UK surfing community, who objected on the basis of negative effects to surfing waves at beaches far removed from the site (McLachlan, 2009). This objection was enough to hinder the Wave Hub consenting process (West et al., 2009), and instigated a number of modelling studies to investigate the potential impacts (Millar et al., 2007, Black, 2007, Li and Phillips, 2010).

This presents a new concern which is uniquely associated with offshore renewables, and thus far has received little scientific attention: the potential to affect the recreational value of the coast. This can occur through different impacts, such as physical impacts to waves, or visual impacts to the seascape. A questionnaire study by Ladenburg and Dubgaard (2009) found that recreational coastal users were more concerned than non-recreational users about the proximity of offshore wind farms to the coast because of their visual impact (Fig. 2.1). They therefore proposed that wind farms should be positioned further from shore if they are to be installed in coastal regions with high recreational value. Such decisions are likely to be overshadowed by economic factors however, and in the case of wave farm deployments Kim et al. (2012) identified a balance between siting further offshore where the available wave power can be higher, and closer to shore where the cost of transmission to the electricity grid is reduced. Voke et al. (2013) conducted interviews with 400 visitors to the Pembrokeshire coast and found that over a quarter of respondents visits would be negatively affected if wave heights were reduced by a wave farm there. However they add that < 5% of respondents would be prevented from visiting again if this actually occurred. Although a magnitude of wave height reduction was not specified in their study, these interviews indicate that a reasonable reduction in wave height is unlikely to reduce visitor numbers significantly. This may vary with location however, and is likely to depend on how wave conditions are perceived in the region (Voke et al., 2013).

The public perception of Wave Hub has now been explored in a number of papers
Although only a test site, it is amongst the first wave energy facilities in the world, and therefore provides an early glimpse into attitudes towards wave farms. Most studies have attempted to understand positions of support and opposition to Wave Hub. In simplistic terms the objections raised by surfers are understood, as they were openly articulated during the conflict and in previous research (West et al., 2009, Bailey et al., 2011). These include concerns about reduced wave height and surfing wave quality at the coast (Baxendale, 2006, 2007), as well as a concern about the sensitivity of coastal sedimentation to such changes in the wave climate (Farwagi, 2006). However, there is a lack of understanding about whether these concerns apply to the surfing and water-using community as a whole, and how these concerns might change or develop when future wave farms are proposed.

One of the key arguments from the Wave Hub objectors was that the surfing industry supposedly threatened by Wave Hub is worth more to the economy of Cornwall than the relatively modest 30 MW of electricity that Wave Hub will generate (Baxendale, 2006, 2007). This economic argument has since been reiterated in interviews with other members of the surfing community (McLachlan, 2009, West et al., 2009). The economy of Cornwall is heavily reliant on tourism, which provides around one in five jobs in the region (Visit Cornwall, 2010) and many of its coastal communities are dependent on the economic income from surfing (estimated at £21 million in Cornwall by Arup (2001)), or some form of water based activity (estimated at £300 million in Cornwall by the Environment Agency (2007)). A survey conducted in 2004 estimated that annual turnover from the surfing industry in Cornwall was higher than that of the sailing and golf industries in the region (Surfers Against Sewage, 2009). Generation of local jobs was also one of the arguments used to support Wave Hubs development however (McLachlan, 2009, West et al., 2009), and the economic status of Cornwall has therefore been used as a leverage point by both supporters and opposers of Wave Hub. West et al. (2009) point out that the economic and recreational benefits of surfing provide valid arguments against MRE, but stress that the use and perception of the marine environment is poorly understood.

The Wave Hub objectors proposed that the facility would be better sited elsewhere, which at first glance fits well with the NIMBY branding; however it has been shown that the concerns were related to the high value placed on the surfing resource in the region by the surfing community. This sentiment is embodied in a quote from an interview on support and opposition to Wave Hub - “You don’t do a chemistry experiment in your best china” (McLachlan, 2009). The perception was therefore that the highly valued surfing resource in Cornwall was about to be
subjected to a test facility with unknown outcomes. ‘Place-protective action’ is a concept that has been used to explain such opposition (Devine-Wright, 2009b). It is proposed that when changes to a place threaten to disrupt emotional attachments and aspects of identity, action may be taken by a community to avoid the changes. This provides a reasonable explanation for the concerns of surfers, who have been described as having a “passionate and emotional attachment to wave quality, surfing locations and broader concerns about the protection of marine environments” (West et al., 2009). A lack of fit between an individual’s interpretations of place and project is also thought to be a precursor to opposition (McLachlan, 2009, Devine-Wright, 2011). Being relatively broad concepts, ‘place-protective action’ and ‘place and project interpretation’, encompass the opposition raised by the surfers opposed to Wave Hub, but they struggle to predict when a particular group will take action, especially one with unique concerns such as surfers.

Such theoretical explanations have also been critiqued for ignoring ‘materialistic’ considerations (Bailey et al., 2011); indeed, it is possible that many of the objecting surfers merely saw a threat to a commodity which they use. Bailey et al. (2011) conducted a quantitative survey of public perceptions of the Wave Hub, including questions regarding the possibility of changes to wave quality. Interestingly they found that only 10% of respondents anticipated that wave conditions would be negatively affected by Wave Hub. However, the study did not target water-users, nor was it conducted in the region that is predicted to be affected by such changes. They conclude however that notions of ‘risk and reward’ better encapsulate the reasoning process that individuals use. This approach is useful, but only if an understanding exists of what an acceptable risk is to a given group. In other words, an understanding is needed of the point at which the perceived risks (e.g. coastal impacts) outweigh the perceived rewards (e.g. local economic benefits, mitigation of climate change etc.), and therefore warrant opposition. It is arguable that the perceived rewards of MRE are better understood than the perceived risks, as they are more generic across projects and stakeholder groups, whereas the risks may be more stakeholder-specific.

2.2 Effects of Wave Energy Extraction on Wave Climate

2.2.1 Effects of wave energy extraction

Although the design of WECs dates back to at least the 18th century (Ross, 1995), interest in harnessing energy from waves increased in the 1970’s during a period
of uncertainty over energy security. In particular the seminal research and design work of Stephen Salter during the oil crisis of the 1970’s greatly advanced the design of WECs (Salter, 1974). Contemporary offshore WEC designs convert kinetic and potential wave energy to electrical energy in a number of ways. For example an overtopping device captures an elevated volume of water and converts the positive potential energy via a turbine or other power take-off device (Li and Yu, 2012). Point absorber or attenuator type WECs (Fig. 2.2) use vertical and horizontal wave motion to move device components relative to one another (Waters et al., 2011, Li and Yu, 2012). The principal of energy conservation states that in the process of capturing this kinetic and potential wave energy, an energy deficit in the region behind a WEC (in the direction of wave travel) will be created, causing a shadow zone in the WECs lee where wave height is reduced.

The world’s first full scale, grid-connected offshore WEC was tested at the European Marine Energy Centre (EMEC) in Scotland by Pelamis Wave Power in 2004 (http://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/). However, due to the hostility of the ocean environment and vast costs involved in trialling a WEC in real seas, there have been few prototype-scale deployments like this globally, and all were of short duration. As a result the shadow effects from offshore WECs are yet to be properly investigated at prototype scale. Instead scaled physical models and numerical models have been used far more extensively to determine the
likely near-field (close to WEC) and far-field (close to shore) effects, respectively, of offshore wave farms. Numerical modelling of such coastal effects has been undertaken for case studies in England (Black, 2007, Millar et al., 2007, Li and Phillips, 2010, Smith et al., 2012, Gonzalez-Santamaria et al., 2013, Abanades et al., 2014b,a, 2015), Scotland (Venugopal and Smith, 2007), Spain (Carballo and Iglesias, 2013, Mendoza et al., 2014), Portugal (Le Crom et al., 2008, Palha et al., 2010, Rusu and Soares, 2013), Mexico (Mendoza et al., 2014), and the United States (O’Dea and Haller, 2014), as well as for generalised cases with idealised bathymetry (Alexandre et al., 2009).

Initially WECs were numerically modelled as partially transmitting barriers which allow a portion of wave energy to transmit through the devices. This proportion was determined by a transmission coefficient, which reduces the energy of the transmitted waves by a constant percentage across all frequencies (Millar et al., 2007, Black, 2007, Li and Phillips, 2010). These models unsurprisingly demonstrated that the near and far field attenuation of waves will therefore increase with increasing energy absorption. Wave attenuation has also been shown to decrease with increasing distance from a wave farm (Millar et al., 2007, Black, 2007, Li and Phillips, 2010, O’Dea and Haller, 2014, Abanades et al., 2015). For hypothetical wave farms with no predefined distance to the coast, the nearshore wave attenuation is therefore dependent on both the coast to farm distance, as well as the level of energy absorption at the farm (O’Dea and Haller, 2014, Abanades et al., 2015). The width of the wave farm has also been shown to affect the along-coast extent of the wave shadow (Palha et al., 2010).

In addition to these factors, wave models suggest that the directional spread of the sea state has a particularly large influence on the change in wave height at the coast (Black, 2007, Monk et al., 2013), as well as the along-coast extent of the impact (Black, 2007). Directional spreading is low for seas with a single dominant direction of travel, or high for seas where the individual waves are propagating in a variety of directions. A large directional spread will act to reduce the impact to waves in the lee of WECs, as the energy deficit would be spread over a greater area, and unaffected waves will propagate into the shadow zone, regenerating some of the lost wave energy (Black, 2007, Monk et al., 2013). Swell waves typically have a small directional spread, and under such conditions a wave farm would cause a greater reduction in coastal wave height than during wind-sea or bimodal sea states, which typically exhibit greater directional spreading (Black, 2007, Smith et al., 2012, O’Dea and Haller, 2014).

Using the spectral wave model SWAN, Millar et al. (2007) looked at how varying the transmission coefficient, used to represent the efficiency of WECs at Wave Hub,
would affect the wave height in their lee. Using a ‘realistic’ transmission coefficient of 0.9 (90% of energy is transmitted, 10% is captured) coastal wave height at Perranporth beach reduced by < 2% for all the boundary wave conditions applied. At an ‘unrealistic’ level of absorption (transmission coefficient of 0) the impact was predicted to increase to up to 17%. Li and Phillips (2010) used the MWAVE mild slope equation wave model, and determined transmission coefficients from the breakwater designs of the International Navigation Association (PIANC, 1994). They applied coefficients of 0.68 and 0, which they considered ‘realistic’ for an overtopping device and a point absorber, respectively. Using these transmission levels they predicted that there would be up to 5% reduction in storm wave height, and up to 13% reduction in wave height under monochromatic conditions used to represent idealised surfing waves. Despite the model differences and lack of calibration against local wave conditions, their predictions are similar and act to demonstrate how the coastal impact increases with increasing energy absorption at Wave Hub. However there is clearly a great deal of uncertainty over what constitutes a realistic level of energy absorption, and the results are highly dependent on the transmission coefficient used, and the wave conditions applied at the model boundary. The conclusions drawn would also vary considerably if different directional spreading values had been applied to the models. In particular the default spreading value applied by Millar et al. (2007) is too high to represent swell conditions for the region (Black, 2007), indicating that they are likely to have underestimated the impact to swell waves of interest to surfers.

2.2.2 Frequency Dependent Energy Extraction

These preliminary modelling efforts assumed that WECs could achieve their full energy extraction efficiency during all wave conditions, regardless of the frequency of the incident waves. A number of authors have argued that this is very unlikely to occur in reality however (Alexandre et al., 2009, Smith et al., 2012, O’Dea and Haller, 2014), as devices will naturally resonate at certain wave frequencies, while being insensitive to other frequencies. Their efficiency will therefore be limited to a finite frequency range, resulting in energy being extracted non-uniformly across the frequency spectrum. For a given WEC, a power transfer function (PTF) can be used to describe the proportion of energy captured at each wave frequency (Fig. 2.3), but due to the sensitive nature of the emerging wave energy industry, measured PTF data is currently scarce. In the previous studies that did not consider Frequency Dependent Extraction (FDE), the PTF was effectively a flat line at the chosen transmission coefficient value. More recent studies that have considered the effects of
FDE on wave climate have used idealised PTFs (Smith et al., 2012), or approximated realistic PTFs from numerical (Le Crom et al., 2008, Palha et al., 2010) or physical models (Alexandre et al., 2009, O’Dea and Haller, 2014).

The frequencies containing the bulk of wave energy are logically the most attractive for wave energy capture, and as such it is likely that WECs will be designed to resonate optimally at those frequencies. The resonant (peak) frequency of WEC PTFs will therefore be aligned to the peak frequency of the incident wave climate (Smith et al., 2012). It is also likely that frequencies associated with extremely energetic conditions will be avoided for survivability reasons. Although the design characteristics of commercial WECs are generally unknown at present, the optimal peak period for a WEC PTF ($T_{PTF}$) is usually considered to be the long-term mean energy period, $T_e$ (Mollison, 1994, Black, 2007, Lenee-Bluhm et al., 2011, O’Dea and Haller, 2014), rather than the mean peak period, $T_p$. For a given sea state $T_e$ is the mean period in the spectral distribution of energy (Mollison, 1994), and represents the period of a monochromatic wave containing the equivalent energy as the real sea state in question (Carbon Trust, 2005):

$$T_e = m_{-1}/m_0 \quad (2.1)$$

where

$$m_n = \int f^n ds(f) \quad (2.2)$$

$m_n$ are spectral moments calculated from wave spectra using Eq. 2.2, $f$ is wave frequency and $s$ is the energy density. Ideally WECs would be infinitely efficient at all frequencies, but in reality their efficiency is likely to be maximal at frequencies around $T_e$, and will deteriorate at frequencies further removed from $T_e$, as demonstrated by the PTF in Fig. 2.3 (O’Dea and Haller, 2014).

Smith et al. (2012) modelled FDE scenarios at Wave Hub, by varying the transmission coefficient applied to each wave frequency in their SWAN model. A number of idealised, Gaussian shaped PTFs were used to determine the spread of impacts across the incident frequency range. In their study both directional wave spreading and the spread of frequencies affected by the WECs were varied, and their predictions therefore supersede the previous modelling efforts by Black (2007), Millar et al. (2007), and Li and Phillips (2010) that did not account for directional spreading or FDE. Smith et al. (2012) predict that when FDE is considered, the far field effects of WECs are reduced compared to frequency independent cases. Using a peak transmission coefficient of 0.7 they predict that Wave Hub will change the height of swell waves at the coast by $< 0.5\%$.

Alexandre et al. (2009) propose that one reason that FDE has a reduced impact compared to a constant transmission coefficient, is that natural energy dissipation
Figure (2.3). Example Power Transfer Function (PTF) determined from a scaled physical model of the Manta Buoy, a point absorber type WEC developed by Columbia Power Technologies (Rhinefrank et al., 2013). The vertical axis shows the proportion of energy extracted at each frequency. This PTF has been scaled by O’Dea and Haller (2014) such that the peak aligns with the average annual energy period \( T_e \) from the Oregon coast of 9 s (0.11 Hz).

caused by white-capping and bottom friction is dependent on frequency. They will therefore act differently on the frequency-altered wave field as it propagates to the coast. This may be the case for scenarios where the peak of the WEC PTF and the incident wave spectrum are aligned, as was modelled by Alexandre et al. (2009). However Smith et al. (2012) note that the greatest difference between a FDE case and a frequency independent case would occur when the peak frequency of the incident wave field is outside the efficient operating range of the WEC. During such conditions they predict that the energy capture and consequent coastal impacts will be significantly reduced at Wave Hub, due to the reduced efficiency of the WECs over the peak incident frequencies. A narrow PTF affecting a small range of frequencies was found to impact wind-sea and swell conditions very differently, as the peaks of the sea states were spaced close to and far from the PTF peak, respectively. Additionally, a wide PTF with low peak efficiency was predicted to affect wave height more than a narrow PTF with high peak efficiency during wind-sea, bimodal, and swell conditions, due to energy being extracted across a greater range of frequencies.

The peak frequency, peak efficiency, and width of a WEC PTF therefore all affect how much the energy flux and wave height are affected in the lee of a wave farm. However, as there is presently no prototype-scale PTF data available, the predicted impact to a given wave condition has largely been determined by the hypothetical PTFs applied in the literature. WECs also have other physical effects on the transmitted wave field that have rarely been considered, namely diffraction of wave energy into the shadow zone, and the transmission of radiated waves caused by the vertical
and horizontal motion of the WECs themselves (Monk et al., 2012, 2013). It is likely that for the majority of sea states these effects will not have a significant impact at the coast however, as numerical modelling by Monk et al. (2012, 2013) indicates that directional spreading will mitigate the effects of diffraction, and any radiated waves should be low in energy and will disperse rapidly with distance. Even ignoring these secondary effects, the characteristics of ‘typical’ prototype scale WECs that may be common in the future are still unclear, as there is uncertainty about the PTF that such WECs will exhibit. In addition, the magnitude of wave attenuation at the coast changes significantly with wave directional spreading, a parameter that varies dynamically with changes in sea state. Given these uncertainties, a definitive level of coastal wave impact cannot be predicted for Wave Hub or other WEC sites at present, and as a result their effect on water-users remains unclear.

2.3 The Use and Perception of Waves at the Coast

2.3.1 The Use of Waves at the Coast

Early studies by Walker et al. (1972) and Walker (1974) found that upper limits of wave height and angle exist that determine whether a wave is surfable or not, due to the finite speed a surfer can travel on a wave. These observations were more objectively defined by Hutt et al. (2001) who used bathymetric surveys and nearshore wave data combined with aerial and land based photographs to relate the attributes of breaking waves to surfing ability. They determined that surfable wave heights ranged between 0.7 m to 1 m for beginners and from 0.3 m to > 4 m for expert (top amateur or professional) surfers. The geometric attributes of surfing breaks have also been studied to determine which bathymetric features produce waves that are suitable for wave riding (Mead and Black, 2001b,a). These studies show that some wave conditions and beach morphology are more suitable for surfing activities than others, but there is no indication of which conditions are preferred by different beach water-user groups.

During Wave Hub stakeholder meetings, near monochromatic waves at the peak or lower end of the frequency spectrum, and of heights between 1 - 4 m, were favoured by the surfers who attended (Black, 2007, Li and Phillips, 2010). As both wave height and period were of concern, the impact of wave energy extraction on surfing waves cannot be assumed to depend solely on the attenuation of wave height. The degree to which wave frequencies of interest to water-users are affected will also play a key role (Black, 2007). The lower frequency (longer wavelength) waves identified as important to surfers carry more energy for a given wave height, and can arrive
at the coast as narrow-banded swell where the energy is concentrated into a small range of frequencies (Holthuijsen, 2007). This is a result of wave dispersion, as lower frequency waves propagate faster than higher frequency waves away from the region of generation (Dean and Dalrymple, 1991).

When these dispersed swells arrive at the coast they result in powerful and well organised waves that are prefered for surfing over short period wind seas (Butt and Russell, 2004), which are characterised by a medley of shorter-crested, lower energy waves. Specific conditions are therefore known to be prefered by some surfers. However, the conditions that were identified in the Wave Hub consultation are broad ranging, and the preferred wave periods in particular are unclear. Furthermore the wave conditions were derived from the preferences of only a few individuals. The conditions most valued by surfers therefore remains poorly specified, and the conditions preferred by other water-user groups, as yet, have never been studied.

Wave frequencies containing the bulk of energy are logically the most attractive for wave energy developers to target. As such, wave energy converters (WECs) will be designed to resonate optimally at these frequencies to maximise energy capture, but are unlikely to be able to efficiently extract energy at all frequencies (Alexandre et al., 2009, Smith et al., 2012, O’Dea and Haller, 2014). Whether frequency dependent energy extraction has a positive or negative effect on wave conditions of value to water-users will largely depend on the spread of frequencies that WECs are tuned to extract energy at. If these encroach on the wave frequencies preferred by water-users the impact will of course be negative, but if they attenuate frequencies that are undesirable to water-users, the ‘quality’ of inshore waves could actually be improved.

Butt (2010) anecdotally describes such an effect occurring in the lee of Kelp beds in South Africa and California, which are thought by the local surfers to ‘clean up’ wave conditions by dissipating high frequency wave energy. Elwany et al. (1995) attempted to measure this low-pass filtering effect by comparing waves on either side of the kelp beds in California, but observed no significant effect on wave periods between 3 - 20 seconds. It may be that surfers there are mistakenly perceiving an effect from the kelp on surfing waves, but it is also possible that wave periods of less than 3 seconds (which were not measurable by Elwany et al.) are being attenuated enough to noticeably improve wave quality. It is possible that WECs could have a similar positive effect on coastal waves; specifying the wave frequencies that WECs will be tuned to and those that are preferred by water-users will indicate whether this is likely to occur, or whether a more detrimental effect is likely.
2.3.2 The Perception of Waves at the Coast

Understanding how waves are perceived and described by water-users will be required in order to interpret the conditions that are most valued by this group. A number of studies have investigated the relationship between concurrently recorded visual and measured wave heights and periods, usually for the purpose of validating a long running visual record. These include observations of the height and period of unbroken waves in deep water (Nordenstrom, 1969, Jardine, 1980, Guedes Soares, 1986b,a), and breaking waves at the coast (Perlin, 1984, Plant and Griggs, 1992, Caldwell, 2005, Caldwell and Aucan, 2007), typically using observations made by scientists or mariners.

Wave characteristics are difficult to observe consistently and accurately with the naked eye due to the dynamic and complex nature of waves. The accuracy of visual observations can therefore vary, and have previously been found to vary with the incident wave height and period (Perlin, 1984). Although wave heights are often underestimated by observers at the coast (Perlin, 1984, Plant and Griggs, 1992, Caldwell, 2005), most studies have found correlation between the measured and observed wave heights. Poor correlation and a large degree of scatter tends to occur in comparisons of observed and measured wave period however (Perlin, 1984, Battjes, 1984). Some studies found short wave periods to be overestimated by observers and long wave periods to be underestimated (Perlin, 1984, Plant and Griggs, 1992), while other studies have found the opposite to occur (Nordenstrom, 1969).

A person’s perception of wave height and period will vary depending on the form and extent of averaging they use in order to report a single height or period from a sea of mixed (non-monochromatic) waves, which are ubiquitous in ocean and inshore waters. Comparing observed and measured data from weather ships in the Atlantic ocean, Nordenstrom (1969) found that the average of the largest 1/3rd of measured wave heights, $H_{1/3}$, most closely corresponded to concurrent human observations. Significant wave height ($H_{1/3}$ or $H_s$) is widely used in oceanographic studies as a form of averaging for this reason, and similarly the World Meteorological Organisation recommends that observers average around 20 of the larger waves in several wave groups to determine wave height or period.

Visual observations are clearly variable and subjective, but can also include a considerable degree of bias (Battjes, 1984, Caldwell, 2005). What one person might consider to be a 2 m high wave might be considered a 1.5 m high wave by another person. Systematic bias in observations has been found in visual wave height records made since the 1960’s by Hawaiian lifeguards (Caldwell and Aucan, 2007). Although
the reason for its use is disputed, the ‘Hawaiian scale’ of observation appears to consistently underestimate wave height by approximately half of the measured trough to crest height (Caldwell, 2005, Caldwell and Aucan, 2007). Scarfe et al. (2009) propose that surfers may also perceive wave heights quite differently to measurements, although there is no evidence to suggest whether or not the Hawaiian scale is used elsewhere, or by other water-user groups.

2.4 The Effects of Wave Energy Extraction on Beach Morphology

2.4.1 Beach morphology

When energy travelling in the form of ocean waves arrives at the coast, it is transformed and dissipated into the surrounding environment. This occurs via a number of physical processes such as friction between the wave and seabed, wave breaking, wave reflection, and wave run-up and backwash as the shore is repeatedly wetted and dried by the arriving waves. This transfer of energy causes movement of the beach littoral material, and formation of large scale bathymetric features such as sandbars. The resulting morphology can take on a range of two-dimensional (alongshore uniform) and three-dimensional (alongshore varying) formations.

Much of our conceptual understanding of these morphological forms originates from sequential beach state models developed at single-barred microtidal beaches in Australia (Short, 1979a, Wright and Short, 1984, Wright et al., 1985). Through extensive field observations made over a number of years, Wright and Short (1984) reduced the natural continuum of beach forms into a sequence of 6 discrete states (Fig. 2.4). The end members of the model have a shallow gradient in the Dissipative extreme, or a steep gradient in the Reflective extreme, both of which consist of a planar beach face with little alongshore variability. The intermediate stages (Longshore Bar and Trough - LBT, Rhythmic Bar and Beach - RBB, Transverse Bar and Rip - TBR, Low Tide Terrace - LTT) are typified by greatly increased alongshore variability in the form of rip channels, and crescentic bar formations. The general applicability of this sequence has subsequently been verified at other sites (Lippmann and Holman, 1990, Ranasinghe et al., 2004) and extended to include beaches with meso and macro tidal range (Short, 1991, Masselink and Short, 1993, Masselink and Hegge, 1995, Scott et al., 2011, Masselink et al., 2014), double or multi-bar systems (Short, 1992, Short and Aagaard, 1993, Castelle et al., 2007, Scott et al., 2011), and beaches with dominant headlands or geological features (Short, 1996, Castelle and Coco, 2012, Loureiro et al., 2012).
The alongshore-uniform Dissipative (D) and Longshore Bar-Trough (LBT) states, which comprise one end of the beach state model in Fig. 2.4 (a and b), develop during periods of highly erosive waves such as in winter storms, when the outer sandbar is moved offshore and straightened into a continuous shore-parallel bar (Short, 1979a, Wright and Short, 1984, Lippmann and Holman, 1990). Such morphology will be described as two-dimensional (2D) throughout this thesis, as it only varies in the cross-shore direction (from shore to sea, demonstrated in Fig. 2.4a). The morphology becomes increasingly three-dimensional (3D), with cross-shore and alongshore varying features, during the recovery period following a storm. Smaller, less steep (accretive) waves bring sediment shoreward, and the previously linear subtidal bar(s) begins to migrate back toward shore unevenly (Short, 1979a, Wright and Short, 1984, Lippmann and Holman, 1990, Poate et al., 2014).

Horns in the offshore bar are developed, which move shoreward relatively quickly while the intervening bays progress at a slower rate (Short, 1979a, Wright and Short, 1984). The resulting form is a sinuous crescentic bar, known as the Rhythmic Bar and Beach (RBB) state (Fig. 2.4c). As the name suggests the alongshore variation in the bar crest can be remarkably periodic, but often a range of wavelengths (from 150 m - 2 km) and cross-shore amplitudes (from 5 m - 80 m) can occur (Van Enkevort et al., 2004). Under sustained accretive conditions the bar horns will eventually weld to the shore (Short, 1979a, Wright and Short, 1984, Lippmann and Holman, 1990, Masselink et al., 2014), turning the previously continuous alongshore trough (which separates the bar(s) and shore), into a series of cross-shore rip channels (Wright and Short, 1984).

This Transverse Bar and Rip (TBR) state (Figs. 2.4d and 2.5) exhibits the greatest three-dimensionality, with large alongshore variation in the position of the shore welded horns and offshore bays, and significant difference in elevation between the crests of the horns and intervening channels (Wright and Short, 1984, Lippmann and Holman, 1990, Ranasinghe et al., 2004). The next beach state is the Low Tide Terrace (LTT), which features reduced three-dimensionality, diminishing rip channels, and a bar that is close to shore (Fig. 2.4e). Continued accretive waves bringing sediment shoreward will eventually cause the rip channels to infill, and the alongshore variability will diminish as the beach approaches the reflective end state. The landward return of sediment during this entire downstate sequence forms an important mechanism for beach recovery following erosive, upstate storm conditions. However, the presence of 3D features such as cusps and rip channels can also allow erosive storm swashes to reach further landward and undercut the dune foot (Thornton et al., 2007). 3D morphology therefore heavily influences a beaches response to, and recovery from, storm waves.
Figure (2.4). Sequential beach state model of Wright and Short (1984).
Figure (2.5). Examples of 3D, transverse bar-rip morphology from the microtidal New South Wales coast, Australia (Price et al., 2014), meso-macrotidal Aquitanian coast, France (Castelle et al., 2007), and macrotidal North Cornwall coast, England (left to right panels respectively).

2.4.2 Beach Morphology and Water-Users

Prominent 3D morphology has also been shown to significantly affect beach water-users in the surf-zone. For example, the amenity provided by waves for activities such as surfing and bodyboarding is improved by 3D bathymetric features (Mead and Black, 2001b,a, Scarfè et al., 2009). The degree of surfing difficulty (or ‘surfability’) of a wave is affected by the waves height and the relative angle of the breaking wave crest, known as the peel angle (Walker and Palmer, 1971, Dally, 1989, Hutt et al., 2001, Mead and Black, 2001b, Scarfè et al., 2003, 2009). This factor, defined by Walker and Palmer (1971) as the included angle between the trail of broken white water and the unbroken wave crest as it propagates shoreward (Fig. 2.6), determines how fast a surfer or other water-user must travel to successfully ride the unbroken face of the wave. Waves that arrive with their crests parallel to the bathymetric contours break with small peel angles and are less desirable for surfing activities. This is due to the crest peeling too fast for the unbroken portion of the wave to be ridden (known as a ‘close-out’). Aerial photographs and bathymetric surveys determined that Peel angles of 30° to 70° are suitable for the majority of surfers, with smaller peel angles only being surfable by experts (Hutt et al., 2001).

The large-scale alongshore variations in bathymetry that typify the 3D intermediate (bar-rip) beach states cause alongshore variation in breaking wave height and direction (visible in Figs. 2.5, 2.7 and 2.8). This increases the peel angle of otherwise shore-normal waves to within the surfable limits, and enhances the recreational amenity provided by the waves. Butt and Russell (2004) describe the effect of well-developed 3D sandbars on surfing waves - “If the system works properly then we will have a perfect set-up for surfing: rights and lefts, always breaking in the same spot; a choice of peaks so there is plenty of room for everyone, and convenient paddling
Figure (2.6). Wave peel angle (adapted from Mead and Black (2001b)), defined as the included angle between the trail of broken white water and the unbroken wave crest propagating shoreward (Walker and Palmer, 1971).

Alongshore varying morphology also influences the type and strength of surf-zone currents (Bowen, 1969, Ranasinghe et al., 2004). Rip channels are bathymetric depressions that intersect sandbars (Fig. 2.4d) and allow water set up by wave breaking to funnel back out to sea in concentrated offshore flows (Fig. 2.7) which can take water-users from the shallows out into deeper water (MacMahan et al., 2006, Austin et al., 2010). As a result rip currents are the largest cause of surf-zone rescues and fatalities globally (Scott et al., 2008, 2011, MacMahan et al., 2011, Brighton et al., 2013). A comparison of beach state observations and lifeguard rescue statistics from the Royal National Lifeboat Institute made by Scott et al. (2008) showed that 90% of rip incidents in the UK occur during 3D intermediate low tide bar rip (LTBR) and low tide terrace + rip (LTT+R) beach states, analogous to the TBR and LTT states in Figs. 2.4d and 2.4e. Bar and rip beach states exhibit the greatest degree of three-dimensionality (Ranasinghe et al., 2004), as well as the strongest rip current circulation (Wright and Short, 1984), indicating that these factors are strongly linked. Intermediate beach states with a high degree of three-dimensionality are therefore synonymous with increased rip current flows and bathing hazard (Fig. 2.8).

3D morphology clearly creates a divergence between the safety and amenity provided by the surf-zone for water-users. As such, the degree of three-dimensionality exhibited by a beach is arguably the primary morphological parameter of relevance to beach water-users. In the South West of the U.K. where Wave Hub is located, many beaches have been observed to lie at a classification boundary, moving between a dissipative state and an intermediate state depending on the incident wave conditions (Scott et al., 2008, 2011, Austin et al., 2010, Poate, 2011). The degree
Figure (2.7). Three-dimensional bar-rip morphology at Porthtowan beach, Cornwall, UK, captured in August 2009 using snapshot, time-exposure (timex) and rectified timex camera images (upper, middle, and lower panels, respectively). Water brought shoreward by the breakers over the bars returns seaward through intervening rip channels. Large breaking wave angles induced by the sinuous morphology create optimal surfing conditions for water-users, while the wave driven horizontal (rip current) cell circulation enhances the bathing hazard.
of three-dimensionality can therefore vary significantly from season to season, and in response to storm waves (Poate, 2011). As wave height and period are the key parameters that determine the state of a given beach (Masselink and Short, 1993, Wright and Short, 1984, Short, 1996), there is a potential for offshore wave energy extraction at Wave Hub or future wave farm sites to alter the predominance of 3D beach morphology. This may in turn affect the safety and amenity provided by the surf-zone for beach water-users. 3D morphology will be a key theme throughout this doctoral research, as understanding the processes that generate 3D features is crucial to predicting the likely effect that wave farms will have on beach water-users.

2.4.3 The Development of Three-Dimensional Morphology

A variety of wave, tide and sediment parameters have been associated with the development of 3D morphology. Most notably upstate and downstate beach transitions (towards the Dissipative or Reflective extremes respectively) have often been linked to increasing and decreasing levels of wave energy, respectively (Short, 1979a, Lippmann and Holman, 1990, Ranasinghe et al., 2004, Poate et al., 2014). Short (1979a)
identified potential links between monthly averaged values of incident wave power and a sequence of 10 microtidal beach states (Fig. 2.9). Similar to later sequential models, Short's (1979) model featured planar end states and 3D intermediate states, where the three-dimensionality was highest during intermediate energy levels. Interestingly the 3D morphology observed during periods of increasing wave power varied slightly from that under decreasing wave power, a characteristic often omitted from later models. Recent observations have further confirmed that the level of incident wave power is a significant determinant of beach state (Wijnberg and Kroon, 2002, Scott et al., 2011). From extensive observations at 92 micro to macrotidal beaches in the U.K., Scott et al. (2011) proposed that a minimum wave energy of 3 kW/m was required for 3D low tide bar-rip morphology to develop. Combined with the earlier observations this indicates that incident wave energy has to be at an intermediate level, within a lower and upper threshold, in order for 3D morphology to develop.

There is some contention around how much control wave energy or power alone exerts on beach state. While the field observations of Short (1979a) and later video imagery (Lippmann and Holman, 1990, Ranasinghe et al., 2004) have indicated that higher beach states and linear, offshore bars tend to occur during periods of high waves, others have noted that barlines do not always straighten (i.e. transition upstate) under the influence of high wave energy (Van Enckevort and Ruessink, 2003b, Price, 2013). Multi-year observations at a microtidal beach in Australia showed that highly three-dimensional intermediate beach states can develop during periods of both high and low wave power (Price, 2013). The relationship between state transitions and wave power originally suggested by Short (1979a) is therefore not always valid. Field observations and modelling studies now agree that increasing incident wave power increases the magnitude (Smit et al., 2008a, Gallop et al., 2011) and rate (Wright and Short, 1984, Damgaard et al., 2002) of morphological change, as well having the potential to increase the length scales of barline crescents and rip channels in both alongshore (Huntley and Short, 1992, Van Enckevort et al., 2004, Calvete et al., 2005, 2007) and cross-shore (Gallop et al., 2011, Thiebot et al., 2012, Price, 2013) dimensions under certain conditions. It may be concluded therefore that the level of incident wave energy determines the potential for sediment transport and morphological change, but more complex coastal processes influence whether these changes result in upstate or downstate transition.

For many years template theories were used to explain the formation of 2D and 3D sandbar morphology (Bowen and Inman, 1971, Holman and Bowen, 1982). Template theories propose that a spatial pattern in the incident hydrodynamics forces a matching pattern to emerge in the underlying bathymetry. This appears to provide an intuitive explanation for crescentic bar formation or other alongshore variability,
ascertained morphological features have length scales that match hydrodynamic length scales. For instance the cross-shore amplitude (order of $10^{-2}$ m) and wavelength (order of $10^{2} - 10^{3}$ m) of crescentic bars are close to half the length of incident and infragravity waves respectively (Van Enkevort et al., 2004). Patterns in the nearbed velocities that occur due to the presence of standing edge-waves (waves bound to the nearshore region through refraction or reflection) were a typical explanation for template forcing (Bowen and Inman, 1971). There are a number of deficiencies with template theories however: firstly, they do not allow for the morphology to influence the hydrodynamics, which is regularly observed in the field. Furthermore significant infragravity energy must exist in a single dominant frequency, and field observations suggest that infragravity spectra are often white, lacking a dominant frequency during storms when sufficient energy is available for sediment transport (Holman and Sallenger, 1993, Russell, 1993, Ruessink et al., 1998, Holland and Holman, 1999). Nearbed velocities from edge-waves are also very small compared to other wave driven currents in the surf zone, so are unlikely to contribute significantly to sediment transport (Bryan and Bowen, 1997).

As beach profile dynamics had already been linked to a combination of wave height, period and sediment size, Wright and Short (1984) examined the relationship between beach state and the dimensionless fall velocity parameter of Gourlay (1968) and Dean (1973), which combines the aforementioned parameters in a dimensionless form:

$$\Omega = \frac{H_{s,b}}{(\bar{W}_s T_p)} \quad (2.3)$$

where $H_{s,b}$ is the significant wave height at breaking, calculated as the mean of the largest $1/3$rd of waves, $\bar{W}_s$ is the mean sediment fall velocity, and $T_p$ is the peak wave period associated with the spectral energy maximum. As a waves period is proportional to its length, the ratio of height over period in this parameter conveniently reflects wave steepness, which Dean (1973) associated with beach erosion (steep waves and large $\Omega$) and accretion (low steepness waves and small $\Omega$). Wright and

Figure (2.9). Time series showing correlation between offshore wave power, $P_0$, and beach stage at Narrabeen beach, from Short (1979a).
Short's study identified thresholds of $\Omega$ which discriminated between the reflective, intermediate and dissipative states in Fig. 2.4 with good agreement. Essentially, small values of $\Omega$ occur under accretive waves and lead to steep, reflective beaches, while large values indicate erosion and lead to dissipative morphology. It is noteworthy that as $\Omega$ is most sensitive to changes in wave height (Short and Aagaard, 1993), the observed relationship between $\Omega$ and beach state largely agrees with the previous findings relating beach state to wave power.

Masselink and Short (1993) later extended the relationship between $\Omega$ and beach state to sites with micro to macro tide range (Fig. 2.10), by including a parameter that considers the ratio of tide range and wave height, termed the Relative Tide Range (RTR). Their observations showed that large tides suppress the rate of morphological development and therefore influence the emerging beach state. For example intermediate beaches with large tidal ranges, such as those observed by Poate et al. (2014) in the lee of Wave Hub, were shown to exhibit subdued bar-rip morphology, which tends to be located below the low tide contour (Fig. 2.10).

The horizontal and vertical displacement of swash, surf-zone and shoaling wave processes due to large tides decreases the stationarity of any one process acting on a given beach region, which reduces the opportunity for defined features to emerge (Masselink, 1993, Masselink and Short, 1993, Masselink et al., 2006). Although this has been observed to slow bar migration (Davis et al., 1972) and reduce the relief of bar features (Wright et al., 1986, 1987), its effect on the scale of beach three-dimensionality is less clear.

Although many studies have now confirmed that $\Omega$ and RTR are able to predict the reflective and dissipative extremes relatively effectively, a number have found that intermediate states are not well distinguished by $\Omega$ (Jackson et al., 2005, Jimenez et al., 2008, Almar et al., 2010, Scott et al., 2011). While enabling $\Omega$ to be generalised to a variety of sites, Scott et al. (2011) argue that the non-dimensionality of the parameter ignores the importance of the magnitude of wave period. He points out that high-energy swell environments that favour 3D morphology could achieve similar modal values of $\Omega$ to wind-sea environments with linear morphology. Jimenez et al. (2008) points out that the duration and intensity of wave events is not accounted for if only an instantaneous value of $\Omega$ is considered. Although Wright et al. (1985) found that applying an antecedent weighted-average of $\Omega$ relieved this problem to some extent, the faster rate of beach response under higher energy waves further complicates the relationship. Besides this, the poor correlation between $\Omega$ and the intermediate beach states is exacerbated by self-organisation, whereby hydrodynamic flows and beach state changes are influenced more by the antecedent morphology than the incident wave conditions (Wijnberg and Kroon, 2010).
Figure (2.10). Conceptual beach model from Masselink and Short (1993). Beach state is a function of dimensionless fall velocity ($\Omega$, as previously defined) and relative tide range (RTR), where MSR = mean spring tide range and $H_b$ = mean breaking wave height. HT and LT refer to mean high tide and mean low tide level, respectively.


In recent years process-based numerical models have simulated such free morphological behaviour, successfully reproducing features observed in the field, and adding credence to self-organisation theory (Falqués et al., 2000, Caballeria et al., 2002, Ranasinghe et al., 2004, Reniers et al., 2004, Dronen and Deigaard, 2007, Falqués et al., 2008, Smit et al., 2008a,b, Castelle and Coco, 2012). The results now widely agree that horizontal wave-driven circulation in the nearshore contributes to the growth of 3D morphology, via positive feedback between the developing morphology and local hydrodynamics, termed bed-surf coupling (Falqués et al., 2000, Caballeria et al., 2002, 2003a,b, Ranasinghe et al., 2004). In the case of a 2D sub-tidal bar, this free behaviour could be initiated by preferential wave breaking over shallow anomalies in the sand bar. The dispersion of energy and gradient of the beach then decelerates the shoreward flowing water, promoting a decreasing sediment flux and sand deposition directly shoreward of the bar, further reducing the water depth and enhancing wave breaking in that region (Falqués et al., 2000, 2008).

The water set-up by the breakers locally increases hydrostatic pressure and forces an alongshore flow away from the bar horns. These flows converge at deeper regions where less wave breaking occurs, and return seaward over the deeper sections of the sandbar (Wright and Short, 1984). The offshore directed return flows are coupled
Figure (2.11). 2D numerical model of horizontal circulation driven by wave breaking over alongshore bars and return flows through rip channels (Ranasinghe et al., 2004). The arrow at the bottom right of the figure indicates a vector length corresponding to 1 m/s.

with increasing sediment fluxes and erosion, enhancing the depth of the channels between the bar horns. This onshore, alongshore, and offshore flow sequence forms horizontal circulation in the surf zone (Fig. 2.11) which, through bed-surf coupling, enhances the bathymetric relief of the seabed features (Falqués et al., 2000, Ranasinghe et al., 2004). This feedback process does not continue indefinitely however, as numerical models indicate that under constant forcing the developing morphology eventually approaches equilibrium with the hydrodynamics (Smit et al., 2008a).

According to the linear stability analysis conducted by Caballeria et al. (2003a,b) horizontal circulation is intensified, and the growth rate of 3D features is therefore increased, by two factors:

1. Accentuated relief of bar and trough features,

2. Low water level over the bar crest (freeboard) combined with large wave heights.

Given a constant wave height the first situation would be favoured by smaller tides, which increase the residence time of processes acting on the beach face, enhancing topographic relief. This phenomenon was observed during field measurements at micro tidal beaches that showed topographic relief to be increased (decreased) during neap (spring) tides (Wright et al., 1986, 1987). Conversely the second situation is
favoured by large tides, when the freeboard can be significantly reduced at low tide. Spring low tides can activate subtidal rip systems which are otherwise inactive during neap tides (Scott et al., 2009, Austin et al., 2010), and the increased tide range therefore promotes cell circulation and 3D growth during low tide. Accordingly, both small and large tides can affect the intensity of nearshore circulation and influence beach three-dimensionality.

Process models have also shown that shore-normal wave incidence enhances horizontal circulation and therefore favours the growth of three-dimensional morphology (Smit et al., 2008a, Thiebot et al., 2012). Conversely, the effect of obliquely incident waves on beach three-dimensionality is to inhibit the growth of 3D features by diminishing cellular circulation in favour of alongshore flowing currents (Ranasinghe et al., 2004, Splinter et al., 2011, Garnier et al., 2013). It was previously observed that alongshore oriented wave power from oblique waves can cause 3D features to angle or migrate alongshore (Ruessink et al., 2000, Almar et al., 2010); recently however, supported by field observations (Holman et al., 2006, Thornton et al., 2007, Price et al., 2011, Price, 2013) and model simulations (Ranasinghe et al., 2004, Splinter et al., 2011, Garnier et al., 2013, Price, 2013), alongshore wave power has also been linked to the straightening of subtidal sandbars. Process models revealed that this can occur due to the alongshore current deflecting the rip circulation from the deeper rip channel toward the shallower bar (Garnier et al., 2013); this not only diminishes the bed-surf coupling but also erodes sediment from the crescentic bar horns and deposits the sediment in the intervening rip channels (Ranasinghe et al., 2004).

This indicates that beach three-dimensionality is inversely related to the amount of alongshore oriented wave power, although it is not clear why some have observed migration of bar features, while others observed bar straightening. Recent numerical modelling indicates that larger sediment significantly reduces the alongshore migration of rip channels, and grain size may therefore influence the response to oblique waves (Dong et al., 2015). Considering many field observations have shown that high wave power alone is sufficient to straighten a crescentic bar (Short, 1979b, Lippmann and Holman, 1990, Almar et al., 2010, Poate et al., 2014), the importance of oblique wave incidence as a mechanism for bar straightening is likely to vary between sites with and without significant levels of alongshore oriented wave power.
2.4.4 Predicting the Effect of Wave Energy Extraction on Beach Morphology

A number of studies have sought to investigate the potential effect that wave energy extraction may have on nearshore processes and beach morphology (Li and Phillips, 2010, Poate, 2011, Gonzalez-Santamaria et al., 2013, Rusu and Soares, 2013, Abanades et al., 2014b,a, Mendoza et al., 2014, O’Dea and Haller, 2014, Abanades et al., 2015). As field measurements from active WEC sites do not yet exist, the approach adopted in all modelling efforts to date has been to apply a theoretical alteration to the waves at a WEC site, then propagate these altered waves into the nearshore. The altered inshore wave conditions are then used to assess how morphological parameters may change. For example changes in the cross-shore and alongshore components of wave power have been examined to indicate how trends in alongshore sediment transport might be affected (Rusu and Soares, 2013, Mendoza et al., 2014, O’Dea and Haller, 2014). Process based modelling involving coupled wave, tide and sediment transport models has also been undertaken in order to show more specifically where erosion or accretion of the beach face may occur (Li and Phillips, 2010, Gonzalez-Santamaria et al., 2013, Abanades et al., 2014b,a). These studies universally agree that reduced wave heights in the lee of a wave farm are likely to result in accretion of the beach face, and some have therefore concluded that it is possible for wave farms to provide coastal protection in addition to renewable energy (Abanades et al., 2014a, Mendoza et al., 2014).

Considering the sensitivity of process based models to boundary wave conditions, their use is perhaps too extravagant at this stage, given the uncertainty in the near-field effects of WECs on the energy and frequency of transmitted waves. Additionally such models deal with small spatio-temporal processes, and as described in Section 2.4.5 do not predict morphodynamics well over long time scales. As such, a more empirical approach has been used to investigate the potential effects of wave energy extraction on beach morphological state. As sequential models (such as that of Wright and Short (1984), Masselink and Short (1993), and Scott et al. (2011)) associate specific morphological states to a particular range of wave and tide conditions, hypothetical wave climates modified by energy extraction can be positioned on the models to qualitatively determine the beach state that is likely to develop. Poate (2011) used this approach to examine the likely effect of a 6% reduction in coastal wave height on the dominant morphological state at Perranporth and Porthtowan beaches in the lee of Wave Hub. This level of attenuation was predicted to induce a slight shift from predominantly Dissipative and lower Intermediate states, towards a higher predominance of Intermediate states (Fig. 2.12). It was recognised
however that such a level of wave attenuation is significantly lower than the natural variability in wave conditions in the region, and they concluded that the effect on beach morphology is therefore likely to be insignificant.

This approach was recently extended by Abanades et al. (2015) to a hypothetical scenario at Perranporth beach, where a wave farm was modelled using the spectral wave model SWAN at distances of 2, 4, and 6 km from the coast. The significant wave attenuation predicted to occur at such close proximities unsurprisingly resulted in a much greater change in Perranporth’s modal beach state than Poate’s (2011) Wave Hub case study, positioned 25 km from the coast. Although Abanades et al. demonstrate that close wave farm proximity will have a large effect on beach state, Kim et al. (2012) point out that the wave power available for extraction generally increases with increasing offshore distance, and the close coastal proximity modelled by Abanades et al. (2015) may therefore be unrealistic for the shallow-shelf coast of South-West England. At present the predictions made by Poate for Wave Hub are more relevant, but at future WEC sites with deep water close to the coast, the predictions of Abanades et al. may apply.

Although the beach state models that underpin these studies have a wide applicability and provide the paradigm in which most beach research resides, the wave and tide parameters used to predict beach state (Ω and RTR) are not considered reliable as a predictive tool, for the reasons outlined in section 2.4.3 (Scott et al., 2011). Although reflective and dissipative beaches can often be distinguished using these parameters, they are least capable of predicting the intermediate, bar-rip beach states (Anthony, 1998, Jackson et al., 2005, Jimenez et al., 2008, Almar et al., 2010, Scott et al., 2011) that most greatly influence beach water-users. As a result, predicting the effects of wave energy extraction on 3D beach morphology requires a modelling approach that better resolves the scale and extent of 3D features. It also needs to be applicable over long time periods, and therefore precludes the use of most process models. A novel modelling approach is therefore needed that sits between the fine spatial and temporal resolution offered by process models, and the coarse resolution of beach state offered by Ω.

2.4.5 Modelling Three-Dimensional Morphology

As outlined in Section 2.4.3, idealised process-based models have provided a great deal of causal insight into increasing and decreasing beach three-dimensionality. However, as these models deal with small scale processes, and often over relatively large areas, they are computationally expensive. In addition, they are yet to recreate measured bathymetries under stochastically varying wave conditions; the required
Figure (2.12). Conceptual classification of monthly beach states measured at four beaches in the lee of Wave Hub (PTN = Porthtowan, PPT = Perranporth, CHP = Chapel Porth, GWT = Gwithian Towans), from Poate (2011). Coloured symbols show relative position of states resulting from a 6\% reduction in wave height compared with the measured states (shaded grey symbols). The size of the marker reflects the 3D level as derived using a contour length parameter. On the vertical axis, RTR = relative tide range, MSR = mean spring tide range, $H_b$ = mean wave height at breaking. On the horizontal axis, $\Omega$ = dimensionless fall velocity.

assumptions and non-linear effects within process models are compounded over large spatial and temporal scales (De Vriend et al., 1993, Syvitski et al., 2009), and as a result they still struggle to accurately predict long term (> monthly) 3D morphodynamics. Behavioural models provide an alternative approach that can potentially achieve accurate long term predictions. These models are data driven, and use a bulk representation of processes rather than recreating real-time morphodynamics. They have been criticised for lacking in or consisting of incomplete physical representations (Splinter et al., 2011, Van de Lageweg et al., 2013), or being overly dependent on tuning parameters (Ruessink et al., 2013). Nonetheless they are often capable of explaining substantial amounts of data variance (Plant et al., 1999, 2006, Splinter, 2009), and accurately forecasting large-scale beach changes over multi-year time scales (Plant et al., 1999, Davidson et al., 2010, 2013a), which is presently unachievable using process-based models.

Wright et al. (1985) proposed a behavioural beach state model based on the assumption that state changes occur when instantaneous wave conditions differ from the conditions associated with zero change for each state, termed the disequilibrium
stress, $\Delta \Omega$:

$$
\Delta \Omega = \Omega - \Omega_{eq}
$$

(2.4)

Where $\Omega_{eq}$ and $\Omega$ are the equilibrium and instantaneous dimensionless fall velocity, respectively. Large departures from equilibrium represent an increased potential for change, and upstate and downstate changes occur under positive and negative disequilibrium, respectively. Numerical models have shown that under constant wave forcing, morphodynamic change does not continue indefinitely (Smit et al., 2008a) and equilibrium is eventually reached. This is often termed ‘negative feedback’ as the developing morphology eventually hinders the bed-surf coupling, making the system inherently stable and predictable (Plant et al., 2006). Therefore as instantaneous conditions approach the equilibrium condition in Eq. 2.4 ($\Omega \to \Omega_{eq}$), the disequilibrium stress and predicted morphological change appropriately reduces to zero.

Perhaps due to the assumption that $\Omega_{eq}$ varies instantaneously with beach state, Wright et al. (1985) found few departures from equilibrium and poor agreement between observations and predictions of beach state using Eq. 2.4. Although successful predictions were not achieved, their approach recognizes the importance of negative feedback in maintaining system stability, and the disequilibrium approach may therefore be suited to predicting beach three-dimensionality. Disequilibrium stress has since been used in adapted forms to skillfully predict cross-shore shoreline (Yates et al., 2009, Davidson et al., 2010, Yates et al., 2011, Davidson et al., 2013a, Castelle et al., 2014, Splinter et al., 2014) and barline (Plant et al., 1999, Masselink et al., 2014) migration under varying waves, but is yet to be applied to the prediction of 3D changes. Other attempts to behaviourally model three-dimensionality have either been restricted to single storm cycles (Plant et al., 2006) or have included relatively complex sediment transport parameterisations, with limited predictive improvement (Splinter et al., 2011). The previous successful applications of disequilibrium stress to 2D beach dynamics over multi-year time scales indicates that, with development, such a model may also be capable of predicting the effects of wave energy extraction on 3D beach morphodynamics over multi-year time scales.
Chapter 3

Perception of Marine Renewables and Anticipated Coastal Impacts

3.1 Introduction

3.1.1 Background

Considering their proximity to, and vested interests in the marine environment, the opinions of beach water-users towards marine renewable energy (MRE) has been studied relatively little. Bailey et al. (2011) explored attitudes toward Wave Hub and other marine renewable technologies, and how they may affect inshore wave conditions, wildlife, and the local economy using a quantitative study of residents in three Cornish towns in 2008. They found that the majority of respondents supported local (88.5%) and regional (89.1%) wave energy deployment, and that only 10% were concerned about negative effects to waves. Although this indicates general patterns of support in the region, the surveyed towns were not positioned in the lee of Wave Hub (Fig. 1.7), and the survey did not specifically target beach water-users. It is therefore unwise to assume the attitudes can be generalized to those who live on or use the coast predicted to be affected by energy extraction. A study conducted by Voke et al. (2013) utilized a quantitative questionnaire, and targeted coastal users along the Pembrokeshire coast where tide and wave energy converter (WEC) installations are proposed. Their results provide an interesting comparison to the studies on Wave Hub. They found that over a quarter of respondents were concerned about a reduction in wave height affecting their use of the coast - significantly more than the 10% of respondents concerned about wave effects in the survey by Bailey et al. (2011). This difference may, as Voke et al. suggest, be a result of the modest scale of Wave Hub compared to the full scale deployments that Voke et al. depicted, or a lower perceived abundance of quality surf in Pembrokeshire compared
to Cornwall. Equally, it may be a result of the Pembrokeshire study specifically targeting those who could be affected by the physical coastal impacts of energy extraction (Brownlee et al., 2015), compared to Bailey et al.’s survey of residents in towns outside the potential impact zone.

Previous qualitative research by West et al. (2009) and McLachlan (2009) analysed interviews and statements from members of sea fishing committees, local parish councillors, a surf school owner, and surfing bodies such as the environmental lobby group Surfers Against Sewage, with regards to their opinions of Wave Hub. West et al. (2009) conclude that surfers are particularly concerned about future upscaled deployments, and that other water-user groups (for example Kitesurfers, bodyboarders, and kayakers) may join them in a more collective opposition against future projects. These studies provide a rare view into the attitudes of beach water-users but, as with much of the Wave Hub consultation, surfers are predominantly represented. At future renewables sites where surfing is not the primary beach activity, the same opinions may not necessarily apply. There is therefore a need to investigate the opinions and concerns of beach water-users more generally, and given the disparity in the level of concern over wave impacts reported by Bailey et al. (2011) and Voke et al. (2013), the opinions of coastal users in regions that are predicted to be affected by wave energy extraction should be sought.

3.1.2 Chapter Aims

This chapter aims to explore which physical coastal impacts, if any, beach water-users anticipate from Wave Hub and future upscaled marine renewables deployments. The level of impact that is anticipated, as well as how the anticipations have been formed and may change over time will be fundamental to the investigation. To fill previous knowledge gaps, the opinions of a variety of beach water-users, including surfers and non-surfers, are sought from within the region that is predicted to be affected by wave energy extraction at Wave Hub.

3.2 Methodology

3.2.1 Research Approach

A qualitative approach was deemed most appropriate for this part of the study as we seek to explore what coastal impacts are anticipated, and why they are anticipated. Additionally, underlying meaning that is embedded in participants answers can be revealed and explored, and can enhance the understanding gained (Buston et al., 1998). This deeper exploration of participant’s attitudes is not possible using
a quantitative approach, due to the fixed nature of the questioning (Denzin and Lincoln, 1998). Statistical generalisations about water-users as a population are not being sought at this stage; instead a richer understanding about how they construct their opinion on MRE technology and coastal impacts is sought. The findings should however be transferable, as the methods applied will test the findings amongst the participants of this study, ensuring internal validity and credibility which is considered vital to transferability (Guba, 1981, Sandelowski, 1986, Krefting, 1991).

An interpretive, constructivist perspective was adopted. Briefly, this epistemology studies how people construct meanings about the world around them, and acknowledges the interpretation that is made by both the researcher and the research subject. This is appropriate given that opinions of MRE are constructed via a multitude of information, imagery, and word-of-mouth, and also that the researcher will interpret and reconstruct these opinions from the interviewees. Grounded theory was chosen as the research strategy, as its exploratory and explanatory nature makes it suited to situations where limited previous research has been conducted (Glaser and Strauss, 1967, Strauss and Corbin, 1998, Charmaz, 2006, Pedersen et al., 2007). It is also considered highly suited to investigating a process or experience over time (Morse, 1998), and therefore fits with our desire to explore the formation of opinions of MRE. Grounded theory does not attempt to fit existing theories to empirical data, but instead is predominantly an inductive approach that allows for concepts and theories to form from the data itself. Many of the more positivist (defined in Section 4.2.1) grounded theory techniques condoned by Glaser and Strauss (1967) and Strauss and Corbin (1998) have been used in this study, as they are fundamental to the methodology; however a more contemporary, constructivist analysis will be conducted, and the theory generated will be a construction of the researcher. It is accepted in constructivist grounded-theory that the way the findings are rendered could vary if repeated by another researcher but the findings themselves should not vary significantly (Charmaz, 2006).

Besides having this epistemological standpoint, the study was entered with minimal preconceptions about theories relevant to the topic, so that theory generation could occur in an unbiased and uninfluenced manner. Psychological and social theory will however be called upon in the discussion of the findings, and was incorporated after data analysis. In depth, semi-structured interviews were chosen as the primary data collection technique and were conducted iteratively and simultaneously with coding and data analysis, as is considered fundamental to this methodology (Glaser and Strauss, 1967).
3.2.2 Interviews

Interviews were conducted with water-users in the coastal villages of Perranporth, Porthtowan, and St. Agnes (Fig. 1.8), at a location suggested by each participant (usually at their home, workplace, or a café), to provide a setting in which they would feel at ease (Gratton and Jones, 2004). In the more public venues a quiet and relatively private area was chosen so that the discourse would not be influenced by the presence of others. The interviews lasted on average 40 minutes in each case. Participants were first given an information sheet and brief questionnaire to complete (Appendix A). The questionnaire consisted of 6 tick-box questions intended to gain baseline information on the respondent, including which beach they most often visit, in what way they use the beach, and whether or not they have heard of Wave Hub. The information sheet informed each participant of the aims of the research and told them that their answers would be confidential and purely used for academic research, and could be withdrawn at any time. By these means, the three key elements of informed consent were observed: lay disclosure of necessary information, the capacity of the participant to understand the information, and voluntary participation (Faden et al., 1986). Only participants over 18 years old completed the questionnaire, and ethical permission was granted by Plymouth University to conduct the surveys.

In the first 2 interviews questions focussed solely on anticipated impacts to coastal conditions (i.e. condition of the beach and wave climate), with follow up questions being used to explore emerging areas of interest. As concepts emerged from the initial interviews, questions were added to the schedule to enhance future interviews, in the tradition of theoretical sampling (Charmaz, 2006). The interview schedule eventually included questions on the following topics: participant’s use of the beach, knowledge of Wave Hub, anticipated impacts of Wave Hub and future installations, level of support for Wave Hub and MRE in general, and overall pros and cons of MRE. Participants often asked questions about the subject under discussion to the interviewer; in these situations answers were always delayed until after the interview if the question was to be asked to the participant later in the interview, or if it was felt that the answer would affect the subsequent answers of the respondent. The interviews were conducted, digitally recorded, and transcribed verbatim at a later date by the author.

3.2.3 Sampling

Purposive sampling is an approach which seeks interviewees that exist in a particular cultural domain (Tongco, 2007), or may be experiential experts in the topic of
interest (Morse, 1998). It provides a non-probability sample, and generalisations about the population as a whole cannot be made. This sampling approach was adopted in order to find coastal water-users who frequently (≥ once a week) visit at least one beach in the study area to participate in activities dependent on wave and beach conditions. Participants were not required to have any prior knowledge about MRE or Wave Hub. Many were prominent members of their coastal community (for example business owners and senior lifeguards), and all could be classed as experiential experts, having used the local beaches on a weekly basis, in some cases for over 40 years. Snowball sampling, where previous participants suggest further suitable participants (Noy, 2008), was used to aid the identification of appropriate interviewees.

Table 3.1 shows the water-users represented by the sample group; although this does not cover every possible beach water activity, wave dependent activities were well represented, as were surf-zone dependent professions such as lifeguarding and surf instructing. Sampling was continued until saturation of the developing theory became apparent; in other words, until generic features of the newly coded data consistently replicated the emerging theory (Glaser and Strauss, 1967), and the new data therefore no longer modified or challenged the developed theory (Strauss and Corbin, 1998, Charmaz, 2006). This was apparent after 14 interviews, and 5 more interviews were conducted before saturation was confirmed and sampling stopped (19 interviews were conducted in total).

3.2.4 Analysis

The interview transcripts were coded, in that ‘meaning labels’ were attached to sections of text that summarised the data in question (Charmaz, 2006). This was conducted using the NVivo qualitative data analysis computer software package. Eventually the codes were integrated into larger conceptual categories using the constant-comparative method. This involves comparing incidents in the data, and is used to reveal the defining properties of each category (Glaser and Strauss, 1967). Eventually the categories and their properties became more abstract, and analysis progressed beyond description of the case in hand, to thinking more generally and theoretically (Strauss and Corbin, 1998). Once all the relevant properties of a category were thought to have been identified, each respondent was placed on the ‘dimensional scale’ of each property (for example, a scale might range from small to large). A quote or short summary that identified their position dimensionally was noted. Having identified the first 10 participants’ dimensional position for each property of each category, key themes were sought out by looking at whether or
Table (3.1). Characteristics of the study sample.

<table>
<thead>
<tr>
<th>Study sample</th>
<th>n=19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male participants</td>
<td>n=15</td>
</tr>
<tr>
<td>Female participants</td>
<td>n=4</td>
</tr>
<tr>
<td>Age range</td>
<td>26-61 yrs</td>
</tr>
<tr>
<td>Modal age range</td>
<td>29-39 yrs</td>
</tr>
</tbody>
</table>

Water uses represented

<table>
<thead>
<tr>
<th>Activity</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surfing</td>
<td>18</td>
</tr>
<tr>
<td>Swimming/bathing</td>
<td>11</td>
</tr>
<tr>
<td>Bodysurfing</td>
<td>8</td>
</tr>
<tr>
<td>Lifeguarding/lifeguard training</td>
<td>7</td>
</tr>
<tr>
<td>Surf instructing</td>
<td>2</td>
</tr>
<tr>
<td>Body boarding</td>
<td>2</td>
</tr>
<tr>
<td>Snorkelling</td>
<td>2</td>
</tr>
<tr>
<td>Paddle boarding</td>
<td>1</td>
</tr>
<tr>
<td>Surfboat rowing</td>
<td>1</td>
</tr>
</tbody>
</table>

not respondents aligned dimensionally (Strauss and Corbin, 1998). If three or more respondents aligned dimensionally for a given property, it was tentatively considered a theme. For example, most of the initial respondents predicted ‘impact to wave height’ (property) to be ‘insignificant’ (dimensional position). Variations from the key theme and negative cases were identified and noted. An initial theory was proposed at this stage, based on the themes noted and the relationships observed between the key categories. After the first 10 interviews coding was conducted more selectively (Strauss and Corbin, 1998), with coding focused more on the key categories identified in the initial analysis just described. After every 3 subsequent interviews the theory was tested against, and if necessary, modified by the new data. The theory was therefore developed iteratively, in an inductive-deductive cycle throughout the study.

3.3 Results

Participants anticipated a range of impacts to the coastal environment, varying in magnitude from ‘none at all’ to ‘severe’. The main impacts discussed were reductions in wave height or quality, and changes in sediment transport. Other impacts that were mentioned included coastal erosion, changes in rip current behaviour, and the possibility of devices breaking free and washing ashore. It was observed that when
discussing their anticipations, participants revealed their perception of wave energy technology and their perception of the coastal environment, and often one would be weighed against the other while discussing the likelihood of an impact. The following sections will describe the themes observed in each of these key categories (anticipated impact, perception of technology, and perception of nature), and Interview extracts will be used to evidence the findings. Pseudonyms have been used in all cases, to ensure participant confidentiality.

### 3.3.1 Anticipated Impacts

13 of the 19 participants anticipate that Wave Hub will have an ‘insignificant’ impact on both the height of coastal waves and the quality of surfing conditions. Ryan, a surfer who has lived in the region most of his life, demonstrates this lack of concern in the following quote:

“I can’t believe it will make any difference, maybe on a very small swell, at a very sort of narrow window, you know one strip of beach that’s sort of directly in the swell direction might lose a few inches, but I just can’t see it... making any impact at all to be honest.”

However, despite not being concerned about impacts to wave height, surf-school owner Terry showed some concern about wave quality:

“If you reduce the (wave) period, you’re reducing the energy in the swell, you’re reducing the speed, you’re reducing the potential energy that’s going to land on the beach, you know... so potentially it could affect the actual end result on the shoreline.”

Anticipated impacts to sediment were more varied between participants. Some foresaw no impact to coastal sediments, while others like Ben, a surfer and senior lifeguard in the region, anticipated that the impact could be severe.

“We’re always having that (wave) direction aren’t we? So it could reduce the amount of deposit onto the beach and that kind of renewing of the sand dunes and everything like that... there will be less movement of course, there has to be hasn’t there.”

Impacts to sedimentation were usually informed by the level of wave impact anticipated. Some assumed that if an insignificant impact to waves was foreseen, then the same would apply to coastal sediments and rip current formation. Cassia, a competition level surfboat rower, anticipated a possible change in the characteristics of rip currents, but emphasized that she had no concern about Wave Hub increasing
the hazard they pose, as she saw rips as an existing hazard that has always required awareness.

Participants’ predictions of coastal impacts from upscaled MRE deployments in the future were similarly varied, ranging from no anticipated impact, to potentially severe impacts. Some felt that impacts from larger and more efficient deployments would be determinable from, and proportional to, any impacts from Wave Hub. However most participants, like Sarah (a surf-life-saving club member), suggested that their opinions were not yet formed and would be guided by presently unknown properties of future deployments.

“I think I would need to know the results of the trial with this smaller one and the impact that had, and obviously the kind of modelling you would do on a bigger scale”

3.3.2 Perception of Technology

Four main properties were referred to by participants when describing wave energy technology; these were its ‘form’, its ‘scale’, its ‘siting’, and its ‘use of resource’. Commonly the symbolism of a ‘barrier’ was used when discussing potential impacts to waves, and the properties of form and scale were frequently used to support why the technology had or had not been interpreted as a barrier. Senior lifeguard Ian demonstrates how his perception of form influenced the level of impact he anticipated:

“It does depend on its make up because if it’s a long slender device, that kind that stays in line with the swell, I can’t see that it’s going to cast much shadow, and I can’t see that it’s going to dramatically, you know, reduce the energy in the actual waves... unless there was some different device that was spread wide and cast a big shadow.”

It was often revealed that imagery from media sources had heavily informed perceptions of form and scale, and 18 of the 19 participants had seen an image of a WEC in the media. Conversely, 16 of the participants stated that they had not read, or sought, what they considered to be technical information with regards to the functioning of WECs. Wave energy devices were occasionally compared to similar objects in the ocean that weren’t perceived as creating a barrier to waves because they float and don’t extend far beneath the ocean surface, such as ships. For example Tim, a local surf-clothing business owner and surfer, interpreted the technology as being in harmony with the resource it is there to extract, because he had seen Imagery of wave devices moving with waves.
“A breakwater is a building. Concrete. It doesn’t move. Whereas the wave hub... will rise and fall like a rubber duck... it will work with the environment... when I think of the Wave Hub I think of something far softer, in its presence in the sea.”

Senior lifeguard Joel perceived the scale of the technology to be very small relative to the scale of the environment it will operate in, reassuring him that the technology will not create a barrier to waves. Conversely, some indicated that if the scale of future, upscaled deployments was perceived to be large, then the anticipated impact would be greater than that of Wave Hub.

“I can’t see it dramatically reducing the power of the swell I just can’t, because it is really just a pinpoint in the ocean, so I can’t see it doing that.”

Many participants considered the siting, and in particular the distance of the technology from their local beach, as being strongly connected to the level of impact that might occur. Terry the surf-school owner perceived Wave Hub as being very distant from Perranporth beach:

“I think it’s probably out to sea enough that it’s not going to really affect the local conditions that much really... I can’t see any real sediment issues locally; I think it’s well placed in that respect.”

Equally, surfboat rower Cassia mentioned that future, larger-scaled deployments would need to be sited further from shore to negate an increase in impact. Experienced paddle-boarder and surfer David, demonstrated how a combination of properties (siting and form) constructed his perception of the technology, and determined whether or not an impact to waves was foreseen. He was asked if he thought wave height or recreational wave quality would be affected.

“No if they’re 10 miles off (shore), no. they’ll just roll over it, or through it and round it. It’s not like a barrier, so it won’t have any effect on it at all.”

Participants who used one or more of the previously described properties to substantiate their anticipated impacts often assumed that because the technology is not perceived as a physical barrier (such as a breakwater), that impacts to waves will be insignificant. This assumption potentially ignores the concept of energy extraction, and the technologies ‘use of resource’. All of the participants identified that one of the purposes of Wave Hub was to generate electricity from passing waves, but many of them did not appear to associate this with the potential to take energy away.
from waves in order to achieve this. A number of participants, including surf-school owner Rob, described the technology as ‘only harnessing’ wave energy, which alludes to this assumption and indicates that these participants perceived the extraction of energy to be minimal. An extreme example of this was provided by experienced surf-board shaper Tom.

“They’re not actually taking the energy away; they’re just using it to generate new energy.”

For other participants however it was clearly perceived that if energy is extracted from a wave, then the remaining energy will be less. Describing the technology as ‘taking energy away’ from waves was commonly used by participants who were concerned about significant or severe impacts, like surf-school owner Terry, to support their answers.

“Just from a science background, thinking well, if you’re going to reduce or take energy out of something, it’s going to reduce or impact it in some way, so it’s got to have an effect. So if you’re taking energy out that’s going to reduce the swell size.”

In cases where participants revealed that technical information such as impact assessments had informed their perception of the technology, both significant and insignificant impacts were foreseen. Commonly this information influenced participants’ perception of the technologies use of resource.

3.3.3 Perception of Nature

Certain properties of the coastal environment contributed to each participant’s perception of ‘nature’, in its present context. While properties of the technology were explicitly used by all participants to justify whether or not an impact was foreseen, not all explicitly used properties of nature in the same way. However; those who did not, often revealed their perceptions elsewhere. Perception of nature was used by participants as the context on which to assess the likelihood of impact. The properties that commonly informed perceptions of nature were the ‘abundance of the resource’ and the ‘sensitivity of the environment’.

A common perception was that wave energy is abundant, and a number of people commented on the vast amount of energy in ocean waves. Participants like surfer and lifeguard Mark, were of the opinion that even if energy is extracted from waves, the impact would be negligible, as they believe that there would still be an abundance left. This demonstrates how perception of technology (i.e. use of resource) is weighed
against perception of nature (i.e. abundance of resource), and in this case the former is outweighed by the latter:

“You think about the swell that's 10 miles out to sea. You think of the energy that that's got. I can't see it affecting it.”

Some participants commented on the regular occurrence of large waves or infrequency of small waves at their local beach, indicating that they perceive the resource as being abundant. Conversely, some people mentioned the infrequency of high-quality surfing conditions in the region. Surf-school owner Terry had previously expressed concerns about Wave Hub impacting high-quality surfing waves, by altering wave characteristics. This participant viewed the resource as being scarce and foresaw that the potential impact could be significant.

“Surfing is a fickle thing, you only get those few days a year where it’s that good, so you want to keep that, you know maximise that as best you can.”

Some participants indicated that they perceived coastal sediment as being sensitive, and foresaw that impacts could therefore be significant or severe. Despite anticipating insignificant impacts to wave conditions, Toby, a bodysurfer and swimmer, felt that impacts to sediment transport could be far greater, because of his perception of its sensitivity.

“It won’t affect the size of waves for surfers, but it takes far less of a wave height to change the way sands are shifting and the way coasts are eroding.”

Seasoned lifeguard Ian recalled an occasion when he had perceived that human activities had significantly affected local beach morphology and surfing conditions. In this case, past impacts to the coastal environment informed his perception of the sensitivity of nature:

“I remember one year we had a dredger, quite a big dredger, dredging continually off of Porthtowan and Chapel Porth, and Porthtowan had their worst years surf... it took about three years to recover... that’s the only thing that would worry me is sand movement.”

In some cases participants viewed coastal conditions as being dynamic. This often resulted in the opinion that impacts would be unnoticeable, as they were foreseen as being less than the natural degree of fluctuation. It should be noted that this does not indicate that a lesser impact was anticipated; rather a less-noticeable impact was foreseen. Because of this complexity, this property (degree of fluctuation) has been excluded from the conceptual model described in section 3.4 (Fig. 3.1).
3.4 Discussion

There was a clear interplay between participants’ perception of the proposed technology, and the environment in which the technology is being installed. These perceptions appeared to be influenced by certain properties of the technology and certain properties of nature, and the dimensional location of the participant on these property ‘scales’ ultimately determined whether or not an impact was anticipated. The conceptual model presented in Fig. 3.1 predicts a level of anticipated impact, by positioning a proposed technology on the property scales on the left hand side. This requires an estimation of the likely public perception of the technology. If perceptions about the natural environment can be estimated, then these may also be positioned on the model. The sum of the perceptions qualitatively determines the anticipated impact. Although not all participants discussed all of the observed properties, all of them used at least one or more property to justify their anticipations; the anticipated impact model integrates all of the observations into a predictive framework. Surf-board shaper Tom summarised the observed construction of opinion in the following statement:

“You know it’s only common sense... it’s not like I’ve trawled all through the internet and read everything about it. I’ve just seen it, I understand the technology, and I understand the ocean.”
These findings imply that wave energy technology is likely to be assessed by individuals on a technology-by-technology basis - participants did not merely classify all wave energy technology in the same way. In other words they attributed their anticipations of impact to properties that are not uniform across all wave energy technologies, and in many cases revealed how their level of anticipated impact would change if the properties were perceived differently. This indicates that as different WEC's become commercially deployable, and different scales of deployment are proposed, water-users are likely to anticipate different levels of coastal impact.

This has significant implications for certain devices. For example, compare a shallow water, hinged-flap type WEC (for instance the ‘Oyster’ device developed by Aquamarine Power www.aquamarinepower.com) and a deep water, in-line attenuator WEC (for instance the ‘Pelamis’ device developed by the now defunct Pelamis wave power). When positioned on the anticipated impact model in Fig. 3.1, it becomes apparent that some people may perceive the hinged-flap device (form = relatively wide and stationary, siting = nearshore) to be at the top of the anticipated impact scale, whereas the in-line attenuator device (form = relatively narrow and moving, siting = offshore) may rate at the bottom, regardless of the energy rating of the two devices (i.e. their use of resource). It is not unrealistic to assume that water-users may also perceive other marine renewables technologies in terms of similar properties. A number of participants discussed their perceptions of offshore wind farms or tidal barrages, and mentioned properties such as form, scale and siting. While offshore wind turbines were generally perceived to have a minimal effect on waves (form = narrow, siting = offshore), tidal barrages were perceived as a barrier to waves (form = wide and stationary, scale = large) and generally posed a greater concern. The model may therefore be applicable outside the context of wave energy and possibly even outside the realm of MRE, although would require further validation to be used outside the present context.

The same MRE technology proposed at two different locations might face different levels of support or opposition if the coastal environment is perceived differently in the two regions. This would alter its position on the model in Fig. 3.1, and change the level of impact anticipated by water-users. Different technologies may also be placed in coastal environments with different properties. Although wave energy projects are likely to be sited in regions with ‘abundant’ wave energy, tidal energy installations may be proposed in locations with ‘scarce’ wave energy, and may therefore invoke fears of a significant impact to waves. As with perceptions of technology, perception of nature is highly subjective, but common perceptions may exist in a region allowing a position on the model to be estimated. The way that the natural environment is valued by a community is likely to influence this
perception (Van der Horst, 2007). Regions that historically have been influenced by engineering or industrial activity may be perceived as more or less robust than untouched environments. For example, if past changes in coastal conditions have been attributed to human interference, this might enhance the perception of the environments sensitivity to MRE. Conversely, communities along a heavily industrialised coastline may welcome the green qualities of MRE in their locality, if it improves symbolic attachments to the region (Devine-Wright, 2007, Wustenhagen et al., 2007).

The participants’ perceptions were largely uninfluenced by technical information or impact assessments. Firm views existed, despite there often being a lack of technical understanding, which has been observed before in wind farm studies (Devine-Wright, 2007). As Slovic (1987) observed, risk is assessed by the majority of people using intuitive judgements (‘risk perceptions’) and not through technical information. This is precisely what has been observed in the present study. Sometimes these risk perceptions aligned with scientific understanding, such as when participants perceived that wave farms positioned closer to the coast would have a greater wave impact, agreeing with wave modelling (Millar et al., 2007, Black, 2007, Li and Phillips, 2010, O’Dea and Haller, 2014, Abanades et al., 2015). In other cases, misconceptions were apparent, such as surf-board shaper Tom’s perception that new energy could be created without causing any energy deficit, contradicting the principal of energy conservation.

This study indicates that Environmental Impact assessments (EIA) and consultation cannot be relied upon to relay information to the wider public, nor can the public be relied upon to seek out information for themselves. Media was seen to be the most powerful informer (also observed by West et al. (2010)), and is likely to play a significant role in influencing peoples intuitive judgements of technologies to come in the future. With this in mind it is suggested that where possible, the properties described in the anticipated impact model (Fig. 3.1) are carefully considered when engaging with coastal water-users, or preparing media content regarding a new technology. The results also suggest that there are areas of misunderstanding with regards to wave energy technology. In particular, the concept of extracting energy was poorly understood by a number of participants and this issue warrants better public education.

It has been proposed in some papers that opposition is likely to arise when a mismatch occurs between an individual’s interpretation of ‘place’ and their interpretation of ‘technology’ (McLachlan, 2009, Devine-Wright, 2011). At first glance this appears to fit well with the anticipated impact model presented here, but it should be noted that only a part of the interpretation of the technology has been considered
in this study: a person’s symbolic interpretation is made up of more than just their perceptions of form and scale etc. Other factors, such as the ‘environmental status’ of the project and the ‘significance of the electricity produced’, have also been found to affect an individual’s interpretation (McLachlan, 2009). Bailey et al. (2011) propose that a better descriptor of the reasoning process undertaken by individuals, is the notion of a wager between perceived risks and perceived rewards. This resonates well with the findings in this study; however, the results presented here go a step further in that they start to allow for prediction of when risks will be perceived as being high or low in the specific context of water-users (assuming that physical coastal impacts are a priority risk to coastal water-users).

Many participants believed that impacts would be insignificant and their perception of risk was therefore low, allowing the perceived rewards (local economic benefits, energy security, mitigating climate change etc.) to easily outweigh the risks. This may explain the high levels of support observed for the Wave Hub project in this and other studies (Bailey et al., 2011). The perceived risks may well increase as new technologies are proposed and the scale of deployments is increased. Many participants suggested they were awaiting the ‘results’ of initial deployments such as Wave Hub, in order to make more informed opinions about coastal impacts from larger-scale deployments that may occur in the future. If the effects of Wave Hub or other test sites were perceived, rightly or wrongly, to be large, then risk perceptions of MRE technology could be severely altered and may be difficult to rectify (Slovic, 1987).

3.5 Conclusions

This Chapter aimed to explore what physical coastal impacts are anticipated by water-users in the run up to the first trials of wave energy converters at the Wave Hub facility. An additional aim was to explore how these opinions were formed, in order to foresee how coastal water-users might react to future MRE proposals, and inform the public consultation and engagement process. During interviews, participants discussed the likelihood and severity of various coastal impacts; namely, reductions in wave height or wave quality, changes in sediment transport, coastal erosion, changes in rip current behaviour, and the possibility of devices breaking free and washing ashore. The anticipated level of impact varied, depending on the type of impact being discussed. In summary, impacts to wave height were generally anticipated to be insignificant, anticipated impacts to wave quality ranged from insignificant to significant, impacts to sedimentation and rip currents were anticipated to be insignificant to severe (varying widely between participants), and
opinions on impacts from future installations were mostly unformed.

It was observed that these opinions were formed through interplay between the individual's perception of the technology, and their perception of 'nature'. The properties that made up these perceptions are summarised in the anticipated impact model in Fig. 3.1. The model enables a level of anticipated impact to be predicted, by categorising technologies and coastal environments in terms of their perceived properties. Although positions of support or opposition may not be predicted using this model alone, it provides a novel framework which not only summarises the way that water-users currently perceive MRE technology, but begins to predict how they will perceive future technologies and related coastal impacts. The implications of the model are quite severe for certain technologies. Marine renewables proposals which are perceived to be large scale, close to shore, wide, stationary, or extracting high percentages of wave energy are likely to invoke anticipations of significant or severe coastal impacts. Conversely, those which are perceived to be small scale, far from shore, narrow, moving, or extracting low percentages of wave energy are more likely to invoke anticipations of insignificant or no coastal impact. Interestingly, the level of anticipated impact was most often based on device properties such as form or siting, and was rarely influenced by device extraction efficiency. This has not been previously documented to our knowledge.

Media sources, as much as impact assessments, will be crucial in alleviating concerns and gaining support for MRE from water-users, as few participants had seen any technical information about Wave Hub. Longitudinal studies of opinion are needed, and water-user perceptions should be further investigated once devices are deployed and active at Wave Hub. Other studies have provided a superficial examination of the concerns of surfers over the wave hub proposal (McLachlan, 2009, West et al., 2009), or quantified public support and opposition to marine renewables (Bailey et al., 2011, Voke et al., 2013). This chapter however, for the first time provides insight into how concerns over coastal impacts from MRE are formed, and how these concerns vary amongst water-users in general. A framework for understanding future attitudes towards marine renewables and coastal impacts has been developed through the anticipated impact model. The properties in the model that were observed to make up people’s perception of MRE technology (form, scale, siting and use of resource) should be carefully considered when engaging with water-users. Projects which are likely to invoke greater concern from coastal water-users may then be identified early in the proposal stages, which will benefit subsequent consultation.
Chapter 4

The Use and Perception of Coastal Waves

4.1 Introduction

4.1.1 Background

To manage waves as a shared commodity, and avoid clashes of interest between renewables and recreational stakeholders, it is necessary to understand what wave conditions are of most interest to each group. Apart from a small sample of surfers who were interviewed during the Wave Hub consultation (Black, 2007, Li and Phillips, 2010) there has been little research to indicate what surf conditions are ‘preferred’ by recreational water-users globally. Perhaps more fundamentally, how they perceive and describe different wave conditions is also poorly understood, and has either been overlooked in previous research (Black, 2007, Li and Phillips, 2010) or has to be assumed to match the perceptions of trained mariners or scientists from previous studies (Perlin, 1984, Plant and Griggs, 1992, Caldwell, 2005, Caldwell and Aucan, 2007). These are compounding problems, as without an understanding of how waves are perceived and described by water-users, their wave preferences cannot be interpreted correctly. For example the 1 - 4 m preferred wave height range expressed by individuals during the Wave Hub consultation could equate to 2 - 8 m significant breaking wave heights according to the ‘Hawaiian scale’ of observation (Caldwell, 2005, Caldwell and Aucan, 2007). The wave conditions of interest to beach water-users therefore remains poorly understood globally, and without this information it is difficult to assess how much impact wave energy extraction will have on recreational waves at the coast.

The interviews described in chapter 3 revealed that the way participants perceived the coastal environment influenced the way that they constructed their opin-
ions on coastal impacts. One of the key properties discussed in the interviews was the perceived abundance of waves. For some, a perceived abundance of energy in ocean waves reassured them that the effects of wave energy extraction on coastal waves would be minimal. Others perceived quality surfing waves to be scarce, and therefore anticipated a more severe impact. Understanding the way that coastal waves are used (the preferred conditions for recreation) and perceived (the perception of height, period and wave abundance) will therefore clarify both the likely impact, and the impact anticipated by water-users, on recreational waves at the coast.

4.1.2 Chapter Aims

This chapter has three main aims. The first is to characterise the population of water-users at two beaches in the lee of Wave Hub. The second aim is to investigate how different water-user groups perceive wave height and period. This includes their perception of the wave resource, in terms of the abundance of wave energy and quality surf, at their beach. The third aim is to determine specific ranges of wave height and period that are preferred by different water-user groups for recreation.

4.2 Methodology

4.2.1 Research Approach

A quantitative approach was adopted for this part of the study as statistical generalisations about the population of water-users in the lee of Wave Hub are sought. In contrast to the constructivist approach used in Chapter 3, a post-positivist epistemology is adopted here and in subsequent chapters. This assumes that knowledge is restricted to what can be directly observed and measured, but compared to the traditional positivist science of the early 20th century, post-positivism accepts that reality can only be measured with some degree of uncertainty or probability. Although a predominantly quantitative paradigm, it is considered more compatible with qualitative findings (such as those from Chapter 3) than pure positivism (Guba and Lincoln, 1994). Although positivist paradigms have been widely critiqued, especially in social tourism research (Botterill, 2001), for failing to appropriately handle values, emotions, and perceptions (Jones, 1998), they are suited to objective quantitative studies where no deeper exploration of meaning or the construction of perceptions is required.

A structured, quantitative interview survey was conducted over a period of one year at Perranporth and Porthtowan beaches in the lee of Wave Hub. To achieve
the previously outlined research aims the characteristics and wave preferences of a wide demographic of water-users, and visual wave observations made during a wide range of conditions, were required. Hence it was necessary to collect data across each season of the year to ensure that the participants were representative of the entire population of water-users, and also to ensure the wave conditions varied significantly. To investigate the participant’s perception of waves, visual observations of wave attributes made by the participants were compared to measurements from the nearshore wave buoy at Perranporth, collected in approximately 14 m water depth and transformed to breaking height using linear wave theory. For brevity, throughout this chapter wave measurements made visually with the human eye will be referred to as ‘observations’ and measurements made with instrumentation such as wave gauges or buoys will be called ‘measurements’.

### 4.2.2 Sampling

Interview data were collected on 36 survey dates between April 2013 and March 2014. In order for the interview responses to represent the population of water-users at the two sites, a random or probability sample was sought. Veal (2006) states that to achieve this all users must have an equal chance of being selected, and the interviewer should not select users on any basis besides the predefined sampling strategy. During each survey participants were sampled from areas that overlooked the water, typically including the intertidal and upper beach, the water’s edge, or an adjacent car park (Fig. 4.1). The interviewer(s) walked in circuits around these areas, and would ask the closest available person if they used the water at that beach and if they would like to take part in the survey. After completing each interview the interviewer would continue the lap and approach the next closest person, until 2 hours were completed. Typically participants were entering or leaving the water, preparing to go in the water (Fig. 4.2), or watching the wave conditions, although many were simply in the vicinity of the beach. Survey dates were predetermined using a random number generator on a computer, along with survey start times between 8 am and 6 pm. The two beaches were visited alternately, and interviews were collected for 2 hours on each visit. On 29 of the survey dates a single interviewer collected responses, with an average of 9 interviews completed on each visit. On 7 randomly selected survey dates a second interviewer assisted in the data collection, resulting in (on average) 21 responses on those dates. The total number of interviews completed was \( n = 403 \).

The choice to conduct interviewer completed surveys rather than respondent completed questionnaires was made on the basis that often a larger sample can be
achieved, with a more complete set of responses (Veal, 2006). Non-response rates can be high for postal surveys for example, and this can introduce uncertainty as to the sample bias introduced by the non-respondents (Veal, 2006, Bailey et al., 2011). A respondent completed questionnaire would also make it extremely difficult to accurately compare wave observations to concurrent wave measurements. However, as is the case with a qualitative interview, the effect of the interviewer on the responses during a structured, quantitative interview has to be considered. Three potential sources of 'error' were identified by Fontana and Frey (1998); these are: whether the respondent gives a 'socially desirable' answer to please the interviewer, whether the wording of the questions is suitable, and whether or not the wording of the questions changes from one interview to another. The structured nature and scripted wording of the present interviews aimed to minimize these errors, and it has to be assumed that respondents answered rationally and truthfully. However it is recognised that this potentially overlooks the effect of emotions and social interaction on each person's response, which is recognised as a limitation of the survey. In particular, the respondents may have answered differently to the male and female interviewers who conducted the surveys, or may have altered their wave observations or preferences to impress or please the interviewers, but such 'errors' are assumed to have a minimal effect on the overall findings.

Each potential participant was informed that we were conducting research on people's use of the sea, and perception of wave conditions. Respondents were also told that their answers would be confidential and purely used for academic research, and could be withdrawn at any time. By these means, the three key elements of informed consent were observed: lay disclosure of necessary information, the capacity of the participant to understand the information, and voluntary participation (Faden et al., 1986). Only participants over 18 years old completed the interview, and ethical permission was granted by Plymouth University to conduct the surveys.

4.2.3 Administering the Interviews

The interview was administered using a digital tablet device ('Apple Ipad') and survey software ('Isurvey'); this allowed for quick and accurate logging of the answers in a digital format. In addition, the exact time each answer was given was logged by the software, which enabled concurrent comparisons to be made between wave observations and wave buoy measurements. The interview was designed to avoid jargon, ambiguity and loading in the questions (Veal, 2006). Each question was asked verbally, and the answers were input to the digital device by the interviewer. All questions were closed-ended in format, either offering a single selection from
Figure (4.1). Interview sampling areas used at Perranporth beach (left panel) and Porthtowan beach (right panel). The location of the nearshore wave buoy in approximately 14 m depth is shown as an upwards triangle.

a randomly ordered list, or a numeric answer. The closed-ended nature of the answers ensured that the researcher could not inadvertently alter the meaning of the answer in the process of analysing the response. The full list of questions is given in Appendix B; in summary, participants were asked questions from four main sections:

1. Demographic information and water use habits: such as the water activity they most often participate in at that beach, the number of years they have participated in that activity, and how frequently they participate.

2. Visual estimation of the average breaking wave height, $H_{vis}$, and period, $T_{vis}$, over the 30 minutes prior to the interview, or as long as they had been within view of the sea if less than 30 minutes. Estimation of annual mean wave height was also made. Wave height was defined as ‘the face height of the waves as they break’ and period as ‘the time in seconds between each wave passing a fixed point’. These definitions were intended to provide a guideline, while remaining relatively vague so that the perception of the individual would be apparent.
3. Their preferred wave conditions for water use at that beach: preferred breaking wave height, and period.

4. To investigate the perception of the wave resource in the study region, participants were asked to estimate the annual mean wave height, as well as how often they think ‘large’ wave conditions, arbitrarily defined as $H_{s,b} > 6$ ft. (1.83 m) occur. In addition, participants were asked how often they think their preferred combination of wave height and period jointly occur. For ease of estimation these probabilities were expressed by participants as a percentage of days in a typical year, but were later converted to a standard decimal probability scale (0 to 1).

4.2.4 Bias and Non-Response

To achieve externally valid results that are generalizable to the population of water-users in the area, a probability sample was sought (Payton, 1994). In this respect, all members of the population should have an equal chance of being included in the study (Veal, 2006), otherwise biases start to be introduced. Randomization of dates and times, as well as a strict sampling route and approach were adopted; however some bias towards certain groups is still likely to exist. Across the different survey
dates an average of 23% of participants declined to take part in the interview. If a reason was given, it was often because they rarely or never used that beach for water recreation and were therefore not part of the target population, or because they felt they wouldn’t be able to answer questions relating to wave conditions.

Sarantakos (1993) propose that a lack of interest or awareness in a topic is a common reason for non-response, while willing participants may be more interested and/or hold stronger views. It is therefore acknowledged that there may be some bias against those with very little experience or interest in wave conditions. When couples or mixed gender groups were approached it was noted that men would more often volunteer to answer the questions than women. This may explain some of the disparity in response numbers between men and women (Fig. 4.5, upper right panel), but the vast majority of the disparity is thought to be due to lower female water-user numbers and is therefore a characteristic of the population.

There is also a likelihood of some bias towards non-peak time water-users. This is a result of the fact that, on the whole, there were the same number of interviewers (either one or two) on each survey date, yet the population of beach users fluctuates massively. In peak summer season a lower proportion of the water-users present will have been surveyed compared to a day in winter, when in some cases all of the water-users present could be surveyed. This reduces the probability of a peak-season water-user being sampled slightly, compared to an off-season user. This effect is reduced somewhat by the increased number of responses that were often achieved on summer survey dates however, and the sample should still largely represent the population. A limitation of using the digital devices was that surveys could not be conducted in the rain, excluding some survey dates. As observations of wave conditions were being sought, days when waves were forecast to be < 1 ft (0.3 m) were also avoided, which occurred only once. Whenever wave or weather conditions were unsuitable, the next suitable day was used instead.

4.2.5 Water User Groups

To investigate how much perceptions vary between different water-user groups, observations were grouped by each participant’s ‘experience factor’, $E_f$, gender, and preferred water activity. $E_f$ is defined as the product of the number of years they have been participating in their preferred water activity and the percentage of days in a year they typically participate. $E_f$ therefore provides a crude approximation of the total number of days the individual has participated in their lifetime, expressed in units of years. ‘Novice’ water-users were classed as those with $0 < E_f < 0.3$, ‘experienced’ water-users as $0.3 \leq E_f < 4$, and ‘expert’ water-users as $4 \leq E_f$. These
thresholds are approximately the 25\textsuperscript{th} and 75\textsuperscript{th} percentile, respectively, of the experience levels within the sample (Fig. 4.4, lower panel). Two preferred activity bins were created, those from participants who put surfing as their preferred activity, and those who stated any other preferred activity (53.6\% and 46.4\% of the sample respectively; Fig. 4.4, upper panel). The activities were grouped in this way to create relatively large and evenly sized sub-samples; when other activities were considered on their own, they were found to produce undesirably small sub-samples in some cases. In the following analysis experience level, activity, and gender will be considered separately to maximize the size of each sub-sample. A minimum sub-sample size of $n = 10$ was used throughout the study.

4.2.6 Wave Data

Wave Data was provided by a Datawell Waverider III buoy maintained by the Channel Coastal Observatory (www.channelcoast.org) and located just offshore of Perranporth beach, moored at a water depth of approximately 14 m (Fig. 4.1). Vertical heave and horizontal displacement were logged over 30 minute periods at 1.28 Hz, to generate directional spectra and statistics including significant and maximum wave height, peak and zero-crossing wave period, wave direction associated with the spectral peak and directional spread. To ensure that wave measurements were near concurrent with observations, only measurements made within 30 minutes of each observation were considered. The depth of the measurements was taken as the approximate buoy depth, plus or minus the tidal elevation at the time of each wave observation. Wave measurements were unavailable on four of the survey dates due to technical issues with the buoy, and consequently the total number of usable wave observations is $n = 367$.

In order to compare the breaker observations to measurements, wave heights from the nearshore buoy were transformed to breaking heights using linear wave theory. Significant wave height at breaking, $H_{s,b}$, was computed using the formula of Larson et al. (2010), which is an efficient, non-iterative algorithm for solving the combined conservation of wave energy flux (Eq. 4.1) and Snell’s law for refraction (Eq. 4.2) equations. Their formula approximates incipient breaking conditions from wave measurements at a location of arbitrary depth, denoted with subscripts $b$ and $m$, respectively. The two underlying equations for the formula are written as follows:

$$H_m^2 C_{g,m} \cos \theta_m = H_b^2 C_{g,b} \cos \theta_b$$

(4.1)

$$\frac{\sin \theta_m}{C_m} = \frac{\sin \theta_b}{C_b}$$

(4.2)
where $H$ = wave height, $C_g$ = group speed, $\theta$ = wave angle, and $C$ = phase speed. Assuming shallow water wave theory at the point of incipient breaking, these equations are coupled as follows:

$$H^2_m C_{g,m} \cos \theta_m = \frac{\gamma_b}{h_b} \sqrt{gh_b \cos \left[ \arcsin \left( \sin \theta_m \frac{C_b}{C_m} \right) \right]}$$

(4.3)

where $g$ = the acceleration of gravity, $\gamma_b$ = breaker depth ratio and $h_b$ = water depth. Using a parametric formula that corrects for the error introduced by assuming small breaking wave angles, Larson et al. demonstrate that the water depth at breaking can be derived from Eq. 4.3. $\gamma_b$ is then used to infer the wave height at breaking from the relationship, $H_b = \gamma_b h_b$. Depth limited breaking was imposed in the present study using a commonly applied depth breaker ratio ($\gamma_b$) of 0.78 (Sverdrup and Munk, 1946). Error in the estimation of breaking wave height may be introduced by the assumptions of linear and shallow water wave theory, as well as through the breaker depth ratio used. In addition, assuming wave energy conservation between the offshore and breaking locations means that frictional losses between the wave and seabed (bed friction) are ignored, which may cause an overestimation of $H_b$. For the purposes of this study, these errors are assumed to be small compared to the variation in the visual observations. $H_{s,b}$ was computed by applying significant wave heights to Eqs. 4.1 - 4.3.

Wave period was not transformed from the buoy and was taken as the significant period, $T_{1/3}$. This was approximated as either $T_{1/3} = 0.95 T_p$ for windsea spectra (Goda, 1978), or $T_{1/3} = T_p$ for swell (Goda, 1988), where peak period, $T_p$, is the wave period associated with the spectral energy peak. Plant and Griggs (1992) argue that when bimodal spectra occur, featuring both a swell and windsea component, an observer is likely to report a significantly reduced wave period, due to the interaction of the swell and windsea. Despite this, for bimodal cases, the $T_{1/3}$ value associated with the dominant component (swell or wind sea) was used, as this resulted in the best agreement with the visual observations from the study. Swell and windsea were identified in the 1 dimensional spectra, and bimodal spectra partitioned, using the method described by Portilla et al. (2009). Their approach aims to ignore spurious peaks in the spectra, in order to provide a consistent partitioning point between significant windsea and swell components. Spurious peaks are defined as having very high frequency ($> 0.35$ Hz), low energy ($< 8\%$ of the total energy), being within two frequency bins of the minimum or maximum spectral frequency, or having a lower peak energy than that of any surrounding partitions. Having disregarded spurious peaks, the remaining significant components are then identified as windsea or swell by comparing their peak energy with the energy of a Pierson-Moskowitz fully developed sea (Pierson and Moskowitz, 1964) with the same peak frequency.
As there is no other source of wave data more local to Porthtowan, it has to be assumed that there are no significant differences in the nearshore conditions between Porthtowan and the Perranporth wave buoy, despite their 10 km separation and slight difference in orientation (292° and 283° from North, respectively, Fig. 4.1). Scott (2009) and Poate (2011) used data output by a Mike21 wave model at the 15 m depth contour to assess differences in the wave climate along the North coast of Cornwall. They found that differences in the annual wave statistics were negligible under non-extreme conditions, with 0.8% difference in $H_{s, 50\%}$ between Perranporth and Porthtowan (1.24 m and 1.23 m respectively) and 2% difference in $T_p$ between Perranporth and Porthtowan (9.7 and 9.5 s respectively). Under larger wave conditions the disparity between the sites increases however, with 13.6% difference in $H_{s, 10\%}$ between Perranporth and Porthtowan (2.95 and 2.55 m respectively). Given that the waves considered in this study are generally $H_s < 2$ m, the Perranporth wave buoy is considered to provide a sufficient surrogate source of data for Porthtowan. The different shoreline orientations at the two sites were considered in order to calculate breaking heights specific to each site.

### 4.2.7 Statistical Analysis

Fig. 4.3 shows frequency histograms of wave height and period observations made by the participants. Outliers in the observations were objectively removed, as they are unlikely to represent typical water-user perceptions and will reduce the quality of the regression analysis to be performed on the data. Firstly ratios of observed over measured wave height ($H_{vis}/H_{s,b}$) and period ($T_{vis}/T_{1/3}$) were calculated for each participant. A boxplot approach was used to identify unusually large or small ratios, whereby outliers lie outside the range: IQR ± (1.5IQR), where IQR is the interquartile range of the ratios. This method doesn’t rely on the assumption of normally distributed data, as the IQR depends on the median of the data and not the mean (McGill et al., 1978). In total, 3.7% of wave height observations and 6.9% of wave period observations were excluded from the data set (Fig. 4.3).

To provide an estimate of how well the statistics derived from this sample represent the entire population of water-users at the two sites, and to identify when statistics are significantly different to one another, 95% confidence intervals are reported. These indicate the bounds within which the true population parameter is likely to lie, based on the distribution of data. Bootstrapping was used to calculate this as it performs well for non-normally distributed data (DiCiccio and Efron, 1996), and provides accurate confidence bounds for relatively small samples, which was beneficial for the smaller sub-samples examined. Bootstrapping simulates the
Figure (4.3). Frequency distributions of visually observed breaking wave height, $H_{vis}$, and period, $T_{vis}$ (upper panels), and the ratio of visually observed over measured breaking wave height ($H_{vis}/H_{s,b}$) and period ($T_{vis}/T_{1/3}$) (lower panels). Red dashed lines indicate the lower and upper limits used to determine outliers in the ratios.

A bootstrap task of re-sampling from the population, making many ‘artificial’ samples by randomly re-sampling from the available data. 5000 bootstrap samples were used to calculate each mean value and confidence interval, and stabilization of the statistics occurred before this number was reached in each case. For the regression confidence intervals described later, the percentile bootstrapping method was used, and for the mean ratios the accelerated and bias corrected method was used. DiCiccio and Efron (1996) provide an assessment and summary of each method.

4.3 Results

4.3.1 Characteristics of the Population

Fig. 4.4 indicates that surfers make up the majority (53%) of water-users at the two sites; the next most popular activities were bodyboarding (29%) and swimming/bathing (11%) respectively. Experience factors, $E_f$, varied from $E_f = 0$ years (first time partaking in their preferred activity), up to $E_f = 27$ years of (daily) participation. Although the proportions of novice, experienced and expert water-users were predefined (25%, 50%, and 25% respectively), the percentage of water-users with $< 365$ days participation experience (i.e. $E_f \leq 1$) was high (34.5%) compared to any other $E_f$ value. The number of water-users with higher experience levels decays logarithmically. Fig. 4.5 shows that the large majority of respondents were male.
Figure (4.4). Water use statistics for the sample. The upper panel shows the ‘preferred’ water activity that respondents most often participate in. The lower panel shows their experience levels, calculated as the product of the number of years of experience of each participant and the typical percentage of days in a year they participate. Dashed lines are thresholds between novice, intermediate and expert water-users respectively (25th and 75th percentiles).

Figure (4.5). Demographics of the sample. Age (upper left panel), gender (upper right panel), and highest educational qualification (lower panel). The dashed line in the upper left panel shows the median age of the sample.

(75%), and ages ranged from 18 to 77 years of age, with a median age of 38 years old. The water-users at the sites are well educated compared to national figures; 47% have a degree or higher level qualification, compared to the national figure of 27% (Office for National Statistics, 2013).
4.3.2 Wave Perceptions

Fig. 4.6 shows visual observations of wave height and period plotted against concurrent measurements. At all measured heights (periods) the majority of participants under-predicted the breaking wave height (period). There is a fair degree of scatter in the relationships, particularly between observed and measured wave period, which shows that participant’s perceptions varied widely. To model these relationships, power law curves were least-squares fitted to the data and are plotted in Fig. 4.6 as solid curves (root-mean-square error (RMSE) = 0.57 m (left panel) and RMSE = 2.19 s (right panel)) alongside dot-dashed power law curves that were fitted by Nordenstrom (1969) in a similar study (RMSE = 0.58 m (left panel) and RMSE = 5.49 s (right panel)). Our power law curves fit the data reasonably well up to $H_{s,b} = 2$ m, and $T_{1/3} = 10$ s, and suggest that a water user’s observations can be estimated from $H_{s,b}$ and $T_{1/3}$ by the following relationships -

$$H_{vis} \approx \frac{0.50 H_{s,b}}{1.57}, \quad \text{for} \quad 0.5m \leq H_{s,b} \leq 2m$$

(4.4)

$$T_{vis} \approx \frac{0.24 T_{1/3}}{5.82}, \quad \text{for} \quad 6s \leq T_{1/3} \leq 10s$$

(4.5)

A simpler relationship is the mean ratio of observation over measurement - the ‘perception ratio’, $P_r$, plotted as thick dashed lines in Fig. 4.6 (RMSE = 0.62 m (left panel) and RMSE = 3.42 s (right panel)). These do not fit the bulk of the data as well as our power law curves, but better intersect the data at large heights ($2 \text{ m} < H_{s,b} < 3.5 \text{ m}$) and periods ($10 \text{ s} < T_{1/3} < 15 \text{ s}$). Like the data, the perception ratios suggest that larger heights and periods will be under predicted by water-users. From Fig. 4.6 the mean wave height perception ratio, $P_{r,H}$, for all participants was 0.62 (standard deviation = 0.24), while the mean wave period perception ratio, $P_{r,T}$, was 0.83 (standard deviation = 0.30). Therefore on average the perceptions can be estimated by -

$$H_{vis} \approx 0.62H_{s,b}, \quad \text{for} \quad 0.5m \leq H_{s,b} \leq 3.5m$$

(4.6)

$$T_{vis} \approx 0.83T_{1/3}, \quad \text{for} \quad 3s \leq T_{1/3} \leq 15s$$

(4.7)

4.3.3 Effect of Varying Wave Conditions on Wave Perception

To investigate how much perceptions change under different incident wave conditions, observations were binned by measured wave height (0.5 - 1 m, 1 - 1.5 m, 1.5 - 2 m) and measured wave period (6 - 8 s, 8 - 10 s, 10 - 12 s, 12 - 14 s). Mean $P_{r,H}$
and $P_{r,H}$ values, along with 95% confidence bounds, were then calculated for each height and period bin containing 10 or more observations, shown in Fig. 4.7 as grey diamonds. Significant variations in $P_{r,H}$ or $P_{r,T}$ due to the incident conditions are evident where there is no overlap between the confidence bounds in different height or period bins. The upper panels of Fig. 4.7 show that there was no significant change in $P_{r,H}$ between any of the different measured wave height or period bins. Although some small but statistically significant changes in $P_{r,T}$ occurred at wave periods of 8 - 12 s (Fig. 4.7, bottom right panel), there were no significant changes in $P_{r,T}$ at different measured wave heights. Importantly the binned perception ratios all overlap with the confidence bounds of the overall mean perception ratios from Eq. 4.6 and Eq. 4.7 (Fig. 4.7; dashed and dotted lines, respectively), suggesting they sufficiently describe the average perception of water-users within any of the height and period bins considered.

### 4.3.4 Effect of Differing Experience Level on Wave Perception

Next the observations were divided into groups based on the experience level of each participant. Significantly different wave height and period perceptions by the
different experience level groups can be identified in Fig. 4.8 where there is no overlap between the confidence bounds for novice, experienced, and expert water-users. Additionally, a group’s perception is not significantly different to the overall mean perception if the confidence bounds for that group overlap the confidence bounds from Eq. 4.6 and Eq. 4.7, shown as dotted lines. There were significant differences in $P_{r,H}$ for participants with different experience levels. At small wave heights ($0.5 \text{ m} < H_{s,b} < 1.5 \text{ m}$) and medium periods ($8 \text{ s} < T_{1/3} < 10 \text{ s}$) there was disparity between $P_{r,H}$ for novices and experts. During these conditions wave height was heavily underestimated by the expert water-users, while novices underestimated wave height less. The perception of novices and experts was also significantly different to the overall mean $P_{r,H}$ under these conditions.

At large wave heights ($1.5 \text{ m} < H_{s,b} < 2 \text{ m}$) and periods ($10 \text{ s} < T_{1/3} < 14 \text{ s}$) however there was more agreement, as the $P_{r,H}$ of each experience level was statistically alike, and agreed with the overall mean $P_{r,H}$. Being the majority group, the $P_{r,H}$ of experienced water-users was adequately described by the overall mean $P_{r,H}$ at all measured heights and periods. There were no significant differences

![Figure (4.7).](image)

**Figure (4.7).** Mean perception ratios for all water-users at different measured wave heights and periods. The dashed line indicates the overall mean perception ratio for all water-users at all heights and periods. 95% confidence intervals are shown as vertical error bars and dotted lines. Upper panels: mean ratios of observed over measured wave height ($P_{r,H}$) plotted against mean $H_{s,b}$ (left panel) and mean $T_{1/3}$ (right panel) within each bin. Lower panels: mean ratios of observed over measured wave period ($P_{r,T}$) plotted against mean $H_{s,b}$ (left panel) and mean $T_{1/3}$ (right panel) within each bin.
in $P_{r,T}$ for participants of differing experience level, or during different measured heights and periods. With one marginal exception (Fig. 4.8, bottom right panel) the overall mean $P_{r,T}$ adequately described $P_{r,T}$ for each experience level group and at all heights and periods.

### 4.3.5 Effect of Preferred Activity Type on Wave Perception

Significantly different perceptions by participants with different preferred activity types can be identified in Fig. 4.9 where there is no overlap between the confidence bars for surfing and non-surfing water-users. Differences in the $P_{r,H}$ of surfers and non-surfers occurred at wave heights of $1 \text{ m} < H_{s,b} < 1.5 \text{ m}$ and periods of $6 \text{ s} < T_{1/3} < 8 \text{ s}$, where surfers underestimated wave height more than non-surfers (Fig. 4.9, upper panels). Differences in $P_{r,T}$ occurred at wave periods of $10 < T_{1/3} < 12 \text{ s}$, where non-surfers had a significantly lower $P_{r,T}$ than surfers (Fig. 4.9, lower right panel). Within all other height and period bins the two groups’ perceptions were statistically alike, and were well described by the overall mean $P_{r,H}$ and $P_{r,T}$ values.

**Figure (4.8)**. Mean perception ratios for novice, experienced and expert water-users at different measured wave heights and periods. The dashed line indicates the overall mean perception ratio for all water-users at all heights and periods. 95% confidence intervals are shown as vertical error bars and dotted lines. Upper panels: mean ratios of observed over measured wave height ($P_{r,H}$) plotted against mean $H_{s,b}$ (upper left panel) and mean $T_{1/3}$ (upper right panel) within each bin. Lower panels: mean ratios of observed over measured wave period ($P_{r,T}$) plotted against mean $H_{s,b}$ (lower left panel) and mean $T_{1/3}$ (lower right panel) within each bin.
The wave height and period perceptions of surfers were well described by the overall mean $P_{r,H}$ value from Eq. 4.6 and Eq. 4.7 for all the wave height and period bins considered.

### 4.3.6 Effect of Gender on Wave Perception

The effect of gender on the perception of wave height and period was also explored, and significantly different perceptions can be seen in Fig. 4.10 where there is no overlap between the confidence bars for male and female water-users. The only significant differences in perception that occurred between men and women were at small wave heights ($0.5 \text{ m} < H_{s,b} < 1 \text{ m}$) when men tended to underestimate wave height more than women. The overall mean $P_{r,H}$ adequately described the binned $P_{r,H}$ values for men at all wave heights and periods, but differed from the $P_{r,H}$ of women at small heights ($0.5 \text{ m} < H_{s,b} < 1 \text{ m}$) and periods ($6 \text{ s} < T_{1/3} < 8 \text{ s}$), when women tended to observe wave height closer to the measured value.

**Figure (4.9).** Mean perception ratios for surfing and non-surfing water-users at different measured wave heights and periods. The dashed line indicates the overall mean perception ratio for all water-users at all heights and periods. 95% confidence intervals are shown as vertical error bars and dotted lines. Upper panels: mean ratios of observed over measured wave height ($P_{r,H}$) plotted against mean $H_{s,b}$ (upper left panel) and mean $T_{1/3}$ (upper right panel) within each bin. Lower panels: mean ratios of observed over measured wave period ($P_{r,H}$) plotted against mean $H_{s,b}$ (lower left panel) and mean $T_{1/3}$ (lower right panel) within each bin.

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4.3.7 Summary of Wave Perceptions

The overall mean perception ratios for the whole sample of water-users, described by Eq. 4.6 and Eq. 4.7, were not significantly different to the average perceptions within each wave height and period bin considered (0.5 m $< H_{s,b} < 2$ m and $6$ s $< T_{1/3} < 14$ s). Therefore it can be said that when averaged across all water-users, the perception of wave height and period did not change significantly as wave conditions changed. With very few exceptions the mean binned perception ratio within each experience level group, activity type, and gender also did not significantly change during the different wave conditions studied. Therefore an average perception ratio for each group is adequate to describe their perceptions for the whole range of heights and periods considered. There were however significant differences between the water-user groups during different measured wave heights and periods, and it is therefore necessary to use a different perception ratio for each water-user group to differentiate their perceptions.

A single $P_{r,H}$ and $P_{r,T}$ value averaged across all the studied conditions for each of the water user groups is shown in Fig. 4.11. The upper panel suggests that

![Figure (4.10)](image)

**Figure (4.10).** Mean perception ratios for male and female water-users at different measured wave heights and periods. The dashed line indicates the overall mean perception ratio for all water-users at all heights and periods. 95% confidence intervals are shown as vertical error bars and dotted lines. Upper panels: mean ratios of observed over measured wave height ($P_{r,H}$) plotted against mean $H_{s,b}$ (upper left panel) and mean $T_{1/3}$ (upper right panel) within each bin. Lower panels: mean ratios of observed over measured wave period ($P_{r,T}$) plotted against mean $H_{s,b}$ (lower left panel) and mean $T_{1/3}$ (lower right panel) within each bin.
Figure (4.11). Mean perception ratios across all wave conditions studied for the different water-user groups considered. 95% confidence intervals are shown as vertical error bars. Upper panel: mean ratio of observed over measured wave height ($P_{r,H}$). Lower panel: mean ratio of observed over measured wave period ($P_{r,T}$).

Table (4.1). Mean perception ratio for each joint category of experience level and activity type. The left hand side shows the mean wave height perceptions, $P_{r,H}$, and the right hand side shows the mean period perceptions, $P_{r,T}$. Note that the mean perception of wave period was not found to vary significantly, and as such the overall mean $P_{r,T}$ value was used for all water-user groups.

<table>
<thead>
<tr>
<th></th>
<th>Surfing</th>
<th>Other Activities</th>
<th>Surfing</th>
<th>Other Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novice</td>
<td>0.68</td>
<td>0.75</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>Experienced</td>
<td>0.57</td>
<td>0.64</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>Expert</td>
<td>0.54</td>
<td>0.53</td>
<td>0.83</td>
<td>0.83</td>
</tr>
</tbody>
</table>

gender does not significantly affect the mean perception of wave height, as there is no significant separation between the $P_{r,H}$ of men and women when averaged across all conditions. Experience level and activity type however do significantly change a person’s perception of wave height, as there is significant separation between the $P_{r,H}$ of novice water-users and experienced or expert water-users, and also significant separation between the $P_{r,H}$ of surfing and non-surfing water-users. Conversely the lack of separation in $P_{r,T}$ apparent in the lower panel indicates that the average perception of wave period does not vary significantly from one water-user group to another, and the overall mean value ($P_{r,T} = 0.83$) can therefore be used to describe the perception of wave period for all water-users.
4.3.8 Preferred Wave Conditions

The range of preferred wave conditions stated by water-users was surprisingly small considering the range of activities and experience levels of the participants (Fig. 4.12, blue bars). The overall mean preferred wave height and period stated by the participants was 1.3 m (std. dev. 0.54 m) and 12 s (std. dev. 4.8 s), respectively, and across the water-user groups considered the mean preferred height ranged between 1.0 m for women and 1.5 m for expert water-users. As experience level and activity type were found to have the greatest influence on a person’s perception of wave height (section 4.3.7), the stated wave height preference of each participant was adjusted based on their experience and preferred activity. Gender was not accounted for in the adjustment, as it was found that average perceptions did not vary significantly between men and women. The intention is to adjust the stated preference to a value that better represents the measured significant wave height at breakpoint \( (H_{s,b}) \) and is therefore on a universal scale that is uninfluenced by different perceptions.

Stated wave heights were adjusted by finding the mean perception ratio for each joint category of experience level and activity (novice surfer, experienced surfer, expert surfer, novice non-surfer, experienced non-surfer, expert non-surfer), resulting in the 6 \( P_{r,H} \) values shown in Table 4.1. Stated wave heights were then divided by the \( P_{r,H} \) value associated to each person. As an example, expert surfers perceive wave height to be approximately half of the actual measured height (from Table 4.1 \( P_{r,H} = 0.54 \)), and their stated wave height preferences are therefore almost doubled when adjusted. Stated wave period preferences were also adjusted, but as \( P_{r,T} \) did not vary significantly between any of the water-user groups the overall mean value \( (P_{r,T} = 0.83) \) was used for all participants (Table 4.1).

After adjusting the wave preferences to account for the different perceptions, the magnitude and range of the preferred conditions increased (Fig. 4.12, red bars). The mean preferred wave height and period for all water-users when adjusted is \( H_{s,b} = 2.2 \) m (std. dev. 0.94 m) and \( T_{1/3} = 14.7 \) s (std. dev. 5.8 s) respectively. After adjusting the preferences there were significant differences between the mean preferred breaking wave height for novice (\( H_{s,b} = 1.7 \) m), experienced (\( H_{s,b} = 2.1 \) m) and expert (\( H_{s,b} = 2.8 \) m) water-users, surfers (\( H_{s,b} = 2.4 \) m) and non-surfers (\( H_{s,b} = 1.8 \) m), and men (\( H_{s,b} = 2.3 \) m) and women (\( H_{s,b} = 1.6 \) m). Preferred wave period increased when it was adjusted, but was not significantly different for any of the water-user groups \( (T_{1/3} = 14.7 \) s) except for women \( (T_{1/3} = 11.1 \) s), who had significantly lower mean preferred wave period than most other groups before and after adjusting. An indication of the range of wave heights and periods that are preferred by each water-user group can be inferred from their mean adjusted
Figure (4.12). Mean wave height (upper panel) and wave period (lower panel) preferences for each of the water-user groups studied. Blue bars show the stated preferences and red bars the preferences after adjusting for different perceptions of wave height and period. 95% confidence bounds are shown as vertical error bars.

preference, ± 1 standard deviation of their adjusted preferences. These ranges are shown in Fig. 4.13, and indicate that a range of conditions could be considered ‘optimal’ for each water-user group, with a large degree of overlap in the preferred conditions between groups. When considering all beach water-users, the range of optimal wave heights and periods are $1.2 \text{ m} < H_{s,b} < 3.1 \text{ m}$, and $9.0 \text{ s} < T_{1/3} < 20.6 \text{ s}$ respectively (Fig. 4.13). The smallest wave heights were preferred by novices, non-surfers, and women, while the largest heights were preferred by experts, surfers and men.

4.3.9 Perception of the Wave Resource

After adjusting for differences in wave perception as previously described, the perceived annual mean breaking wave height (averaged across all water-users) was $H_{s,b} = 2.02 \text{ m}$, with a standard deviation of 0.66 m. The mean measured wave height at breaking (recorded between 19th Dec 2006 - 30th Apr 2014) is almost identical to this value, at $H_{s,b} = 2.03 \text{ m}$ (Fig. 4.14, upper panel). The perceived mean $H_{s,b}$ averaged across each group did not vary significantly between the different water-user groups, and each group’s estimate was statistically indifferent to the measured value, except
Figure (4.13). Range of preferred breaking wave heights (upper panel) and periods (lower panel) for different water-user groups, accounting for differences in wave perception. The range for each group was quantified as the mean value of their adjusted preferences, ±1 standard deviation of their adjusted preferences.

for novices who underestimated it by approximately 7%.

Averaged across all water-users, large wave conditions \((H_{s,b} > 1.83 \text{ m})\) were perceived to occur on 34% of days in a typical year (std. dev. 19%). The perceived probability varied little between the different water user groups (Fig. 4.14, middle panel), ranging from 0.31 (surfers) to 0.38 (women), and none of the groups had a mean perception that was statistically different to the overall (all water-users) mean perception. To compare each group’s perception of large wave abundance to a measured value, the different perceptions of wave height were again accounted for. This is because the arbitrary definition of large waves used in this study \((H_{s,b} > 1.83 \text{ m})\) will invoke different responses depending on the individual’s perception of wave height. To achieve this, the perception ratio for each water-user group from Table 4.1 was used to scale the arbitrary threshold to an adjusted threshold for each group. The number of days with a daily-averaged measured \(H_{s,b}\) greater than the adjusted threshold was then counted, yielding a measured probability of large waves occurring for each group. The perceived and measured probabilities are compared in Fig. 4.14 (middle panel). It can be seen that each water-user group overestimated the occurrence of large wave conditions by between 12% (novices) and 22% (experts), and averaged across all water-users the probability was overestimated by 17%. This indicates that water-users in the study region, and in particular those with a lot of experience, perceive the wave climate to be more energetic than it actually is.

The perceived abundance of ‘ideal’ wave conditions (Fig. 4.14, lower panel)
varied more significantly than the perceptions of mean wave height or large wave occurrence. There were significant differences between novice, experienced, and expert water-users, who perceived ideal waves to occur on 48%, 37%, and 27% of days in a typical year, respectively. Surfers and non-surfers also had different perceptions, at 32% and 43% of days, respectively, as did men and women, at 35% and 45% of days, respectively. The joint probability of the measured wave height ($H_{s,b}$) and period ($T_p$) being within the (perception-adjusted) preferred range for each group was then calculated to compare to these perceptions. As the measured probabilities came from daily-averaged wave conditions, $T_p$ was assumed to be equivalent to $T_{1/3}$ (used to determine preferred wave period) rather than attempting to account for the 5% overestimation of $T_{1/3}$ during windseas (Goda, 1978). Fig. 4.14 (lower panel) shows that experts, surfers, and men accurately estimated the occurrence of preferred wave conditions, with their average estimates being statistically indifferent to the measured probabilities. Novice, experienced, non-surfing, and female water-users all underestimated the occurrence of ideal waves, by between 11% (novices) and 36% (non-surfers). The range of preferred wave periods is largest for non-surfers, which explains why the measured probability of their preferred wave conditions occurring is also the largest, but doesn’t necessarily explain the disparity with their perceptions.

4.4 Discussion

4.4.1 Wave Perceptions - Scatter and Sources of Error

The scatter in Fig. 4.6 (left and right panels) demonstrates the large degree of variability in people’s perception of wave heights and periods. Perceptions can vary due to the presence or absence of a comparison object (e.g. a person or a rock) to provide scale for estimating wave height, or a benchmark for timing wave period (Caldwell and Aucan, 2007). It might also be affected by the position and elevation of the observer or their level of observational experience (Perlin, 1984, Guedes Soares, 1986a, Caldwell and Aucan, 2007). In addition the observer may have made an observation based on very few waves, whereas the wave buoy averages many waves over a 30 minute window. Further to these potential sources of observational ‘error’, bias also undoubtedly contributes to the variation in perception. It has not been possible in this study to differentiate between error and bias in each observation, but observational errors (noise) should average out over a number of observations, while systematic bias should remain apparent (signal).

The pronounced scatter in the wave period observations is not unusual (Battjes,
Figure (4.14). Comparison of perceived and measured wave cases for different water-user groups. Upper panel shows the perceived annual mean breaking wave height ($H_{s,b}$), averaged across each water-user group (symbols). The dotted line indicates mean measured $H_{s,b}$ from $\sim$7.5 years of wave buoy data. Middle and lower panels show the perceived probability of large wave conditions, and preferred wave conditions occurring, respectively, averaged across each water-user group (symbols). x’s in the middle and lower panel show the corresponding measured probabilities, relevant to each group. 95% confidence bounds are shown as vertical error bars in each panel.
1984, Perlin, 1984, Plant and Griggs, 1992), but does mean that the relationship between $T_{vis}$ and $T_{1/3}$ must be considered cautiously. In other studies variability has been attributed to difficulties in counting wave period, or even identifying one wave from another during mixed seas (Perlin, 1984, Plant and Griggs, 1992). It was noted that the untrained participants in this study rarely counted wave period assiduously. Their observations were therefore either a quick estimate, or may have been based on a wave forecast as 53% of participants mentioned that they had recently seen a forecast or wave report. Despite the scatter in $P_{r,T}$, the overall mean value found here ($P_{r,T} = 0.83$) was not significantly different to any of the individual water-user groups perceptions, and is similar to $P_{r,T}$ values found by Battjes (1984), which ranged between 0.89 - 0.95. This provides some confidence in its generality.

The power law curves in Fig. 4.6 suggest that wave heights (periods) under 2.5 m (10 s) will be under predicted and larger heights (periods) will be over predicted, despite the fact that there is predominantly under prediction occurring in the data. This results from the curves fitting to the bulk of the data at wave heights (periods) $< 2$ m (10 s), while at greater heights (periods) they fit the data poorly. The divergence of our wave height curve from that of Nordenstrom (1969) at heights $> 1.5$ m could be a result of the difference between observing/measuring wave height in deep water (Nordenstrom’s study) and observing/estimating breaking height with linear theory, as has been done here. However Nordenstrom’s curve is fitted over a greater range of heights, considering waves of up to 10 m, and it is therefore likely that with data from larger waves our curve would be closer to theirs, and would no longer suggest that large waves will be over predicted. This is also indicated by observations of breaking waves made by Hawaiian lifeguards, which consistently under predict height for $H_{s,b}$ as large as 20 m (Caldwell and Aucan, 2007).

The perception ratios in Eq. 4.6 and Eq. 4.7 adequately describe the average perception of water-users at wave heights between $0.5$ m $< H_{s,b} < 2$ m and periods between $6$ s $< T_{1/3} < 14$ s (Fig. 4.6). Additionally the perception ratios intersect the data at wave heights and periods of 2 to 3.5 m and 14 to 16 s respectively, unlike the power law curves. Like the data, the ratios indicate that water-users will consistently under predict breaking wave height and period, as was found for trained observers by Perlin (1984), Plant and Griggs (1992), and Caldwell (2005). Because of these factors, Eq. 4.6 and Eq. 4.7 are considered to provide a better model of average wave height and period perceptions than the power law relationships in Eq. 4.4 and Eq. 4.5.

It should be noted that the relationships determined from this study all depend on the calculation of $H_{s,b}$ and $T_{1/3}$ as determined using linear wave theory and a breaker depth ratio of 0.78. Linear shoaling is widely applied to estimate breaking
conditions, but is not infallible, and on shallow coasts usually overestimates $H_{s,b}$ because bottom friction is not considered. Another factor that is not considered is the effect of wind speed and direction, which has previously been found to reduce the breaking depth (therefore increasing $\gamma_b$ in Eq. 4.3) and increase the breaking height of waves if directed towards the incoming waves, and vice versa (Chen et al., 2004, Feddersen and Veron, 2005). While the omission of bottom friction is likely to result in systematically smaller height perception ratios, the omission of wind effects will add random errors into the perception ratios. The method used here therefore provides lower-limit perception ratios for water-users, under the assumption of average wind conditions. Equally, the wave conditions adjusted using these ratios provide upper-limit estimates of their likely value. Encouragingly, the perception ratios are comparable to those determined in previous studies using trained observers, which have also estimated breaking height through linear wave theory using the same $\gamma_b$ and ignoring wind effects (Perlin, 1984, Plant and Griggs, 1992, Caldwell, 2005).

4.4.2 Wave Perceptions - Bias in Observation

One hypothesis for the observed variation and underestimation of wave height is that each individual may define the face of a wave differently. While the peaked crest of a shoaling wave is usually very apparent to an observer, the shallow gradient of the trough (assuming a Stokes or Cnoidal wave form) makes it difficult to visually determine the trough-to-crest height. The consideration of the wave face may also be affected by a person’s experience level, as novices may consider the entire wave face while experienced or expert water-users may only consider the steep upper part of the wave, where the potential energy required to ride the wave is stored. It was noted that in some cases novice water-users and non-surfers had wave height perceptions closer to measurements than expert water-users and surfers, who tended to under predict wave height more, especially for small ($0.5 \text{ m} < H_{s,b} < 1.5 \text{ m}$) or short period waves ($6 \text{ s} < T_{1/3} < 10 \text{ s}$). The perceived height of small, short period waves therefore changes through increased water use, which may be a result of these waves seeming less significant as experience and water ability increases.

There may also be a culturally bred bias in the surfing world that has not permeated into other water sports, which would explain why surfers under estimated wave height more than non-surfers under some conditions. This may well have originated from the Hawaiian scale of height observation, where $P_{r,H} \approx 0.5$ (Caldwell, 2005), as Hawaiian culture has had a widespread influence on global surf culture. The origins of the Hawaiian scale of observation are disputed (Caldwell, 2005), but machismo or bravado is one explanation for the wave height underestimation. An observer
may seek to play down the size of waves to inflate their apparent confidence in the water. Indeed displays of masculinity have been found to be common in the male-dominated sport of surfing (Waitt and Warren, 2008, Beaumont, 2011). However, the only gender based divide in wave perception seen in this study occurred during small wave conditions ($0.5 \, \text{m} < H_{s,b} < 1 \, \text{m}$) where women under predicted wave height less than men, but on the whole men and women had statistically similar average perceptions of waves. Bravado is perhaps therefore more likely to explain the disparity in perceptions than machismo.

4.4.3 Wave Preferences

A key assumption made in this study is that the perception of wave height and period that was determined using participants’ wave observations does not vary once a participant is asked to describe their preferred wave conditions. It is feasible that while incident wave height may be underestimated by some participants to play down the size of waves, the same participant may not play down wave height in the same manner when stating their preferences, or may even inflate their preferred wave height as a further act of bravado. As there is no reason to assume this occurred often, such effects are assumed to be averaged out across the sample as with other random errors.

Considering the range of wave periods preferred by participants in this study (typically $9.0 \, \text{s} < T_{1/3} < 20.6 \, \text{s}$) are at the lower end of gravity wave frequencies, it is possible that inshore surf conditions could actually be improved if WECs were tuned to higher frequencies. The optimal ‘peak’ frequency or period for WEC design is not usually considered to be the one associated with the instantaneous peak in the energy spectrum, but rather the long-term mean energy period, $T_e$ (Eq. 2.1), which represents the mean frequency in the spectral distribution of energy (Mollison, 1994, Black, 2007, Smith et al., 2012, O’Dea and Haller, 2014). To provide an indication of which wave frequencies are most likely to be targeted for energy extraction at Wave Hub, the mean $T_e$ was calculated from the 7.5 year record of half-hourly wave spectra at Perranporth. The mean energy spectrum from this data is plotted in Fig. 4.15, with the mean $T_e$ (8.1 s or 0.12 Hz) plotted as a dashed line. The range of wave periods preferred by the sample of water-users was converted to frequencies (frequency = $1/T_{1/3}$), and is plotted as a filled area on the figure.

Fig. 4.15 indicates that the mean $T_e$ is outside the range of frequencies preferred by water-users. While this suggests that WECs are likely to be designed to perform optimally at shorter wave periods (higher wave frequencies) than those desirable to water-users, WECs will extract energy over a range of frequencies, not just a single
The greatest attenuation of wave energy will occur at frequencies around the mean $T_e$, and the attenuation will decrease at frequencies increasingly separated from $T_e$ (Rhinefrank et al., 2013). The power transfer function (PTF) of a given WEC determines this spread, and will also determine the degree of overlap with the frequencies preferred by water-users. Devices with a broad PTF will therefore affect the wave frequencies preferred by water-users more than WECs with a narrow PTF. As the PTF of devices to be installed at Wave Hub is presently unknown, hypothetical PTFs with varying widths will need to be considered in order to foresee the range of impacts that may occur to wave conditions of interest to water-users.

4.4.4 Perception of the Wave Resource

Water-users at the study sites have an accurate intuition of the mean height of breaking waves. This is surprising given that the daily-average wave height at Perranporth varies around its mean value by an average of 1 m, and between December 2006 and April 2014 varied by up to 7.5 m. Although the average conditions are accurately perceived, large conditions were perceived to occur between 12% and 22% more often than they actually did. Wave energy is clearly perceived to be more abundant than it actually is, but it should be noted that as the majority of data was collected before 2014, these perceptions are not overly influenced by the unprecedented swells observed in January 2014, some of which were the largest wave conditions observed in the last 65 years (Masselink et al., 2015). This provides a
proxy for the perceived abundance of the wave resource in the region, a property of the coastal environment which was seen to reduce water-users level of anticipated coastal impact from MRE in Chapter 3.

Conversely, waves with a suitable height and period for water use were perceived to occur less often than they actually do. This may be due to other factors that affect wave breaking and surfability, such as the wind conditions or bathymetric features, reducing the number of days when the surf quality is perceived to be just right for water use. Experts and surfers perceived ideal waves to occur least often of any of the studied groups, but they were also accurate in their perception, with ideal conditions occurring on < 30% of days. This indicates that these two groups are the most likely to anticipate significant impacts to coastal waves from wave energy extraction, as the conceptual model from chapter 3 suggests a higher level of impact will be anticipated when the wave resource is perceived to be scarce. Interestingly these two groups also over perceived the abundance of large waves, which raises questions as to whether the perceived abundance of energy, or the perceived scarcity of quality surf, will most influence their perception of the effects of wave energy extraction.

4.5 Conclusions

The population of water-users at two study sites in the lee of Wave Hub has been studied, and the characteristics of the group have been determined for the first time. The population is predominantly made up of surfers (53%), but bodyboarding and swimming/bathing are also popular activities at the sites (29% and 11%, respectively). There is a large contingent of inexperienced water-users, with around 35% having less than 365 days of experience in the water. However a quarter of the water-users could be considered highly experienced, having more than four years (≈ 1500 days) of equivalent daily experience. Most of the water-users are male, but the exact proportion is unclear due to a slight bias towards male respondents when approaching mixed groups. The group is better educated than the UK population, according to national figures.

To investigate the perception of wave conditions by beach water-users, nearshore wave buoy measurements collected in approximately 14 m water depth and transformed to breaking height, were compared to concurrent visual observations of mean breaker height and period made by 367 participants. Ratios of observed over measured wave height and period were used to quantify their perceptions. The vast majority of water-users underestimated significant wave height and period at breaking, and their average perceptions can be approximated by $H_{vis} \approx 0.62 \ H_{s,b}$ and $T_{vis} \approx$
$0.83 \ T_{1/3}$, for waves $0.5 \ m \leq H_{s,b} \leq 3.5 \ m$ and $3 \ s \leq T_{1/3} \leq 15 \ s$. Although perceptions were highly varied, the average perception ratios did not change significantly as the measured wave height and period changed between $0.5 \leq H_{s,b} \leq 2 \ m$ and $6 \leq T_{1/3} \leq 14 \ s$. The experience level and preferred activity type of the participants was found to significantly affect their perception of wave height. Expert water-users and surfers generally underestimated wave height the most, especially for small and/or short period waves, while novices and non-surfing water-users made wave height observations closer to measurements. Gender was not found to significantly alter the mean perception of wave height, and the perception of wave period did not change significantly between any of the different water-user groups considered.

Preferences towards certain wave conditions were stated, and the preferences were adjusted to account for different wave perceptions. Besides previously determined preferences derived from small samples of surfers (Black, 2007, Li and Phillips, 2010), the wave preferences of different water-users has never been studied or compared before. The range of preferred wave heights and periods for water-users as a whole are $1.2 \ m < H_{s,b} < 3.1 \ m$, and $9.0 \ s < T_{1/3} < 20.6 \ s$ respectively, but the preferences varied between the different groups studied. Expert water-users and surfers accurately estimated the probability of their preferred waves occurring, and of all the groups had the lowest perceived and measured probabilities. These groups also overestimated the occurrence of large waves. It is therefore unclear whether their perception of the abundance of wave energy, or the perceived scarcity of quality surf, will most influence their perception of the effects of wave energy extraction as per the anticipated impact model developed in Chapter 3.

It is proposed that the long term mean energy period at the site ($T_e = 8.1 \ s$) indicative of the optimal frequency for wave energy extraction, is outside the preferred range of wave periods for most water-users. However the impact that energy extraction at Wave Hub will have on wave conditions of interest to water-users will depend on the efficiency of wave energy converters, as well as the spread of the power transfer function around the mean energy period. These factors will need to be explored in order to predict the potential impact to wave conditions of interest to water-users.
Chapter 5

Three-Dimensional Beach Morphology and Associated Wave and Tide Forcing

5.1 Introduction

5.1.1 Background

Previous research indicates that three-dimensional (3D) beach morphology, with bar and rip features, significantly increases the bathing hazard for water-users by enhancing rip current circulation (Scott et al., 2008, 2011, MacMahan et al., 2011, Brighton et al., 2013). These beach types also enhance the quality of surfing conditions by increasing the angle of breaking waves to within limits suitable for wave riding (Hutt et al., 2001, Mead and Black, 2001b, Scarfe et al., 2003, 2009). A number of beaches in the lee of Wave Hub, including our two study sites, sit at a classification boundary at the dissipative-intermediate end of Wright and Short’s 1984 beach state model. As a result, they regularly transition from a 2D dissipative state to a 3D intermediate state featuring crescentic bars and rip channels. Such increases in beach three-dimensionality (downstate transitions) have previously been associated with reduced wave heights and lower steepness waves that often occur following a storm (Poate, 2011, Poate et al., 2014). Extended periods of calm waves have also been seen to infill the rip channels and can therefore eventually lead to a reduction in beach three-dimensionality (Poate et al., 2014). The storm dominated changes in beach three-dimensionality observed by Poate et al. (2014) were not seen to be coupled to the seasonally varying wave signal.

As wave height and period are key parameters governing these transitions (Wright and Short, 1984), changes in either parameter caused by wave energy extraction
could alter the morphological state, bathing hazard, and quality of surfing waves at these beaches considerably. However, morphological parameters such as the dimensionless fall velocity, $\Omega$ (Gourlay, 1968, Dean, 1973), or surf-similarity parameter, $\epsilon$ (Bauer and Greenwood, 1988) that are often used to investigate such changes, have been found to relate poorly to intermediate beach state transitions (Jackson et al., 2005, Jimenez et al., 2008, Almar et al., 2010, Scott et al., 2011). Accurate predictions of beach three-dimensionality under the influence of wave energy extraction can therefore not be made using these parameters alone. As previously identified in section 2.4.3, their shortcomings are that they do not consider the absolute wave energy (Scott et al., 2011), or duration of wave events (Jimenez et al., 2008). They also cannot account for free-morphological behaviour (bed-surf coupling - Section 2.4.3), which reduces the correlation between the morphology and the instantaneous wave conditions. Despite this latter effect, hydrodynamics have still been found to govern the overall scale of beach three-dimensionality (Wright and Short, 1984, Wright et al., 1985, Ranasinghe et al., 2004), and the system is thought to be deterministic (Plant et al., 2006, Splinter et al., 2011). Consequently, different manifestations of wave parameters, such as using an antecedent weighted-average of $\Omega$ (Wright et al., 1985), may improve their explanatory power. However, such manifestations have not yet been successfully used to explain changes in beach three-dimensionality.

5.1.2 Chapter Aims

In order to understand the effect that wave energy extraction may have on beach morphology of relevance to water-users, the temporal variability in beach three-dimensionality and the role of hydrodynamic forcing needs to be better understood. This chapter aims to investigate the variability of subtidal and intertidal three-dimensionality over seasonal and inter-annual time scales, and examine the hydrodynamic conditions that force such changes. Correlated behaviour between the subtidal and intertidal regions is examined using 5.5 years of monthly intertidal surveys and quasi-weekly video barline observations, and a range of novel wave parameterisations are used to explore the associated hydrodynamic forcing.

5.2 Methodology

5.2.1 Research Approach

As with Chapter 4 of this thesis, a quantitative research approach and post-positivist paradigm (described in Section 4.2.1) is employed in this chapter, as the data involved is highly quantitative.
5.2.2 Remotely Sensed Video Imagery

The harsh and dynamic surf zone environment often prohibits the use of in-situ surveying methods and instrumentation with which to measure hydro and morphodynamics (Lippmann and Holman, 1989). In an effort to overcome this barrier, remote sensing camera systems have been increasingly used over the past 30 years to investigate nearshore processes (Holman and Stanley, 2007). These ‘Argus’ systems autonomously collect images of the sub and intertidal beach regions throughout daylight hours, and produce a number of image products with which various morphological and hydrodynamic measurements can be made. These include the position of subtidal sandbars (Lippmann and Holman, 1989), the period and angle of incident waves (Lippmann and Holman, 1991), the intertidal bathymetry (Plant and Holman, 1997), and the celerity of incident waves, which has been used to estimate nearshore bathymetry (Stockdon and Holman, 2000). Of interest to the present research, the shape and position of sandbars can be inferred from patterns of wave breaking in Argus images, which has been applied widely in previous literature (Lippmann and Holman, 1989, 1990, Van Enkevort and Ruessink, 2001, 2003b,a, Ranasinghe et al., 2004, Van Enkevort et al., 2004, Poate, 2011, Price et al., 2011, 2013, Poate et al., 2014, Price et al., 2014, including).

At both Perranporth and Porthtowan semi-permanent Argus systems are installed on buildings on the cliffs overlooking the intertidal and subtidal beach (Fig. 5.1). These systems have been operational at Perranporth since 1993 (Davidson et al., 1997) and at Porthtowan since September 2008 (Poate, 2011), and continue to collect images. The Argus data used in this chapter spans the period 2008 - 2014 since both camera systems have been operational. The cameras are triggered half-hourly by an external computer that transmits the collected images to a server via the internet. The autonomous nature of the image collection enables data to be collected at a high temporal resolution (images every half-hour) over long temporal scales (years), and with a large spatial coverage (km’s). This makes it an ideal method for collecting data on large-scale morphodynamic changes (Larson et al., 2003, Kroon et al., 2008). A limitation of the system is that images are often unusable due to poor lighting and weather conditions, such as rain and fog, or due to technical problems with the camera system, both of which can introduce gaps in the imagery time series. There are three cameras at Porthtowan and four at Perranporth, which cover almost the entire sub and intertidal regions of each beach. Images from each camera can be merged to create a panoramic view of the beach, but the process of merging can cause areas of abrupt pixel intensity change in the merged image, which was found to reduce the effectiveness of the bar detection.
Therefore rather than merging the images, images from a single camera covering the subtidal region of each beach (Fig. 5.1) were used.

The cameras have a pixel resolution of 1024 x 768 and the spatial footprint of each pixel on the beach face increases with distance from the camera. Points further from the camera are therefore captured at a lower spatial resolution. For example, the alongshore (cross-shore) resolution of points 500 m and 1500 m in front of the Porthtowan camera is approximately 10 m (5 m) and 40 m (15 m), respectively. Each image is geo-rectified from pixel coordinates \((u,v)\) to a local coordinate system \((x,y)\). This process involves mapping each pixel to known locations on land (ground control points), using established geometric techniques (Holland et al., 1997). The ground control points, which must be visible in the camera images and measured when the camera system is installed, provide a geometry solution with which to rectify all subsequent images. This rectification changes the image view from an oblique vantage point, to an overhead plan view of the beach (Fig. 5.2) where each image grid point has a known position in the local coordinate system. Although the geometry solution can be considered constant, slight movement of the cameras due to strong winds or subsidence can alter the geometry, and the ground control points were therefore intermittently updated to maintain the accuracy of the image coordinates (Fig. 5.3). During the rectification the horizontal position of the image is corrected depending on the tide level at the time of image capture. This removes the artificial shifting of the pixel geometry across the sea surface, caused by the rising and falling of the tide within the oblique field of view.

At each site snapshot images, time exposure images and pixel variance images are generated (Holman and Stanley, 2007). For the purposes of sandbar detection and measurement, time exposure (Timex) images are used in this chapter (Fig. 5.2). These are created by averaging the intensity of each pixel across 1200 images, taken at 2 Hz over a 10 minute period. The resulting image shows areas of bright pixel intensity where wave breaking often occurs and darker areas where wave breaking is absent. As a result of the preferential breaking of waves over the shallow bar crests, foam is often visible on the water surface at the position of the sandbars, creating conspicuous bands of high pixel intensity that reveal the position of the underlying bars (Lippmann and Holman, 1989). A barline intensity mapping tool (Pape et al., 2007) was used to detect the inner and outer bar crest positions by the alongshore tracking of the intensity maxima within the surf zone (Figs. 5.8 and 5.10). Separate regions of interest were defined for the inner and outer bar to guide the tracking of the intensity maxima; these were then updated if the barlines moved significantly in subsequent images. Although this method of bar crest detection is automated, the detected bar crest in each image was manually checked, and the
region of interest modified if necessary. This process yields a matrix $x_i(y, t)$ of the cross-shore bar position $x_i$ at alongshore positions $y$ and at times $t$ for each of the bars. At Perranporth the barline was measured at 1 m intervals alongshore between $-1700 \text{ m} < y < -200 \text{ m}$, and at Porthtowan between $-81 \text{ m} < y < 629 \text{ m}$.

To ensure there was sufficient contrast between the sea and the white-water to accurately detect the barline, data were only recorded from images with sufficient contrast. Following Price (2013), the mean pixel intensity along a 500 m predefined offshore line, where wave breaking never occurred, was measured; if the offshore intensity was $> 0.75$ times the mean pixel intensity along each of the detected barlines, then the barline data was not used. It was therefore possible for either the inner or outer barline to be detected in isolation, for example when waves broke at the inner bar, but not at the outer bar.

The detected barline positions can be artificially shifted due to tide and wave conditions altering the position of depth induced breaking onset (Kingston et al., 2000, Van Enckevort and Ruessink, 2001). To minimize tidal shifting, a single low tide image was used for each day (Van Enckevort and Ruessink, 2001). Images were also constrained by the concurrently recorded $H_s$ to ensure that sufficient breaking occurred to reveal the bar position, yet avoid days when the surf-zone was saturated causing ambiguity in the bar position. To minimize the combined effects of a large tide range and large waves, or a small tide range with small waves, images were also constrained by the Hydrodynamic Forcing Index (Almar et al., 2010):

$$HFI = \frac{H_s}{d_{min}}$$  (5.1)

where $H_s$ is averaged over a tidal cycle and $d_{min}$ is the level above Lowest Astronomical Tide of the lowest water level experienced during a tidal cycle. This quantifies the wave-tide relationship such that large values are given when the tide range and waves are large, and small values when both are small. Subsequently, only images collected within the following hydrodynamic constraints were used:

$$0.5 \text{ m} < H_s < 2 \text{ m}$$
$$0.9 < HFI < 2$$

These values were determined through visual inspection of a year of images, so as to maximise clear breaking over the individual bars. As a result of these constraints, the occasional poor lighting/weather conditions, and technical issues with the camera system, 254 usable images were obtained at Perranporth, and 200 at Porthtowan, over the 2067 days of the study period. The images had minimum, mean and maximum intervals of 1 (1), 8 (10) and 74 (93) days, respectively at Perranporth (Porthtowan).
Figure (5.1). Overview of the study sites, showing intertidal survey extents (dashed lines, lower panels) and Argus camera field of view (open triangles, lower panels) at Porthtowan (1) and Perranporth (2). In the upper panel the upwards triangle shows the position of the nearshore wave buoy at Perranporth, and the downwards triangle, circle and hollow square in the inset map show the position of the Sevenstones buoy, Wave Hub site, and extents of the main map, respectively.
Figure (5.2). Example Snapshot (upper), Timex (middle), and rectified Timex (lower) images revealing highly 3D subtidal morphology at Porthtowan on the 23rd of August 2009.
Figure (5.3). Example snapshot image from the Perranporth Argus system in March 2013, showing the checkerboard (circled) used in the image geometry solution to relate image pixels to measured ground control points.

Figure (5.4). Real Time Kinematic Global Positioning System (RTK-GPS) survey equipment. (1) Trimble 5800 base-station receiver; (2) Trimble PDL450 radio transmitter; (3) Battery pack; (4) Levelling tribrach and tripod positioned over a ground control point (out of frame); (5) Trimble TSC2 handset; (6) Trimble 5800 ATV receiver, showing measured offset from ground level (dashed line).
5.2.3 Intertidal Topographic Surveys

To complement the subtidal imagery, topographic surveys of the intertidal beach region were conducted at Perranporth and Porthtowan each month. These were conducted around the largest spring tide of the month, so as to maximize the coverage of the intertidal region. Positional measurements were taken using a Real-Time Kinematic Global Positioning System (RTK-GPS) mounted on an all-terrain vehicle (ATV), as shown in Fig. 5.4. This enables rapid collection of data over large spatial areas and with high-positional accuracy. RTK-GPS errors were $\leq 0.03$ m in both the horizontal and vertical, achieved through the use of a base station receiver set up over a known ground control point. The base-station transmits positional corrections to the ATV mounted receiver, increasing the accuracy of the rover measurements compared to standard GPS. The vertical offset (Fig. 5.4) and movement of the ATV mounted receiver has been shown to cause minor additional errors ($\leq 0.08$ m) in the GPS data (Poate, 2011).

The typical survey extents at Perranporth (Porthtowan) cover an area of approximately 1600 m (850 m) alongshore by 600 m (600 m) cross-shore, and are shown in Fig. 5.1. The ATV was driven along a number of alongshore and cross-shore transects in a quasi-regular grid, and the horizontal and vertical position was automatically logged every meter along each transect. The alongshore and cross-shore transects were spaced approximately 15 m (10 m) and 100 m (50 m) apart, respectively, at Perranporth (Porthtowan). Example surveys from each site are shown in Figs. 5.5 and 5.6 (top panels), demonstrating typical alongshore and cross-shore survey transects. During the study period (October 2008 to April 2014) a total of 64 monthly surveys were conducted at Perranporth (27 specifically for this thesis), with a minimum, mean and maximum interval of 16, 32 and 73 days respectively. At Porthtowan only 52 monthly surveys were conducted (27 specifically for this thesis) as there was a 15 month gap in the data collection between October 2010 and January 2012. The minimum, mean and maximum data intervals are 14, 39 and 474 days respectively.

The collected topographic data were used to generate Digital Elevation Models (DEM's), which were converted from OSGB36 coordinates by rotation and translation to the same local grid used by the Argus camera system. Survey data from Perranporth (Porthtowan) were gridded at 20m (10m) resolution in both the alongshore and cross-shore directions with a quadratic loess interpolation scheme (Plant et al., 2002, 2008). This scale controlled interpolation minimizes the effects of measurement error and aliasing via the selection of various smoothing scales, $\lambda_{xy}$. At each grid point the interpolation is fitted using the smallest $\lambda_{xy}$ that does not exceed
the maximum permissible interpolation error. \( \lambda_{xy} \) must be greater than four times the sampling distance, and less than half the length scales of interest in order for those scales to be preserved by the interpolation (Plant et al., 2002). The sampling distance varies between 1 and 15 m (1 and 10 m) at Perranporth (Porthtowan) and morphological length scales >10 m were preserved using smoothing scales of 5, 10, 30, and 60 m (5, 10, 20, and 30 m), with a maximum permissible interpolation error of 0.05 m.

The mean intertidal beach surface at each site is relatively void of alongshore variation, with the exception of some persistent headland features, evident at Perranporth (Porthtowan) in the middle panel of Fig. 5.5 (Fig. 5.6) at 0 m (600 m) alongshore by 300 m (300 m) cross-shore. However, the lower intertidal region at each site exhibits much greater alongshore variability through time than the upper beach, demonstrated at Perranporth (Porthtowan) by the increased standard deviation in elevation in the bottom panel of Fig. 5.5 (Fig. 5.6) between 300 m (300 m) and 700 m (500 m) cross-shore. The degree of three-dimensionality of the lower intertidal region, below MSL, was therefore the information of interest from the intertidal DEM’s at each site.

5.2.4 Parameterisation of Three-Dimensionality

To objectively quantify the three-dimensionality of the subtidal bars, the standard deviation, \( \alpha \), about the alongshore averaged cross-shore position, \( X_c \), of the detected barlines was used, in keeping with previous studies of barline variability (Plant et al., 2006, Splinter et al., 2011). To obtain a single representative measure of \( \alpha \) at the lower intertidal beach, contours were extracted from each DEM every 0.2 m between +0.2 m Ordnance Datum Newlyn (ODN) and -2.4 m ODN, measured at 20 m (10 m) intervals alongshore, between -1100 m < \( y < 200 \) m (250 m < \( y < 1000 \) m) at Perranporth (Porthtowan). For reference, 0 m ODN is approximately Mean Sea Level (MSL) at the two sites. The mean of the highest 1/3\(^{rd}\) of \( \alpha \) values across these contours was used to represent the degree of three-dimensionality. Short contours covering less than 2/3\(^{rd}\) of the alongshore length of the survey area were omitted to avoid erroneous \( \alpha \) values. It is recognised that across flat, non-sloping sections this parameter could incorrectly yield large values of \( \alpha \). As the lower beach regions at Perranporth and Porthtowan were either planar and gently sloping, or exhibited 3D features during the study period, this was not deemed to be an issue and \( \alpha \) was used in the form described above for consistency with the barline measurements. At sites which exhibit flat profile sections, other computations of \( \alpha \) should be considered however. The MLWN contour was chosen to represent the cross-shore position (\( X_c \))
Figure (5.5). Intertidal survey data and bulk statistics from Perranporth. Example survey track and DEM from Nov. 2012 (top panel), mean elevation over the study period (middle panel), and elevation standard deviation over the study period (bottom panel). Increasing offshore distance is towards the bottom of each panel. In the middle panel thick contours show from top to bottom MHWS, MHWN, MSL, MLWN, and MLWS. In the lower panel note the high alongshore variation in standard deviation below the MSL line.
Figure (5.6). Intertidal survey data and bulk statistics from Porthtowan. Example survey track and DEM from Nov. 2012 (top panel), mean elevation over the study period (middle panel), and elevation standard deviation over the study period (bottom panel). Increasing offshore distance is towards the bottom of each panel. In the middle panel thick contours show from top to bottom MHWS, MHWN, MSL, MLWN, and MLWS. In the lower panel note the high alongshore variation in standard deviation below the MSL line.
of the lower beach. Examples of the Argus detected barlines and DEM contours used to measure $\alpha$ and $X_c$ at the subtidal and lower intertidal regions at each site are shown in Figs. 5.7 to 5.10.

Before calculating $\alpha$, the barlines and contours were linearly de-trended then band-pass filtered between 25 m and 1000 m to simultaneously remove small scale noise and any beach rotation or curvature larger than the length scales of interest. Argus detected barlines from both sites were compared to barlines from 11 bathymetric surveys (Appendix C), and after correcting for systematic errors in the Argus data the remaining Root-Mean-Square (RMS) measurement errors, $\Delta X_c$ and $\Delta \alpha$, were determined. Averaged across both sites, $\Delta X_c$ and $\Delta \alpha$ were 13.82 m and 4.78 m, respectively, at the outer bar and 14.99 m and 16.55 m, respectively, at the inner bar (Table 5.1). The larger $\Delta \alpha$ at the inner bar is thought to be due to smoothing of the pixel intensity barline, which can occur when the inner surf zone is saturated with wave breaking at low tide when the Argus images are collected. Because $\Delta \alpha$ at the inner bar is of a similar magnitude to the standard deviation in $\alpha$ (Table 5.1), the inner bar data will be treated with caution. The measurement error from the intertidal contours was also estimated, and was achieved by summing the maximum RTK-GPS error ($\pm 0.03$ m) and interpolation error ($\pm 0.05$ m), and propagating the combined error into the equations used to calculate $X_c$ and $\alpha$ (Appendix C). This resulted in conservative estimates of $\Delta X_c = 0.08$ m and $\Delta \alpha = 0.16$ m for the lower beach contours.

As seasonal and inter-annual changes in $\alpha$ are of primary interest, the time series of $X_c$ and $\alpha$ were low-pass filtered using a frequency domain Fourier filter with 1/42 day cut off, to reveal any seasonality in the data (Fig. 5.11). The 42 day filter length was chosen as it is sufficiently longer than the time scale of individual storms but much shorter than an individual season, and will therefore divide between the high and low frequency variability without losing information about the seasonal/inter-annual changes of interest. In order to directly compare the unevenly sampled barline (quasi-weekly) and lower beach (quasi-monthly) data to the evenly sampled (daily average) wave data, the low-pass filtered time series were re-sampled to a regular weekly interval. This approximately replicates the mean sampling interval in the raw barline data and therefore resulted in a re-sampled data set of a similar size. The monthly beach contour data were processed in the same way and therefore had approximately four times more data points after re-sampling to a weekly interval. Although Poate et al. (2014) observed the morphology at the two sites to respond to storm events rather than exhibiting a seasonal signal, recovery from storms occurs over a period of months (Poate, 2011, Masselink et al., 2014). Aliasing in the re-sampled signals is therefore unlikely, as the typical frequency of
Figure (5.7). Example DEM’s from Perranporth (PPT) showing 3D (left panel) and 2D (right panel) intertidal morphology. Increasing offshore distance is towards the bottom of each panel. $X_c$ is the alongshore averaged cross-shore MLWN contour (dashed line) position, and $\alpha$ (three-dimensionality) is the mean of the largest 1/3rd of standard deviations of the lower beach contours (dotted lines). Thin contours show elevation (m) above ODN. Thick contours show (from top to bottom) MHWS, MHWN, MSL, and MLWS.

an upstate-downstate sequence is sufficiently longer than the sampling frequency of both the raw and re-sampled data.

5.2.5 Wave and Tide Data

Wave Data were provided by a Datawell Waverider III buoy maintained by the Channel Coastal Observatory (www.channelcoast.org) and located just offshore of Perranporth beach, moored at a water depth of approximately 14 m (Fig. 5.1). Vertical heave and horizontal displacement were logged over 30 minute periods at 1.28 Hz, to generate directional spectra and statistics including significant and maximum wave height, peak and zero-crossing wave period, wave direction associated with the spectral peak and directional spread. The half hourly wave statistics were used to calculate daily mean values of significant wave height, $H_s$, peak wave period, $T_p$, and peak wave direction, $\theta_p$ (Fig. 5.12). Occasional gaps exist in the wave series; daily mean parameters were calculated for days with at least 75% of measurements present, leaving 203 days (7.6%) over the period of interest (2007 - 2014) with missing measurements. These gaps were filled using adjusted wave data from the Sevenstones lightship (www.previmer.org), which is located in deep water approximately 70 km South West of the Perranporth wave buoy (Fig. 5.1). Daily mean values were calculated from the hourly Sevenstones measurements and a linear fit between the Perranporth and Sevenstones data was used to adjust the deep water data to approximate nearshore conditions (Appendix D). Correlation between the available Perranporth measurements and the concurrent adjusted Sevenstones
Figure (5.8). Detected bar crest positions at Perranporth (PPT), demonstrating 3D (upper) and 2D (lower) subtidal morphology. \( X_c \) is the alongshore averaged cross-shore bar position, and \( \alpha \) is the standard deviation (three-dimensionality) of the barline. Increasing offshore distance is towards the bottom of each panel.

Figure (5.9). Example DEM’s from Porthtowan (PTN) showing 3D (left panel) and 2D (right panel) intertidal morphology. Increasing offshore distance is towards the bottom of each panel. \( X_c \) is the alongshore averaged cross-shore MLWN contour (dashed line) position, and \( \alpha \) (three-dimensionality) is the mean of the largest \( 1/3 \)rd of standard deviations of the lower beach contours (dotted lines). Thin contours show elevation (m) above ODN. Thick contours show (from top to bottom) MHWS, MHWN, MSL, and MLWS.
Figure (5.10). Detected bar crest positions at Porthtowan (PTN), demonstrating 3D (upper) and 2D (lower) subtidal morphology. $X_c$ is the alongshore averaged cross-shore bar position, and $\alpha$ is the standard deviation (three-dimensionality) of the barline. Increasing offshore distance is towards the bottom of each panel.

Figure (5.11). Example of the measured outer barline standard deviation time series from Perranporth (PPT) decomposed into trend, seasonal, and storm frequency components. The seasonal and storm components were divided using a low-pass filter with $1/42$ days cut off.
Table (5.1). Statistics of the filtered three-dimensionality time-series at Perranporth (PPT) and Porthtowan (PTN) for the outer bar (OB), inner bar (IB), and lower beach contours (LC). $\Delta \alpha$ is the mean error in the raw measurements. The last three columns show the percentage of the total variance contributed by the linear trend, low-pass (> 42 day) signal, and high-pass (< 42 day) signal. The latter could not be calculated at the lower beach due to the monthly sampling interval.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \alpha$ (m)</th>
<th>Min. $\alpha$ (m)</th>
<th>Max. $\alpha$ (m)</th>
<th>Mean $\alpha$ ± std. dev. (m)</th>
<th>Trend (%)</th>
<th>Seasonal (%)</th>
<th>Storm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPT OB</td>
<td>4.78</td>
<td>14.61</td>
<td>57.32</td>
<td>31.83 ± 8.60</td>
<td>0.13</td>
<td>90.97</td>
<td>8.85</td>
</tr>
<tr>
<td>PPT IB</td>
<td>16.55</td>
<td>11.54</td>
<td>70.23</td>
<td>35.19 ± 13.05</td>
<td>3.24</td>
<td>92.29</td>
<td>4.46</td>
</tr>
<tr>
<td>PPT LC</td>
<td>0.16</td>
<td>5.17</td>
<td>25.81</td>
<td>12.41 ± 4.57</td>
<td>1.99</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>PTN OB</td>
<td>4.78</td>
<td>9.21</td>
<td>53.80</td>
<td>31.96 ± 9.14</td>
<td>3.12</td>
<td>90.69</td>
<td>5.95</td>
</tr>
<tr>
<td>PTN IB</td>
<td>16.55</td>
<td>5.23</td>
<td>72.24</td>
<td>31.16 ± 16.87</td>
<td>10.47</td>
<td>86.37</td>
<td>3.08</td>
</tr>
<tr>
<td>PTN LC</td>
<td>0.16</td>
<td>5.90</td>
<td>24.25</td>
<td>13.08 ± 4.32</td>
<td>12.88</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

measurements was high, at $R = 0.92$ and $0.81$ (RMSE 0.36 m and 1.68 s) for $H_s$ and $T_p$ respectively. As wave direction is not recorded at Sevenstones, time series mean values of $\theta_p$ were used to fill gaps in the direction series. The remaining 16 days (0.6%) where no data were available were filled using time series mean values of $H_s$ and $T_p$. Tide data was provided by a pressure transducer deployed at Porthtowan over a period of 1 year (Poate, 2011); from this, tidal constituents were calculated and used to generate a continuous prediction of tide over the period of interest (Fig. 5.12).

5.2.6 Hydrodynamic Parameters

From the time series of daily-averaged $H_s$, $T_p$ and $\theta_p$, four main hydrodynamic parameters were computed: deep water wave power ($P_o$), the alongshore component of wave power at breaking ($P_{y,b}$), the dimensionless fall velocity ($\Omega$), and the relative tide range (RTR). $P_o$ was selected as it has long been associated with state transitions, and in particular, barline straightening (Short, 1979a, Lippmann and
Wave and tide measurements at \(~14\) m depth over the study period. From top to bottom panels: significant wave height \((H_s)\), peak wave period \((T_p)\), peak wave direction \((\theta_p)\) with angle of shore normal wave incidence (horizontal dashed line), and maximum daily tide range. Daily averaged values are shown in grey while the black lines show the seasonal signal from the wave data low-pass filtered with a 1/42 day cut off.
Holman, 1990, Ranasinghe et al., 2004). $P_{y,b}$ was selected based on recent findings relating barline straightening to alongshore directed wave power from oblique waves (Holman et al., 2006, Thornton et al., 2007, Price et al., 2011, Price, 2013). $\Omega$ was selected as it has been shown in many cases to discriminate between dissipative, intermediate and reflective beach states (Wright and Short, 1984, Ranasinghe et al., 2004, Scott et al., 2011). RTR will be tested as it reflects the influence of tide range Vs wave height on forming either subdued or well defined bar features, as well as governing the freeboard over the bar crest and therefore the potential for wave driven circulation (Masselink and Short, 1993, Caballeria et al., 2003a,b).

Significant wave height at breaking $H_{s,b}$, wave angle at breaking $\theta_b$, and water depth at breaking $h_b$ were first computed using the formula of Larson et al. (2010), described in Section 4.2.6. The wave buoy data was also de-shoaled to obtain estimates of Root-Mean-Square (RMS) deep water wave height ($H_{rms,o}$), by first approximating the inshore RMS wave height, $H_{rms}$, using $H_{rms} = H_s/1.42$ (Thornton and Guza, 1983), then examining the ratio of wave group celerity at the wave buoy and deep water depth (in this case 1000 m) estimated using linear wave theory. Deepwater wave power reflects the rate at which energy is transferred by waves, and accordingly is computed from linear theory as the product of the offshore wave energy density ($E_o$), and wave group celerity ($C_{g,o}$):

$$P_o = E_o C_{g,o}$$

(5.2)

$E_o$ is calculated using $H_{rms,o}$, the density of seawater ($\rho = 1025 \text{ kg/m}^3$), and gravitational acceleration ($g = 9.81 \text{ m/s}$):

$$E_o = (1/8) \rho g H_{rms,o}^2$$

(5.3)

$C_g$ is calculated directly from the wave period ($T_p$), which was not de-shoaled:

$$C_{g,o} = (1/(4\pi)) g T_p$$

(5.4)

The alongshore component of wave energy flux at incipient breaking ($P_{y,b}$) was calculated as:

$$P_{y,b} = (E_b C_{g,b}) \sin \theta_b \cos \theta_b$$

(5.5)

where the wave energy at breaking ($E_b$) was calculated by applying the RMS breaking wave height ($H_{rms,b}$) to Eq. 5.3, and calculating wave group celerity at breaking ($C_{g,b}$, approximately equal to the individual shallow water wave celerity) using:

$$C_{g,b} = \sqrt{(g h_b)}$$

(5.6)

$\Omega$ is calculated from Eq. 2.3, where representative $\bar{W}_s$ at the mid-tide region for Perranporth and Porthtowan were taken to be 0.04 and 0.05 m/s respectively (Poate
Hydrodynamic parameters used in the study. From top to bottom panels: offshore wave power ($P_o$), alongshore component of wave power at breaking ($P_{y,b}$), Dimensionless fall velocity ($\Omega$), and Relative Tide Range (RTR). Daily averaged values are shown in grey while the black lines show the seasonal signal from the parameters low-pass filtered with a 1/42 day cut off. Solid vertical lines indicate the start of each year.

RTR is determined as the ratio of the tide range, TR, and breaker height (Masselink and Short, 1993):

$$RTR = \frac{TR}{H_{s,b}}$$

To obtain daily-average values the maximum daily TR was used with the daily-averaged $H_{s,b}$. The time series of each wave parameter is shown in Fig. 5.13, along with the seasonal (low-pass) signal.

5.2.7 Novel Manifestations of Hydrodynamic Parameters

Instantaneous values of forcing parameters are often found to have little correlation with beach morphology (Wright et al., 1985, Van Enckevort and Ruessink, 2003b, Jimenez et al., 2008, Fairley et al., 2009, for example), even when an impulse-response type relationship might seem intuitive. This can be caused by morphological change lagging changes in the forcing due to extended relaxation time (Wright...
et al., 1985, Davidson et al., 2013a, Masselink et al., 2014), and the morphology responding to both antecedent and contemporary forcing (Wright et al., 1985, Fairley et al., 2009). To tackle these complications, four different manifestations of each wave parameter will be compared to beach three-dimensionality as well as a fifth parameter that combines $P_o$ and $\Omega$. The 5 manifestations of the forcing parameters are as follows:

1. The daily-averaged forcing parameters (section 5.2.5), denoted $k$ for the following definitions, but subsequently referred to by the notation used in section 5.2.5 (grey lines, Fig. 5.13).

2. The forcing parameters low-pass filtered with a 1/42 day cut off, denoted $k_{LP}$ (black lines, Fig. 5.13). This reveals seasonality in the forcing data; as with the morphological data the filter cut off is designed to be longer than storm duration, but shorter than a single season.

3. An optimised, weighted average of each parameter, denoted $k_{WA}$ (Fig. 5.14, upper panel). This considers all recent values and therefore encapsulates response to antecedent and instantaneous conditions, with a greater importance (higher weighting) given to the most recent values. The calculation is based on the formula proposed by Wright et al. (1985), where the weighting function decreases exponentially for values increasingly further in the past:

$$k_{WA} = \left[ \sum_{i=1}^{2\phi} 10^{-i/\phi} \right]^{-1} \sum_{i=1}^{2\phi} k_i 10^{-i/\phi}$$

(5.8)

The index $i$ is the number of days prior to the present time-step. The decay parameter $\phi$ controls the weighting, which at $\phi$ days prior to the measurement time-step reaches 10% of the instantaneous weighting. The optimisation of the weighted average parameters was achieved by iteratively changing $\phi$ between 1 day (a rapid response) and 365 days (a seasonal response), and adopting the $\phi$ that yielded the highest correlation with $\alpha$. To reduce data requirements, the decay was limited to a minimum weighting of 1% ($2\phi$ days in the past).

4. The cumulative integral of the demeaned wave parameters, denoted $k_{CI}$ (Fig. 5.14, middle panel). This parameterisation assumes that beaches have an equilibrium condition related to the long term mean wave condition (Fairley et al., 2009). Deviations from equilibrium forcing (mean conditions) are assumed to promote deviations from the equilibrium state of the beach. To reflect the cumulative effects of the antecedent forcing, the cumulative integral is used:

$$k_{CI}(n) = \int_{t_0}^{t_n} (\bar{k} - k) dt$$

(5.9)
where $k_{CI}(n)$ denotes the cumulative integral of the wave parameter up to time-step $n$. Periods of lower than average waves lead to positive gradients in $k_{CI}$, periods of higher than average waves lead to negative gradients, and during transnational periods the gradient of $k_{CI}$ is zero. Local maxima and minima in the cumulative integral time series therefore represent equilibrium, with peaks (troughs) indicating a transition from a period of low (high) waves to a period of high (low) waves. Seasonality is evident in the time series in Fig. 5.14 (middle panel), with winter periods having an overall negative gradient and summer periods a positive gradient.

5. A disequilibrium stress term, denoted $\Omega_{DS}$ (Fig. 5.14, lower panel). Similar to the parameterisation of $k_{CI}$, the disequilibrium stress term examines departures from mean wave conditions (the assumed equilibrium), but following Davidson et al. (2013a) $\Omega_{DS}$ incorporates the offshore wave power to determine the magnitude of morphological change, while the disequilibrium in $\Omega$ determines the direction of change:

$$\Omega_{DS}(n) = \langle \int_{t_0}^{t_n} P_o^{0.5} (\bar{\Omega} - \Omega) dt \rangle$$

(5.10)

The angular brackets denote a de-trending of the cumulative time series; this is necessary as negative disequilibrium (when waves are steeper than average) is often associated with high wave power. Without de-trending, the cumulative time series would therefore have a significant negative trend, while no equivalent trend is expected in the morphological time series. $P_o$ is raised to the 0.5 exponent following the relationship noted by Davidson et al. (2013a, pp. 195).

A total of 17 hydrodynamic forcing time series were therefore generated, as follows: $P_o, P_{o,LP}, P_{o,WA}, P_{o,CI}, P_{y,b}, P_{y,b,LP}, P_{y,b,WA}, P_{y,b,CI}, \Omega, \Omega_{LP}, \Omega_{WA}, \Omega_{CI}, \Omega_{DS}, \text{RTR}, \text{RTR}_{LP}, \text{RTR}_{WA}, \text{RTR}_{CI}$. These were compared to the time series of $\alpha$ at the lower beach, inner bar and outer bar at both sites using Pearson product-moment correlation (R) and cross correlation analysis (section 5.3.3). To enable direct comparison, the low-pass filtered and weekly re-sampled morphological time series were used, along with forcing parameters sampled at the same weekly instances. The correlations were tested for significance at the 99% confidence level using a two-sided t test, applying $n-2$ degrees of freedom to calculate the confidence intervals, where the sample size, $n$, is the number of available morphological observations at a given lag.
5.3 Results

5.3.1 Temporal Description of Beach Three-Dimensionality

The filtered $\alpha$ time series at Perranporth and Porthtowan show that the scale of three-dimensionality at the lower beach, inner barline and outer barline ranges from 5 - 25 m, 5 - 70 m, and 10 - 60 m, respectively (Figs. 5.15 and 5.16, and Table 1). The time series reveal some complex annual periodicity in the barline and lower beach three-dimensionality.

At Perranporth (Fig. 5.15) outer bar $\alpha$ displays pronounced minima in winter each year (December), after which $\alpha$ begins to increase in the new-year and usually displays a local maximum ($\alpha > 40$ m) in spring between March and June. Summer is characterised by slightly lower outer bar three dimensionality ($20 \text{ m} < \alpha < 30 \text{ m}$), although 2009 and 2013 are notable exceptions, when high three-dimensionality ($\alpha > 35$ m) was maintained between March and September. The last third of each year sees a reduction in outer bar $\alpha$ back to its annual minimum in winter. A similar pattern can be seen in the inner bar $\alpha$ time series, where low $\alpha$ occurs at the end of each year and clear peaks occur in the first third of the new-year. There is also a secondary peak in three-dimensionality at the inner bar that occurs around September in most of the years observed. Similarly the lower beach displays reduced three-dimensionality in winter, and an annual maximum occurs in the following months.
This sequence of low to high three-dimensionality at the lower beach generally occurs slightly earlier than at the bars, with $\alpha$ typically at its lowest and highest annual values in November and February respectively.

At Porthtowan the annual signal is less clear, but the inner and outer bar does show a familiar sequence of low three-dimensionality around December, and peaks in March and September (Fig. 5.16). 2010 appears to be an exceptional year; $\alpha$ was particularly low from March through to December, and the outer bar was positioned landward and closer to the inner bar than at other points in the time series (Fig. 5.16, upper panel). Unlike Perranporth, A bi-annual sequence in the three-dimensionality is apparent at Porthtowan, where $\alpha$ was high throughout 2009, 2011 and 2013, but subdued throughout 2010 and to some extent in 2012. The gap in intertidal survey data at Porthtowan makes it difficult to identify a corresponding pattern at the lower beach.

5.3.2 Autocorrelation and Cross-Correlation

To investigate the observed annual periodicity, the autocorrelation of each $\alpha$ time series at Perranporth (Fig. 5.17) and Porthtowan (Fig. 5.18) was computed. To satisfy the regular sampling interval required, the low-pass filtered and weekly re-sampled data was used. At Perranporth the autocorrelation function reveals an annual signal at the outer bar, with significant positive and negative correlations at lags of 1 year and 1.5 years respectively. For the inner bar the significant positive correlation at 20 - 30 weeks lag demonstrates a sub-annual periodicity, previously
seen as the spring and autumn peaks in $\alpha$. The lower beach also has a sub-annual periodicity, with a shorter time scale than the inner bar, revealed by the peaks in autocorrelation at 15 and 30 weeks lag. Autocorrelation of the Porthtowan outer bar $\alpha$ time series confirms there is a bi-annual periodicity, with significant negative and positive correlations at lags of 1 year and 2 years respectively. The inner bar also shows negative correlation at approximately 1 year lag, and therefore shares the bi-annual signal. No clear periodicity can be determined from the autocorrelation of lower beach $\alpha$ at Porthtowan.

At Perranporth significant cross-correlation between outer and inner bar $\alpha$ centred around zero lag shows that the three-dimensionality of the bars changes almost concurrently (Fig. 5.19) with neither the outer or inner bar leading the other, and an annual signal between the barlines is apparent at lags up to 2 years. Significant positive correlation between the outer bar and lower beach at negative lags up to 15 weeks indicates that the lower intertidal beach becomes 3D 1 to 4 months before the outer bar. The relationship between the inner bar and the lower beach is the most complex, with significant positive correlations at both positive lags (inner bar leading the lower beach) and negative lags (inner bar lagging the lower beach), resulting from the sub-annual periodicities in the two data series. Inspection of the time series in Fig. 5.15 confirms that the peak in lower beach $\alpha$ at the start of each year occurs before the peak at the inner bar however. As was seen in the autocorrelation of the individual time series, Porthtowan beach displays a notable bi-annual correlation between the outer and inner barline three-dimensionality (Fig. 5.20),
Figure (5.17). Autocorrelation of $\alpha$ at Perranporth’s (PPT) outer bar, inner bar, and lower beach, at lags up to 250 weeks.

with significant negative and positive correlations at lags of 1 year and 2 years respectively. Significant positive correlations around zero lag show that neither barline predominantly becomes 3D before the other. Outer bar and lower beach $\alpha$ varies in a similar manner, albeit with weaker correlation. Positive correlations at ±10-20 weeks lag between $\alpha$ at the inner bar and lower beach show that increases and decreases in three-dimensionality were offset in time between these regions, although the stronger correlation at positive lags indicates that the lower beach tends to lead the inner bar.

5.3.3 Correlation with Offshore Wave and Tide Forcing

The instantaneous Pearson product-moment correlation between the filtered $\alpha$ time series and the hydrodynamic parameters is presented in Table 2. No significant correlation was found between the instantaneous wave parameters and $\alpha$ at any of the beach regions, and the seasonal (low-pass filtered) wave parameters similarly had few significant correlations with $\alpha$. In contrast, the optimised weighted-average, cumulative integral, and disequilibrium stress parameters had significant correlations with beach three-dimensionality at many of the beach regions. The strongest correlation between forcing and three-dimensionality occurred at the lower beach (Table 5.2, columns 4 and 7), with weaker correlations at the inner and outer bars. At Perranporth outer bar $\alpha$ was best correlated with $RTR_{CI}$ ($R = 0.39$) and $\Omega_{DS}$ ($R = -0.38$), the inner bar three-dimensionality was best correlated to $P_{y,b,CI}$ ($R = -0.54$), and lower beach three-dimensionality was strongly correlated to $\Omega_{DS}$ ($R = -$.
**Figure (5.18).** Autocorrelation of $\alpha$ at Porthtowan’s (PTN) outer bar, inner bar, and lower beach, at lags up to 250 weeks.

**Figure (5.19).** Cross correlation functions between Perranporth’s (PPT) outer bar, inner bar, and lower beach, at lags up to 250 weeks.
Figure (5.20). Cross correlation functions between Porthtowan’s (PTN) outer bar, inner bar, and lower beach, at lags up to 250 weeks.

0.82). At Porthtowan’s outer bar $\alpha$ was only weakly correlated to $RTR_{CI}$ ($R = 0.17$) and $P_{y,b,WA}$ ($R = -0.17$), while inner bar three-dimensionality was best correlated with $P_{o,CI}$ ($R = -0.39$), and lower beach three-dimensionality was best correlated to $RTR_{CI}$ ($R = -0.69$).

Due to the likelihood of a lag in the beach response, the low-pass filtered and weekly re-sampled morphological data were next assessed for cross-correlation with forcing parameters at different lag times of up to 250 weeks. As the cumulative integral and disequilibrium stress parameters displayed the strongest instantaneous correlations (Table 5.2), the cross-correlation will be performed on those manifestations of the data. Table 5.3 and Fig. 5.21 show that three-dimensionality at the outer bar at Perranporth had a distinct lag in response to each of the tested forcing parameters of 5 - 12 weeks. The strongest correlation was with $RTR_{CI}$ at 11 weeks lag ($R = 0.57$), and comparable correlations were also found with $\Omega_{CI}$ and $\Omega_{DS}$ at 12 and 11 weeks lag respectively. The inner bar at Perranporth had distinctly less lag in response, demonstrated by the correlation with $P_{y,b,CI}$ ($R = -0.58$) at 4 weeks lag. The lower beach displayed zero (< 1 week) lag in response and stronger correlations than those observed at the bars, with the strongest correlation of any of the test cases being between lower beach $\alpha$ and $\Omega_{DS}$ at zero lag ($R = -0.82$). Porthtowan beach also demonstrated decreasing lag in response moving from the outer bar, to the inner bar, and to the lower beach (Table 5.3 and Fig. 5.22). Weak but significant correlation ($R = 0.23$) between the outer bar and $RTR_{CI}$ occurred with a lag of 13 weeks, the inner bar was significantly correlated with each parameter at
Table (5.2). Pearson correlation coefficients, R, between forcing parameters and $\alpha$ at Perranporth (PPT) and Porthtowan (PTN) for the outer bar (OB), inner bar (IB), and lower beach contours (LC). Values significant at the 99% confidence level are shown in bold font and the strongest correlation for each morphological time series is shown in red font. For the weighted average parameters ($k_{WA}$), the value of the memory decay term $\phi$ is shown in brackets.

<table>
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<th>Forcing parameter</th>
<th>PPT OB $\alpha$</th>
<th>PPT IB $\alpha$</th>
<th>PPT LC $\alpha$</th>
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<th>PTN IB $\alpha$</th>
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0 - 8 weeks lag, and best correlated with $\Omega_{CI}$ (R = -0.42) at 8 weeks lag. The lower beach demonstrated zero lag (< 1 week) in response, and the highest correlation with RTR$_{CI}$ (R = 0.69).
Table (5.3). Maximum cross-correlation coefficients, $R$, at lags up to 1 year between forcing parameters and $\alpha$. Optimal lag time in weeks is shown in brackets. Values significant at the 99% confidence level are shown in bold font, and the strongest correlation for each morphological time series is shown in red font.

<table>
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<tr>
<th>Forcing parameter</th>
<th>PPT OB $\alpha$</th>
<th>PPT IB $\alpha$</th>
<th>PPT LC $\alpha$</th>
<th>PTN OB $\alpha$</th>
<th>PTN IB $\alpha$</th>
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Figure (5.21). Cross-correlation functions between the cumulative integral forcing parameters and $\alpha$ at Perranporth’s (PPT) outer bar (left panel), inner bar (middle panel) and lower beach (right panel).
5.4 Discussion

Seasonal changes in three-dimensionality, which contributed 86 - 92% of the total variance in subtidal $\alpha$ (Table 1), clearly occur at a much slower temporal scale than the rapid variation in the wave conditions. The improved correlation between forcing parameters and beach three-dimensionality that was achieved using cumulative integral rather than instantaneous forcing parameters indicates that seasonal changes in three-dimensionality are dictated by the cumulative effects of antecedent wave and tide conditions, rather than individual wave events.

Interestingly, three-dimensionality at the lower intertidal beach was seen to respond more rapidly to these cumulative changes in the waves, and developed earlier than three-dimensionality at the subtidal bars. Coupling between 3D beach and sandbar features has previously been observed in the field (Coco et al., 2005, Thornton et al., 2007, Almar et al., 2010, Van de Lageweg et al., 2013, Castelle et al., 2015), but few have proposed where the three-dimensionality was initiated. From the present results it could tentatively be assumed that three-dimensionality at the lower beach provided the initial perturbation required to instigate bed-surf coupling and development of three-dimensionality at the subtidal bars. However, both Almar et al. (2010) and Castelle et al. (2015) proposed that the antecedent outer bar shape on meso-macrotidal beaches in France provided the template for 3D patterns that emerged further inshore. It is therefore unwise to conclude, without further evidence from a higher resolution data set, that three-dimensionality at Perranporth and Porthtowan is initiated in the intertidal region. As the aim of this
chapter is to assess hydrodynamic forcing associated with 3D growth, the remaining discussion will focus on the relationship between waves and three-dimensionality, rather than the relationship between the sub and intertidal regions.

5.4.1 Alongshore Oriented Wave Power

Oblique wave approach has been shown to be a dominant mechanism for straightening barlines at some beaches (Garnier et al., 2013, Price, 2013). In this study, the cumulative alongshore oriented wave power ($P_{y,b,CI}$) was seen to have significant correlation with beach three-dimensionality, and was the most correlated parameter with $\alpha$ at the inner bar at Perranporth. At the inner bar at Porthtowan $\alpha$ was best correlated with the cumulative dimensionless fall velocity ($\Omega_{CI}$), but $P_{y,b,CI}$ had comparable correlation. Interestingly $P_{y,b,CI}$ explained more variance in the data than the cumulative offshore wave power ($P_{o,CI}$) in all but one case, despite contributing an order of magnitude less power. The cumulative alongshore oriented wave power can therefore explain some of the variance in beach three-dimensionality at the inner barlines, but perhaps due to its relatively small contribution to the total wave power at these sites, it does not explain the straightening that occurred at the lower beach or outer bar as well as other parameters. The relatively large measurement error ($\Delta\alpha$) at the inner bars may also be influencing the correlation with $P_{y,b,CI}$.

5.4.2 Relative Tide Range

The cumulative relative tide range ($RTR_{CI}$) was the only parameter to have significant correlation with beach three-dimensionality at all three regions at both sites, as well as having the best correlation with outer bar three-dimensionality at Perranporth and Porthtowan. Tide range therefore clearly influences the growth of 3D features, and especially at the bars where it can determine the degree of wave breaking that occurs. Field observations (Van Enckevort et al., 2004) and modelling (Smit et al., 2008a) suggest that the increased lag in response between the lower beach, inner bar, and outer bar are likely to be due to the increasing volume of sediment that has to be moved at these regions, but lag will also be exacerbated by the non-stationarity of wave processes (Masselink and Short, 1993) as well as reduced breaking at the bars caused by tidal variation (Splinter et al., 2011). From the Argus images, wave breaking frequently did not occur at the outer bar and occasionally did not occur at the inner bar. During these periods breaking wave processes and wave driven circulation at the bars will be minimal, which significantly reduces the rate of morphological change (Splinter et al., 2011).
The fraction of wave breaking at the bars can be described by a relative wave height parameter such as that used by (Splinter et al., 2011, pp. 3), which examines the ratio of wave height to water depth at the bar. For a given cross-shore bar position, the relative wave height is proportional to the relative tide range; $RTR_{CI}$ therefore approximates the proportion of wave breaking in a cumulative sense, which may explain its better correlation with outer bar three-dimensionality than other parameters. The lagged correlation with $RTR_{CI}$ indicates that maximum outer bar three-dimensionality occurred some three months after each peak in $RTR_{CI}$. These peaks occur at a transition between a period of small RTR (small tide/ large waves) and a period of large RTR (large tide/ small waves). Outer bar three-dimensionality therefore increased during periods when the relative tide range and the proportion of wave breaking at the bars was increasing. This supports the hypothesis that small tides (promoting defined bar growth), followed by large tides (promoting more intense rip circulation), increase the likelihood of 3D bar growth.

### 5.4.3 Disequilibrium Stress

Compared to $RTR_{CI}$, the disequilibrium stress parameter ($\Omega_{DS}$) had comparable correlations at Perranporth’s inner and outer bar, significant correlations at Porthtowan’s inner bar and lower beach, and the highest overall correlation observed, at the lower beach at Perranporth. Relative tide range is therefore not solely responsible for 3D growth, as $\Omega_{DS}$ is not influenced by tide range at all. Wave power and steepness considered in $\Omega_{DS}$ are clearly also important factors. To demonstrate the influence of disequilibrium stress on beach three-dimensionality, the time series of $\alpha$ at the lower beach at Perranporth is compared to $\Omega_{DS}$ in Fig. 5.23. In the winter (November to February) $\Omega_{DS}$ has a negative gradient ($\Omega > \bar{\Omega}$), and from spring to autumn (February to November) the gradient is positive ($\Omega < \bar{\Omega}$). These negative and positive gradients are associated with increases and decreases in three-dimensionality at the lower beach, respectively. The strong negative correlation at zero lag between the cumulative wave parameters and lower beach $\alpha$ observed in the cross-correlation analysis is evident in Fig. 5.23, where peaks in $\alpha$ align with local minima in $\Omega_{DS}$. This is particularly apparent in the winters of 2009 to 2010, 2012 to 2013, and 2013 to 2014. The scatter plot in Fig. 5.24 shows the same relationship, with information about the cross-shore position of the MLWN contour ($X_c$) included. Larger (smaller) markers indicate more seaward (landward) contour positions. The most three-dimensional beach conditions (large $\alpha$) are clearly associated with the most landward positions of the MLWN contour, and occur during periods of negative disequilibrium stress.
This relationship at first seems counter intuitive as negative gradients in $\Omega_{DS}$ occur when $\Omega$ is higher than average, and upstate transition (erosion and beach straightening) might be expected. However the troughs in $\Omega_{DS}$ that align with periods of high three-dimensionality actually represent a return to equilibrium $\Omega$ after a sustained period of higher than average waves, for example after winter. This confirms that Perranporth beach becomes increasingly 3D shortly after winter when energetic waves are subsiding, and $\Omega_{DS}$ is reaching its annual minimum. While Poate et al. (2014) noted a storm-recovery cycle in beach state at Perranporth, the results here indicate that the seasonal changes occur in a cumulative manner, with three-dimensionality responding to seasonal fluctuations in wave forcing. It is therefore seasonal changes in the wave regime from erosive to accretive (and vice versa), here represented by troughs and peaks in $\Omega_{DS}$, that lead to periods of high and low beach three-dimensionality, respectively.

An unusual winter occurred in 2010 to 2011, with a particularly short period of decreasing $\Omega_{DS}$ (Fig. 5.23), caused by smaller than average waves (Fig. 5.12); the net result was a much smaller increase in lower beach three-dimensionality the following spring than in other years. This suggests that larger winter waves may actually promote greater three-dimensionality in the post-winter recovery period. Between December 2013 and February 2014 an unprecedented series of long period, high energy swell events occurred, making it the most energetic 8-week period of waves in the last 65 years (Masselink et al., 2015). One storm swell ‘Hercule$\ddot{a}$’ featured wave heights and periods of 9.6 m and 22 s, respectively (Castelle et al., 2015). During that stormy winter the lower beach and inner bar at Perranporth retreated landward, but became highly three-dimensional in the spring of 2014. The outer bar became increasingly linear and moved offshore, but due to a subsequent lack of wave breaking over the stranded offshore bar after the storms, there are no measurements post February 2014 to indicate its recovery behaviour. The behaviour at Porthtowan during this period is less distinctive compared to other years. Castelle et al. (2015) also observed large subtidal and intertidal 3D length scales on the Gironde coast in SW France following the winter of 2013 to 2014, which supports the theory that the scale of 3D features that develop after winter increases with increasing winter wave activity.

Overall, the highest correlation with beach three-dimensionality at the two sites came from RTR$_{CI}$ and $\Omega_{DS}$. The $R^2$ from the cross-correlation shows that these two parameters explained up to 67% of the variance in three-dimensionality at the lower beach, 26% at the inner bar, and 32% at the outer bar. They therefore provide a strong basis for predictive modelling of beach three-dimensionality, especially if the terms can be combined.
Figure (5.23). Time series of the disequilibrium stress parameter (top panel) and low-pass filtered time series of lower intertidal beach three-dimensionality, $\alpha$, at Perranporth (PPT, bottom panel). The horizontal dashed line in each plot shows the time series mean. Solid vertical lines indicate the start of each year.

Figure (5.24). The disequilibrium stress parameter scattered against lower intertidal beach three-dimensionality, $\alpha$, at Perranporth (PPT). The values are concurrent (no lag). The size and colour of the markers represents the cross-shore position of the MLWN contour (between 437 and 497 m cross-shore), with larger markers and hotter colours showing more seaward positions.
5.5 Conclusions

5.5 years of video derived bar positions and RTK-GPS intertidal surveys were used to investigate the temporal variability in the three-dimensionality of subtidal and intertidal beach morphology, at two energetic dissipative-intermediate macrotidal beaches. Seasonal variation accounted for 86 - 92% of the variance in subtidal three-dimensionality, and clearly occurs much more slowly than the time scale of individual wave events. Rather than relating to instantaneous forcing parameters, changes in three-dimensionality were therefore seen to be dictated by the cumulative effects of antecedent wave and tide conditions.

Significant annual periodicity in the barline three-dimensionality was observed, with annual minima and maxima occurring in winter and spring, respectively. The lower intertidal beach displayed a similar periodicity, but with less lag time (< 1 week lag) in response to changes in the forcing, developing three-dimensionality 1 - 4 months before the outer bar. While the opposite behaviour has been observed at other sites before (Almar et al., 2010, Castelle et al., 2015), three-dimensionality has never before been observed to develop at the intertidal beach before the subtidal beach, which raises questions about the initiation of bed-surf coupling.

Tide range was important at the outer bar, and periods of high three-dimensionality were associated with periods of increasing relative tide range, represented by the cumulative integral of the demeaned relative tide range. At the inner bar the cumulative alongshore oriented wave power explained the most variance in the three-dimensionality. Points of equilibrium between periods of erosion and accretion in the wave regime, represented by a disequilibrium stress parameter, were associated with the highest three-dimensionality at the lower beach, and explained 67% of the variance.

Cumulative demeaned forcing parameters that vary on the same seasonal time scale as the morphology offer the greatest potential to forecast changes in beach three-dimensionality. Tide range, wave steepness and wave power represented in the cumulative relative tide range and disequilibrium stress parameters, overall explained the greatest amount of variance in the seasonal three-dimensionality at the different beach regions tested, and provide a basis for further work developing a predictive model for beach three-dimensionality.
Chapter 6

Predicting Seasonal to Inter-annual Changes in Beach Three-Dimensionality Using a Simple Equilibrium Model

6.1 Introduction

6.1.1 Background

In section 2.4.4 it was identified that a novel modelling approach is needed in order to predict the effects of wave energy extraction on 3D beach morphology over seasonal to annual time scales. Such a model must sit between the fine spatial and temporal resolution offered by process models, and the coarse prediction of beach state achievable using the dimensionless fall velocity, $\Omega$. In Chapter 5 relative tide range, wave steepness and wave power were all found to explain a significant amount of variance in 3D beach morphology, but only when parameterised as cumulative, demeaned terms that vary on the same seasonal time scale as the morphology. In particular, the disequilibrium stress term was capable of explaining the majority of 3D variance at the lower intertidal beach, and therefore provides a starting point from which to develop a predictive model for beach three-dimensionality.

Disequilibrium stress was originally deemed a concept suited to modelling beach state change, and has now been used in adapted forms to predict cross-shore shoreline (Yates et al., 2009, 2011, Davidson et al., 2010, 2013a, Castelle et al., 2014, Splinter et al., 2014) and barline (Plant et al., 1999, Masselink et al., 2014) migration under varying waves. As such it clearly has the potential to model a variety of morphodynamic behaviour. Although the conceptual foundation for this modelling
approach was proposed some decades ago (Wright et al., 1985), it has thus far only been used to model alongshore uniform dynamics, and has never been applied to the prediction of beach three-dimensionality. Other attempts to behaviourally model three-dimensionality have either been restricted to single storm cycles (Plant et al., 2006) or have included relatively complex sediment transport parameterisations with limited predictive improvement (Splinter et al., 2011).

In this chapter, two behavioural beach three-dimensionality models will be explored. The first is based on the concept of disequilibrium stress, and will be developed from an existing equilibrium shoreline change model (Davidson et al., 2010, 2013a). The second approach uses a linearized feedback equation and was used by Plant et al. (2006) to skilfully predict three-dimensionality, but only over a single storm-recovery time scale. The following sections outline the two approaches.

### 6.1.2 Disequilibrium Stress Model

Davidson et al. (2010, 2013a) developed the disequilibrium stress concept proposed by Wright et al. (1985) in order to predict seasonal to inter-annual changes in the cross-shore shoreline position at two Australian beaches. Their model predicts that when incident waves are more erosive than the equilibrium condition the shoreline will retreat, whereas waves that are more accretive result in shoreline progradation. When waves are equal to the equilibrium condition, no shoreline change is predicted to occur and a temporary equilibrium is reached. While Wright et al. (1985) assumed that an appropriate equilibrium value was the instantaneous value of $\Omega$ concurrent with periods of zero change in beach state, this does not allow the beach to lag behind waves in reaching a state of equilibrium. Davidson et al. (2013a) therefore defined their temporally-varying equilibrium value ($\Omega_{eq}$) as a weighted average of the wave conditions preceding each time step, assuming that the influence waves have on the shore position decays exponentially through time. A further modification was to allow the level of incident wave power, $P$, to determine the rate of shoreline change. Despite the model ignoring longshore sediment transport, Davidson et al. (2013a) achieved significant inter-annual predictive skill, accounting for around 60% of the variability in shoreline position over 3 years of validation data. Their model, herein referred to as DST13, will be modified in this chapter to suit the prediction of 3D morphology. In particular the effect of tide range will be included in the adapted model, as it was found in Chapter 5 to be correlated to 3D changes at the outer bar.
6.1.3 Linearized Feedback Model

Recognising the coupling between the cross-shore position \( (X_c) \) and three-dimensionality \( (\alpha) \) of a barline, Plant et al. (2006) proposed an alternative modelling approach with the aim of predicting bar position, \( X_c \). Rather than examining wave disequilibrium, this model assumes that the rates of change in \( X_c \) and \( \alpha \) are dependent on one another, as well as the squared RMS wave height, \( H_{rms}^2 \). This linearized feedback approach simultaneously estimates \( X_c \) and \( \alpha \), and can therefore be used to predict either \( X_c \) (as was the focus of Plant et al. (2006)) or \( \alpha \) (as is the focus here). Applied to two months of bar and wave data, covering a single storm cycle that caused decreasing then increasing (offshore then onshore) barline three-dimensionality (bar migration), significant predictive skill was achieved \( (R^2 = 0.9) \). Their data only included small deviations from the mean values of \( X_c \) and \( \alpha \) however, and calibration and validation were performed against the same data, so it’s predictive skill for longer data sets or values outside the training data range is unknown. Nonetheless, the model (herein referred to as PHH06) allowed for the interplay between self-organisation and time-varying wave forcing to be explored, and the strong links between the driving terms indicate that \( X_c \) and \( \alpha \) are inter-dependent, and knowledge of both is necessary to forecast either parameter.

6.1.4 Aims

The 5.5 year data set of sub and intertidal three-dimensionality described in Chapter 5 presents an opportunity to develop the DST13 model, and apply disequilibrium stress to the prediction of three-dimensionality for the first time. Furthermore this will be the first time that inter-annual changes in three-dimensionality have been modelled at a macrotidal beach. Various measures of predictive skill will be used to assess the model and predictions will be compared to those made by the PHH06 model (a comparable existing model) as well as a linear fit to the data (a baseline model).

6.2 Methodology

6.2.1 Research Approach

As with Chapters 4 and 5 of this thesis, a quantitative research approach and post-positivist paradigm (described in Section 4.2.1) is employed in this chapter, as the data involved is highly quantitative.
6.2.2 Data

The DST13 and PHH06 models were calibrated and validated against four data sets, comprised of the time series of outer bar and lower beach contour three-dimensionality, \( \alpha \), at Perranporth beach and Porthtowan beach. As described in Section 5.2.4, \( \alpha \) is quantified as the standard deviation of the linearly de-trended and band-pass filtered barline or contours, and has estimated measurement errors, \( \Delta \alpha \), of 4.78 m and 0.16 m, respectively. The inner bar data at the two sites were deemed to have excessively large measurement error (\( \Delta \alpha \approx 17 \) m), on the same order of magnitude as the standard deviation in the data, and as such were not included in the modelling in this chapter. For the PHH06 model, time series of \( X_c \) are also required, and were quantified at the outer bar and lower beach as the alongshore averaged cross-shore position of the outer barline and MLWN contour, respectively (Section 5.2.4). The estimated measurement error, \( \Delta X_c \), at the outer bar and lower beach is 13.82 m and 0.08 m respectively (Section 5.2.4). Examples of subtidal and intertidal data from Perranporth are shown in Fig. 6.1, with their associated \( \alpha \) and \( X_c \) values.

The outer bar and lower beach data were used to test the ability of the models to predict three-dimensionality in the subtidal and intertidal regions respectively, and will indicate whether the physics of those regions have been sufficiently captured by either model. For each data set the time series was low-pass filtered with a 1/42 day cut off (Section 5.2.4), and the models are therefore tasked with predicting seasonal to inter-annual changes in \( \alpha \). The \( \alpha \) time series were re-sampled by interpolation to generate a continuous daily time series for the purpose of the low pass filtering, but the filtered time series were later re-sampled back to the original measurement times for the hindcast, calibration and validation stages of the modelling.

Wave Data used to drive the models were provided by the Datawell Waverider III buoy at Perranporth beach, moored at a water depth of approximately 14 m. The half hourly wave statistics were used to calculate daily mean values of significant wave height at breaking, \( H_b \), and peak wave period, \( T_p \), for each beach (Section 4.2.6). Gaps in the wave time series were filled using adjusted deepwater measurements from the Sevenstones lightship (Appendix D). To calculate \( \Omega \) (Eq. 2.3), a constant representative sediment fall velocity, \( \bar{W}_s \), was determined from monthly samples taken over a period of three years from the mid-tide region at each site (\( \bar{W}_s = 0.04 \) and 0.05 m/s for Perranporth and Porthtowan respectively). Tide data for the DST13 model were provided by a pressure transducer deployed at Porthtowan over a 1 year period by Poate (2011); from this, tidal constituents were calculated and used to generate a continuous prediction of tide over the period of interest.
**Figure (6.1).** Combined topographic survey data (semi-transparent contour plots) and rectified timex images from Perranporth beach, demonstrating seasonal changes in three-dimensionality. The thin dashed lines and thick subtidal line in each plot show the lower beach contours and outer barline respectively, used to determine the three-dimensionality, $\alpha$, of the intertidal and subtidal regions respectively. The thick dashed line shows the MLWN contour used to represent the cross-shore position of the lower beach. The solid contours show elevation (m) above ODN, and the thick contours indicate (from top to bottom) MHWS, MSL, and MLWS, respectively.
6.2.3 Assessment of Model Skill

4 objective measures of the models predictive ability will be assessed:

1. The squared correlation, \( R^2 \), between the model predictions \( x_m \) and measured data \( x \). This indicates how well the pattern of variability in the data is replicated by the model, as well as how much variance is explained. However, large \( R^2 \) values can be attained even when large residuals exist.

2. The Root-Mean-Squared error between model predictions and measured data (angular brackets denote a time series average value):

\[
RMSE = \sqrt{\langle (x - x_m)^2 \rangle} \tag{6.1}
\]

3. The Brier Skill Score (BSS) quantifies the improvement that the model predictions provide over that of a predefined benchmark model, \( x_b \) (Brier, 1950). BSS also considers the estimated measurement error in the data, \( \Delta x \) (m), and is therefore deemed highly suited to assessment of morphological models (Sutherland et al., 2004). For our assessment a linear fit to the data is used as a benchmark model, which provides a more rigorous test than a benchmark such as the data mean, which is often used for model comparisons.

\[
BSS = 1 - \left[ \frac{\langle \left| x - x_m \right|^2 \rangle}{\langle (x - x_b)^2 \rangle} \right] \tag{6.2}
\]

Brier Skill Scores exceeding 0.0, 0.3, 0.6, and 0.8 are respectively classed as ‘poor’, ‘fair’, ‘good’ and ‘excellent’.

4. The Akaike’s information criterion (AIC) (Akaike, 1974, Kuriyama, 2012, Davidson et al., 2013a), provides an additional comparative assessment of model skill which considers the number of free parameters used, \( m \).

\[
AIC = n[log2\pi + 1] + nlog\sigma^2 + 2m \tag{6.3}
\]

where \( n \) is the sample size, and \( \sigma^2 \) is the variance of the residuals between validation data and the baseline or model predictions. A penalty is incurred for each additional free parameter used, and a model with fewer free parameters but the same skill will therefore be scored favourably. If a model’s AIC score is smaller than another model’s AIC score by at least 1, it is considered more appropriate (Kuriyama, 2012). Differences in AIC score (\( \Delta AIC \)) are shown in Table 6.3.
6.2.4 DST13 Model

The DST13 formula will be developed to better suit the prediction of three-dimensionality, but the adapted model is conceptually similar to that used by Davidson et al. (2010, 2013b,a) to predict shoreline migration and takes the following form:

\[
\frac{d\alpha}{dt} = b + c(F^+ + rF^-)
\]  

(6.4)

The model predicts the rate of change of alongshore variability, \(\frac{d\alpha}{dt}\), using regression parameters, \(c\), which influences the rate of change, and \(b\), which accounts for any linear trend in the data. Davidson et al. (2013a) define the forcing term \(F\) as the product of the incident wave power raised to the 0.5 exponent, \(P^{0.5}\), and the disequilibrium term \(\Delta\Omega\):

\[
F = P^{0.5} \frac{\Delta\Omega}{\sigma\Delta\Omega}
\]  

(6.5)

\(\Delta\Omega\) controls the direction of beach change (2D to 3D or 3D to 2D) and for convenience positive values are associated with increasing three-dimensionality by changing the sign of Eq. 2.4 (therefore \(= \Omega_{eq} - \Omega\)). Following Splinter et al. (2014) \(\Delta\Omega\) is normalised by its standard deviation (denoted \(\sigma\Delta\Omega\) in Eq. 6.5), so that the rate of change in \(\alpha\) is predominantly controlled by the rate parameter, \(c\), and the wave power \((P^{0.5})\), rather than the magnitude of \(\Delta\Omega\). \(\Omega_{eq}\) is determined from weighted antecedent values of \(\Omega\), and is highly dependent on a memory decay parameter \(\phi\), which determines the number of days, \(i\), prior to the present time at which the weighting function has dropped to 10%:

\[
\Omega_{eq} = \left[ \sum_{i=1}^{2\phi} 10^{-i/\phi} \right]^{-1} \sum_{i=1}^{2\phi} \Omega_i 10^{-i/\phi}
\]  

(6.6)

Low \(\phi\) values (< 30 days) indicate a short, storm dominated response time, whereas large values (> 100 days) indicate that variations from the long-term mean conditions cause changes in \(\alpha\) (Davidson et al., 2013a). Example weightings are discussed in section 6.4.2.

Water depth over the bar crest, and by association tidal range, have been recognised as important modulators of wave driven horizontal circulation and therefore the development of 3D morphology (Caballeria et al., 2003a,b, Almar et al., 2010, Austin et al., 2013). Austin et al. (2013) for example found that rip currents at Perranporth reached maximum velocities around spring low tide, which is likely to enhance the sediment transport potential. Davidson et al.’s forcing term \(F\) is therefore modified here to include the combined effects of a large tidal range and high wave power by adapting a previously used parameter, the normalised wave power, \(P_{\eta_0}\) (Morris et al., 2001, Loureiro et al., 2012):

\[
P_{\eta_0} = P^{0.5} \left( \frac{\eta_{dtr}}{\eta_{str}} \right)
\]  

(6.7)
where $\eta_{dtr}$ and $\eta_{str}$ are the maximum daily and spring tide ranges respectively. When the tide range approaches its overall (spring tide) maximum, the ratio on the right-hand side approaches unity and the normalised wave power is maximised. Conversely during neap tides the ratio drops to around $1/2$, reducing the normalised wave power by half. In initial tests, inclusion of this tidally modulated power term made little difference to the lower beach predictions ($R^2$ was 0.61 in both cases), but significantly improved model skill at the outer bar, increasing $R^2$ from 0.32 to 0.42. The Relative Tide Range, RTR (Masselink and Short, 1993), and Hydrodynamic Forcing Index, HFI (Almar et al., 2010), were also tested but did not yield comparable model improvements.

Recognising that increasing and decreasing three-dimensionality are caused by different physical processes, the forcing term $F$ is broken into positive and negative elements in Eq. 6.4:

$$F = P\eta_o \frac{\Delta \Omega}{\sigma \Delta \Omega}$$  \hspace{1cm} (6.8)

$$F^+ = P\eta_o \frac{\Delta \Omega}{\sigma \Delta \Omega} \quad (\text{when } \Omega < \Omega_{eq})$$  \hspace{1cm} (6.9)

$$F^- = P\eta_o \frac{\Delta \Omega}{\sigma \Delta \Omega} \quad (\text{when } \Omega > \Omega_{eq})$$  \hspace{1cm} (6.10)

The relative weighting of $F^+$ and $F^-$ are determined by the ratio term $r$ in Eq. 6.4; this is calculated from the wave data and is therefore not considered a model free parameter. $r$ describes the relative efficiency of positive and negative disequilibria in altering the beach three-dimensionality, and long-term equilibrium is maintained if:

$$r = \left| \frac{\sum_{i=0}^N \hat{F}_i^+}{\sum_{i=0}^N \hat{F}_i^-} \right|$$  \hspace{1cm} (6.11)

$N$ is the length of the time series, and the triangular over-bar represents a numerical operation that removes any linear trend in $F$, but retains the time-series mean. As negative disequilibrium (e.g. storms) often has higher associated wave power, a strong tendency towards beach straightening would be predicted if only $F$ was considered. Instead $r$ is determined such that zero trend in the forcing results in zero trend in $\alpha$, and therefore the term $(F^+ + rF^-)$ only contributes to a predicted trend if one exists in the wave forcing series. Any trend in $\alpha$ not explained by trends in the wave series is handled (albeit crudely) by the trend term $b$ in Eq. 6.4.

To predict values of $\alpha$ at times $t$, $F$ and $r$ are computed from the wave data and Eq. 6.4 is numerically integrated with respect to time, yielding the final model equation:

$$\alpha(t) = a + bt + c \int_0^t (F^+ + rF^-) dt$$  \hspace{1cm} (6.12)
where \( a \) is an offset that deals with non-zero mean values of \( \alpha \). Eq. 6.12 is regressed against observed values of \( \alpha(t) \) using a least squares method to optimize the coefficients \( b, c \) and offset \( a \). The optimal \( \phi \) value is determined iteratively by changing \( \phi \) from 1 to 1000 days, each time regressing the model against calibration data, and finally using the \( \phi \) that yields the greatest \( R^2 \).

### 6.2.5 PHH06 Model

Plant et al.’s model involves two coupled differential equations, predicting the rates of change in \( X_c \) and \( \alpha \) (here denoted \( \dot{X}_c \) and \( \dot{\alpha} \) for brevity), and takes the following combined form:

\[
\begin{bmatrix}
\dot{X}_c \\
\dot{\alpha}
\end{bmatrix} = A \begin{bmatrix} X_c \\ \alpha \end{bmatrix} + B \begin{bmatrix} \frac{1}{H_b^2} \end{bmatrix}
\]  

(6.13)

A and B are \([2 \times 2]\) coefficient matrices determined through linear least-squares regression; examples from Plant et al. (2006) are as follows:

\[
A = \begin{bmatrix}
-0.071 \pm 0.03[\text{d}^{-1}] & -0.70 \pm 1.0[\text{d}^{-1}] \\
0.0047 \pm 0.001[\text{d}^{-1}] & -0.022 \pm 0.03[\text{d}^{-1}]
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0.50 \pm 1.0[(\text{md})^{-1}] & 2.1 \pm 0.4[(\text{md})^{-1}] \\
-0.014 \pm 0.03[(\text{md})^{-1}] & -0.040 \pm 0.01[(\text{md})^{-1}]
\end{bmatrix}
\]

Matrix \( A \) defines the inter-relationship between \( X_c \) and \( \alpha \). The diagonal terms in \( A \) describe self-interaction, or how the current value affects further changes in that value (e.g. how \( \alpha \) affects \( \dot{\alpha} \)). Negative self-interaction terms indicate negative feedback or a stabilising nature, as larger input values would decrease further rates of change. The off-diagonal terms in \( A \) describe cross-interaction, or how \( \dot{\alpha} \) is affected by \( X_c \) and vice versa. If diagonal terms are negative (e.g. the system has a stabilising tendency), then the off diagonal terms do not affect the systems stability if they are oppositely signed (Plant et al., 2006). \( B \) contains offset coefficients for \( X_c \) and \( \alpha \) that deal with non-zero mean values, and coefficients describing the effect of wave height (parameterised as \( H_b^2 \)) on \( X_c \) and \( \alpha \).

Values of either \( X_c \) or \( \alpha \) are predicted by integrating all terms in Eq. 6.13 with respect to time, then separately optimising the coefficients through least squares regression against observations:

\[
X_c(t) = A_{1,1} \int_0^{t-1} X_c dt + A_{1,2} \int_0^{t-1} \alpha dt + B_{1,1} + B_{1,2} \int_0^{t-1} H_b^2 dt
\]  

(6.14)

\[
\alpha(t) = A_{2,1} \int_0^{t-1} X_c dt + A_{2,2} \int_0^{t-1} \alpha dt + B_{2,1} + B_{2,2} \int_0^{t-1} H_b^2 dt
\]  

(6.15)
To make forward predictions of either value, the model is initialized with observations of $X_c$ and $\alpha$, then driven forward with observations of $H_b^2$, iteratively feeding prior predictions of $X_c$ and $\alpha$ back into the model.

6.3 Results

6.3.1 Model Hindcasts

Figs. 6.2 and 6.3 show model hindcasts made by the DST13 model at Perranporth and Porthtowan, respectively. Summary statistics of the model's hindcast performance is given in Table 6.1, and show that the model performs well at Perranporth. At the outer bar the hindcast was able to explain 42% of the variance in the data set ($R^2$), and had RMSE = 6.55 m. At the lower beach the model explained 61% of the variance in the data set, with RMSE = 2.84 m. At Perranporth the model hindcast achieves 'good' Brier Skill Scores for the outer bar and lower beach (BSS = 0.77 and 0.63 respectively). The outer bar predictions are scored slightly higher than those at the lower beach despite the other statistics suggesting that the model performs better at the lower beach. The reason for this is that BSS scores sympathetically towards data with larger estimated errors; as $\Delta\alpha$ (filled areas in Fig. 6.2) at the lower beach (0.16 m) is an order of magnitude smaller than at the outer bar (6.9 m), it is given a lower BSS. At Porthtowan the model performs less well, predicting some of the trend and seasonal variability at the lower beach, but only capturing the trend at the outer bar. The model explains 17% and 32% of the variability, with RMSE of 8.26 m and 3.53 m, at the outer bar and lower beach respectively. The BSS scores for the outer bar and lower beach are 'fair' and 'poor', respectively.

6.3.2 Model Validation

Next the predictive skill of the DST13 model will be more rigorously tested by validating its predictions against an unseen portion of the data, as well as comparing the predictions to those made by the PHH06 model. Initially, poor results were achieved when the DST13 model was calibrated using only the first half of the Perranporth outer bar data, as a localised trend of decreasing three-dimensionality between January 2009 and December 2010 misled the calibration of $b$ in Eq. 6.12. Fig. 6.4 shows the sensitivity of the model to the length of the calibration data set. Following this analysis it was deemed that the model was optimised (the validation RMSE was minimised) using the first 60% of available data, and validation was performed using the remaining unseen 40% of the data. All assessments of model skill described below are made against the validation data, unless specified otherwise.
Figure (6.2). DST13 Model hindcasts plotted alongside the seasonal (low pass-filtered) $\alpha$ data at Perranporth’s outer bar (top panel) and lower beach (bottom panel). The thickness of the data lines indicates the measurement error ($\Delta\alpha$).

Figure (6.3). DST13 Model hindcasts plotted alongside the seasonal (low pass-filtered) $\alpha$ data at Porthtowan’s outer bar (top panel) and lower beach (bottom panel). The thickness of the data lines indicates the measurement error ($\Delta\alpha$). Note that there is a gap in lower beach data between October 2010 and January 2012.
Figure (6.4). Model sensitivity to varying the % of calibration data used for the Perranporth outer bar predictions. As indicated by the dashed vertical line, 60% of data was subsequently used for calibration. RMSE for the other data sets converged at ≤ 60% calibration length.

Comparisons between the DST13 model predictions and validation data are shown in Figs. 6.5 and 6.6 for Perranporth and Porthtowan respectively, and summarised in Table 6.1. As with the hindcast, the DST13 model performed well for the outer bar and lower beach contours at Perranporth, explaining 57 - 59% of the variance in the validation data, with low RMSE (5.9 m and 3.2 m respectively) and achieving ‘good’ and ‘fair’ Brier Skill Scores (BSS = 0.71 and 0.53 respectively). The frequency and timing of the annual fluctuations in the lower beach data were well reproduced by the model, although sub-annual signals were not predicted. Although the magnitude and timing of some changes at the outer bar were not accurately predicted, DST13 did predict the large increase in $\alpha$ between January and April 2012, and decrease in $\alpha$ between October 2013 and February 2014. Conversely, at Porthtowan the model Brier Skill Scores for the outer bar and lower beach were both ‘bad’. Although the dominant annual signal was reproduced at the lower beach, there were large residuals and overall only a small amount of the variance in $\alpha$ was explained by the model at Porthtowan.

The comparable PHH06 model also performed well for the lower beach contour data at Perranporth (Fig. 6.5 and Table 6.2), where the model explained 61% of the variance in the validation data, with low RMSE (3.46 m) and a ‘fair’ Brier Skill Score (BSS = 0.46). Interestingly, the DST13 model and the PHH06 model made remarkably similar predictions at the lower beach, despite the differences in their driving parameters. Although PHH06 explained some of the variance in the lower beach contour data at Porthtowan, the large model residuals and low measurement error in the data resulted in a ‘bad’ Brier Skill Score. The model also performed poorly for the barline data sets, explaining less than 8% of the variance in $\alpha$. For
Figure (6.5). Calibration (cal) and validation (val) model predictions for the alongshore variability of the outer bar (upper panel) and lower beach (lower panel) at Perranporth. The thickness of the data lines indicates the measurement error ($\Delta \alpha$).

The outer bar at Perranporth, the model predicted some annual variability but the phase and amplitude of the data were not reproduced. At Porthtowan the model only reproduced the linear trend in the outer bar data and could not predict any of the sub-seasonal variability.

### 6.3.3 AIC Scores

For three of the four data sets the PHH06 model had higher AIC values than a simple linear fit to the data (Table 6.3), meaning that when the complexity of the model (8 free parameters) is taken into consideration, it did not outperform a simple baseline estimate (in this case a linear fit with 2 free parameters). It is therefore not considered to be an appropriate model for any of the data except for the Perranporth LC data. The DST13 model (4 free parameters) had consistently lower AIC values than the PHH06 model, indicating a better model for the data, and achieved lower AIC values than a simple linear fit for the Perranporth outer bar data, and the Perranporth and Porthtowan lower beach contour data. The DST13 model therefore outperformed the PHH06 model and a baseline estimate for 3 of the 4 data sets.
Table 6.1. Model coefficients and skill assessment results for the DST13 model, for the outer bar (OB) and lower beach contours (LC) at Perranporth (PPT) and Portreath (PTN). Model skill values are given for hindcast, (calibration), and [validation] data. Ratio \( r \) is grouped here as a parameter, but was not counted as one in the calculation of AIC. Values are given to 3 significant figures.

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DST13

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Table (6.2). Model coefficients and skill assessment results for the PHH06 model, for the outer bar (OB) and lower beach contours (LC) at Perranporth (PPT) and Porthtowan (PTN). Model skill values are given for (calibration) and [validation] data. Values are given to 3 significant figures.

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<td>B</td>
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<td>B</td>
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Figure (6.6). Calibration (cal) and validation (val) model predictions for the alongshore variability of the outer bar (upper panel) and lower beach (lower panel) at Porthtowan. The thickness of the data lines indicates the measurement error ($\Delta \alpha$). Note that there is a gap in lower beach data between October 2010 and January 2012.

Table (6.3). Difference in AIC scores between a linear fit to the data, the PHH06 model, and the DST13 model, for the outer bar (OB) and lower beach contours (LC) at Perranporth (PPT) and Porthtowan (PTN). Values greater than 1 (shown in bold font) indicate that the second model in parentheses is significantly better than the first.

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<th>$\Delta$AIC (Linear fit - DST13)</th>
<th>$\Delta$AIC (PHH06 - DST13)</th>
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6.4 Discussion

6.4.1 Differences Between the PHH06 and DST13 Models

The AIC scores indicate that, given the number of free parameters used, the PHH06 model did not predict beach three-dimensionality as skilfully as the DST13 model. Both models predicted three-dimensionality better at the lower beach than at the outer bar; this suggests that the barline measurement error is masking the relationship with incident waves, but it is also likely that some physical processes at the bar are not being captured by either model (see Section 6.4.3). Despite poorly predicting outer bar $\alpha$, the PHH06 model made accurate predictions of lower beach $\alpha$. Unlike DST13, the PHH06 coefficients can describe positive or negative feedback depending on the results of the least squares regression. The self-interaction terms (left to right diagonal) in matrix A (Table 6.2) for the lower beach are both negative, showing that increases in $\alpha$ reduce the rate of further changes in $\alpha$, suggesting a stable and deterministic system, as was also observed by Plant et al. (2006). The fact that these terms are negative adds credence to the negative feedback approach used in the DST13 model and explains the remarkably similar predictions of lower beach $\alpha$ made by the two models, despite the differences in driving parameters.

The inclusion of a tidally modulated power term in DST13 may explain why it performed better than PHH06 at Perranporth’s outer bar, which is often inactive during small tides. While DST13 is forced by wave and tide parameters, PHH06 requires knowledge of wave height and $X_c$ in order to predict changes in $\alpha$. Plant et al. (2006) argue that knowledge of both $X_c$ and $\alpha$ is necessary to predict either parameter, but as the DST13 model was able to predict $\alpha$ with significant skill, and without knowledge of $X_c$, this may not necessarily be the case. Fig. 6.7 reveals that seaward and landward lower beach contour positions that occur as the beach flattens (erodes) and steepens (accretes), are often associated with low and high three-dimensionality, respectively. This dependency may allow DST13 to predict $\alpha$ without explicit knowledge of $X_c$.

6.4.2 Effect of Varying Memory Decay Length, $\phi$, and Rate Term, $c$

Fig. 6.8 shows the effect of varying the value of $\phi$ on the performance and memory decay of the DST13 model at Perranporth. The peaks at $\phi = 67$ days and $\phi \geq 1000$ days reveal that the memory decay for the outer bar and lower beach are more than an order of magnitude different. Fig. 6.9 further demonstrates that over a single year the equilibrium condition varies greatly at the outer bar (storm-dominated
Figure (6.7). Measured vs modelled lower intertidal three-dimensionality, \( \alpha \), at Perranporth (PPT). The measured data were low-pass filtered and re-sampled at weekly intervals, and the DST13 model predictions were re-sampled at the same instances. The size and colour of the markers represents the alongshore averaged cross-shore position of the MLWN contour, \( X_c \), with larger markers and lighter colours showing more seaward positions. The dotted line shows a 1:1 relationship for reference.

timescale), but very little at the lower beach (seasonal response). The slight peak in model performance for the lower beach at \( \phi = 10 \) days indicates that a shorter response may also occur there, but data with a higher temporal resolution would be needed to investigate this further. Interestingly, the peak \( \phi \) value for the outer bar is associated with a drop in model skill at the lower beach (Fig. 6.8, left panel). This is likely to be due to the lagged behaviour of the outer bar, which was previously shown to reach peak values of \( \alpha \) up to 15 weeks after the lower beach (Section 5.3.2). Because high \( \alpha \) at the lower beach can occur alongside low \( \alpha \) at the outer bar (Fig. 5.15), a model suited to predicting one (i.e. with \( \phi = 67 \) days) is likely to perform poorly for the other. This lag also results in rate coefficients (\( c \)) with opposing signs at the outer bar and lower beach. As the outer bar becomes 3D weeks to months after annual peak wave conditions, the increase in \( \alpha \) coincides with positive \( \Delta \Omega \), yielding a positive \( c \) term. Conversely at the lower beach, three-dimensionality begins to increase immediately following the annual peak wave conditions while \( \Delta \Omega \) is decreasing but still negative, and therefore yields a negative \( c \) term.

Although the DST13 model performed less well at the lower beach at Porthtoawan compared to Perranporth, the two beaches share a common lower beach memory decay (\( \phi \)), and statistically indifferent rate coefficient (\( c \)). This suggests that the physical processes governing the lower beach region may be similar at both sites, and occur on the same time scales. The model did not make skillful predictions of
Figure (6.8). Left panel: Model sensitivity to the value of \( \phi \) for the outer bar (solid line) and lower beach (dashed line) at Perranporth beach. The \( \phi \) associated with the largest calibration \( R^2 \) was chosen as the optimal value for each data set, denoted as a cross (\( \phi = 67 \)) and an x (\( \phi = 1000 \)). Right panel: example of memory decay used to determine the weighted-average antecedent wave conditions for \( \phi = 67 \) (solid line) and \( \phi = 1000 \) (dashed line). Note the logarithmic x axis.

Figure (6.9). Time series of \( \Omega_{eq} \) over the period of interest for the outer bar (solid line) and lower beach (dashed line) at Perranporth beach.

three-dimensionality at the outer bar at Porthtowan, and this indicates that there is some process occurring at Porthtowan that the model cannot account for, such as strong headland circulation or other geological control. The reasonable predictions at Porthtowan’s lower beach provide some encouragement for the wider applicability of the model however.

6.4.3 Model Limitations and Improvements

Although processes are not explicitly modelled, DST13 assumes changes in three-dimensionality occur as a result of normal, open beach circulation. For example the model presently ignores the effects of alongshore oriented wave power, which idealised modelling (Ranasinghe et al., 2004, Splinter et al., 2011, Garnier et al., 2013, Price et al., 2013) and field studies (Holman et al., 2006, Thornton et al.,
2007, Price et al., 2011, 2013) have shown to be an important cause of sandbar straightening at some sites. It is proposed that this could be accounted for simply in the model by incorporating the absolute value of the alongshore component of wave power $|P_y|$, either as an additional model parameter at the cost of one extra regression term, or by incorporating it into forcing term $F$. When tested, this altered the model results very little due to the small contribution of obliquely incident waves at Perranporth, where alongshore-oriented power is typically an order of magnitude smaller than the total wave power. This modification was therefore not included in the present model, but provides a basis for further model development at sites with significant alongshore wave power.

As the degree of three-dimensionality at dissipative-intermediate sites such as Perranporth and Porthtowan is inversely related to $\Omega$ (Wright and Short, 1984), $\Omega_{eq}$ provides a suitable equilibrium value for three-dimensionality. However, beaches that transition from the Transverse Bar and Rip to Low Tide Terrace beach states and eventually to the Reflective end state, feature decreasing three-dimensionality as $\Omega$ decreases. Therefore in order to generalise the model to sites that feature intermediate-reflective beach states the model would need to be adapted, such that when $\Omega_{eq}$ exceeds an appropriate threshold, the sign of the disequilibrium is inverted. At that point, increases in $\Omega$ would appropriately change from driving an increase in $\alpha$ to driving a decrease in $\alpha$.

The improvements achieved at the outer bar by moderating the wave power based on the tidal range reflect the fact that significant sediment transport can only occur under sufficient wave breaking (Splinter et al., 2011). A large tide range reduces the water depth over the outer bar at low tide, and therefore increases breaking and sediment transport which enhances the rate of change in the bar. Conversely under neap tides, when water depth over the bar is large relative to the wave height, sediment transport (and therefore changes in the bar) can significantly reduce due to the lack of breaking. These processes may also explain the storm-dominated timescale of the outer bar response, as a previously inactive bar can rapidly change when larger storm waves break. Although the tidally modulated wave power term reduces the rate of morphological change under small tides and waves, completely reducing bar change to zero when the subtidal bar is inactive may yield further improvements.

6.4.4 Conclusions

A simple equilibrium model, DST13 (Davidson et al., 2010, 2013b,a), was developed and applied to the prediction of intertidal and subtidal beach three-dimensionality.
The model predicts increases or decreases in three-dimensionality by examining the difference between instantaneous wave conditions and a temporally varying equilibrium condition, based on a weighted average of antecedent waves. To suit the prediction of beach three-dimensionality, a new tidally modulated wave power term was integrated into the existing model to determine the rate of morphological change.

At Perranporth beach the DST13 model made skilful hindcast and calibration-validation predictions, explaining 42% and 61% of the hindcast variability in outer bar and lower beach three-dimensionality respectively. At the more geologically constrained site of Porthtowan the model performed less well, explaining 18% and 32% of the variability at the outer bar and lower beach respectively. The disparity in performance at the two sites is thought to be a result of open beach horizontal (bar-rip) circulation behaviour at Perranporth, which is well represented by the model, and geologically controlled headland circulation that occurs at Porthtowan, which is not represented in the model. Presently the main limitations of the model relate to the assumption that open beach, cross-shore processes, such as horizontal wave driven circulation control the morphodynamics. The model in its present form is also only suited to predicting three-dimensionality at dissipative-intermediate beaches, although a generalised form of the model is proposed that may widen its application to beaches that feature reflective states.

Negative feedback was found to be an important process governing the changes in beach three-dimensionality; while free morphological behaviour may drive three-dimensional growth, negative feedback processes exert stability in the system, making it inherently predictable using a temporally varying equilibrium approach as used here. In its present form the model outperformed a simple baseline model (a linear fit), as well as a comparable linearized feedback model from the literature (Plant et al., 2006), providing the first long term (multi-year) predictions of seasonal to inter-annual beach three-dimensionality at a macrotidal beach.
Chapter 7

Predicting the Effects of Wave Energy Extraction on Wave and Beach Conditions of Relevance to Water-Users

7.1 Introduction

7.1.1 Background

In Chapter 4 the wave conditions preferred by beach water-users in the lee of Wave Hub were quantified in a robust manner, accounting for differences in wave perception. The observations and model predictions in Chapters 5 and 6 revealed that three-dimensional beach morphology varies due to integrated cumulative disequilibrium between instantaneous and antecedent waves. With these results we can now explore how a wave climate that has been altered by energy extraction might influence both the preferred wave conditions for water-users and the key morphological parameter that determines the safety and amenity of the surf-zone for water-users.

In order to achieve this, a number of wave attenuation scenarios from the literature are considered in this chapter, and the effects of Frequency Dependent Extraction (FDE) are explored using theoretical Wave Energy Converter (WEC) Power Transfer Functions (PTFs).

7.1.2 Predicted Wave Height Attenuation

A number of studies have modelled the effects of wave energy extraction at Wave Hub on inshore wave conditions at the coast (Millar et al., 2007, Black, 2007, Li and Phillips, 2010, Smith et al., 2012, including). Rather than repeating these efforts,
the level of wave attenuation that has previously been predicted is considered in this Chapter. The level of attenuation varies between the studies, depending on the boundary conditions applied and the way in which energy extraction is modelled. Surprisingly few commonalities in the approach to modelling Wave Hub exist. However, three of the studies (Millar et al., 2007, Li and Phillips, 2010, Smith et al., 2012) simulated a scenario where the Wave Hub array has a 70% energy transmission coefficient (30% of energy at each frequency is captured, 70% is transmitted through the devices), as it represents the upper limit of the energy capture that is thought to be possible (Li and Phillips, 2010, Smith et al., 2012).

Narrow banded swell is predicted to incur the greatest impact from a WEC array, as the typically narrow directional spread of such sea states inhibits the regeneration of waves in the lee of the WEC array (Black, 2007, Smith et al., 2012, O’Dea and Haller, 2014). Under a 70% transmission scenario, the maximum predicted reduction in nearshore $H_s$ at Perranporth beach during swell conditions varies between 0.4% (Smith et al., 2012), 4.93% (Millar et al., 2007), and up to 13% (Li and Phillips, 2010), depending on the amount of directional spreading applied in each study. Windsea, bimodal, or other spectral cases were predicted to incur smaller changes (< 5%) due to their increased directional spread. The lowest and highest predicted swell attenuation (0.4% and 13%, respectively) are used in the present study to provide a realistic range of attenuation at the coast under a 70% transmission scenario, regardless of sea state. In reality the attenuation is likely to be lower during non-swell conditions and will vary dynamically with the spectral shape and directional spread of the sea state, but this simplification provides a conservative estimate to use in the present study.

### 7.1.3 Extreme Wave Attenuation Scenario

An extreme case of 100% energy capture at Wave Hub is also investigated. This scenario is not considered possible in reality, but provides context by which to compare the other more realistic impacts. Black (2007) conducted a theoretical study into wave shadowing effects from Wave Hub, and ran a model scenario using a 0% transmission coefficient. While the actual bathymetry at the site was not considered, an estimate of the wave height attenuation at the coast was provided by examining wave conditions at a distance equivalent to that between Wave Hub and Perranporth. For narrow banded, narrowly spread swell conditions Black (2007) predicted that $H_s$ could be reduced by as much as 30% at the coast, and this value is applied in the present Chapter as an extreme attenuation scenario.
7.1.4 Simulating Frequency Dependent Extraction

For comparability the previously mentioned attenuation values were taken from simulations where a constant transmission coefficient was applied at Wave Hub, and they therefore do not account for the effects of FDE. Smith et al. (2012) previously modelled FDE at Wave Hub using Gaussian shaped PTFs and predicted that when FDE is considered, the far field effects of WECs are significantly reduced compared to a case with a flat impact across all frequencies (i.e. using a constant transmission coefficient). Wave heights were shown to be least affected when the peak frequency of the incident wave field is outside the efficient operating range of the WEC, or in other words when the PTF and wave spectrum are not aligned. In this Chapter the influence of FDE is therefore investigated by altering the level of inshore wave attenuation based on the separation between the incident wave spectrum peak, \( T_p \), and a hypothetical WEC PTF peak, \( T_{PTF} \).

However, for cases where the peak of the wave spectrum and the PTF are aligned, Smith et al. predicted that the coastal wave attenuation will be greater, and will only be negligibly different to a frequency independent case (0.3% reduction in \( H_s \) compared to 0.4%, respectively). In addition they found that the width of the PTF no longer had a significant effect on the shape of the wave spectrum or level of attenuation once the waves had propagated more than 20 km past the WEC array (Smith et al., 2012). It is therefore assumed here that the shape of the PTF at Wave Hub has no effect on the shape of the wave spectrum at Perranporth beach due to their 35 km separation, and that the level of coastal attenuation is considered equal to that predicted in the frequency independent cases described earlier, when the peaks of the wave spectrum and PTF are aligned.

7.1.5 Aims

This Chapter aims to explore the degree to which wave conditions and beach morphology relevant to water-users may be affected by hypothetical wave climates that have been altered by energy extraction. Realistic and extreme energy extraction scenarios at Wave Hub will be explored, by varying both the maximum efficiency of wave energy capture, and the spread of impacts over the incident frequency range.
7.2 Methodology

7.2.1 Research Approach

As with Chapters 4 to 6 of this thesis, a quantitative research approach and post-positivist paradigm (described in Section 4.2.1) is employed in this chapter, as the data involved is highly quantitative.

7.2.2 Frequency-Impact Scenarios

To generate time series of altered wave data, three peak levels of wave height attenuation, $\delta$, at the coast were considered: $H_s$ reduced by 0.5% (rounded up from the prediction of Smith et al. (2012)), $H_s$ reduced by 13% (from the prediction of Li and Phillips (2010)), and $H_s$ reduced by 30% (from the theoretical prediction made by Black (2007)). The first two attenuation levels provide a range of realistic impacts under a 70% transmission scenario, while the last attenuation level provides an extreme, unrealistic scenario for comparison. Each of these predicted impacts relates to nearshore conditions prior to breaking and will therefore be applied to the Perranporth wave buoy data, at a depth of approximately 14 m. For each attenuation level three frequency-impact scenarios were considered. Firstly a `flat’ reduction of all daily-averaged $H_s$ values by each percentage was applied. In these scenarios FDE is ignored, and energy is therefore assumed to be captured evenly at all wave frequencies. For the next two frequency-impact scenarios the effects of FDE were mimicked by varying the percentage reduction in $H_s$ depending on the concurrent (daily-averaged) value of $T_p$. A wide Gaussian curve and a narrow Gaussian curve are used in these scenarios to simulate a wide or narrow range of wave frequencies being affected by Wave Hub, respectively.

As mentioned in Section 2.2.2 the optimal peak period for a WEC PTF ($T_{PTF}$) is usually considered to be the long-term mean energy period, $T_e$ (Mollison, 1994, Black, 2007, Lenee-Bhuhm et al., 2011, O’Dea and Haller, 2014), calculated from wave spectra with Eqs. 2.1 and 2.2. For a given sea state $T_e$ is the mean period in the spectral distribution of energy (Mollison, 1994), and represents the period of a monochromatic wave containing the equivalent energy as the real sea state in question (Carbon Trust, 2005). $T_e$ was calculated for each half-hourly wave spectrum from 7 years of nearshore wave buoy data at Perranporth (collected in approximately 14 m depth; Section 5.2.5); a histogram of the occurrence of $T_e$ is shown in Fig. 7.1, with the long term mean $T_e$ indicated with a dashed line.

It is assumed for the purposes of this study that $T_e$ measured at the coast represents the inshore wave frequency most affected by Wave Hub, and $T_{PTF}$ was
Figure (7.1). Left panel: Frequency histogram of energy period, $T_e$, from 7 years of half-hourly nearshore wave buoy data at Perranporth. Right panel: Mean energy (variance) spectrum from the same data. The vertical dashed lines indicate the mean energy period used in this study as a hypothetical PTF peak, $T_{PTF} = 8.09$ s (0.12 Hz). For comparison the mean peak period, $T_p = 9.41$ s (0.11 Hz), is plotted in the right panel as a dot-dashed line.

Therefore set at 8.09 s. When the peak incident wave period is equal to $T_{PTF}$ (i.e. the hypothetical PTF and wave spectrum are aligned) $H_s$ is reduced by the maximum amount. For wave conditions where $T_p$ is increasingly separated from $T_{PTF}$, $H_s$ is decreasingly affected. Gaussian curves were used to approximate the change in attenuation as the distance between $T_p$ and $T_{PTF}$ increases, therefore simulating varying degrees of overlap between the hypothetical PTF and incident wave spectra. It should be noted that while the PTF peak ($T_{PTF}$) can be considered a realistic estimate, the Gaussian curves are not used here to describe the WEC extraction efficiency at different frequencies, as a PTF would. Instead they are used to simulate the change in inshore wave height with frequency, and are therefore referred to as frequency-impact curves rather than PTFs.

The Gaussian or normal probability density function is calculated as:

$$y(T_p, \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(T_p-\mu)^2}{2\sigma^2}}$$  \hspace{1cm} (7.1)

where $y$ is the relative impact for a given peak wave period ($T_p$). $\mu$ is the central period of the distribution and is therefore set to the target frequency ($T_{PTF}$) of 8.09 s. $\sigma$ is the standard deviation of the distribution and allows the width of the Gaussian curve to be varied, therefore changing the spread of impacts across the frequency range. $\sigma$ was set at 0.5 and 5 to generate impact curves that affect a narrow and wide portion of the incident frequency range respectively. For each peak attenuation level ($\delta$) and width ($\sigma$) a Gaussian curve was generated by calculating values of $y$ for $T_p = 1 - 30$ s, then normalising $y$ by $\delta$ (Fig. 7.2). To generate altered
wave data for each frequency-impact scenario, each daily-averaged measurement of $H_s$ from the Perranporth wave buoy was reduced by a given percentage ($y$). This was determined from the Gaussian impact curves in Fig. 7.2 by looking up the $y$ value associated with the $T_p$ on that day. Despite altering $H_s$ in this way, $T_p$ was not adjusted as it is assumed that the shape of the inshore wave spectrum is unaffected.

7.2.3 Predicting Changes to Wave and Beach Conditions of Relevance to Water-Users

Nine different time series of altered wave heights were generated using combinations of the three peak attenuation levels and the three frequency-impact scenarios previously described. The parameters used to generate these nine scenarios are summarised in Table 7.1, and a sample of the altered wave data is plotted in Fig. 7.3. Each altered time series of $H_s$ at the Perranporth wave buoy was used to calculate significant breaking wave height, $H_{s,b}$, as described in Section 4.2.6. The wave data used in this study therefore consists of time series of altered daily-average $H_{s,b}$ and unaltered daily-average $T_p$. To investigate how the altered wave climates might affect beach water-users, the joint probability of $H_{s,b}$ and $T_p$ being within the range of preferred values for each water-user group (all water-users, novices, experienced water-users, experts, surfers, other activities, males and females) on any given day was calculated. These probabilities were compared to the joint probability from the measured (unaltered) time series, to determine the change in occurrence of preferred wave conditions under each wave energy extraction scenario. As there is < 5% difference between $T_{1/3}$ and $T_p$ (Goda, 1978, 1988), the preferred $T_{1/3}$ values from Chapter 4 were assumed equal to $T_p$ in this study.

The altered wave time series were also used to calculate deep water wave power, $P_o$, and dimensionless fall velocity, $\Omega$ from Eqs. 5.2 and 2.3, providing the required inputs to drive the DST13 three-dimensional beach morphology model described in Chapter 6. Changes in beach three-dimensionality ($\alpha$) were then investigated by comparing predictions of $\alpha$ with the model driven by the altered and unaltered wave time series. The model was built using the regression parameters obtained from the hindcast model fit described in Section 6.3.1. The model free parameters were held constant, while the input wave conditions were varied according to the nine extraction scenarios. The $r$ parameter, which determines the ratio of positive to negative forcing, was recalculated for each of the altered wave climates, as it is dependent on the incident wave conditions. Given that the model performs significantly better at Perranporth than at Porthtowan, only impacts to beach three-dimensionality at Perranporth are investigated in this chapter.
Table (7.1). Parameters used to generate the nine altered wave scenarios. The width and peak value of the Gaussian frequency-impact curves were determined by $\sigma$ and $\delta$, respectively. Frequency independent (flat) scenarios are indicated as having infinite ($\infty$) $\sigma$.

<table>
<thead>
<tr>
<th>Level of Impact</th>
<th>Narrow</th>
<th>Wide</th>
<th>Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$\sigma = 0.5, \delta = 0.5$</td>
<td>$\sigma = 5, \delta = 0.5$</td>
<td>$\sigma = \infty, \delta = 0.5$</td>
</tr>
<tr>
<td>High</td>
<td>$\sigma = 0.5, \delta = 13$</td>
<td>$\sigma = 5, \delta = 13$</td>
<td>$\sigma = \infty, \delta = 13$</td>
</tr>
<tr>
<td>Extreme</td>
<td>$\sigma = 0.5, \delta = 30$</td>
<td>$\sigma = 5, \delta = 30$</td>
<td>$\sigma = \infty, \delta = 30$</td>
</tr>
</tbody>
</table>

Figure (7.2). The nine Gaussian frequency-impact scenarios used to alter the inshore wave climate, each with a target period of $T_e = 8.09$ s. The blue (bottom) and magenta (middle) lines show a range of realistic frequency-impacts that may occur under a 70% transmission scenario at Wave Hub. The red (upper) lines show extreme frequency-impact scenarios, with 100% energy extraction and narrow directional spreading of incident waves.
Figure (7.3). Example time series of daily-average peak period ($T_p$, panel (a)), inshore significant wave height ($H_s$) attenuation percentage ($\delta$, panel (b)) determined from $T_p$, and the resulting attenuated breaking wave heights ($H_{s,b}$, panel (c)). This example shows two months of data from January to February in 2012. The nine frequency impact scenarios are shown with dotted, dashed and solid lines in panels (b) and (c). The dashed line in panel (a) shows the target period ($T_{PTF}$) of 8.09 s; when $T_p$ approaches this value the maximum attenuation occurs in the dotted and dashed scenarios in panels (b) and (c).
Figure (7.4). Joint probability of significant wave height at breaking, $H_{s,b}$, and peak period, $T_p$, between 2007 and 2014. Data were measured at the Perranporth wave buoy in approximately 14 m water depth, and transformed to breaking height with linear theory.

7.3 Results

7.3.1 Altered Wave Climates

Fig. 7.4 shows the joint probability of $H_{s,b}$ and $T_p$ at Perranporth beach, where the most frequently occurring wave conditions have $T_p$ and $H_{s,b}$ of approximately 11 s and 1.5 m, respectively. Fig. 7.5 demonstrates how the joint probability distribution changes under each of the nine extraction scenarios considered. As would be expected, increasing the frequency width (moving from left to right panels) increases the range of wave periods that are affected, while increasing the attenuation level (moving from top to bottom panels) increases the magnitude of the change in probability. The plots demonstrate that the attenuation decreases the probability of larger wave heights (blue), while the probability of smaller wave heights increases (red). For the wide and flat frequency-impact scenarios the greatest changes in probability occur between $8 \text{ s} < T_p < 12 \text{ s}$ (Fig. 7.5, middle and right panels), as this range covers the targeted and most frequently occurring wave periods (Fig. 7.4). The narrow frequency-impact (Fig. 7.5, left panels) only affects those periods directly around the target period (8.09 s), and there is no change in probability to waves with $7 \text{ s} > T_p > 11 \text{ s}$. 


Figure (7.5). Change in the joint probability of $H_{s,b}$ and $T_p$ for the nine altered wave cases. Blue represents a reduction in probability, while red represents an increase in probability. The panels show from left to right the narrow, wide and flat frequency-impacts and from top to bottom the low, high and extreme attenuation levels, respectively.

7.3.2 Predicting Changes to Preferred Wave Conditions for Water-Users

Figs. 7.6a and 7.6b, show the range of breaking wave heights and periods preferred by each of the studied water-user groups (from Section 4.3.8). As was previously described, these were calculated as the mean stated wave preferences of each group, adjusted to represent measured conditions using the mean perception ratios for each group, plus or minus the standard deviation in the adjusted preferences. Fig. 7.6c shows the measured (unaltered) joint probability of these preferred conditions occurring. After applying the wave attenuation scenarios to the measured data, the occurrence of preferred conditions either increased or decreased depending on the water-user group’s preferences (Fig. 7.6d). For example, the occurrence of wave conditions preferred by male or expert water-users decreased under all of the scenarios considered, whereas the occurrence of wave conditions preferred by women increased in every scenario. For other groups however, the occurrence of preferred wave conditions increased in some scenarios while decreasing in other scenarios.
Both the percentage attenuation and the width of the impact curve also have distinct effects on the occurrence of preferred wave conditions (Fig. 7.6d). For instance, the scenario of 13% wave height attenuation with a flat frequency-impact (solid magenta line) on average increased the occurrence of preferred conditions for the ‘all water-users’ group, whereas the same attenuation applied with a wide Gaussian impact curve (dashed magenta line) caused a reduction in occurrence of preferred waves for that group. The latter scenario (13% attenuation, wide impact curve - dashed magenta line) can be considered a realistic worst-case scenario, and will be examined as a test case. The water-user groups that would on average benefit from such a scenario are novices, surfers, non-surfers, and females, as the occurrence of preferred wave height and period would increase by up to 4%. Conversely, experienced, expert, and male water-users, would on average experience a decrease in the occurrence of preferred wave conditions by up to 1%. When considered as one group, the entire sample of water-users would experience a decrease in preferred conditions of < 0.5%.

To objectively judge whether these changes are significant (in a practical sense), they are compared in Fig. 7.6d to the natural variability in the wave climate. Changes can be considered significant if they are larger than one standard deviation of the annually measured joint probability of preferred $H_{s,b}$ and $T_{1/3}$, as this indicates the change would be greater than the average natural variability in the wave climate. It is clear for all the attenuation levels, including the extreme attenuation case, that the change in occurrence of preferred wave conditions at the coast due to Wave Hub is less than the natural variability in occurrence, and is therefore not significant.

### 7.3.3 Predicting Changes to Three-Dimensional Beach Morphology

Figs. 7.7 and 7.8 show the DST13 beach three-dimensionality model predictions for Perranporth’s outer bar and lower beach respectively. In many cases the most apparent effect of the realistic wave attenuation range (red filled area) as well as the extreme attenuation level (red dashed line) is to increase the three-dimensionality ($\alpha$) of the outer bar and lower beach compared to the predictions driven by unaltered waves (black solid line). There are instances where $\alpha$ is decreased by the wave attenuation however, such as between 2012 and 2014 in the Gaussian impact cases for the lower beach (Figs. 7.8b and 7.8c). The overall effect of the attenuation is to reduce the variability in $\alpha$. Additionally, the variability was reduced more under the wide and flat frequency-impact scenarios, compared to the narrow frequency-impact scenario. As may be expected, the realistic attenuation range had a smaller
Figure (7.6). Change in the occurrence of preferred $H_{s,b}$ and $T_{1/3}$ for different water user groups under the nine extraction scenarios. Panels (a) and (b) show the range of preferred $H_{s,b}$ and $T_{1/3}$ respectively for each group. Panel (c) shows the measured joint probability of these conditions occurring (points), plus or minus the inter-annual standard deviation in the probability, indicating the natural variability (bars). Panel (d) shows how the occurrence of preferred conditions changes under each of the nine extraction scenarios (lines), compared to the natural variability (filled area).
effect than the extreme attenuation case, however changing the attenuation level did not alter the direction of the change (less 3D rather than more 3D or vice versa). Considering FDE did affect the direction of the change however, notably at the lower beach between 2012 and 2014 where the wide and narrow frequency-impacts reduced $\alpha$ (Figs. 7.8b and 7.8c), and the frequency independent case increased $\alpha$ (Fig. 7.8a).

To indicate how significant these changes are in a practical sense, the predicted changes in $\alpha$ from the different extraction scenarios are compared to the natural variability in $\alpha$, shown as the grey filled area in Figs. 7.7 and 7.8. The natural variability was computed as $\alpha$ predicted by the model using the unaltered wave data, ± the standard deviation in $\alpha$ calculated for each month of the year, across all years of data. Wave Hub induced changes in $\alpha$ that fall outside this range can be considered significant, as the change in $\alpha$ caused by the wave attenuation would be larger in magnitude than the predicted natural variation. For the realistic attenuation range, as well as the wide and narrow frequency-impact scenarios, the modelled changes caused by Wave Hub can be considered insignificant as they fall within one standard deviation of the unaltered prediction. Only under the extreme attenuation case, and with frequency independent extraction, do the changes in outer bar and lower beach $\alpha$ exceed the natural variation (Figs. 7.7a and 7.8a).

7.4 Discussion

7.4.1 Changes to Preferred Wave Conditions

Under the modelled extraction scenarios the occurrence of preferred wave conditions either increased or decreased depending on the attenuation level, the frequency-impact curve, and the conditions preferred by each water-user group. In some cases the probability of preferred waves increased as the wave attenuation reduced wave heights to within the preferred range. In other cases the probability of preferred waves decreased as the attenuation reduced wave heights below the preferred range. The impact that Wave Hub is likely to have on preferred wave conditions is therefore complex and varies from one water-user group to another. There will not necessarily be a net negative effect on preferred conditions at any level of energy extraction, as was perhaps assumed by the collective of surfers who opposed the initial proposal. Instead, whether the effects of wave attenuation are positive or negative depends on the preferred conditions of each water-user group.

Assuming that frequency dependent extraction is likely to occur in reality, drawing conclusions from frequency independent scenarios such as those modelled by
Figure (7.7). DST13 model predictions of alongshore variability at Perranporth’s (PPT) outer bar driven by measured waves (solid line) and attenuated waves (dashed line and red filled area). Frequency independent extraction (constant $H_s$ reduction at all frequencies) is shown in panel (a), and frequency dependent extraction using wide and narrow Gaussian impact curves is shown in panels (b) and (c) respectively. The natural variability is shown as a grey filled area, and was computed as the unaltered model predictions ± the standard deviation from each month.
Figure (7.8). DST13 model predictions of alongshore variability at Perranporth’s (PPT) lower beach driven by measured waves (solid line) and attenuated waves (dashed line and red filled area). Frequency independent extraction (constant $H_s$ reduction at all frequencies) is shown in panel (a), and frequency dependent extraction using wide and narrow Gaussian impact curves is shown in panels (b) and (c) respectively. The natural variability is shown as a grey filled area, and was computed as the unaltered model predictions $\pm$ the standard deviation from each month.
Millar et al. (2007), Black (2007), and Li and Phillips (2010), would wrongly predict whether preferred wave conditions were increased or decreased in many cases. Importantly however, the predicted increases and decreases in the occurrence of preferred waves were found to be within one standard deviation of the natural variation in occurrence and can all therefore be considered insignificant as the changes would be smaller than the average variation that occurs naturally. In practical terms water-users would therefore not notice any change in the occurrence of their preferred wave conditions under realistic or extreme extraction scenarios at Wave Hub.

7.4.2 Changes to Three-Dimensional Beach Morphology

The reduction in the variability of beach three-dimensionality ($\alpha$) under the different wave extraction scenarios can be attributed to the fact that wave height attenuation reduces wave power ($P$), as well as reducing the magnitude and variability in the dimensionless fall velocity ($\Omega$). As the rate of change in $\alpha$ is influenced by these variables in the DST13 model, reducing wave power and disequilibrium therefore reduces the rate at which $\alpha$ changes. The reduced variability in $\alpha$ is therefore a result of the beach responding slower due to less powerful and less varied wave conditions. The predominant increases in $\alpha$ predicted under the modelled extraction scenarios is indicative of the beach becoming less dissipative and more intermediate, as three-dimensionality increases between the dissipative and intermediate states (Wright and Short, 1984, Ranasinghe et al., 2004). This is also indicated by the mean value of $\Omega$, which decreases from 4.8 in the unaltered wave climate down to as little as 3.6 in the extreme attenuation, flat frequency-impact scenario, suggesting a move towards more 3D, intermediate beach states, as was predicted by Poate (2011) and discussed in Section 2.4.4.

Although a less variable and in most cases more 3D beach is predicted by the model, the changes can be considered insignificant, and will not therefore alter the overall safety or amenity of the surf-zone for beach water-users. For the realistic wave height attenuation range (0.5% - 13% reduction in coastal $H_s$), the predicted change in $\alpha$ is smaller in magnitude than the natural variability (one standard deviation) in $\alpha$. Even under the extreme case of 30% coastal wave height attenuation, which is predicted under 100% energy extraction at Wave Hub (Black, 2007), the predicted changes in $\alpha$ only occasionally exceed the natural variability, and only when FDE is ignored. This further demonstrates that FDE must be considered when modelling the effects of wave energy extraction, as if FDE had been ignored in this study, different conclusions about the effects of extreme energy extraction would have been
7.5 Conclusions

To investigate the effect that Wave Hub might have on wave conditions and beach morphology of relevance to beach water-users a number of altered wave climates have been considered. These were generated by reducing measured inshore wave heights by given percentages, determined in previous wave modelling studies from the literature. To consider the effect that frequency dependent wave energy extraction might have, the percentage wave attenuation was reduced from its maximum value at the ‘target’ peak wave period of 8.09 s (determined from the time series mean energy period, $T_e$), to zero at wave periods far removed from the target period. Gaussian curves were used to approximate this effect, and allowed for exploration of different variations of impact over the frequency range.

The attenuation of wave heights decreased the probability of large waves occurring, while increasing the probability of smaller waves occurring. Under the modelled extraction scenarios the wave conditions preferred by each of the studied water user groups from Chapter 4 either increased or decreased in probability, depending on the attenuation level, the width of the Gaussian frequency-impact curve, and the conditions preferred by each group. None of the scenarios had a universally positive or negative effect on the probability of preferred conditions. Regardless of the attenuation level, frequency-impact, or preferences, the predicted changes in the occurrence of preferred waves were all smaller in magnitude than the natural variability (one standard deviation) in the wave conditions, and are therefore considered to be insignificant. In practical terms this means that water-users are unlikely to notice any change in the occurrence of their preferred wave conditions under realistic or extreme extraction scenarios at Wave Hub.

The attenuated wave climates were then used to drive the DST13 beach three-dimensionality model described in Chapter 5, to investigate the effect of Wave Hub on 3D morphology at Perranporth beach. The dominant effect was to reduce the variability in the three-dimensionality of the beach. As the realistic wave height attenuation range caused changes that were within the natural variability (one standard deviation) in beach three-dimensionality, the predicted changes are considered to be insignificant.

The inshore wave attenuation from Wave Hub that has been predicted in the literature is therefore likely to have an insignificant effect on wave conditions and beach morphology of relevance to beach water-users. Even an extreme and unrealistic level of wave energy extraction (100% energy capture) was shown to have an insignificant
effect on the occurrence of preferred waves, and only under a frequency independent extraction scenario did this level of attenuation have a significant effect on beach three-dimensionality. Frequency Dependent Extraction therefore significantly affected the results of this investigation. Although disregarded in some previous wave modelling studies, and never before considered in terms of its effect on beach morphology, Frequency Dependent Extraction will be an essential consideration in future studies of coastal impacts from wave energy extraction.
8.1 Introduction

The overarching aim of this thesis (identified in Section 1.2.1) was to investigate the interaction between wave conditions, beach morphology, and beach water-users, and to propose how a wave climate altered by wave energy extraction is likely to alter these interactions. Each chapter sought to tackle the specific objectives listed below that were set out in the introduction to achieve this aim, and a number of new insights were achieved:

1. **Investigate the concerns of beach water-users with regards to potential coastal impacts from wave energy extraction** - In Chapter 3 a new conceptual model was developed describing the way that water-users construct their opinions on marine renewables and their potential coastal impacts through a weigh-off between their perceptions of the technology and the natural environment.

2. **Determine how different beach water-user groups perceive and use the surf-zone environment** - In Chapter 4 the characteristics of the population of water-users in the lee of Wave Hub were studied. Comparison of visual wave observations to wave buoy measurements revealed common wave perceptions; using these, stated wave preferences were adjusted to determine, for the first time, the range of wave conditions most valued by different water-user groups.

3. **Investigate how beach morphology of relevance to water-users varies in response to changes in wave climate** - In Chapter 5 three key hydrodynamic parameters (dimensionless fall velocity, wave power, and relative tide range) were found to explain the majority of variance in beach three-dimensionality - a parameter that has a major influence on the safety and
amenity of the surf zone. From this, a model that compares instantaneous and antecedent wave conditions was developed in Chapter 6 and used to make the first multi-year predictions of three-dimensionality at a macrotidal beach.

4. Predict changes to waves and beach morphology of relevance to water-users under different wave energy extraction scenarios - In Chapter 7 realistic and extreme levels of coastal wave attenuation, with varying impacts across the incident wave frequencies, were used to predict the effects of wave energy extraction on preferred wave conditions, and three-dimensional beach morphology.

The aim of this chapter is to synthesise the findings from this thesis in order to provide an overall picture of how wave energy extraction may alter waves and beach morphology of relevance to beach water-users. Many of the findings described are specific to the Wave Hub case study, but where possible the methods and findings are generalised in this chapter to inform future research at other sites. Fig. 8.1 combines the findings from this thesis in a conceptual model. The centre of the model describes the natural interactions that have been observed between wave conditions, beach morphology and water-users. Outside the central circle the effects of wave energy extraction on the various interactions are shown. On the right hand side of the model the predicted effects on beach water-users are shown, and the predicted significance of these impacts (in the context of Wave Hub) is depicted by the colour of the filled areas around the impacts. The perception of wave energy extraction by water-users is shown as an output of the system on the right hand side, as this may influence the acceptability and successful proposal of future wave energy sites.

Although the findings relate to the Wave Hub case study, the conceptual model can be considered applicable to the main Atlantic facing surf beaches in SW England, South Wales and the West coast of France, as these sites feature dissipative-intermediate beach morphology (Castelle et al., 2007, Scott et al., 2011), have a similar wave climate, and as a result are likely to have a similar activity demographic as that found in North Cornwall. Although the morphological findings are only applicable to dissipative-intermediate beaches with a similar geological setting to Perranporth and Porthtowan, the opinions, perceptions, and preferences of the studied beach water-user groups may have a wider applicability to all high-energy coastlines. Sections 8.3 to 8.6.3 describe the interactions and synthesised findings in more detail.
8.2 Disciplinary Context

As the aims of this thesis raised both physical and sociological research questions, the findings of the thesis are essentially multidisciplinary. Although the research was designed and conducted without imposing the restrictions of a single particular discipline, it’s aims and findings undeniably fit within the disciplinary context of Integrated Coastal Zone Management (ICZM). ICZM is interdisciplinary in it’s nature and aims to identify and work with coastal stakeholders, of all varieties, to avoid conflicts and ultimately to achieve sustainable development of the coast (Krishnamurthy et al., 2008).

This ethos is broken into three main dimensions by Scura et al. (1992); these are management issues, management processes, and management actions. The ‘issue’ in this context is the competing use of the wave resource between wave energy developers and beach water-users, as well as potential impacts on coastal safety and wave amenity. This thesis provides a number of findings and methods that may now feed into future management ‘processes’ and ‘actions’, which will involve planning, implementation, and monitoring (Thia-Eng, 1993) to remedy the issues surrounding wave energy extraction. The findings that are most relevant to planning, implementation, and monitoring are summarised in the conceptual model in Fig. 8.1, and are described in more detail in Sections 8.3 to 8.6.3.

Fig. 8.1 is useful to ICZM as it synthesises the issues under discussion in an integrated model, but also demonstrates the potential significance of the issues in the case of Wave Hub. Understanding the significance of the potential effects of wave energy extraction is key to planning and implementing future interactions with stakeholders. It also points to specific wave and beach conditions (e.g. waves of 9 - 20 s period and highly 3D beach morphology) that require monitoring in order to manage the issue under question.

8.3 Potential Impacts to Preferred Wave Conditions

In Chapter 4 the characteristics of the population of water-users in the lee of Wave Hub were investigated. The wave preferences of different groups of water-users (novice, experienced, and expert water-users; surfers and other activities; males and females) were studied and compared for the first time anywhere in the world. This allowed for the occurrence of preferred wave conditions to be determined, and changes to this occurrence resulting from wave energy extraction were predicted in Chapter 7. In the context of Wave Hub it was predicted that a universally negative effect on waves preferred by water-users was unlikely to occur, even under an extreme
and unrealistic level of coastal wave attenuation.

This is due to the fact that although water-users were found to share a common preference towards wave periods of 9 - 20 s, different water-user groups were found to have different ranges of preferred wave height. This means that attenuation of breaking wave heights caused by wave energy extraction will actually benefit those groups that prefer smaller waves, and will disadvantage those groups that prefer larger waves. For example, under any of the wave attenuation scenarios examined in Chapter 7, expert water-users will experience a decrease in the occurrence of preferred wave conditions, while female water-users will experience an increase in the occurrence of preferred waves. Female expert water-users have not been studied in isolation, so it is unclear whether they would experience an increase or decrease. Finding that wave energy extraction could potentially benefit some water-user groups has not previously been reported, as prior predictions made by Millar et al. (2007) and Li and Phillips (2010) did not consider which wave conditions were preferred by water-users.

In the Wave Hub extraction scenarios modelled in Chapter 7, none of the scenarios (realistic or extreme) were predicted to cause a change in the occurrence of preferred waves that would be noticeable to water-users amongst the far larger natural fluctuations in the occurrence of preferred waves. Essentially this means that any increase or decrease in the occurrence of preferred wave conditions would be balanced (or even dwarfed) by opposing changes that occur naturally. Of course there may be a year when preferred waves naturally occur less than average; then wave energy extraction may cause a further decrease in their occurrence. Based on the predictions this could result in up to a further 1% reduction, or approximately 3 days less in a year, of preferred waves occurring in a ‘realistic’ worst-case scenario at Wave Hub (for expert water-users and a wide Gaussian frequency impact with a maximum inshore wave height attenuation of 13%). This would however be compensated by much larger, naturally occurring increases in preferred wave occurrence in other years. This highlights a limitation of using the natural variability (standard deviation) to determine whether an impact will be practically significant, as natural variability causes increases and decreases in wave occurrence, while wave attenuation is likely to cause a systematic offset in the occurrence. Further research may seek to determine what an acceptable change in the occurrence of preferred wave conditions would constitute for different water-users, which would improve the definition of a ‘significant’ impact.

In terms of the potential impact that such changes in wave conditions might have on surf tourism and more generally on beach user behaviour in the lee of Wave Hub, it is likely that if the changes are unnoticeable as predicted, then beach user behaviour
should not change as a result. There should therefore be no economic implications related to beach water-users under any of the modelled scenarios. However, it could be argued that the perceived effects of Wave Hub are far more important than any changes that actually happen in reality. From the findings in chapter 3, these perceptions are likely to depend heavily on how the media or other communicators depict the devices that are to be installed at Wave Hub. Therefore the insignificant predicted changes, and especially the potential increases in preferred waves for certain water-user groups should be conveyed to water-users before deployment at Wave Hub to avoid any unnecessary detriment to the local economy, or even boost income from certain groups such as novices and females. Furthermore, the measured effects (post-deployment) should be communicated to the public to prevent potentially inaccurate perceptions of coastal impacts from developing.

8.4 Potential Impacts to Three-Dimensional Beach Morphology

Previous research indicates that 3D morphology is the primary controller of surf-zone hazard, and also strongly influences the quality of surfing waves at the coast (Mead and Black, 2001b,a, Scott et al., 2008, Scarfe et al., 2009, Scott et al., 2011, MacMahan et al., 2011, Brighton et al., 2013). Highly 3D morphology, that was observed in Chapter 5 to occur predominantly in spring and summer at beaches in the lee of Wave Hub, causes strong rip current flows (Scott et al., 2008) and enhanced breaking wave quality (Mead and Black, 2001b,a, Scarfe et al., 2009). Conversely, 2D beach morphology that is common in winter will have little in the way of rip hazards or bathymetric features to enhance wave breaking. Throughout this thesis the degree of three-dimensionality, parameterised using the standard deviation of the barlines and topographic contours, has been used as a proxy for beach safety and amenity and is considered the primary morphological parameter of relevance to beach water-users.

Integrated, cumulative fluctuations in the wave conditions that occur over seasonal time scales were shown in Chapter 5 to be well correlated to seasonal fluctuations in beach three-dimensionality. In particular, wave steepness (represented in the dimensionless fall velocity parameter, $\Omega$), wave power ($P$) and relative tide range (RTR), explained a significant amount of the variance in beach three-dimensionality when represented as cumulative integral parameters. 3D morphology was well related to a disequilibrium term that examines the disparity between instantaneous and weighted-average antecedent wave conditions. This indicates that periods of
wave regime change between erosive winter conditions (with steep waves) and accre- 
tive summer conditions (with low steepness waves) are related to the growth of 3D 
features, and vice versa, while extended periods with similar wave conditions drive 
the beach towards equilibrium.

This results in significant annual periodicity in the barline three-dimensionality, 
where the lowest and highest three-dimensionality occur in winter and spring, re-
spectively. Interestingly the lower intertidal beach systematically developed three-
dimensionality 1 - 4 months before the outer bar. While the opposite behaviour 
has been observed at other sites before (Almar et al., 2010, Castelle et al., 2015), 
three-dimensionality has never before been observed to develop in this sequence. 
This raises questions over the instigation of bed-surf coupling between the intertidal 
and subtidal regions, and may be due to tidally induced periods of inactivity at the 
outer bar slowing the growth of 3D features compared to the intertidal region.

The disequilibrium approach complements the contemporary process-based the-
ory that bed-surf coupling drives 3D growth through feedback between the morphol-
ogy and hydrodynamic flows (Falqués et al., 2000, Caballeria et al., 2002, 2003a,b, 
Ranasinghe et al., 2004). It also captures the so called ‘negative feedback’ which has 
previously been observed in modelling (Smit et al., 2008a) and field data (Plant et al., 
2006) to curtail bed-surf growth and lead to equilibrium, making the system deter-
ministic. By capturing the effects of these two processes, the disequilibrium term 
is able to predict seasonal changes in three-dimensionality in a behavioural sense. 
A beach three-dimensionality model (‘DST13’) was developed in Chapter 6 from a 
disequilibrium model that had previously been used for shoreline change (Davidson 
et al., 2010, 2013a), and improved prediction of barline three-dimensionality was 
achieved by incorporating a tidally modulated wave power term in the model. With 
this, the first multi-year predictions of seasonally varying beach three-dimensionality 
have been made at a macrotidal beach, where 42% and 61% of the variability in the 
standard deviation of the outer barline and lower intertidal beach contours, respec-
tively, were explained by the model.

The development of the DST13 model allowed the effects of wave energy extrac-
tion on the morphodynamic system to be explored. Attenuated inshore wave heights 
are likely to reduce the wave power available to move sediment, and reduce the vari-
ability in wave conditions. Reduced variability in the waves means that the seasonal 
disequilibrium between erosive and accretive waves will be less pronounced. When 
various wave attenuation scenarios were applied to the DST13 model in Chapter 7, 
the predicted effect was a reduction in the variance in beach three-dimensionality. 
Although three-dimensionality was predicted to increase at some points and de-
crease at other points, overall an increase in the mean level of three-dimensionality
was predicted. A higher occurrence of intermediate bar-rip beach states is therefore likely, which supports the modal beach state predictions in the lee of Wave Hub made by Poate (2011). Here however, reduced variance and specific temporal variation in three-dimensionality has been predicted using a validated model, which was not previously achieved by Poate (2011) or Abanades et al. (2015) who both used the dimensionless fall velocity and relative tide range parameters to predict modal beach state.

Under the realistic attenuation scenarios applied in Chapter 7 the changes in beach three-dimensionality were predicted to be less than the typical fluctuations that occur naturally, determined from the monthly standard deviation in three-dimensionality. Under an extreme level of wave attenuation beach three-dimensionality did occasionally increase beyond the natural fluctuations, indicating that the system is sensitive to levels of inshore wave height attenuation of 30% or more. As with the prediction of preferred wave occurrence, using the natural variability in beach three-dimensionality to determine whether an impact will be practically significant, or ‘noticeable’ to water-users, is not an ideal solution. Determining thresholds of three-dimensionality that relate to specific beach states, hazard levels, or surfing amenity levels would provide an improved approach to predicting the significance of the impacts of wave energy extraction on beach morphology. Only when this is achieved can changes in the number of hazardous days, or number of days with high surfing amenity, be predicted more precisely.

The DST13 model and the predicted changes in three-dimensionality are not universally applicable. As discussed further in Section 8.6.3 the model predictions currently only apply to dissipative-intermediate beaches in Cornwall, and only those where open beach circulation dominates. Buscombe and Scott (2008) identified 15 ‘main’ beaches in the potential lee of Wave Hub (between St Ives and Trevose head near Padstow), only 3 of which exhibited reflective states (Fistral, Portreath, and Porthmeor) and in those 3 cases the beach was only considered reflective for the upper, high-water portion of the beach. This is encouraging for the wider applicability of the model predictions for the Wave Hub case, and suggests that the predicted changes in three-dimensionality potentially apply to the low to mid tide morphology of all of the major beaches in Wave Hub’s lee, excluding particularly small or embayed beaches where headland circulation dominates.

8.5 The Perception of Coastal Impacts

The interviews conducted in chapter 3 provide insight into how concerns over coastal impacts from MRE are formed, as well as how these concerns may alter in different
situations, which has not been studied in the context of water-users before. The interviews indicate that water-user perceptions of MRE and its potential coastal impacts are constructed using intuitive risk perceptions (Slovic, 1987), rather than technical understanding of wave energy extraction. These risk perceptions were constructed by participants through a weighing of their perception of wave energy devices (‘technology’) and their perception of the coastal environment (‘nature’). This is illustrated by the conceptual model developed in Chapter 3 (Fig. 3.1), which provides a framework for understanding future attitudes towards coastal impacts from MRE. At this early stage in the development of Wave Energy Converter (WEC) technology, the interviewees’ technology perceptions were relatively unformed and were largely influenced by media imagery of WECs and an intuitive (and in some cases inaccurate) understanding of physics. Perceptions of the coastal environment varied, and the perception of the wave resource in particular was a key point that influenced the level of impact anticipated by participants. Some perceived the wave resource to be abundant, in that energetic waves were perceived to occur frequently; others perceived the wave resource to be scarce, in that ideal surfing conditions were perceived to be rare.

Water-user perceptions of the coastal environment, which make up one side of the balance in the anticipated impact model in Chapter 3, were explored further in Chapter 4 of the thesis. On the whole, water-users in the lee of Wave Hub underestimated the occurrence of ideal wave conditions and overestimated the occurrence of large wave conditions. This makes it difficult to determine from the anticipated impact model how much of an effect water-users in general will anticipate, as it suggests that the wave resource is perceived to be both abundant and scarce in different contexts. In Chapter 4 expert water-users and surfers emerged as two key water-user groups, as both groups have a low measured and perceived occurrence of ideal wave conditions for water use. Assuming for simplicity that water-users have a common perception of WEC technology, the anticipated impact model from Chapter 3 predicts that these two groups are likely to anticipate larger coastal impacts from WECs than other water-user groups, as their wave ‘resource’ is correctly perceived to be scarce. Expert water-users were also predicted in Chapter 7 to experience a reduction in the occurrence of their preferred wave conditions under realistic or extreme levels of energy extraction. Although the magnitude of such effects is predicted to be unnoticeable, expert water-users may intuitively anticipate significant or severe impacts to coastal waves, due to their perception of the wave resource.

Given that experts are essentially role models for water activities, their opinions are likely to permeate through to less experienced water-users even if they don’t initially anticipate the same impacts as expert water-users. Furthermore, surfers
were the largest activity group represented in the interview survey of over 400 water-users in Chapter 4, and therefore represent the majority of water-users in the region in the lee of Wave Hub. Given these two factors, expert water-users and surfers should be considered key stakeholders in wave energy projects that are proposed in areas with a similar activity demographic, as they may anticipate greater impacts than other water-users and are likely to influence opinions amongst the water using community.

8.6 Suggestions for Future Research

A goal of this thesis was to develop a sound and robust methodological approach that can be used to investigate the effects of wave energy extraction on beach water-users at future wave farm sites. In this respect a number of observations and recommendations can be made, which are described in the following sections.

8.6.1 Wave Modelling

Wave energy extraction and its effect on the inshore wave climate have not been directly modelled in this thesis. Instead findings from wave modelling studies in the literature have themselves been synthesised and used to estimate the range of inshore wave attenuation levels that are feasible under realistic and extreme energy extraction scenarios at Wave Hub. Contemporary ‘best-practice’ considerations with regards to the wave impact have been applied in these scenarios; namely wave directional spreading (Black, 2007, Monk et al., 2013) and frequency dependent energy extraction (Alexandre et al., 2009, Smith et al., 2012, O’Dea and Haller, 2014). Wave directional spreading, which has a large influence on the amount of wave height regeneration in the lee of wave farms (Black, 2007, Monk et al., 2013), was accounted for by applying impact scenarios which assumed a narrow directional spread. While it is unrealistic to assume that this would occur all the time, it means the impacts considered are at the upper limit of what is likely to occur and allow for conservative worst-case predictions to be made. Frequency dependent extraction was emulated by varying the inshore wave height attenuation depending on the incident wave period. This is a simplification of the real effect that frequency dependent extraction will have on a particular sea state, but is more appropriate than assuming that impacts will be constant across all wave frequencies, and allowed a range of frequency-impact scenarios to be investigated.

As the findings of this study relate specifically to the Wave Hub case study, for future WEC deployments the scale, siting, and frequency characteristics of the wave
Figure (8.1). Conceptual model demonstrating the synthesised findings from this thesis. The natural interactions between waves, beach morphology and beach water-users are shown on the left-hand side of the model, with coloured boxes indicating the likely practical significance of the effects of Wave Hub, described in the lower box.
farm must be reconsidered, as well as the frequency content and directional spreading of typical sea states for that region. Even when modelling the same wave energy site, different extraction characteristics, and directional spreading values applied in the modelling by Millar et al. (2007), Black (2007), Li and Phillips (2010), and Smith et al. (2012) resulted in predicted wave attenuation values that were an order of magnitude different, and hence a range of possible impact levels were considered in this thesis. In particular, the frequency characteristics of WECs (Frequency Dependent Extraction) and directional spreading of typical sea states was shown to greatly affect modelling results at Wave Hub (Black, 2007, Smith et al., 2012). Site specific wave modelling is therefore essential in order to account for these factors, and the findings from a previous deployment cannot be assumed to apply at other sites with different characteristics. The impact levels predicted in this thesis should therefore not be assumed to apply to other sites, but the methods used can be applied elsewhere.

The consideration of frequency dependent extraction influenced whether a positive or negative effect on the occurrence of preferred wave conditions was predicted. It also determined whether beach three-dimensionality was predicted to increase or decrease at certain points in time. In some cases attenuation over a narrow or wide range of frequencies resulted in opposing conclusions to cases in which all wave frequencies had been altered equally. Studies which do not consider frequency dependent extraction could therefore wrongly predict that preferred waves or 3D beach states will increase or decrease in occurrence as a result of wave energy extraction. While this highlights the importance of considering frequency dependent extraction when modelling coastal impacts, none of the scenarios in the Wave Hub case study caused a change that could be considered significant to water-users. At future Wave farm sites however, increased attenuation from larger, closer, or more efficient WECs may cause the effects of frequency dependent extraction to become significant.

### 8.6.2 Water-Users

It is recommended that water-users are considered in terms of sub-groups of activities and abilities, rather than as one homogeneous group, as the individual preferences of each group were seen to affect the scale and outcome (positive or negative) of the effects of inshore wave attenuation on preferred wave occurrence in the Wave Hub case study. Longitudinal studies on water-user opinions of MRE technology are needed, and perceptions should be further investigated once wave devices are deployed and active at Wave Hub. This will also provide further validation of the anticipated impact model presented in Chapter 3 (Fig. 8.1).
Media was seen as a key informer of wave energy perceptions, and will be an important point of education and consultation for the public prior to, and during, wave energy deployments. To enhance consultation with water-users it would be beneficial to pre-emptively engage with appropriate media sources. These should be especially geared towards expert water-users and surfers, as in the Wave Hub case study they were considered to be high-concern groups who have a large influence or representation in the region. Given that over 50% of water-users who participated in the interview survey in Chapter 4 had used a wave report or forecast prior to visiting the beach, such websites are clearly frequently and widely used by water-users in this region. Their power as a forum for water-users has already been seen during the Wave Hub controversy in 2006, as a surf forecast website provided the platform from which opposition to Wave Hub developed (McLachlan, 2009). Articles explaining monitoring and modelling results could similarly be disseminated at these contact points, and used to convey the low significance of the impacts that are realistically likely from WEC deployments. Then widespread buy-in and support from the water-using community is likely to occur before less informed opposition has a chance to develop.

A framework for understanding future attitudes towards marine renewables and coastal impacts has been developed through the anticipated impact model in Chapter 3. The properties in the model that were observed to make up people’s perception of MRE technology (form, scale, siting and use of resource) should be carefully considered when engaging with water-users. Projects which are likely to invoke greater concern from coastal water-users may then be identified early in the proposal stages, which will benefit subsequent consultation.

8.6.3 Beach Morphology

The DST13 model can be applied at other sites with a similar range of dissipative-intermediate beach states and open beach circulation, or could even be applied more universally if appropriate modifications (discussed in Section 6.4.3) were made to account for the decreasing three-dimensionality that occurs as beaches approach the reflective end state. Future developments of the model should first concentrate on improving its accuracy, especially in the prediction of subtidal three-dimensionality. This may be achieved by calibrating the model with more accurate subtidal data; for example, wave celerity based depth estimation from Argus images has recently been shown to yield bathymetries at high temporal resolution, and with an accuracy in the order of 10’s of centimetres, even in macrotidal environments (Bergsma et al., 2014).
A limitation of the approach used in the DST13 model is that behavioural models are data driven and generally require multiple years of data to make useful, calibrated predictions. To avoid the need to collect such demanding data sets at beaches in the lee of future wave farm sites it would be extremely beneficial to generalise the coefficients used to calibrate the model, as was achieved for a similar equilibrium shoreline model by Splinter et al. (2014). Their approach was to gather extensive data sets with five or more years of shoreline measurements at 12 beaches around the world, and then to determine common model coefficients by examining the dependency of the coefficients on wave and sediment parameters. To achieve a similar goal with DST13 would require global collaboration and availability of high quality morphological data, but would potentially enable beach three-dimensionality to be predicted at future sites with no morphological data available. This could considerably expedite the morphological impact assessment process, and may help in achieving the ambitious goals for wave energy deployment in the UK.
Chapter 9

Conclusions

The overarching aim of this thesis was to investigate the interaction between wave conditions, beach morphology, and beach water-users, and to propose how a wave climate altered by wave energy extraction is likely to alter these interactions. To achieve this aim a multidisciplinary research approach, encompassing sociological and physical research questions, has been taken. This has involved the collection of qualitative in-depth semi-structured interviews with 19 participants, a quantitative interview survey of over 400 water-users, the collection of over 5 years of wave and beach morphology data, and predictive modelling of beach three-dimensionality. The observations and predictions made in this thesis are the first time that the occurrence of wave conditions preferred by beach water-users, and changes in the scale of beach three-dimensionality have ever been studied under the context of an altered wave climate. From this, a number of novel findings and new insights have been drawn, and the following conclusions can be made:

9.1 Perception of Marine Renewables and Anticipated Coastal Impacts

- Water-user perceptions of marine renewable energy and its potential coastal impacts were seen to be constructed using intuitive risk perceptions, rather than technical understanding of wave energy extraction. These risk perceptions were constructed by participants through a balancing of their perception of wave energy devices (‘technology’) and their perception of the coastal environment (‘nature’).

- The properties that make up these perceptions are summarised in the anticipated impact model in Fig. 3.1. The model enables a level of anticipated impact to be predicted, by categorising technologies and coastal environments
in terms of their perceived properties, and provides new insight into how concerns over coastal impacts from MRE are formed, and how these concerns vary amongst water-users in general.

- The implications of the anticipated impact model are quite severe for certain technologies. Marine renewables proposals which are perceived to be large scale, close to shore, wide, stationary, or extracting high percentages of wave energy are likely to invoke anticipations of significant or severe coastal impacts. Conversely, those which are perceived to be small scale, far from shore, narrow, moving, or extracting low percentages of wave energy are more likely to invoke anticipations of insignificant or no coastal impact.

- Interestingly, the level of anticipated impact was most often based on device properties such as form or siting, and was rarely influenced by device extraction efficiency. This has not been previously documented to our knowledge.

9.2 The Use and Perception of Coastal Waves

- The population of water-users at two sites in the lee of Wave Hub are predominantly made up of surfers (53%), but bodyboarding and swimming/bathing are also popular activities at the sites (29% and 11%, respectively). There is a large contingent of inexperienced water-users, with around 35% having less than 365 days of experience in the water. However a quarter of the water-users could be considered experts, having more than four years of daily-equivalent experience.

- When observing breaking waves, the vast majority of surveyed water-users underestimated significant wave height and period, and their average perceptions can be approximated by $H_{vis} \approx 0.62H_b$ and $T_{vis} \approx 0.83T_{1/3}$, for waves $0.5 \leq H_b \leq 3.5$ m and $3 \leq T_{1/3} \leq 15$ s. Although perceptions were highly varied, the average perception ratios did not change significantly as the measured wave height and period varied between $0.5 \leq H_b \leq 2$ m and $6 \leq T_{1/3} \leq 14$ s.

- The experience level and preferred activity type of water-users was found to significantly affect their perception of wave height. Expert water-users and surfers generally under predicted wave height the most, especially for small and/or short period waves, while novices and non-surfing water-users made wave height observations closer to the measurements of a nearshore wave buoy. Gender was not found to significantly alter the mean perception of wave height,
and the perception of wave period did not change significantly between any of the different water-user groups considered.

- Wave preferences for different water-user groups were determined for the first time. Water-users were found to share a common preference towards wave periods of 9 - 20 s, but different water-user groups were found to have different ranges of preferred wave height, with women preferring the smallest waves ($H_{s,b} = 0.8 - 2.3$ m) and experts preferring the largest waves ($H_{s,b} = 1.9 - 3.7$ m).

- Expert water-users and surfers accurately estimated the probability of their preferred waves occurring, and of all the groups had the lowest perceived and measured probability of preferred wave occurrence. Expert water-users and surfers should therefore be considered key stakeholders in wave energy projects that are proposed in areas with a similar activity demographic, as they may anticipate greater impacts than other water-users due to their perception of the wave resource, and are likely to influence opinions amongst the water using community.

### 9.3 Three-Dimensional Beach Morphology and Associated Wave and Tide Forcing

- Integrated, cumulative fluctuations in the wave conditions that occur over seasonal time scales were shown to be well correlated to seasonal fluctuations in beach three-dimensionality. In particular, wave steepness (represented in the dimensionless fall velocity parameter, $\Omega$), wave power ($P$) and relative tide range ($R_{TR}$), explained a significant amount of the variance in beach three-dimensionality when represented as cumulative integral parameters.

- 3D morphology was well related to a disequilibrium term that predicts increases or decreases in three-dimensionality by examining the difference between instantaneous wave conditions and a temporally varying equilibrium condition, based on a weighted average of antecedent waves. This indicates that periods of wave regime change between erosive winter conditions and accretive summer conditions are related to the growth of 3D features, and vice versa, while extended periods with similar wave conditions drive the beach towards equilibrium.

- This results in significant annual periodicity in the barline three-dimensionality, where the lowest and highest three-dimensionality occur in winter and spring,
respectively. Interestingly the lower intertidal beach systematically developed three-dimensionality 1 - 4 months before the outer bar; while the opposite behaviour has been observed at other sites before (Almar et al., 2010, Castelle et al., 2015), three-dimensionality has never before been observed to develop in this sequence.

- Negative feedback was found to be an important process governing the changes in beach three-dimensionality. While free morphological behaviour may drive 3D growth, negative feedback processes exert stability in the system making it inherently predictable using a temporally varying equilibrium value, as used in the DST13 beach three-dimensionality model in Chapter 6.

- To improve the prediction of beach three-dimensionality, a tidally modulated wave power term was integrated into the DST13 model to determine the rate of morphological change. This improved the subtidal predictions, enabling the model to explain 10% more of the variance in the outer barline three-dimensionality.

- The developed disequilibrium model outperformed a simple baseline model (a linear fit), as well as a comparable linearized feedback model from the literature (Plant et al., 2006), providing the first long term (multi-year) predictions of seasonal to inter-annual beach three-dimensionality at a macrotidal beach.

9.4 Predicting the Effects of Wave Energy Extraction

- Examining the occurrence of preferred wave conditions for different water-user groups, and changes in this occurrence caused by wave energy extraction, it was found that wave attenuation could actually benefit those water-user groups that prefer smaller waves, and disadvantage those groups that prefer larger waves.

- Using a range of realistic and extreme coastal wave height attenuation levels determined from previous wave modelling studies, it was shown that none of the scenarios had a universally positive or negative effect on the probability of preferred wave conditions.

- Regardless of the attenuation level, frequency-impact, or preferences, the predicted changes in the occurrence of preferred waves in the lee of Wave Hub
were all smaller in magnitude than the natural variability (one standard deviation) in the wave conditions, and are therefore predicted to be insignificant and unnoticeable to beach water-users.

- The attenuated wave climates were used to drive the DST13 model described in Chapter 6, to investigate the effect of Wave Hub on 3D morphology at Perranporth beach. The dominant effect was to reduce the variability in the three-dimensionality of the beach. As the realistic wave height attenuation range caused changes that were within the predicted natural variability (one standard deviation) in beach three-dimensionality, the predicted changes are considered to be insignificant to water-users.

- The inshore wave attenuation from Wave Hub that has been predicted in the literature is therefore likely to have an insignificant effect on wave conditions and beach morphology of relevance to beach water-users. Even an extreme and unrealistic level of wave energy extraction (100% energy capture) was shown to have an insignificant effect on the occurrence of preferred waves, and only under a frequency independent extraction scenario did this level of attenuation have a significant effect on the predicted beach three-dimensionality.

This thesis demonstrates a number of novel methods to investigate the interaction between wave conditions, beach morphology, and beach water-users, and has proposed how a wave climate altered by wave energy extraction is likely to alter these interactions. It is hoped that these methods may be used at future wave farm sites to enhance consultation with beach water-users, and foresee potential coastal impacts from wave energy extraction. This will help to expedite sensible deployment of Wave Energy Converters, finally enabling us to harness the energy of ocean waves.
Appendices
A Semi-Structured Interview Consent Form
Participant Consent Form and Pre-Interview Questionnaire

CONSENT TO PARTICIPATE IN RESEARCH PROJECT - researchers copy

Name of Principal Investigator - Christopher Stokes
Title of Research - Coastal Impacts of Marine Renewable Energy
Brief statement of purpose of work - To explore water users’ knowledge of the Wave Hub and how they learned about it. To explore water users’ opinions on how the Wave Hub will or will not affect their local beaches and the waves at those beaches.

☐ The objectives of this research have been explained to me.
☐ I understand that I am free to withdraw from the research at any stage, and ask for my data to be destroyed if I wish.
☐ I understand that my anonymity is guaranteed, unless I expressly state otherwise.
☐ I understand that the Principal Investigator of this work will have attempted, as far as possible, to avoid any risks, and that safety and health risks will have been separately assessed by appropriate authorities (e.g. under COSHH regulations)
☐ I confirm that I am over 18 years old.
☐ Under these circumstances, I agree to participate in the research.

Signature: Reference number:

Your opinions are really important to my research, so thanks again for helping me with this study. Would you be willing to take part in another similar interview in a years time? If so, please put down your telephone number and/or Email below. Your email or telephone will only be used to contact you about this study and will not be passed on to any third parties.

Telephone: Email:

CONSENT TO PARTICIPATE IN RESEARCH PROJECT - participants copy

Name of Principal Investigator - Christopher Stokes
Title of Research - Coastal Impacts of Marine Renewable Energy
Brief statement of purpose of work - To explore water users’ knowledge of the Wave Hub and how they learned about it. To explore water users’ opinions on how the Wave Hub will or will not affect their local beaches and the waves at those beaches.

☐ The objectives of this research have been explained to me.
☐ I understand that I am free to withdraw from the research at any stage, and ask for my data to be destroyed if I wish.
☐ I understand that my anonymity is guaranteed, unless I expressly state otherwise.
☐ I understand that the Principal Investigator of this work will have attempted, as far as possible, to avoid any risks, and that safety and health risks will have been separately assessed by appropriate authorities (e.g. under COSHH regulations)
☐ I confirm that I am over 18 years old.
☐ Under these circumstances, I agree to participate in the research.

Signature: Reference number:
INFORMATION ABOUT YOURSELF

1. Gender -
   □ Male   □ Female

2. Please indicate your age range -
   □ 18 - 28 yrs old □ 29 - 39 yrs old □ 40 - 50 yrs old □ 51 - 61 yrs old □ 62 yrs old or over

3. Please indicate, on average, how often you go in the sea at the following beaches (tick one box only for each beach) -
   never   less than once   once every 6 months   once a month   once a week   almost every day
   Perranporth
   St. Agnes
   Chapel Porth
   Porth Towan

4. Please circle which one of the above beaches you consider your 'most regularly visited beach'

5. and in what way do you use the sea at that beach? (tick all that apply)
   □ surfing   □ skimboarding   □ bathing
   □ bodyboarding   □ kayaking   □ swimming
   □ bodysurfing   □ kitesurfing   □ snorkeling
   □ other, please state -

6. Before receiving this questionnaire, did you know what the 'Wave Hub' was? (tick only one)
   □ yes   □ I had heard of it   □ no

DEBRIEFING

Thank you very much for taking part in this study. If you want to find out any more information on the Wave Hub, please have a look at the following web pages -

www.wavehub.co.uk
en.wikipedia.org/wiki/Wave_Hub
www.southwestrda.org.uk

If you have any further questions about this study or would like to withdraw from the study at any time, please contact me on -
07972 266481
or Email me at -
christopher.stokes@plymouth.ac.uk
B Structured Interview Schedule
**Survey Name:** Copy of Coastal water-user observations and opinions  
**Description:**  
**Introduction:** Hi, do you go in the water here at this beach? I'm from Plymouth University, we're conducting research into what people think about the wave conditions here, would you be able to spare 5 minutes to answer a couple of questions? Your answers will be confidential, and we will use them purely for academic research. You can withdraw your answers at any stage.  
**Conclusion:** Thank you for completing the survey  
**Survey Created by:** Plymouth Uni  
**Survey Created on:** 5/6/2013 1:57:13 PM

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<td>What water based activity do you most often do at this beach?</td>
<td>Randomize</td>
<td>Surfing</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Answer Required</td>
<td>Bodyboarding</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specify Answer</td>
<td>Body surfing</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Swimming</td>
<td>2</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Stand up paddleboarding</td>
<td>2</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Kayaking</td>
<td>2</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Kite surfing</td>
<td>2</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Other</td>
<td>2</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Numeric</td>
<td>How long have you been doing your preferred water activity?</td>
<td>Answer Required</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Suffix-yrs</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decimal</td>
<td>5</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Places-1</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numeric</td>
<td>On average, how many days a month do you do your preferred activity in the warmer months (summer/autumn)?</td>
<td>Answer Required</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Suffix-days/ln</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decimal</td>
<td>9</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Places-1</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numeric</td>
<td>On average, how many days a month do you do your preferred activity in the colder months (winter/spring)?</td>
<td>Answer Required</td>
<td>11</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Suffix-days/ln</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decimal</td>
<td>13</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Places-1</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numeric</td>
<td>Please estimate the average height of the waves over the last half an hour (face height at breaking, in feet (1 m = 3.3ft)).</td>
<td>Suffix-ft</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decimal</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Places-1</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numeric</td>
<td>Please estimate the average wave period over the last half an hour (the time in seconds between one wave passing a fixed point and the next wave passing that point).</td>
<td>Suffix-Secs</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decimal</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Places-1</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Select</td>
<td>Which of the following words/images do you think best describes the waves over the last half an hour?</td>
<td>Specify Answer</td>
<td>Softly breaking waves</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sleep, peeling waves</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fast, hollow (barreling) waves</td>
<td>23</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Waves are 'closing out'</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Messy irregular waves</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flat sea (no waves at all)</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Don't know</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Other</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td></td>
</tr>
</tbody>
</table>
8: What do you think is an average wave height for this beach (i.e. happens most often throughout the year)?
   - Suffix-Ft
   - Decimal Places-1
   Numeric

9: When doing your activity, what wave height do you prefer at this beach?
   - Suffix-Ft
   - Decimal Places-1
   Numeric

10: When doing your activity, what wave period do you prefer at this beach?
    - Suffix-Seas
    - Decimal Places-1
    Numeric

11: What type of wave do you prefer at the height you just specified?
    - None of the Above
    - Specify Answer
    Single Select
    Softly breaking waves
    Sleep, peeling waves
    Fast, hollow (barreling) waves
    Waves that ‘close out’
    White water
    Messy irregular waves
    Flat sea (no waves at all)
    Don’t know
    None of the above

12: In a few words please explain why you prefer those conditions
    Text

13: On a scale of 0-10, with 0 being ‘never’ and 10 being ‘every day’, how often do you think the following things happen at this beach?
    Grid Scale
    The waves are the height, period and type that you just specified
    There are rip currents
    The waves are over 6ft
    The water is too dangerous for you to do your preferred activity
    Yes
    No
    Randomize

14: Have you been in the water yet today?
    Single Select
    Yes
    No

15: Did you use a surf/weather forecast to get a prediction of the wave conditions today?
    Single Select
    Yes
    No

16: What is the highest level of education you have completed?
    Single Select
    No qualifications
    GCSE / O levels
    AS levels
    A levels
    Vocational qualification (NVQ etc)
<table>
<thead>
<tr>
<th>Year of birth</th>
<th>17</th>
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<tbody>
<tr>
<td>Gender</td>
<td>18</td>
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<td>Single</td>
<td>19</td>
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<tr>
<td>Male</td>
<td>19</td>
</tr>
<tr>
<td>Female</td>
<td>19</td>
</tr>
<tr>
<td>Signature</td>
<td>20</td>
</tr>
<tr>
<td>This questionnaire was completed at</td>
<td>21</td>
</tr>
<tr>
<td>Single</td>
<td>21</td>
</tr>
<tr>
<td>Perranporth beach</td>
<td>21</td>
</tr>
<tr>
<td>Porthtowan beach</td>
<td>21</td>
</tr>
<tr>
<td>Other</td>
<td>21</td>
</tr>
<tr>
<td>Date and time of questionnaire completion</td>
<td>22</td>
</tr>
<tr>
<td>Text</td>
<td>22</td>
</tr>
</tbody>
</table>
C Determining the Accuracy of Measured Morphological Parameters

To determine the accuracy of the Argus derived barline parameters, a number of bathymetric surveys were compared to near-concurrent Argus images. The same Argus methods and hydrodynamic constraints used to collect the barline data set described in Section 5.2.2 were used for the comparison. A total of 11 bathymetry surveys were used: 9 were conducted at Perranporth beach at approximately 2 month intervals between October 2010 and October 2011, as part of the Dynamics of Rips and Implications for Bather Safety (DRIBS) field study (Austin et al., 2014, Scott et al., 2014), and two additional surveys were conducted specifically for this thesis, one each at Perranporth and Porthtowan in April 2014.

The bathymetry surveys were conducted using either a Jetski or Rigid Inflatable Boat, with a side mounted single-beam Valeport MIDAS depth sounder logging at 1 Hz. A Trimble 5800 RTK-GPS receiver was mounted directly above the depth sounder, with GPS corrections provided by an on land base station receiver (Section 5.2.3). This provided depth-concurrent vertical and horizontal positional measurements at centimetre accuracy, which were later used to geolocate the depth measurements and correct them for vertical wave and tide offsets.

The 9 bathymetries collected between 2010 and 2011 were compared to near concurrent overlapping intertidal RTK-GPS surveys (Fig. C.1), which allows the surveys to be compared in the lower intertidal region with minimal temporal offset, usually of the order of half a tidal cycle. These comparisons indicate that the bathymetry points are accurate to within approximately 0.03 m of the land surveyed points, with a standard deviation in the accuracy of 0.10 m. With the additional 0.03 m of typical RTK-GPS error, the surveyed bathymetries are approximately accurate to 0.06 m (± 0.10 m std. dev.) in the intertidal region. Without further validation it is difficult to assess the accuracy in the deeper subtidal region, but it will be assumed to be of the same order of magnitude.

The data from each bathymetry survey were converted from OSGB36 coordinates by rotation and translation to local Argus coordinates, and Digital Elevation Models (DEM’s) were generated at Perranporth (Porthtowan) by gridding the data at 20 m (10 m) resolution using the quadratic loess interpolation scheme described in Section 5.2.3 (Plant et al., 2002, 2008).

To compare the Argus derived barline to the bathymetry barline, the barline must first be identified in the bathymetry data. In previous literature, bar crest positions have been identified from surveyed bathymetries using either the cross-shore maxima in the seabed elevation (Lippmann and Holman, 1989) or the maximum
Figure (C.1). Example comparison of cross-shore profiles from an ATV mounted RTK-GPS intertidal survey (black lines) and Jetski mounted depth sounder with RTK-GPS bathymetry survey (red lines) at Perranporth. The cross-shore profile elevations are only used for relative comparison, and do not represent the actual elevation from a vertical datum. The displayed mean and standard deviation differences were computed for the overlapping area between the two surveys.
Figure (C.2). Bathymetry DEM from Perranporth, surveyed on the 10th of April 2014. Increasing offshore distance is towards the bottom of the figure. Grey contours show the elevation from ODN (m), and thick lines indicate from top down: MHWS, MHWN, MSL, MLWN, and MLWS. The dashed box indicates the data subset shown in the upper panel of Fig. C.3.

Profile deflection from a long-term average profile (Van Enckevort and Ruessink, 2001), or fitted planar profile (Masselink et al., 2014). The maxima in cross-shore pixel intensity from Argus images, used in Chapter 5 to approximate the bar crest position, has been found to be more comparable to the maximum profile deflection than the maximum seabed elevation, especially in the presence of platform shaped bars (Van Enckevort and Ruessink, 2001). The maximum profile deflection was therefore used in this study to determine the barline position in each bathymetry survey.

For each cross-shore profile at Perranporth (Porthtowan), spaced at 20 m (10 m) intervals alongshore, a linear slope was least-squares fitted and subtracted from the actual profile, yielding a ‘residual’ bathymetry map (Masselink et al., 2014). An example bathymetry DEM is shown in Figs. C.2 and C.3 (upper panel), demonstrating the subtle presence of the outer bar. The residual bathymetry from this survey is shown in Fig. C.3 (lower panel), clearly displaying two bar crests. The cross-shore maxima in the residual bathymetry for the inner and outer bars are shown as dashed lines, and the equivalent Argus detected barlines are shown with dotted lines.

As the bathymetry surveys were conducted around high tide, and the Argus
images collected at low tide, there is an inherent temporal offset in the data being compared. Additional temporal offsets occurred as a result of the hydrodynamic and quality constraints placed on the Argus images (Section 5.2.2), which increased the offset when suitable images were not available. The resulting temporal discrepancies were relatively small however, with a mean and maximum gap between bathymetry surveys and Argus image dates of 2.8 days and 4.5 days, respectively. The bathymetry surveys were conducted during calm periods, and no energetic wave conditions are known to have occurred between the survey and Argus image dates. It is therefore assumed that actual changes in the bar shape and position are negligible, and any observed differences (beyond the estimated bathymetry measurement error of 0.06 m) are a result of error in the measurement of the bar position using the cross-shore pixel intensity maximum, described in Section 5.2.2.

The cross-shore position of the inner and outer bar crests detected in the residual bathymetry, $X_b$, and corresponding Argus images, $X_i$, were compared at 20 m intervals alongshore for each of the 11 surveys (Fig. C.4). From this data the Root-Mean-Square (RMS) difference, $\Delta X$, at Perranporth (Porthtowan) was 57.78 m and 43.97 m (60.75 m and 54.56 m) for the outer and inner bars respectively. As per the example in Fig. C.5, the outer (inner) bar positions were mostly detected shoreward
Table (C.1). Summary of errors in the sub and intertidal morphological parameters used in Chapters 5, 6, and 7. Linear regression coefficients ($a$ and $b$) used to correct systematic errors in the Argus barline data (shown in Figs. C.6 and C.7) are shown.

<table>
<thead>
<tr>
<th></th>
<th>Error (m)</th>
<th>Regression coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncorrected</td>
<td>Corrected</td>
</tr>
<tr>
<td>Outer bar $\Delta X$</td>
<td>57.11</td>
<td>13.82</td>
</tr>
<tr>
<td>Outer bar $\Delta \alpha$</td>
<td>11.70</td>
<td>4.78</td>
</tr>
<tr>
<td>Inner bar $\Delta X$</td>
<td>20.89</td>
<td>14.99</td>
</tr>
<tr>
<td>Inner bar $\Delta \alpha$</td>
<td>19.45</td>
<td>16.55</td>
</tr>
<tr>
<td>Lower beach $\Delta X$</td>
<td>0.08</td>
<td>n/a</td>
</tr>
<tr>
<td>Lower beach $\Delta \alpha$</td>
<td>0.16</td>
<td>n/a</td>
</tr>
</tbody>
</table>

(seaward) of their actual position, and $\Delta X$ was greater at the outer bar than at the inner bar. Comparison of the alongshore averaged cross-shore bar crest positions (Fig. C.6) further demonstrates that the Argus positions are seaward (shoreward) of their actual position at the inner bar (outer bar). From Table 1, $\Delta X$ is again larger at the outer bar (57.11 m) than at the inner bar (20.89 m), although the inner bar errors have reduced with the alongshore averaging.

Conversely, the alongshore standard deviation of the de-trended and band-pass filtered barlines, $\alpha$, used to describe the three-dimensionality of the bars, was more accurately determined at the outer bar than at the inner bar. Comparing $\alpha$ from the residual bathymetries, $\alpha_b$, and corresponding Argus images, $\alpha_i$, at Perranporth and Porthtowan (Fig. C.7), the RMS error, $\Delta \alpha$, is 19.45 m and 11.70 m for the inner and outer bars respectively (Table C.1). The larger $\Delta \alpha$ at the inner bar is thought to be due to smoothing of the pixel intensity barline, which can occur when the inner surf zone is saturated with wave breaking at low tide when the Argus images are collected.

As there appears to be a systematic and relatively linear nature to the errors in the Argus derived bar data (Figs. C.6 and C.7, left panels), some of the error can be corrected with a simple linear regression model. The correction is performed separately for the inner and outer bars, and is calculated using a linear least-squares fit between the Argus and residual bathymetry data, where the slope and intercept of the fitted line provide the parameters to adjust each data point (Table C.1). A robust fitting algorithm was used, that iteratively re-weights the least squares regression such that outliers have less influence on the fitted line (Holland and Welsch, 1977). The morphological data is therefore corrected using the bulk of data points, but is not biased by Argus data with unusually large error, such as the outlying inner bar
measurement at $\alpha_i = 3, \alpha_b = 42$ in Fig. C.7, left panel. The corrected data is plotted in Figs. C.6 and C.7, right panels. Although the correction did not remove all of the Argus measurement error, the accuracy of the barline parameters is improved, with $\Delta X$ and $\Delta \alpha$ reduced to 13.82 m and 4.78 m, respectively at the outer bar, and 14.99 m and 16.55 m, respectively at the inner bar (Table 1). The corrected alongshore averaged cross-shore position of the Argus detected bar crests is used in Chapters 5 and 6, and is referred to as $X_c$.

To determine equivalent values of $\Delta X$ and $\Delta \alpha$ from the intertidal contour data, the maximum RTK-GPS measurement error (0.03 m) and interpolation error (0.05 m) from the topographic DEM’s was summed ($\Delta xy$) and propagated into the mean and standard deviation equations respectively used to calculate $X_c$ and $\alpha$ for the lower beach contours (Eqs. 1 and 2). The number of alongshore points, $n$, used to measure $X_c$ and $\alpha$ at Perranporth and Porthtowan are $n = 65$ and $n = 75$, respectively. The intertidal measurement errors therefore equate to $\Delta X = 0.08$ m and $\Delta \alpha = 0.16$ m at both sites (Table C.1).

\begin{align*}
\Delta X &= \frac{1}{n} \sum_{i=1}^{n} \Delta xy \\
\Delta \alpha &= \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\Delta xy + \Delta X)^2}
\end{align*}

(1)  
(2)
**Figure (C.4).** Comparison of the cross-shore position of the detected bar crest at 20 m alongshore intervals in the Argus images, $X_i$, and residual bathymetries, $X_b$, for the inner and outer bar at Perranporth (black x’s and circles, respectively) and inner and outer bar at Porthtowan (red +’s and squares, respectively). The data is from 11 different bathymetry surveys and their corresponding Argus images. The dotted line shows a 1:1 relationship for reference.

**Figure (C.5).** Alongshore averaged (-1200 to -200 m alongshore) cross-shore profile from a bathymetry survey at Perranporth on the 10th of April 2014. The alongshore averaged residual barcrest positions are shown as black +’s, and the alongshore averaged Argus derived bar positions are shown as red x’s.
Figure (C.6). Linear adjustment of the alongshore averaged cross-shore position of the Argus detected bar crests, to correct for systematic errors. The left panel compares the alongshore averaged cross-shore position of the detected bar crest in the Argus images, $X_i$, and residual bathymetries, $X_b$, for the inner and outer bar at Perranporth (black x’s and circles, respectively) and inner and outer bar at Porthtowan (red + and square, respectively). The right panel shows the same relationship having adjusted inner bar (outer bar) $X_i$ using a robust least-squares fit to the raw data, shown as a solid (dashed) line in the left panel. The dotted line in each panel shows a 1:1 relationship for reference.
Figure (C.7). Linear adjustment of the Argus derived barline three-dimensionality, to correct for systematic errors. The left panel compares the alongshore standard deviation of the detected bar crest in the Argus images, $\alpha_i$, and residual bathymetries, $\alpha_b$, for the inner and outer bar at Perranporth (black x’s and circles, respectively) and inner and outer bar at Porthtowan (red + and square, respectively). The right panel shows the same relationship having adjusted inner bar (outer bar) $\alpha_i$ using a robust least-squares fit to the raw data, shown as a solid (dashed) line in the left panel. The dotted line in each panel shows a 1:1 relationship for reference.
D Filling gaps in the wave data time series

Due to technical issues with the nearshore wave buoy at Perranporth, occasional gaps in the wave data time series exist over the study period (September 2008 - April 2014). For days with at least 75% of the half hourly Perranporth wave measurements present, daily mean wave parameters were calculated, leaving 203 days (7.6%) over the study period with no wave data.

These gaps were filled using adjusted wave data from the Sevenstones lightship (www.previmer.org), which is located in deep water approximately 26 km off the south west tip of Cornwall, some 70 km South West of the inshore wave buoy at Perranporth (Fig. 5.1). Daily mean values were calculated from the hourly Sevenstones measurements and a simple linear adjustment was applied in order to shoal them to equivalent heights and periods for the Perranporth buoy. The adjustment was calculated using a linear least-squares fit between the Perranporth and Sevenstones data (Fig. D.8 left panels), where the slope and intercept of the fitted line provide the parameters to adjust each data point. A robust fitting algorithm was used, that iteratively re-weights the least squares regression such that outliers have less influence on the fitted line (Holland and Welsch, 1977). The wave data is therefore adjusted using the bulk of data points, but is not biased by outliers which may have occurred due to erroneous measurements at either Perranporth or Sevenstones. The correlation between the available Perranporth measurements and concurrent adjusted Sevenstones measurements is $R = 0.92$ and $R = 0.81$ (RMSE 0.36 m and 1.68 s) for $H_s$ and $T_p$ respectively (Fig. D.8 right panels). The measured and adjusted inshore wave time series are compared in Fig. D.9.

Having filled the majority of data gaps with the adjusted Sevenstones data, 16 days (0.6 %) with no wave data still remained due to missing Sevenstones measurements. These remaining gaps were filled using time series mean values of $H_s$ and $T_p$ from the available Perranporth wave data. As no directional information is available at the Sevenstones location, the time series mean peak wave direction ($\theta_p$) was used to fill all gaps in the wave direction data.
Figure (D.8). Linear adjustment of the Sevenstones lightship wave data to approximate inshore conditions measured by the Perranporth wave buoy. Left panels compare daily-averaged measurements of significant wave height ($H_s$, upper panel) and significant ($T_s$) and peak ($T_p$) wave period (lower panel). Right panels show the same relationships having adjusted the Sevenstones data using a robust least-squares fit to the raw data, shown as solid lines in the left panels. The dotted line in each panel shows a 1:1 relationship for reference.
Figure (D.9). Time series of daily-averaged significant wave height ($H_s$, upper panel) and peak wave period ($T_p$, lower panel), comparing measured wave buoy data from Perranporth (PPT) to the adjusted Sevenstones (SS) data.
Observation and prediction of three-dimensional morphology at a high-energy macrotidal beach

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Abstract

Three-dimensional beach features such as crescentic sandbars and rip channels influence beach response to, and recovery from, storm waves, as well as significantly affecting the safety and amenity provided by the surf-zone for beach water-users. In this contribution temporal variations in subtidal and intertidal beach three-dimensionality are observed at a high-energy macrotidal beach, and a simple equilibrium model is developed to predict the changes over multi-year timescales. A dataset of 5.5 years of quasi-weekly bar measurements, and quasimonthly intertidal surveys from Perranporth beach (Cornwall, UK) were used to quantify seasonal to interannual changes in three-dimensionality. The three-dimensionality of the outer bar displayed significant annual periodicity, with annual minima and maxima occurring in winter and spring, respectively. The lower intertidal beach displayed a similar periodicity, but developed three-dimensionality 1–4 months before the outer bar. The model predicts increases or decreases in the scale of three-dimensional features by examining the disparity between instantaneous wave conditions and a temporally varying equilibrium wave condition. A tidallymodulated wave power term determines the rate of morphological change. Negative feedback was found to be an important process governing the changes in three-dimensionality; while free morphological behaviour may drive three-dimensional growth, negative feedback exerts stability in the system, making it inherently predictable using a temporally varying equilibrium value. The model explained 42% and 61% of the overall variability in outer bar and lower beach three-dimensionality, respectively. It skillfully predicted changes outside the training data range, during the most energetic 8-week period of waves measured in the last 65 years off SW England, in winter 2013/14. The model outperformed a simple baseline model (a linear fit), as well as a comparable fine-grained feedback model from the literature, providing the first long-term (multi-year) predictions of seasonal to interannual beach three-dimensionality for a macrotidal beach.

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1. Introduction

1.1. Background and rationale

Much of our conceptual understanding about the variability of beach morphology comes from sequential models developed for single-barred microtidal beaches in Australia (Short, 1979; Wright and Short, 1984; Wright et al., 1985). Through extensive field observations made over a number of years, Wright and Short (1984) reduced the natural continuum of beach forms into a sequence of 6 discrete states. The end-members of the model have a shallow gradient in the Dissipative (D) extreme, or a steep gradient in the Reflective (R) extreme, both of which consist of a planar beach face with little alongshore variability. The intermediate stages (Longshore Bar and Trough — LBT, Rhythmic Bar and Beach — RBB, Transverse Bar and Rip — TBR, Low Tide Terrace — LTT) are typified by greatly increased alongshore variability in the form of rip channels, and crescentic bar formations. The general applicability of this sequence has subsequently been verified at other sites and extended to include beaches with meso- and macro-tidal range (Short, 1991; Masselink and Short, 1993; Masselink and Hegge, 1995; Scott et al., 2011; Masselink et al., 2014), double or multi-bar systems (Short, 1992; Short and Aagaard, 1993; Castelle et al., 2007; Scott et al., 2011), and beaches with dominant headlands or geological features (Short, 1996; Castelle and Coco, 2012; Loureiro et al., 2012). Although the intermediate beach forms observed in the different studies vary slightly, they all feature alongshore non-uniformities such as rip channels and crescentic bars, collectively referred to as three-dimensional (3D) morphology (see Fig. 1 for example images).

Beach morphology often becomes 3D during the recovery period following energetic waves, when the straightened, offshore bar(s) migrates back towards shore unevenly under the action of accretive, low-steepness waves (Short, 1979; Wright and Short, 1984; Lippmann and Holman, 1990; Poate et al., 2014). The result is a sinuous, crescentic bar which can either be rhythmic in form, or a range of wave-lengths (from 150 m to 2 km) and cross-shore amplitudes. From 5 to
80 m) can occur (Van Enckevort et al., 2004). Under sustained accretive conditions the shoreward bar horns will eventually weld to the shore, resulting in the highly 3D TIR beach state. The final states in the ‘downstate’ sequence feature diminishing three-dimensionality, and a bar that is close to shore (LT and R). The landward return of sediment during this downstate sequence forms an important mechanism for beach recovery following erosive, ‘upstate’ conditions. Conversely the presence of 3D features such as cusps and rip channels during a storm can potentially allow erosive swashes to reach further landward and undercut the dune foot (Thornton et al., 2007). 3D morphology therefore heavily influences a beach’s response to, and recovery from, storm waves.

3D features also significantly affect the safety and amenity provided by the surf-zone for beach water-users. The alongshore varying morphology causes localised refraction and breaking; while these factors improve the amenity provided by waves for popular recreational activities such as surfing (Mead and Black, 2001a, 2001b; Scarfe et al., 2009), they also influence the type and strength of surf-zone currents (Bower, 1969; Ranasinghe et al., 2004). Rip channels allow water set-up by wave breaking to funnel back out to sea in concentrated offshore flows (Fig. 1) which can take water-users from the shallows out into deeper water (MacMahan et al., 2006; Austin et al., 2010). As a result rip currents are the largest cause of surf-zone rescues and fatalities globally (Scott et al., 2007), and macrotidal North Cornwall coast, England (left to right panels respectively). Arrows demonstrate typical wave-driven horizontal cell circulation with seaward directed rip current component.

2.1. Approaches to modelling 3D morphology

Process-based models have shown that horizontal wave-driven circulation in the nearshore contributes to the growth of 3D morphology through positive feedback between the developing morphology and local hydrodynamics, termed bed-surf coupling (Falqués et al., 2000; Caballeria et al., 2002, 2003a, 2003b; Ranasinghe et al., 2004). In the case of subtidal bars, this process starts with waves breaking preferentially over the shallowest bar sections. The dispersion of energy and gradient of the beach degrades the shoreward flowing water, promoting a decreasing sediment flux and sand deposition directly shoreward of the bar, further reducing the water depth and enhancing wave breaking in that region (Falqués et al., 2000, 2008). The water set-up by the breakers locally increases hydrostatic pressure and forces an alongshore flow away from the region of breaking. These flows converge at points between the shallow regions of wave breaking, and return seaward over the deeper portions of the sandbar crest, creating horizontal circulation (Fig. 1) (Falqués et al., 2000; Ranasinghe et al., 2004). The offshore-directed return flows are coupled with increasing sediment fluxes and sand erosion, enhancing the depth of the channels between the bars. Eventually the developing morphology begins to hinder the sediment transport and the initial positive feedback diminishes as equilibrium is approached (Smit et al., 2008). This ‘negative feedback’ has been shown to play an important role in controlling free morphological behaviour, making the system inherently predictable (Plant et al., 2006).

Behavioural models provide an alternative approach to process-based modelling of 3D morphology. Although sometimes criticized for consisting of incomplete physical representations (Splinter et al., 2011; Van de Lageweg et al., 2013) or being overly dependent on tuning parameters (Ruessink et al., 2013), behavioural models are often capable of explaining substantial amounts of data variance and accurately forecasting large-scale beach changes over multyear timescales (e.g. Plant et al., 1999; Yates et al., 2009; Davidson et al., 2010; Splinter et al., 2011; Davidson et al., 2013a), which is presently unachievable using process-based models. Wright et al. (1985) proposed a behavioural beach state model based on the assumption that state changes occur when instantaneous wave conditions differ from the conditions associated with zero change for each state, termed the disequilibrium stress, ∆Ω:

\[
\Delta \Omega = \Omega - \Omega_{eq}
\]

where \(\Omega\) and \(\Omega_{eq}\) are the instantaneous and equilibrium dimensionless fall velocity respectively (Gourlay, 1968; Dean, 1973):

\[
\Omega = \frac{H_b}{\bar{u}} \frac{1}{T_p}
\]

\(H_b\) is the significant wave height at breaking, \(\bar{u}\) is the mean sediment fall velocity, and \(T_p\) is the peak wave period. Large departures from equilibrium (large \(\Delta \Omega\)) represent an increased potential for change, and upstate and downstate changes occur under positive and negative disequilibrium, respectively. As instantaneous conditions approach the equilibrium condition (\(\Omega \approx \Omega_{eq}\)), the morphological change appropriately reduces to zero. Although successful predictions of beach state were not achieved by Wright et al. (1985), their approach recognises the importance of negative feedback in maintaining system stability, and the concept may therefore be suited to predicting beach three-dimensionality. Disequilibrium stress has since been used in adapted forms to predict cross-shore shoreline (Yates et al., 2009; Davidson et al., 2010; Yates et al., 2011; Davidson et al., 2013a; Castelle et al., 2014; Splinter et al., 2014) and barline (Plant et al., 1999; Masselink et al., 2014) migration under varying waves, but it is yet to be applied to the prediction of alongshore non-uniform changes. Other attempts to behaviourally model three-dimensionality have either been restricted...
to single storm cycles (Plant et al., 2006) or have included relatively complex sediment transport parameterisations, with limited predictive improvement (Splinter et al., 2011).

1.3. Aims

This study aims to investigate the temporal variability of seasonal to inter-annual, subtidal and intertidal beach three-dimensionality at a high energy, macrotidal beach (Perranporth, Cornwall, UK). A morphological data set consisting of 5.5 years of monthly intertidal surveys and quasi-daily Argus barline observations presents an opportunity to apply disequilibrium stress to the prediction of subtidal and intertidal three-dimensionality for the first time. Furthermore this will be the first attempt to model multi-year changes in three-dimensionality at a macrotidal beach.

2. Methods

2.1. Study area

Perranporth (PPT) beach on the North West coast of Cornwall, UK (Fig. 2) is fully exposed to the dominant westerly wave approach, receiving an energetic wave climate of Atlantic swell and locally generated wind seas (Davidson et al., 1997). The directional wave rider buoy located just offshore in approximately 15 m water depth (upwards triangle, Fig. 2) measured mean and maximum significant wave heights, $H_s$, of 1.6 m and 7.2 m, respectively, and a mean peak period, $T_p$, and direction, $\theta_p$, of 10.6 s and 283°, respectively, between January 2007 and May 2014. The region is macrotidal, with mean neap and spring tide ranges of 3.1 m and 6.1 m, respectively. The beach is 3.4 km long with a cross-shore extent of approximately 500 m at spring low tide. Devonian hard rock cliffs and steep vegetated dunes surround the beach. The sediment is composed of medium quartz sand with a median grain size $D_{50}$ (mean fall velocity $W_s$) of 0.35 mm ($0.04 \text{ m s}^{-1}$) (Poate et al., 2014). The lower beach gradient is shallow ($\tan \beta \approx 0.012$), but compared to the subdued (<1 m vertical range) and alongshore-uniform morphology that characterise the upper beach, the region below mean-low-water-neap (MLWN) is highly dynamic (2 m vertical range), and the double bar system regularly exhibits pronounced crescentic bar and rip features (see example in Fig. 3) (Poate, 2011; Austin et al., 2013; Masselink et al., 2014).

2.2. Observation of beach three-dimensionality

2.2.1. Video data

An elevated Argus video camera located at the southern end of the beach (Fig. 2) collected time exposure (timex) images of the lower intertidal and subtidal regions between September 2008 and April 2014. As a result of the preferential breaking of waves over the shallow bar crests, foam is often visible on the water surface at the position of the sandbars, creating conspicuous bands of high pixel intensity that reveal the position of the underlying bars (Lippmann and Holman, 1989). A barline intensity mapping tool (Pape et al., 2007) was used to detect the inner and outer bar crest positions by the alongshore tracking of the intensity maxima within the surf zone (Fig. 3). The barlines were measured at 1 m intervals, between –1700 m and –200 m alongshore. The detected barline positions can be artificially shifted due to tide and wave conditions (Kingston et al., 2000; Van Enckevort and Ruessink, 2001). To minimize tidal shifting, a single low tide image was selected for each day (Van Enckevort and Ruessink, 2001), and to minimize the...
combined effects of a large tide range and large waves, or a small tide range with small waves, images were also constrained by the Hydrodynamic Forcing Index (Almar et al., 2010):

$$HFI = \frac{H_s}{d_{\text{min}}}$$

where $H_s$ is averaged over a tidal cycle and $d_{\text{min}}$ is the lowest water level above the lowest astronomical tide experienced during a tidal cycle. To maximise clear breaking over the bars, only images collected within the following hydrodynamic constraints were used:

- $0.5 \text{ m} < H_s < 2 \text{ m}$
- $0.9 < HFI < 2$

Images were also unavailable during poor light and weather conditions, or occasionally due to technical issues with the camera system.
Of the 2067 days of the study period 254 usable images were obtained, with a minimum, mean and maximum interval of 1, 87 and 74 days, respectively.

2.2. Topographic surveys

Topographic surveys were conducted using an RTK-GPS system mounted on an all terrain vehicle (ATV) every month between October 2008 and April 2014. The surveys were conducted around low tide during the largest spring tide of each month, to maximise beach coverage. Typical survey extents are shown in Fig. 2. A total of 64 monthly surveys were conducted, with a minimum, mean and maximum interval of 16, 32 and 73 days respectively. The collected topographic data were used to generate digital elevation maps (DEM’s), which were converted from OSGB36 coordinates by rotation and translation to the same local grid as used by the Argus camera system (Fig. 3). The data were gridded at 20 m resolution in both the alongshore and cross-shore directions with a quadratic loess interpolation scheme (Plant et al., 2002).

2.2.3. Parameterisation of three-dimensionality

To objectively quantify the three-dimensionality of the subtidal bars, the standard deviation, $\alpha$, about the alongshore averaged cross-shore position, $X_c$, of the barlines was measured in keeping with previous studies of barline variability (Plant et al., 2006; Splinter et al., 2011). To obtain a single representative measure of $\alpha$ at the lower beach, contours were extracted from each DEM every 0.2 m between +0.2 m Ordnance Datum Newlyn (ODN) and −2.4 m ODN (between −1100 m and 200 m alongshore, thin dashed lines in Fig. 3), and the mean of the highest 1/3rd of $\alpha$ values was used. Shunt contours covering less than 2/3rd of the alongshore length of the survey area were omitted to avoid erroneous $\alpha$ values. It is recognised that across flat, non-sloping sections this parameter could incorrectly yield large values of $\alpha$. As the lower beach region at Perranporth was either planar and gently sloping, or exhibited 3D features in this data set, this was not deemed to be an issue and $\alpha$ was used in the form described above for consistency with the barline measurements. At sites which exhibit flat profile sections, other computations of $\alpha$ should be considered however. The MLWIN contour (thick dashed line in Fig. 3) was chosen to represent the cross-shore position ($X_C$) of the lower beach. Before calculating $\alpha$ the barlines and contours were linearly de-trended, then band-pass filtered between 25 and 1000 m. For reference, 0 m ODN is approximately Mean Sea Level (MSL) at this beach.

To estimate measurement errors Argus detected barlines were compared to residual barlines (Masseink et al., 2014) from 10 bathymetric surveys. The root-mean-square measurement errors, $\Delta X$ and $\Delta \alpha$, were 13.82 m and 4.78 m, respectively, at the outer bar. The inner bar data were deemed to have excessively large $\Delta \alpha$ (16.55 m), which is thought to be due to saturation of the inner surf-zone at low tide when the Argus images were collected. As such the inner bar data are not included in this study. The measurement error from the intertidal contours was conservatively estimated by summing the accuracy of the RTK-GPS equipment (+/−0.05 m) and maximum interpolation error (+/−0.05 m). Results of $\Delta X$ and $\Delta \alpha$ of 0.08 m and 0.16 m, respectively. As seasonal and inter-annual changes are of primary interest, the $\alpha$ and $X_c$ time series were low-pass filtered using a frequency domain Fourier filter with 1/42 days cut off, chosen to be sufficiently longer than the timescale of individual storms yet shorter than an individual season. Examples of $\alpha$ and $X_c$ measured at the lower beach, and outer bar are shown in Fig. 3. The data time series are plotted in Fig. 5, where vertical dotted lines indicate the data measured in Fig. 3.

2.3. Wave and tide data

Wave data were provided by a nearshore Datawell Wavegauge III buoy (Fig. 2), moored at a water depth of approximately 15 m. The half hourly wave statistics were used to calculate daily mean values of significant wave height, $H_s$, peak wave period, $T_p$, and peak wave direction, $\theta_p$. Occasional gaps exist in the wave series; daily mean parameters were calculated for days with at least 75% of measurements present, leaving 203 days (7.6%) over the period of interest (2007–2014) with missing measurements. These gaps were filled using adjusted wave data from the Sevenstones lightship, located in deep water approximately 70 km south-west of PPT (Fig. 2). A linear fit between the PPT and Sevenstones data was used to adjust the deep water data to approximate nearshore conditions. Correlation between the available PPT measurements and the concurrent adjusted Sevenstones measurements was high ($r=0.92$ and 0.81, RMSE = 0.36 m and 1.68 s, for $H_s$ and $T_p$, respectively). Remaining $H_s$ and $T_p$ data gaps (16 days, 0.6%) and all gaps in $\theta_p$ (203 days, 7.6%) were filled using time-series mean values. $H_s$ was calculated from linear theory using the formula of Larson et al. (2016), and depth-limited breaking was imposed using a commonly applied depth breaker ratio of 0.78 (Svendrup and Munk, 1946). A continuous prediction of tidal elevation over the period of interest was generated from pressure transducer data from a 3 month deployment (Poate, 2011). Example wave and tide data are shown in Fig. 4.

2.4. Modelling beach three-dimensionality

2.4.1. DST13 model

Davidson et al. (2010, 2013a, 2013b) applied the concept of disequilibrium stress to the prediction of cross-shore shoreline position at two Australian beaches; their formula are developed here to better suit the prediction of three-dimensionality ($\alpha$). The adapted model predicts the rate of change in $\alpha$, taking the following form (herein referred to as DST13):

$$\frac{\Delta \alpha}{\Delta t} = b + c \left( F + r F \right)$$

The forcing term $F$ is defined as the product of the incident wave power raised to the 0.5 exponent, $P_0^{0.5}$, and the normalised disequilibrium stress ($\Delta\Omega$):

$$F = P_0^{0.5} \frac{\Delta \Omega}{\Omega_{eq}}$$

$\Delta\Omega$ controls the direction of beach change (2D to 3D or 3D to 2D) and for convenience positive values are associated with increasing three-dimensionality by changing the sign of Eq. (1) (therefore $\Delta\Omega = \Omega_{eq} - \Omega$). Following Splinter et al. (2014) $\Delta\Omega$ is normalised by its standard deviation (denoted by $\alpha_{eq}$ in Eq. (5)), so that the rate of change in $\alpha$ is predominantly controlled by the rate parameter, $c$, and the wave power ($P_0^{0.5}$), rather than the magnitude of $\Delta\Omega$. $\Omega_{eq}$ is determined from weighted antecedent values of $\Omega$, and is highly dependent on a memory decay parameter $\phi$, which determines the number of days, $t$, prior to the present time at which the weighting function has dropped to 10%:

$$\Omega_{eq} = \frac{\sum_{i=1}^{t-10} \Omega(t-i)}{\sum_{i=1}^{t} \Omega(t-i) 0.1^{i-10}}$$

Low $\phi$ values (<30 days) indicate a short, storm dominated response time, whereas large values (>100 days) indicate that variations from the long-term mean conditions cause changes in $\alpha$ (Davidson et al., 2013a). Example weightings are discussed in Section 4.2.

Water depths over the bar crest, and by association tidal range, have been recognised as important modulators of wave driven horizontal circulation and therefore the development of 3D morphology (Caballeria et al., 2003a, 2003b; Almair et al., 2010; Austin et al., 2013). Austin et al. (2013) for example found that rip currents at Perranporth reached maximum velocities around spring low tide, which is likely to enhance the sediment transport potential. The forcing term $F$ is therefore
modified to include the combined effects of a large tidal range and high wave power by adapting a previously used parameter, the normalised wave power, $P_\eta_o$ (Morris et al., 2001; Loureiro et al., 2012):

$$P_\eta_o = \frac{P_0}{\eta_d}$$(7)

where $\eta_d$ and $\eta_s$ are the maximum daily and spring tide ranges respectively. When the tide range approaches its overall (spring tide) maximum, the ratio on the right-hand side approaches unity and the normalised wave power is maximised. Conversely during neap tides the ratio drops to around $\frac{1}{2}$, reducing the normalised wave power by half. In initial tests, inclusion of this tidally modulated power term made little difference to the lower beach predictions ($R^2$ was 0.61 in both cases), but significantly improved model skill at the outer bar, increasing $R^2$ from 0.32 to 0.42. The Relative Tide Range parameter (Masselink and Short, 1993) and HFI parameter (Almar et al., 2010) were also tested but did not yield comparable model improvements.

Recognising that increasing and decreasing three-dimensionality are caused by different physical processes, the forcing term $F$ is broken into positive and negative elements in Eq. (4):

$$F = P_{\eta_o} \frac{\Delta \Theta}{\Delta \Omega}$$ (8)

where $\Delta \Theta$ and $\Delta \Omega$ are the changes in the forcing term. The relative weighting of $F^+$ and $F^−$ is determined by the ratio term $r$ in Eq. (4); this is calculated from the wave data and is therefore not considered a ‘model free’ parameter. $r$ describes the relative efficiency of positive and negative disequilibria in altering the beach three-dimensionality, and long-term equilibrium is maintained if:

$$r = \frac{\sum F^+}{\sum F^-}$$ (5)

$N$ is the length of the time series, and the triangular over-bar represents a numerical operation that removes any linear trend in $F$, but retains the time-series mean. As negative disequilibrium (e.g. storms) often has higher associated wave power, a strong tendency towards beach straightening would be predicted if only $F$ was considered. Instead $r$ is determined such that zero trend in the forcing results in...
zero trend in $\alpha$, and therefore the term $(F^2 + cF^\rho)$ only contributes to a predicted trend if one exists in the wave forcing series. Any trend in $\alpha$ not explained by trends in the wave series is handled (almost crudely) by the trend term $b$ in Eq. (4).

To predict values of $\alpha$ at times $t, i$ and $r$ are computed from the wave data and Eq. (4) is numerically integrated with respect to time, yielding the final model equation:

$$\alpha(t) = a + bt + c \int_0^t (F^2 + rF^\rho) dt$$  \hspace{1cm} (10)

where $a$ is an offset that deals with non-zero mean values of $\alpha$. Eq. (10) is regressed against observed values of $\alpha(t)$ using a least squares method to optimize the coefficients $b, c$ and offset $a$. The optimal $\phi$ value is determined iteratively by changing $\phi$ from 1 to 1000 days, each time regressing the model against calibration data, and finally using the $\phi$ that yields the greatest $R^2$.

2.4.2. PHH06 model

The predictions of the DST13 model will be compared to an existing behavioural model. Recognising the coupling between $X_c$ and $\alpha$, Plant et al. (2006) proposed a linearised feedback model that assumes that rates of change in $X_c$ and $\alpha$ are dependent on their instantaneous values as well as the squared instantaneous wave height, $H_c$. The model involves two coupled differential equations and by necessity simultaneously estimates both $X_c$ and $\alpha$, taking the following combined form (herein referred to as PHH06):

$$\begin{bmatrix} \dot{X}_c \\ \dot{\alpha} \end{bmatrix} = \begin{bmatrix} a & -B \\ B & \frac{1}{N} \end{bmatrix} \begin{bmatrix} X_c \\ \alpha \end{bmatrix}$$  \hspace{1cm} (11)

where, for brevity, $X_c$, and $\dot{\alpha}$ denote rates of change, $X_c$ or $\alpha$ are predicted by integrating all terms in Eq. (11) with respect to time, then separately optimising the $[2 \times 2]$ coefficient matrices ($A$ and $B$) through least squares regression against observations. Full details are given in the original text (Plant et al., 2006).

2.4.3. Assessment of model skill

Four objective measures of the models' predictive ability are assessed, namely:

1. The squared correlation, $R^2$, between the model predictions, $X_c$, and measured data, $x$.

2. The root-mean-squared error (RMSE) between $X_c$ and $x$.

3. The Brier Skill Score, BSS, which quantifies the improvement that the model predictions provide over that of a pre-defined benchmark model, $x_0$ (in this case a linear fit to the data). BSS also considers the estimated measurement error in the data, $\sigma_x$ (m), and is therefore deemed highly suited to assessment of morphological models (Sutherland et al., 2004):

$$\text{BSS} = 1 - \frac{\left(\text{mean}(x - x_0)^2\right)}{\text{mean}((x - x_0)^2)}$$  \hspace{1cm} (12)

Angular brackets denote a time-series average value. Brier skill scores exceeding 0.0, 0.3, 0.6, and 0.8 are respectively classed as ‘poor’, ‘fair’, ‘good’ and ‘excellent’.

4. The Akaike's information criterion (Akaike, 1974; Kuriyama, 2012; Davidson et al., 2013a), AIC, provides an additional comparative assessment of model skill, where a penalty is incurred for the number of free parameter used, $m$.

$$\text{AIC} = n(\log 2\pi m + 1) + n \log \sigma^2 + 2m$$  \hspace{1cm} (13)

$n$ is the sample size, and $\sigma^2$ is the variance of the residuals (between validation data and the baseline or model predictions). Differences in AIC score ($\Delta$AIC) are used to compare the models; if a model's AIC score is smaller than another model's AIC score by at least 1, it is considered more appropriate (Kuriyama, 2012).

3. Results

3.1. Description of the temporal evolution of beach three-dimensionality

Time series of $\alpha$ (Fig. 5) show that the lower beach contours and outer barline range in alongshore standard deviation from 5–30 m to 10–70 m, respectively. The seasonal signals (solid lines) reveal some complex annual periodicity in beach three-dimensionality. Outer bar $\alpha$ displays pronounced minima in winter each year (December), after which $\alpha$ begins to increase in the new year and usually displays a local maximum ($\alpha \approx 40$ m) in spring between March and June. Summer is characterised by slightly lower outer bar $\alpha$ (20 m < $\alpha$ < 30 m), although 2009 and 2013 are notable exceptions, with high $\alpha$ (>35 m) was maintained between March and September. The last third of each year sees a reduction in outer bar $\alpha$ back to its annual minimum in winter. The lower beach similarly displays reduced $\alpha$ in winter (annual minima in December), after which $\alpha$ rapidly increases (annual maxima in January/February).

Between December 2013 and February 2014 an unprecedented series of long period, high energy swell events occurred, making it the most energetic 8-week period of waves in the last 65 years (Maselink et al., in press). One storm swell ‘Hercules’ featured wave heights and periods of 9.6 m and 22 s, respectively (Castelle et al., 2015). During that stormy winter the lower beach retreated landward, and became highly 3D in spring 2014. The outer bar became increasingly linear and moved offshore, but due to a subsequent lack of wave breaking over the stranded offshore bar after the storms, there are no measurements after February 2014 to indicate its recovery behaviour.

Autocorrelation of low-pass filtered and weekly resampled $\alpha$ time series (Fig. 6, upper panel) reveals an annual signal at the outer bar, with significant positive and negative correlations at lags of 1 and 1.5 years, respectively. The lower bar has a sub-annual periodicity, revealed by the peaks in autocorrelation at 15 and 30 weeks lag. Cross-correlation between $\alpha$ at the lower beach and outer bar (Fig. 6, lower panel) reveals significant positive correlation ($r \approx 0.5$) at negative lags up to 15 weeks, indicating that the lower beach becomes 3D 1–4 months before the outer bar.

3.2. Modelling results

3.2.1. Model hindcast

Fig. 7 shows DST13 model hindcasts. Summary statistics (Table 1) indicate that the model performed well, explaining 42% of the variance in $\alpha$ at the outer bar, (RMSE = 6.55 m) and 61% of the variance in $\alpha$ at the lower beach (RMSE = 2.84 m). Brier Skill Scores were ‘good’ for both the outer bar and lower beach (0.77 and 0.63, respectively). The outer bar predictions achieved higher BSS than those at the lower beach despite the other statistics suggesting that the model performed better for the lower beach. This is due to BSS scoring sympathetically towards data with larger estimated errors (the data lines in Fig. 7 demonstrate the greater measurement error, $\sigma_x$, at the outer bar).

3.2.2. Model validation

The predictive skill of the DST13 model was more rigorously tested by validating its predictions against an unseen portion of the data, as well as comparing the predictions to those made by the PHH06 model. Both models were calibrated using the first 60% of available data, and validation was performed using the remaining unseen 40% of the data (Fig. 8). As with the hindcast, the DST13 model predicted $\alpha$ well at the outer bar and lower beach, explaining 57–59% of the variance in the validation data (RMSE = 5.9 m and 3.2 m) and achieving ‘good’ and ‘fair’ Brier Skill Scores (BSS = 0.71 and 0.53, respectively).
frequency and timing of the annual fluctuations in the lower beach data were well predicted by the model, although sub-annual signals were not well reproduced. Although the magnitude and timing of some changes at the outer bar were not accurately predicted, DST13 did predict the large increase in $\alpha$ between January and April 2012, and decrease in $\alpha$ between October 2013 and February 2014. The PHH06
model also performed well for the lower beach contour data (Fig. 8 and Table 1), explaining 61% of the variance in the data (RMSE = 3.46 m) and achieving a ‘fair’ Brier Skill Score (BSS = 0.46). For the outer bar the PHH06 model predicted some annual variability but the phase and amplitude of the data were not reproduced. The positive ΔAIC scores (Table 2) achieved by the DST13 model (4 free parameters) indicate that the model out-performed a linear function to the data (2 free parameters) and the PHH06 model (8 free parameters), when the complexity of each model is taken into consideration.

4. Discussion

The model results indicate that disequilibrium stress is suited to modelling changes in beach three-dimensionality. It is particularly encouraging that the DST13 model performed well between December 2013 and February 2014 when an unprecedented series of long period, high energy swell events occurred. Throughout this period the model skilfully predicted three-dimensionality at the lower beach and outer bar, under wave conditions well outside the calibration data set. The time-varying equilibrium value ($\Omega_{eq}$) in the DST13 model is a weighted function of the antecedent dimensionless fall velocity and therefore accounts for antecedent waves, but also estimates the likely state that the beach is approaching, due to the relationship between $\Omega$ and beach state (Wright and Short, 1984). As process models have shown that alongshore non-uniformities do not grow indefinitely under constant wave forcing (e.g. Smit et al., 2008), the negative feedback implicitly represented in this temporally varying term maintains the stability of the system, appropriately constraining 3D growth. Allowing $\Omega_{eq}$ to

![Fig. 7. DST13 Model hindcasts plotted alongside the seasonal (low pass-filtered) PPT data at Perranporth’s outer bar (upper panel) and lower beach (lower panel). The thickness of the data lines indicates the measurement error (1σ).](image)

Table 1

<table>
<thead>
<tr>
<th>DST13 model</th>
<th>Free parameters</th>
<th>Model skill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>PPT OB</td>
<td>47.5 ± 3.16</td>
<td>(48.6 ± 4.75)</td>
</tr>
<tr>
<td>PPT LC</td>
<td>13.3 ± 1.40 (12.9 ± 2.32)</td>
<td>0.03000 ± 0.00148</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PHH06 model</th>
<th>Free parameters</th>
<th>Model skill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$</td>
<td>$B$</td>
</tr>
<tr>
<td>PPT OB</td>
<td>$-0.0000964 \pm 0.0000217$</td>
<td>$-0.00115 \pm 0.0000942$</td>
</tr>
<tr>
<td>PPT LC</td>
<td>$0.634 \pm 0.585$</td>
<td>0.628 ‘good’</td>
</tr>
</tbody>
</table>

Notes: Values are given to 3 significant figures for hindcast, (calibration) and [validation] data; note that a hindcast was only performed with the DST13 model. Ratio $r$ is grouped here as a parameter, but was not counted as one in the calculation of AIC. Values are given to 3 significant figures.
vary also permits for hysteresis to occur, which is often observed as beaches change state (Lippmann and Holman, 1990; Ranasinghe et al., 2004).

4.1. Comparison of the PHH06 and DST13 models

Both models predicted three-dimensionality better at the lower beach than at the outer bar, suggesting that the barline measurement error may be masking the relationship with incident waves. Despite poorly predicting outer bar \( \alpha \), the PHH06 model made accurate predictions of lower beach \( \alpha \). Unlike DST13, the PHH06 coefficients can describe positive or negative feedback depending on the results of the least squares regression. The self-interaction terms (left to right diagonal) in matrix \( A \) (Table 1) for the lower beach are both negative, showing that increases in \( \alpha \) reduce the rate of further changes in \( \alpha \), suggesting a stable and deterministic system (Plant et al., 2006). The fact that these terms are negative adds credence to the negative feedback approach used in the DST13 model and explains the remarkably similar predictions of lower beach \( \alpha \) made by the two models, despite the differences in driving parameters.

The inclusion of a tidally modulated power term in DST13 may explain why it performed better than PHH06 at the outer bar, which is often inactive during small tides. While DST13 is forced by wave and tide parameters, PHH06 requires knowledge of wave height and \( X_c \) in order to predict changes in \( \alpha \). Plant et al. (2006) argue that knowledge of both \( X_c \) and \( \alpha \) is necessary to predict either parameter, but as the DST13 model was able to predict \( \alpha \) with significant skill, and without knowledge of \( X_c \), this may not necessarily be the case. Fig. 9 reveals that seaward and landward lower beach contour positions that occur as the beach flattens (erodes) and steepens (accretes), are often associated with low and high three-dimensionality, respectively. This dependency may allow DST13 to predict \( \alpha \) without explicit knowledge of \( X_c \).

4.2. Effect of varying memory decay length (\( \phi \))

Fig. 10 (upper panels) shows the effect of varying the value of \( \phi \) on the performance and memory decay of the DST13 model. The peaks at \( \phi = 67 \) days and \( \phi = 1000 \) days reveal that the memory decay for the outer bar and lower beach is more than an order of magnitude different. Fig. 10 (lower panel) further demonstrates that equilibrium conditions vary greatly over a single year at the outer bar (storm-dominated timescale), but very little at the lower beach (seasonal response). The slight peak in model performance for the lower beach at \( \phi = 10 \) days indicates that a shorter response may also occur there, but data with a higher temporal resolution would be needed to investigate this further. Interestingly, the peak \( \phi \) value for the outer bar is associated with a drop in model skill at the lower beach (Fig. 10, upper left panel). This is likely to be due to the lagged behaviour of the outer bar, which was previously shown to reach peak values of \( \alpha \) up to 15 weeks after the lower beach (Fig. 6). Because high \( \alpha \) at the lower beach can occur alongside low \( \alpha \) at the outer bar (Fig. 6), a model suited with \( \phi = 67 \) days is likely to perform poorly for the other.

This lag also results in rate coefficients (c) with opposing signs at the outer bar and lower beach. As the outer bar becomes 3D weeks to months after annual peak wave conditions, the increase in \( \alpha \) coincides with positive \( \Delta \Omega \), yielding a positive c term. Conversely at the lower beach three-dimensionality begins to increase immediately following the annual peak wave conditions while \( \Delta \Omega \) is decreasing but still negative, and therefore yields a negative c term. The lagged increase in \( \alpha \) at the outer bar relative to the lower beach raises questions about whether 3D features formed at the lower beach influence or initiate the bed-surf coupling required to develop 3D features at the bars, but this question cannot be answered with the present data alone.

### Table 2

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<th></th>
<th>ΔAIC (Linear fit – PHH06)</th>
<th>ΔAIC (Linear fit – DST13)</th>
<th>ΔAIC (PHH06 – DST13)</th>
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<td>87</td>
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<td>PPT LC</td>
<td>13</td>
<td>18</td>
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</table>
4.3. Model limitations and improvements

Although processes are not explicitly modelled, DST13 assumes that changes in three-dimensionality occur as a result of normal, open beach circulation. For example the model presently ignores the effects of alongshore oriented wave power, which idealised modelling (Ranasinghe et al., 2004; Splinter et al., 2011; Garnier et al., 2013; Price et al., 2013) and field studies (Holman et al., 2006; Thornton et al., 2007; Price et al., 2011; Price et al., 2013) have shown to be an important cause of sandbar straightening at some sites. It is proposed that this could be accounted for simply in the model by incorporating the absolute value of the alongshore component of wave power $|P_a|$, either as an additional model parameter at the cost of one extra regression term, or by incorporating it into forcing term $F$. When tested, this altered the model results very little due to the small contribution of obliquely incident waves at Perranporth, where alongshore-oriented power is typically an order of magnitude smaller than the total wave power. This modification was therefore not included in the present model, but provides a basis for further model development at sites with significant alongshore wave power.

As the degree of three-dimensionality at dissipative-intermediate sites (such as Perranporth) is inversely related to $\Omega$ (Wright and Short, 1984), $\Omega_{eq}$ provides a suitable equilibrium value for three-dimensionality. However, beaches that transition from the TBR to LTT states and eventually to the R end state, feature decreasing three-dimensionality as $\Omega$ decreases. Therefore in order to generalise the model to sites that feature intermediate-reflective beach states the model would need to be adapted, such that when $\Omega_{eq}$ exceeds an appropriate threshold the sign of the disequilibrium is inverted. At that point increases in $\Omega$ would change from driving an increase in $\alpha$ to driving a decrease in $\alpha$.

The improvements achieved at the outer bar by moderating the wave power based on the tidal range reflect the fact that significant sediment transport can only occur under sufficient wave breaking (Splinter et al., 2011). A large tide range reduces the water depth over the outer bar at low tide, and therefore increases breaking and sediment transport which enhances the rate of change in the bar. Conversely under neap tides, when water depth over the bar is large relative to the wave height, sediment transport (and therefore changes in the bar) can significantly...
reduce due to the lack of breaking. These processes may also explain the storm-dominated timescale of the outer bar response, as a previously inactive bar can rapidly change when larger storm waves break. Although the tidally modulated wave power term reduces the rate of morphological change under small tides and waves, completely reducing bar change to zero when the subtidal bar is inactive may yield further improvements.

5. Conclusions
A dataset of 5.5 years of quasi-daily bar measurements, and quasi-monthly intertidal beach surveys from Perranport beach (Cornwall, UK) were used to quantify seasonal to inter-annual changes in beach three-dimensionality ($\alpha$), the outer bar displayed significant annual periodicity, with annual minima in winter and spring respectively. The lower intertidal beach displayed a similar periodicity, but developed three-dimensionality 1–4 months before the outer bar. A simple equilibrium model (DST13) was developed, which made skilful hindcast and calibration-verification predictions of $\alpha$, explaining 42% and 61% of the variability in outer and lower bar beach three-dimensionality, respectively. The model was able to make skillful predictions during an unprecedented series of long period, high energy swell events, including the most energetic 8-week period of waves measured in the last 65 years (December 2013 to February 2014), which were outside the training data range.

At present the model assumes that open beach, cross-shore processes, such as horizontal wave-driven circulation control the morphodynamics, but alongshore-oriented wave power should be considered at sites where it is significant relative to the normally oriented power. Negative feedback was found to be an important process governing the changes in beach three-dimensionality. While free morphological behaviour may drive 3D growth, negative feedback processes exert stability in the system, making it inherently predictable using a temporally varying equilibrium value, as used here. In its present form the model out-performed a simple baseline model (a linear fit) as well as a comparable linearized feedback model from the literature (Plant et al., 2006), providing the first long-term (multi-year) predictions of seasonal to inter-annual beach three-dimensionality for a macrotidal beach.

Acknowledgements
We would like to thank Martin Austin, Tim Poate, Tim Scott, Erwin Bergsma and Sam Proctor for their hard work in collecting much of the survey data. Thanks also go to Peter Gardenton and Megan Sheridan for their technical support. We would also like to thank the NERC DRRBS project (code: NE/H004262/1), the EU SWOFFIA project, and the Plymouth University Marine Institute for funding the beach surveys.

References
Anticipated coastal impacts: What water-users think of marine renewables and why

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Abstract

This article explores the physical coastal impacts that are anticipated by coastal water-users in the lee of the Wave Hub marine renewables test facility (Cornwall, UK). In depth, semi-structured interviews were analysed using a grounded theory approach in order to explore contemporary anticipations as well as the process of opinion formation that has occurred for participants. The interviews focused on anticipated impacts to inshore wave conditions, beach sedimentation, rip current formation and beach safety. The results indicate that participants constructed their anticipations by weighing their perceptions of the technology against their perceptions of the coastal environment. A conceptual model is presented which allows the degree of anticipated coastal impact to be predicted, by categorizing technologies and coastal environments in terms of their perceived properties. The model indicates that wave energy deployments which are perceived to be large scale, close to shore, wide, stationary, or extracting high percentages of energy are likely to invoke anticipations of significant or severe coastal impacts. Conversely, those which are perceived to be small scale, far from shore, narrow, moving, or extracting low percentages of wave energy are more likely to invoke anticipations of insignificant or no coastal impact. Interestingly, the level of anticipated impact was most often based on device properties such as form or siting, and was rarely influenced by device extraction efficiency. The implications for future marine renewables deployments are discussed.

1. Introduction

The UK government plans to install sufficient renewable energy capacity to supply 15% of the UK’s gross energy consumption by 2020 (H.M. Government, 2009). This has been incentivised by EU targets to help mitigate climate change and improve energy security (Commission of the European Communities, 2008). Marine renewable energy (wave and tidal) is calculated to have a large exploitable capacity in the UK, with wave and tidal energy capacity at 50 TWh/y and 21 TWh/y respectively, equating to approximately 20% of the UK’s present electricity needs (Carbon Trust, 2011). Marine renewable energy (MRE) is hoped to provide a significant contribution to the UK’s renewables mix in the long term, potentially providing 20% of the UK’s electricity demands by the year 2050 (H.M. Government, 2009).

Despite these targets, the uptake of renewable energy has been slower than was hoped, and it has been widely observed that local opposition from stakeholders and the general public has created a considerable barrier to terrestrial projects in the UK (Walker, 1995; Bell et al., 2005; Devine-Wright, 2005; Wolsink, 2006; Wüstenhagen et al., 2007; Haggett, 2008; McLachlan, 2009). Additionally, the physical separation of offshore installations from communities has not allayed concerns or opposition as might have been expected (Bailey et al., 2011). It is apparent that visual, sound and other proximity dependent impacts are far from the only issues that can rouse opposition to renewable energy projects. With the optimistic EU and UK targets for MRE installation, the occurrence of public and stakeholder oppositions to projects is likely to be an ongoing issue that will need to be dealt with case by case; in particular, interactions with coastal stakeholders are likely to increase if this relatively new sector expands at the target rate.

1.1. Wave Hub controversy

The Wave Hub (WH) facility in Cornwall (see Fig. 1) is a marine renewables test site, predominantly designed for the purpose of...
trialling wave energy converters (WECs) prior to commercialisation. The infrastructure was installed in 2010 (Wave Hub, 2010), and although WECs are yet to be deployed at the site, a number of device developers plan to install full scale prototypes between 2014 and 2015 (Wave Hub, 2013a, 2014). These include point absorber (http://www.seatricity.net/) and rotating mass (http://www.wello.eu/) type WECs. There is also a possibility of floating offshore wind devices being trialled at Wave Hub (Wave Hub, 2013b). During the proposal stages the WH project met objections from commercial fishing, shipping and tourism stakeholders, but of specific interest to this study is the objections raised by the surfer community. The North coast of Cornwall is a popular area for coastal recreation, and during the Wave Hub consultation there was an outcry from a collective of UK surfers concerned about the possibility of a reduction in wave height and wave quality, as well as impacts to sediment transport (Baxendale, 2006; Farwagi, 2006). This group rallied over 500 emails of objection (McLachlan, 2009) via a surf forecasting website, arguing that the project would be better sited elsewhere, as the value of the electricity generated would be far less than the value of the surfing industry in Cornwall considered to be threatened by the project (Baxendale, 2006; McLachlan, 2009). It is unclear whether these concerns were limited to the Wave Hub as a test site, or extended to full commercial deployments that may or may not occur in the future.

Although not all surfers and coastal water-users shared this objection (environmental group ‘Surfers Against Sewage’ openly supported the WH), it nonetheless raised concerns among many of the WH stewards. As West et al. (2009) point out, this is not a trivial objection by what appears to be a self-concerned recreational group; there are many coastal communities that are dependent on the economic income from surfing (estimated at £21 million in Cornwall in 2001 (Arup, 2001)), or other water based activities (estimated at £300 million in 2007 (Environment Agency, 2007)). Water-user groups will have both shared and individual concerns about coastal impacts from MRE installations, and despite a disjointed opposition from water-users over the WH, there is a possibility that future proposals could meet a far more collective opposition from this stakeholder group (West et al., 2009). The concerns of water-users with regards to Wave Hub as a test facility need to be fully understood, including the processes through which concerns have come about and have been altered. This will better inform consultation and avoid opposition from this group if commercial deployments are proposed in the future.

1.2. Existing research

A number of studies have investigated public perception of the WH project (McLachlan, 2009; West et al., 2009; Bailey et al., 2011). Although only a test facility, it provides an early glimpse into attitudes towards wave energy and lessons learned at this site may prove extremely useful when engaging with the public in the future. Most studies have attempted to understand positions of support and opposition; in simplistic terms the objections raised by surfers over the WH are already known (see Section 1.1), as they were openly articulated during the conflict and in previous research (West et al., 2009; Bailey et al., 2011). However, there is a
lack of deeper understanding about the opposition raised by surfers, and the concerns of the wider coastal water-using community are still unknown.

'Place-protective action' is a concept that has been used in existing studies to explain such opposition (Devine-Wright, 2009). It is proposed that when changes to a place threaten to disrupt emotional attachments and aspects of identity, action may be taken by a community to avoid the changes. A lack of fit between an individual's interpretations of place and project is also thought to be a precursor to opposition (McLachlan, 2009; Devine-Wright, 2011). Being relatively broad concepts, 'place-protective action' and 'place and project interpretation', encompass the opposition raised by many different stakeholders (including surfers), but they struggle to predict when a particular group will take action, especially one with unique concerns such as surfers. Such theoretical explanations have also been critiqued for ignoring certain 'materialistic' considerations (Bailey et al., 2011); indeed, it is possible that many surfers merely saw a threat to a commodity which they use. Bailey et al. (2011) conducted a quantitative survey of public perceptions of the Wave Hub, but questions were posed in a way which could change wave quality; however, the study did not target water-users, nor was it conducted in the region that is predicted to be affected by such changes. They conclude that notions of 'risk and reward' better encapsulate the reasoning process that individuals use. This approach is useful as a predictive tool, but only if an understanding exists of what an acceptable risk to a given group is. In other words, understanding is needed of the point at which the perceived risks (e.g. coastal impacts) outweigh the perceived rewards (e.g. local economic benefits, mitigation of climate change etc.), and therefore warrant opposition. It is arguable that the perceived rewards of MRE are better understood than the perceived risks, as they are more generic across projects and stakeholder groups, whereas the risks may be more stakeholder-specific. Where other studies have examined public perceptions on the whole, this paper aims to specifically address the perceptions of the water-using community in the lee of the wave hub facility, by investigating the coastal impacts that are anticipated.

2. Research aims

This study aims to explore what physical coastal impacts (if any) coastal water-users anticipate from the Wave Hub facility, what degree of impact is anticipated, and crucially, how these anticipations have been formed. This will fill important knowledge gaps regarding this stakeholder group. Further to this it is hoped that the study will provide sufficient understanding to be of use in planning and public engagement for future MRE projects.

3. Methodology

A qualitative approach was deemed most appropriate for this study as the subject has been poorly investigated thus far, and explorative research is needed (Denzin and Lincoln, 1998). Bailey et al. (2011) argue that in the case of the Wave Hub project, quantitative studies of public opinion are presently needed to clarify issues relevant to a given community before qualitative studies can make a deeper analysis. It was deemed more appropriate in this case to adopt qualitative enquiry first, so as to illuminate unforeseen, salient issues that may otherwise be missed through a quantitative, pre-determined set of answers. Statistical generalisation about water-users as a population are not being sought here; instead a richer understanding about how they construct their opinion on MRE technology and coastal impacts is sought.

3.1. Grounded theory

Grounded theory was the chosen research strategy, as its exploratory and explanatory nature makes it suited to situations where limited previous research has been conducted (Glaser and Strauss, 1967; Strauss and Corbin, 1998; Charmaz, 2006; Pedersen et al., 2007). It is also considered highly suitable when investigating a process or experience over time (Morse, 1998), as it is likely to be the case with the formation of perceptions and opinions of MRE. Grounded theory does not attempt to fit existing theories to empirical data, but instead is predominantly an inductive approach that allows for concepts and theories to form from the data itself. In-depth, semi-structured interviews were chosen as the primary data collection technique and were conducted iteratively and simultaneously with coding and data analysis, as is considered fundamental to this methodology (Glaser and Strauss, 1967).

An interpretive, constructivist perspective was adopted. Briefly, this epistemology studies how people construct meanings about the world around them, and acknowledges the interpretation that is made by both the researcher and the research subject. Many of the more positivist grounded theory techniques condensed by Glaser and Strauss (1967) and Strauss and Corbin (1998) have been used as they are fundamental to the methodology; however a more contemporary, constructivist analysis will be conducted, and the theory generated will be a construction of the researcher. It is accepted in constructivist grounded-theory that the way the findings are rendered could vary if repeated by another researcher but the findings themselves should not vary significantly (Charmaz, 2006). Besides having this epistemological standpoint, the study was entered with minimal preconceptions about theories relevant to the topic, so that theory generation could occur in an unbiased and uninfuenced manner. Psychological and social theory will however be called upon in the discussion of the findings (and was incorporated in Section 3.1 after data analysis).

3.2. Sampling

Purposeful sampling was adopted in order to find coastal water-users who frequently (once a week) visit at least one of the beaches in the study area, to participate in activities dependent on wave and coastal conditions. The area encompasses a 13 km stretch of coastline on the North Coast of Cornwall, UK, between Perranporth and Porthtowan. As is demonstrated in Fig. 1, modelling studies predict that any wave shadowing from the Wave Hub will be most acute in this region (Miliar et al., 2007; Li and Phillips, 2010), hence its selection as the study area. Participants were not required to have any prior knowledge about MRE or WH. Many were prominent members of their coastal community (for example, business owners, senior lifeguards etc.), as these were the most accessible informants. Snowball sampling was also used to aid in accessing suitable participants. The sample group may be classed as ‘experiential experts’ (Morse, 1998) in the local conditions, having used the beaches on a weekly basis in some cases for over 40 years. Table 1 shows the water users represented by the sample group; although this does not cover every possible coastal water activity, wave dependent activities were well represented, as were condition dependent professions such as life-guarding and surf instructing. Sampling was continued until saturation of the theory became apparent; in other words, until freshly collected data was no longer modifying or challenging the theory (Strauss and Corbin, 1998; Charmaz, 2006). This was apparent after 14 interviews, and 5 more interviews were conducted before saturation was confirmed and sampling stopped (19 interviews were conducted in total).
66

Table 1
Characteristics of the study sample.

<table>
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3.3. Interviews

Interviews were conducted at a location suggested by the participant, usually at their home, workplace, or a café, and lasted on average 40 min in each case. Participants were first given a brief questionnaire to complete, with 6 tick-box questions intended to gain baseline information on the respondent, including which beach they most often visit, in what way they use the beach, and to gain baseline information on the respondent, including which of theoretical sampling (Charmaz, 2006). The interview schedule added to the schedule to enhance future interviews, in the tradition of the case in hand, to thinking more generally and theoretically (Strauss, 1967). Eventually the categories and their properties emerged from the initial interviews, questions were added to the schedule to enhance future interviews, in the tradition of the constant-comparative method; this involves comparing incidents in the data, and is used to reveal the defining properties of each category (Glaser and Strauss, 1967). Eventually the categories and their properties became more abstract, and analysis progressed beyond description of the case in hand, to thinking more generally and theoretically (Strauss and Corbin, 1998). Once all the relevant properties of a category were thought to have been identified, each respondent was placed on the ‘dimensional scale’ of each property (for example, a scale might range from ‘small’ to ‘large’). A quote or short summary that identified their position dimensionally was noted. Having identified the first 10 participants’ dimensional position for each property of each category, key themes were sought out by looking at whether or not respondents aligned dimensionally (Strauss and Corbin, 1998). If three or more respondents aligned dimensionally for a given property, it was tentatively considered a theme. For example, most of the initial respondents predicted ‘impact to wave height’ (property) to be ‘insignificant’ (dimensional position). Variations from the key theme and negative cases were identified and noted. An initial theory was proposed at this stage, based on the themes noted and the relationships observed between the key categories. After the first 10 interviews the coding was conducted more selectively (Strauss and Corbin, 1998), with coding focussed more on the key categories identified in the initial analysis just described. After every 3 subsequent interviews the theory was tested against, and if necessary, modified by the new data. The theory was therefore developed iteratively, in an inductive—deductive cycle throughout the study.

4. Results

Participants anticipated a range of impact levels on various elements of the coastal environment, varying in magnitude from ‘none at all’ to ‘severe’. The main impacts discussed were reductions in wave height or wave quality, and changes in sediment transport; other impacts that were mentioned included coastal erosion, changes in rip current behaviour, and the possibility of devices breaking free and washing ashore. It was observed that when discussing their anticipations, participants revealed their perception of wave energy technology and their perception of the coastal environment, and often one would be weighed against the other while discussing the likelihood of an impact. The following sections will describe the themes observed in each of these key categories (anticipated impact, perception of technology, and perception of nature). Interview extracts will be used to evidence the findings; pseudonyms have been used in all cases, to ensure participant confidentiality.

4.1. Anticipated impacts

4.1.1. Impacts to waves

Most participants anticipate that the WH will have an ‘insignificant’ impact on both the height of coastal waves and the quality of surfing conditions, Ryan, a surfer who has lived in the region most of his life, suggested that if there was any impact at all, it would be very localised and limited to small wave conditions only.

“I can’t believe it will make any difference, maybe on a very small swell, at a very sort of narrow window, you know one strip of beach that’s sort of directly in the swell direction might lose a few inches, but I just can’t see it … making any impact at all to be honest.”

However, despite not being concerned about impacts to wave height, surf-school owner Terry was concerned that the quality of surfing waves might be impacted significantly, if the characteristics of transmitted waves are altered.

“If you reduce the (wave) period, you’re reducing the energy in the swell, you’re reducing the speed, you’re reducing the potential energy that’s going to land on the beach, you know … so potentially it could affect the actual end result on the shoreline.”

4.1.2. Impacts to sediment transport and rip currents

Anticipated impacts to sediment were more varied between participants. Some foresaw no impact to coastal sediments, while others like Ben, a surfer and senior lifeguard in the region, anticipated that the impact could potentially be severe.
We’re always having that (wave) direction aren’t we. So it could reduce the amount of deposit onto the beach and that kind of renewing of the sand dunes and everything like that ... there will be less movement of course, there has to be hasn’t there."

Impacts to sedimentation were usually informed by the level of wave impact anticipated. Some assumed that if an insignificant impact to waves was foreseen, then the same would apply to coastal sediments and rip current formation. Cassia, a competition level surfboat rower, anticipated a possible change in the characteristics of rip currents, but emphasized that she had no concern about the WH increasing the hazard they pose, as she saw rips as an existing hazard that has always required awareness.

4.1.3. Impacts from future installations

Participants’ predictions of coastal impacts from future MRE deployments were similarly varied, ranging from no anticipated impact, to potentially severe impacts; most suggested however that their opinions were not yet formed, as they would be guided by presently unknown properties of future deployments. Interestingly, many participants felt that impacts from larger and more efficient deployments in the future would be determinable from, and proportional to, any impacts that might result from initial deployments like the WH. Consequently, Mark (a senior lifeguard) made the assumption that if insignificant impacts resulted from the WH, then the same would be true of future installations.

4.2. Perception of technology

Four main properties were referred to by participants when describing wave energy technology; these were its ‘form’, its ‘scale’, its ‘siting’, and its ‘use of resource’. Commonly the symbolism of a ‘barrier’ was used when discussing potential impacts to waves, and the properties of form and scale were frequently used to support why the technology had not been interpreted as a barrier. Equally some discussed under what conditions they would have interpreted this technology, or other MRE technology, as being a barrier. It was often revealed that imagery from media sources had heavily informed perceptions of form and scale, while most participants stated that they had not seen, or sought, what they considered to be technical information. Those who were concerned about significant impacts to waves generally used reasoning involving the technologies use of resource, rather than referring to its form, scale or siting to support their claims. In cases where participants revealed that technical information (primarily impact assessments) had informed their perception of the technology, both significant and insignificant impacts were foreseen. Commonly this information influenced participants’ perception of the technologies use of resource.

4.2.1. Form

Many participants discussed the form of the WEC’s that they were aware of, Ian, a senior lifeguard in the region, perceived them as being narrow and designed to operate in line with swell (i.e. perpendicular to wave crests, such as the Pelamis device), and consequently argued that they were not creating a barrier and would not significantly affect passing waves. The property ‘form’ was developed and to some extent triangulated by his suggestion that if a device was wide it would have a greater impact.

“It does depend on its make up because if it’s a long slender device, that kind that stays in line with the swell, I can’t see that it’s going to cast much shadow, and I can’t see that it’s going to dramatically, you know, reduce the energy in the actual waves ... unless there was some different device that was ... spread wide and cast a big shadow.”

The technology was occasionally compared to similar objects in the ocean that weren’t perceived as creating a barrier to waves because they float and don’t extend far beneath the ocean surface (such as large ships). Imagery of the technology moving with waves led Tim, a local surf-clothing business owner and surfer, to interpret the technology as being in harmony with the resource it is there to extract. He differentiated it from non-moving, man-made structures which are perceived as a wave barrier.

“A breakwater is a building. Concrete. It doesn’t move. Whereas the wave hub ... will rise and fall like a rubber duck ... it will work with the environment ... when I think of the Wave Hub I think of something far softer, in its presence in the sea.”

4.2.2. Scale

Another property that was often discussed is the perceived scale of the installation. For senior lifeguard Joel, this confirmed that the technology will not create a barrier to waves, as he perceived the scale of the technology as being very small relative to the scale of the environment it will operate in.

“[...] I can’t see it dramatically reducing the power of the swell I just can’t, because it is really just a pinpoint in the ocean, so I can’t see it doing that.”

Participants were asked about a hypothetical, larger-scale deployment of wave energy converters and the impacts it could have. It was indicated by some that if the scale of the technology was perceived as being large, then the anticipated impact would be greater.

4.2.3. Siting

Many participants considered the siting and in particular the distance of the technology from their local beach, as being strongly connected to the impacts that they anticipate. Terry the surf-school owner perceived the WH as being very distant and this symbolised to him that the technology will be unconnected to local sediment transport and would therefore have no impact at all on it.

“I think it’s probably out to sea enough that it’s not going to really affect the local conditions that much really ... I can’t see any real sediment issues locally; I think it’s well placed in that respect.”

Equally, surfboat rower Cassia mentioned that future, larger-scaled deployments would need to be sited further from shore to negate an increase in impact. Experienced paddle-boarder and surfer David, demonstrated how a combination of properties (siting and form) constructed his perception of the technology, and determined whether or not an impact to waves was foreseen. He was asked if he thought wave height or recreational water quality would be affected.

“No if they’re 10 miles off (shore), no, they’ll just roll over it, or through it and round it. It’s not like a barrier, so it won’t have any effect on it at all.”

4.2.4. Use of resource

Participants who used one or more of the previously described properties to substantiate their anticipated impacts, often assumed that because the technology is not perceived as a physical barrier (such as a breakwater), that impacts to waves will be insignificant. This assumption potentially ignores the concept of energy extraction. All of the participants identified that one of the purposes of
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the WH was to generate electricity from passing waves, but many of them did not appear to associate this with the potential to take energy away from waves in order to achieve this. A number of participants, including surf-school owner Rob, described the technology as ‘only harnessing’ wave energy, which alludes to this assumption and indicates that these participants perceived the extraction of energy to be minimal. An extreme example of this was provided by experienced surf-board shaper Tom. “They’re not actually taking the energy away; they’re just using it to generate new energy.”

For other participants however it was clearly perceived that if energy is extracted from a wave, then the energy remaining will be less, and some form of impact could result. Describing the technology as ‘taking energy away’ from waves was commonly used by participants who were concerned about significant or severe impacts, like surf-school owner Terry, to support their answers. “Just from a science background, thinking well, if you’re going to reduce or take energy out of something, it’s going to reduce or impact it in some way, so it’s got to have an effect. So if you’re taking energy out that’s going to reduce the swell size.”

4.3. Perception of nature

Certain properties of the coastal environment made up the participants’ perception of ‘nature’ (in its present context). While properties of the technology were explicitly used by all participants to justify whether or not an impact was foreseen, not all explicitly used properties of nature in the same way. However; those who did not, often revealed their perceptions elsewhere. Perception of nature was used by participants as the context on which to assess the likelihood of impact. The properties that commonly informed perceptions of nature were the ‘abundance of the resource’ and the ‘sensitivity of the environment’.

4.3.1. Resource

A common perception was that waves and wave energy are abundant, with a number of people commenting on the vast amount of energy in ocean waves. Participants like surfer and lifeguard Mark, were of the opinion that even if energy is extracted from waves, the impact would be negligible, as they believe that there would still be an abundance left. This demonstrates how perception of technology (i.e. use of resource) is weighed against perception of nature (i.e. abundance of resource), and in this case the former is outweighed by the latter.

“You think about the swell that’s 10 miles out to sea. You think of the energy that that’s got. I can’t see it affecting it.”

Some participants commented on the regular occurrence of large wave conditions at their local beach, or similarly the infrequency of small or flat wave conditions, also indicating that they perceive the resource as being abundant. Conversely, some people mentioned the infrequency of high-quality surfing conditions in the region. Surf-school owner Terry had previously expressed his concern over the potential for the WH to impact high-quality surfing waves by altering wave characteristics. This participant viewed the resource as being scarce and foresaw that the potential impact could be significant.

“Surfing is a fickle thing, you only get those few days a year where it’s that good, so you want to keep that, you know maximise that as best you can.”

4.3.2. Environment

Some participants indicated that they perceived coastal sediment as being sensitive, and foresaw that impacts could therefore be significant or severe. Despite anticipating insignificant impacts to wave conditions, Toby, a body-surfer and swimmer, felt that impacts to sediment could be far greater, because of his perception of its sensitivity.

“It won’t affect the size of waves for surfers, but it takes far less of a wave height to change the way sands are shifting and the way coasts are eroding.”

Seasoned lifeguard Ian recalled an occasion when he had perceived that human activities had significantly affected local morphology and surfing conditions. In this case, past impacts to the coastal environment informed his perception of the sensitivity of the environment.

“I remember one year we had a dredger, quite a big dredger, dredging continually off of Porthtowan and Chapel Porth, and Porthtowan had their worst years surf … it took about three years to recover … that’s the only thing that would worry me is sand movement.”

In some cases participants viewed coastal conditions as being dynamic; this often resulted in the opinion that impacts would be unnoticeable as the anticipated level of impact was foreseen as being less than the natural degree of fluctuation. It should be noted that this does not indicate that a lesser impact was anticipated; rather a less-noticeable impact was foreseen. Because of this complexity, this property (degree of fluctuation) has been excluded from the conceptual model shown in Fig. 2.

4.4. Summary of results

There was a clear interplay between participants’ perception of the proposed technology, and the environment in which the technology is being installed. These perceptions appeared to be influenced by certain properties of the technology and certain properties of nature, and the dimensional location of the participant on these property ‘scales’ ultimately determined whether or not an impact was anticipated. The conceptual model presented in Fig. 2 predicts a level of anticipated impact, by positioning a proposed technology on the property scales on the left hand side. This requires an estimation of the likely public perception of the technology. If perceptions about the natural environment can be estimated, then these may also be positioned on the model. The sum of the perceptions qualitatively determines the anticipated impact. Although not all participants discussed all of the observed properties, all of them used at least one or more properties to justify their anticipations; the conceptual model integrates all of the observations into a predictive framework. Surf-board shaper Tom summarised the observed construction of opinion in the following statement:

“You know it’s only common sense … it’s not like I’ve trawled all through the internet and read everything about it. I’ve just seen it, I understand the technology, and I understand the ocean.”

5. Discussion

The findings of this study imply that wave energy technology is likely to be assessed by individuals on a technology-by-technology basis; participants did not merely classify all wave energy
technology in the same way. In other words they attributed their anticipations of impact to properties that are not uniform across all wave energy technologies, and in many cases revealed how their level of anticipated impact would change if the properties were perceived differently. This indicates that different WECs become commercially deployable, and different scales of deployment are proposed, water-users are likely to anticipate different levels of coastal impact.

This has significant implications for certain devices. By comparing a shallow water, hinged-flap type WEC (for instance the ‘Oyster’ device developed by Aquamarine Power) and a deep water, in-line attenuator WEC (for instance the ‘Pelamis’ device developed by Pelamis wave power), and positioning them on the conceptual model in Fig. 2, it becomes apparent that some people may perceive the hinged-flap device (form = relatively wide and stationary, siting = nearshore) to be at the top of the anticipated impact scale, whereas the in-line attenuator device (form = relatively narrow and moving, siting = offshore) may rate at the bottom, regardless of the energy rating of the two devices (i.e. their use of resource).

It is not unrealistic to assume that water-users may also perceive other marine renewables technologies in terms of similar properties. A number of participants discussed their perceptions of offshore wind farms or tidal barrages, and mentioned properties such as form, scale and siting. The model may therefore be applicable outside the context of wave energy and possibly even outside the realm of MRE. Naturally it would require further validation in order to be used in wider contexts.

It is feasible to say that the same technology, proposed at two different locations, might face different levels of support or opposition if the coastal environment is perceived differently in those two locations. As with perception of technology, perception of nature is highly subjective, but it may well be that common perceptions exist in a certain region. Although wave energy projects are likely to be sited in regions with abundant wave energy, tidal energy installations may be proposed in locations with scarce wave resources, and may therefore invoke fears of a significant impact to waves. Likewise some locations may have experienced past changes in coastal conditions that have been attributed to human interference, and this might enhance the perception of the environments sensitivity to engineering activities.

Participants’ perceptions were largely uninfluenced by technical information or impact assessments. Firm views existed, despite there often being a lack of technical understanding (also found by Devine-Wright (2007)). As Slovic (1987) observed, risk is assessed by the majority of people using intuitive judgements (‘risk perceptions’) and not through technical assessments; this is precisely what has been observed in this study. Environmental Impact assessments (EIA) and consultation cannot be relied upon to relay information to the wider public, nor can the public be relied upon to seek out information for themselves. Media was seen to be the most powerful informer (also observed by West et al. (2010)), and is likely to play a significant role in influencing peoples ‘intuitive judgements’ of technologies to come in the future. With this in mind it is suggested that where possible, the properties described in the conceptual model (Fig. 2) are carefully considered when engaging with coastal water-users, or preparing media content regarding a new technology. The results also suggest that there are areas of misunderstanding with regards to wave energy technology. In particular, the concept of extracting energy was poorly understood by a number of participants and this issue perhaps warrants better public education.

It has been proposed in some papers that opposition is likely to arise when a mismatch occurs between an individual’s interpretation of ‘place’ and their perception of ‘technology’ (McLachlan, 2009; Devine-Wright, 2011). As first glance this appears to fit well with the conceptual model presented here, but it should be noted that only a part of the interpretation of the technology has been considered in this study: a person’s symbolic interpretation is made up of more than just their perceptions of form and scale etc. Other factors, such as the ‘environmental status’ of the project and the ‘significance of the electricity produced’, have also been found to affect an individual’s interpretation (McLachlan, 2009). Bailey et al. (2011) propose that a better descriptor of the reasoning process undertaken by individuals, is the notion of a wager between perceived risks and perceived rewards. This resonates well with the findings in this study; however, the results presented here go a step further in that they start to allow for prediction of when risks will be perceived as being high or low in the specific context of water-users (assuming that physical coastal impacts are a priority risk to coastal water-users). Many participants perceived that impacts in general would be insignificant and their perception of risk was therefore low, allowing the perceived rewards (local economic benefits, energy security, mitigating climate change etc.) to easily outweigh these risks, explaining the high levels of support.

Fig. 2. Conceptual model of the construction of anticipated coastal impacts by participants, showing the weighing of technology and nature perceptions. The sum of the various properties qualitatively predicts the overall anticipated level of impact.
observed for the WH project. These perceived risks may well increase as new technologies are proposed, and the scale of deployments is increased.

Another important point is that many participants suggested they were awaiting the ‘results’ of initial deployments such as the WH, in order to make a more informed assessment of coastal impacts to come from larger-scale deployments. Perceived impacts from the WH are likely to leave a long-lasting impression, and will influence perceptions of future projects and react to future technologies in public perception and react to future technologies (Slovic, 1987). If misconceptions arise over impacts from sites such as the WH, water-user’s perception of MRE technology could be severely altered, and may be very difficult to rectify.

6. Conclusions

This study aimed to explore what physical coastal impacts are anticipated by water-users, in the run up to the first trials of wave energy converters at the Wave Hub facility. An additional aim was to explore how these opinions were formed, in order to foresee how user concerns, in relation to future MRE proposals, inform the public consultation/engagement process. During interviews participants discussed the likelihood and severity of various coastal impacts; namely, reductions in wave height or wave quality, changes in sediment transport, coastal erosion, changes in rip current behaviour, and the possibility of devices breaching free and washing ashore. The anticipated level of impact varied, depending on the type of impact being discussed. In summary, impacts to wave height were generally anticipated to be insignificant, impacts to wave quality were anticipated to be insignificant to significant (varying between participants), impacts to sedimentation and rip currents were anticipated to be insignificant to severe (varying widely between participants), and opinions on impacts from future installations were mostly uniform.

It was observed that these opinions were formed through an interplay between the individuals’ perception of the technology, and their perception of nature. The properties that made up these perceptions are summarised in the conceptual model in Fig. 2. The model enables a level of anticipated impact to be predicted, by categorising technologies and coastal environments in terms of their perceived properties. Although positions of support or opposition may not be predicted using this model alone, it provides a novel framework which not only summarises the way that water-users currently perceive MRE technology, but begins to predict how they will perceive future technologies and possible coastal environments in terms of wave climate and beach morphology needed. Interviews incorporating specific EIA licencing and application data should be used to further gauge pre-installation perceptions, and highlight whether EIA’s are effective in allying concerns. Once devices are deployed and active at the WH, water-user perceptions should further be investigated. The conceptual model presented here (Fig. 2) provides a framework for such research. Equally, long term monitoring using field measurements of wave climate and beach morphology is needed to assess the results of which should be carefully communicated to the public.

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Coastal Impacts of Marine Renewables: Perception of Breaker Characteristics by Beach Water Users

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ABSTRACT

Beach water users such as bathers and surfers are of economic importance to tourism in Cornwall, UK. Wave energy converters soon to be trialled at the ‘Wave Hub’ marine renewables test site in Cornwall, may reduce inshore wave heights and have an unknown effect on wave period, therefore potentially affecting water recreation and tourism on the beaches in its lee. There is little existing research to indicate what surf conditions are ‘preferred’ by various beach water user groups, and how they perceive different wave conditions has never been investigated. Without an understanding of how waves are observed and described by water users, little can be said about how likely they are to be affected by, or if they will correctly perceive, any changes to inshore waves caused by Wave Hub or future renewables projects. To investigate how surfers perceive nearshore wave buoy measurements collected in 10 m water depth and transformed to breaking height, were compared to concurrent visual observations of mean breaker height and period made by 354 participants. Ratios of observed over measured height and period were used to quantify the perceptions. The vast majority of water users underestimated significant wave height and period at breaking, and their average perceptions can be approximated by $H_w = 0.70H_b$ and $T_w = 0.83T_b$ (for waves $0.5 \leq H_b \leq 3.5$ m and $3 \leq T_w \leq 15$ s). Although perceptions were highly varied, average perceptions did not change significantly under different wave conditions. Perception of wave period did not change significantly between the different water user groups considered. Expert water users and surfers generally under predicted wave height the most, especially for short period waves, while novices and non-surfing water users made height observations closer to measurements.

ADDITIONAL INDEX WORDS: Perception, wave observation, water users, wave energy, coastal recreation

INTRODUCTION

Wave Hub controversy

Recreational water users such as surfers and bathers bring ~ £300 million of tourism a year to Cornwall, UK (Environment Agency, 2007). There was initially some concern that wave energy converters soon to be trialled at the ‘Wave Hub’ marine renewables test site (10 km off the coast of St Ives, Cornwall, www.wavehub.co.uk) would reduce inshore wave heights, and have an unknown effect on wave period, potentially affecting water recreation and tourism on beaches in its lee. During the initial Wave Hub consultation, a collective of surfers argued that the facility would be better sited elsewhere (see figure 1), as the potential value of the electricity that would be harvested was considered to be less than the value of the surfing industry in Cornwall considered to be threatened by the project (Baxendale, 2007). Most modelling studies have indicated that the impact to surfing waves will be quite minor. One study predicted an average reduction in inshore wave height of <2% at Perranporth beach in a scenario of 30% energy extraction (Millar et al., 2007). Another study indicated < 0.5% reduction in inshore height under a scenario of 30% energy extraction (Smith et al., 2012)). Nevertheless, surfing and water sports industries are crucial to Cornwall’s economy, and impacts to inshore waves from future renewables deployments may exceed these initial predictions as device efficiency increases, or if arrays of devices increase in size.

To manage waves as a shared commodity, and avoid clashes of interest between renewables and tourism stakeholders, it is necessary to understand what wave conditions are of most value to each group. Globally, there has been little research to indicate what surf conditions are ‘preferred’ by recreational beach water users, and more fundamentally, how such individuals perceive different wave conditions has never been investigated. Without an understanding of how waves are observed and described by water users, their wave preferences cannot be interpreted correctly. It is therefore unknown how likely they are to be affected by, or if they will correctly perceive, any changes to inshore waves caused by Wave Hub or future renewables projects. As part of the E.U. funded project ‘Streamlining of Offshore Wave Farm Impacts Assessment’ (SOWFIA, www.sowfia.eu), a questionnaire survey has been conducted at two beaches on the north Cornish coast in the lee of Wave Hub to investigate water user perceptions of

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breaking waves. Nearshore wave buoy measurements (collected in 10 m water depth and transformed to breaking height) were compared to concurrent visual observations of mean breaker height and period made by participants. This study aims to investigate how different groups of beach water users perceived those wave conditions.

Wave perceptions
A number of studies have investigated the relationship between concurrently recorded visual and measured wave heights and periods, usually for the purpose of validating a long running visual record. Those include observations of the height and period of unbroken waves in deep water (amongst others, Nordenstrom, 1969; Jardine, 1980; Guedes Soares, 1986), and breaking waves at the coast (Peirson, 1984; Plant and Griggs, 1992; Caldwell, 2005; Caldwell and Aucan, 2007), typically using observations made by scientists or mariners. For brevity, measurements made visually with the human eye will herein be referred to as ‘observations’ and measurements made with instrumentation such as wave gauges or buoys will be called ‘measurements’. Wave characteristics are difficult to observe consistently and accurately with the naked eye due to the dynamic and complex nature of waves. Observations are therefore variable and subjective, and often include bias (Battjes, 1984; Caldwell, 2005); what one person might consider to be a 2 m high wave might be considered a 1.5 m high wave from another viewpoint, or by another person.

Another factor influencing a person’s perception of wave height and period is the form of averaging they use in order to report a single height or period from a sea of mixed (non-monochromatic) waves, which are ubiquitous in ocean and inshore waters. Comparing observed and measured data from weather ships in the Atlantic ocean, Nordenstrom (1969) found that the average of the largest 1/3 of measured wave heights, $H_{1/3}$, most closely corresponded to concurrent human observations. Significant wave height ($H_s$ or $H_1$) is widely used for this reason, and the World Meteorological Organisation now recommends that observers average $\sim$20 of the larger waves in several wave groups to determine wave height or period. Although many studies have found good correlation between measured and observed wave heights, poor correlation and a large degree of scatter tends to occur in comparisons of observed and measured wave period (Battjes, 1984; Peirson, 1984).

Systematic bias in observations has been found in visual wave height records made since the 1960’s by Hawaiian lifeguards. Although the reason for its use is disputed, the ‘Hawaiian scale’ of wave height records made since the 1960’s by Hawaiian lifeguards ($H_s$) is widely used for this reason, and the World Meteorological Organisation now recommends that observers average $\sim$20 of the larger waves in several wave groups to determine wave height or period. Although many studies have found good correlation between measured and observed wave heights, poor correlation and a large degree of scatter tends to occur in comparisons of observed and measured wave period (Battjes, 1984; Peirson, 1984).

Figure 1. Location of study sites, Waverider buoy (x), and a ‘worst-case’ model prediction of wave shadowing from the Wave Hub, adapted from Millar et al. (2007). Contours show predicted change in $H_s$ for unidirectional, monochromatic swell and 0% energy transmission. (Reference state: $H_s$ 3.3 m, $T_m$ 11 s, 269° from North).

In addition to answering demographic questions relating to their use of the sea (see figure 2), participants were asked to report a visual estimate of the average wave height, $H_{ave}$ and period, $T_{ave}$, over the 30 minutes prior to the questionnaire, or as long as they had been within view of the sea if less than 30 minutes. Wave height was defined as ‘the face height of the waves as they break’, and period as ‘the time in seconds between each wave passing a fixed point’. These definitions were intended to provide a guideline for the participants, while remaining relatively vague so that the perception of the individual would be apparent. Only participants over 18 years old were asked to partake, and ethical permission was granted by Plymouth University to conduct the surveys.

To investigate how much perceptions vary between different water user groups, observations were binned by each participant’s ‘experience factor’, $E_i$, and by their preferred water activity. $E_i$ is the product of: the number of years they have been participating in their preferred water activity and the percentage of days in a year they typically participate (see figure 2b). $E_i$ therefore approximates the total number of days the individual has participated in their lifetime (units are years). ‘Novice’ water users were classed as those with $0 < E_i < 0.3$, ‘experienced’ water users as $0.3 \leq E_i < 4$, and ‘expert’ water users as $4 \leq E_i$. These
thresholds are approximately the 25th and 75th percentile, respectively, of the experience levels within the sample. Two activity bins were created, those from participants who put surfing as their preferred activity, and those who stated any other preferred activity (approximately 55% and 45% of the sample respectively, see figure 2a). Experience level and activity will be considered separately to maximize the size of each subsample.

Wave data

Wave data was collected by a directional wave-rider buoy just offshore of Perranporth beach located in approximately 10 m depth (see figure 1). In order to compare breaking wave observations to measurements, wave heights from the nearshore buoy were transformed to breaking heights. The rbm wave height at breaking was estimated using linear wave theory that takes into account shoaling and refraction (Plant et al., 1999):

\[ H_{b23} = \left( \frac{g}{\gamma} \right)^{1/5} \left[ \frac{H_0^2 L_p^2 \cos(\theta)}{2} \right]^{2/5} \]  

(1)

where \( g \) is gravitational acceleration and \( \gamma \) is the empirically determined ratio of wave height to water depth at breaking. At Perranporth beach, a conservative value for \( \gamma \) is 0.4, and is used here (Miles et al., 2013 (in press)). \( H_0 \) and \( \theta \) are the rms wave height and peak wave direction relative to shore normal (in radians), respectively, taken at the wave buoy. \( C_p \) is the offshore group velocity calculated using linear wave theory, which considers peak period, \( T_p \), and water depth, both at the location of the buoy. \( H_{\text{break}} \) was adjusted to estimate significant wave height at breaking, \( H_s \), by \( H_s = H_0 \gamma T_p \). Wave period was not transformed from the buoy and was taken as the significant period, \( T_{1/3} \), calculated as either \( T_{1/3} = 0.95 T_p \) for windsea spectra (Goda, 1978), or \( T_{1/3} = T_p \) for swell (Goda, 1988a). Plant and Greggs (1992) argue that when bimodal spectra occur an observer is likely to report a significantly reduced wave period, due to the interaction of the swell and windsea components. Despite this, for bimodal cases, the \( T_{1/3} \) value associated with the dominant component (swell or wind sea) was used, as this resulted in the best agreement with the visual observations. Swell and windsea were identified in the 1D spectra, and bimodal spectra partitioned, using the methods of Portilla et al., (2009).

As there is no other source of wave data more local to Porthtowan, it has to be assumed that there are no significant differences in the nearshore conditions between Porthtowan and Perranporth, despite their 10 km separation and slight difference in orientation (292° and 283° from North, respectively; See figure 1). Scott (2009) and Poate (2011) used data output by a Mike21 wave model at the 15 m depth contour to assess differences in the wave climate along the North coast of Cornwall. They found that differences in the annual wave statistics were negligible under non-extreme conditions, with 0.8% difference in \( H_{\text{rms}} \) between Perranporth and Porthtowan (1.24 and 1.23 m respectively) and 2% difference in \( T_p \) between Perranporth and Porthtowan (9.7 and 9.5 s respectively). Under larger wave conditions the disparity between the sites increases however, with 13.6% difference in \( H_{\text{rms}} \) between Perranporth and Porthtowan (2.95 and 2.55 m respectively). Given that the waves considered in this study are generally under \( H_s \), 2 m, the Perranporth wave buoy should provide a reasonable surrogate source of data for Porthtowan.

Statistical analysis

Outliers in the wave height and period observations were objectively removed, as they are unlikely to represent typical water-user perceptions and will reduce the quality of the regression analysis to be performed on the data. Firstly the ratios of observed over measured wave height (\( H_s/H_b \)) and period (\( T_p/T_{1/3} \)) were calculated for each participant. The ‘boxplot’ approach was then used to identify unusually large or small ratios, whereby outliers lie outside the range: IQR\((1.5\times\text{IQR})\), where IQR is the interquartile range. This method doesn’t rely on the assumption of normally distributed data, as the IQR depends on the median of the data and not the mean (McGill et al., 1978). In total, 3.4% of wave height observations and 7.9% of wave period observations were excluded from the data set.

To provide an estimate of how well the statistics derived from this sample represent the entire population of water users at the two sites, and to identify when statistics are significantly different to one another, 95% confidence intervals are reported. These indicate the bounds within which the true population parameter is likely to lie. Bootstrapping has been used to calculate this, as it provides accurate confidence bounds for relatively small samples and also performs well for non-normally distributed data (DiCiccio and Efron, 1996), which will be beneficial for the small

![Figure 2](image-url)
subsamples examined later (minimum size n = 10). Bootstrapping simulates the task of resampling from the population, making many ‘artificial’ samples by randomly resampling from the available data. 5000 bootstrap samples were used to calculate each confidence interval, and stabilization of the statistic usually occurred well before this number was reached. For the regression confidence intervals described later, the percentile bootstrapping method was used, and for the mean ratios the accelerated and bias corrected method was used. DiCiccio and Efron (1996) provide an assessment and summary of each method.

RESULTS

Figure 3 shows visual observations of wave height and period plotted against concurrent measurements. At all measured heights (periods) the majority of participants under-predicted the breaking wave height (period). There is a fair degree of scatter in the relationships, particularly between observed and measured wave period, which indicates that participant’s perceptions varied widely. To model these relationships, power law curves were least-squares fitted to the data and are plotted in figure 3 (solid curves; RMS error is 0.41 in (a) and 2.03 in (b)) alongside the power law curves derived by Nordenstrom (1969) in a similar study (dot-dashed curves; RMS error is 0.51 in (a) and 5.65 in (b)). Our power law curves fit the data reasonably well up to $H_b$ 1.5 m, and $T_{1/3}$ 10 s, and suggest that a water user’s observations can be estimated from $H_b$ and $T_{1/3}$ by the following relationships:

$$H_b^{est} = 1.14 \frac{H_b}{1.86} \frac{\text{m}}{\text{m}} \quad \text{(for } 0.5 \leq H_b \leq 1.5 \text{ m})$$

$$T_{1/3}^{est} = 0.213 \frac{T_{1/3}}{5.72} \frac{s}{s} \quad \text{(for } 6 \leq T_{1/3} \leq 10 \text{ s})$$

A simpler relationship is the mean ratio of observation over measurement, the ‘perception ratio’, $P$ (figure 3, thick dashed lines; RMS error is 0.52 in (a) and 3.22 in (b)). These do not fit the bulk of the data as well as our power law curves, but do fit better at larger heights ($2 \times H_b > 3.5$ m) and periods ($12 \times T_{1/3} > 15$ s) and, like the data, suggest that these heights and periods will be under predicted by water users. From figure 3 the mean wave height perception ratio, $P_{H_b}$ for all participants was 0.70 (std. dev. 0.28), while the mean wave period perception ratio, $P_{T_{1/3}}$ was 0.83 (std. dev. 0.29). Therefore on average:

$$H_b^{est} \approx 0.70 H_b \quad \text{(for } 0.5 \leq H_b \leq 3.5 \text{ m})$$

$$T_{1/3}^{est} \approx 0.83 T_{1/3} \quad \text{(for } 3 \leq T_{1/3} \leq 15 \text{ s})$$

Effect of varying conditions on perceptions:

To investigate how much perceptions change under different incident wave conditions, observations were binned by measured wave height (0.5-1, 1-1.5, and 1.5-2 m) and measured wave period (6-8, 8-10, 10-12, and 12-14 s). Mean $P_{H_b}$ and $P_{T_{1/3}}$ values were then calculated for each bin with 10 or more observations in, along with 95% confidence bounds. Significant variations in perception due to the incident conditions are seen where there is no overlap between the confidence bounds of different height or period bins in figure 4 (grey bars with diamonds). Although some significant differences in height (period) perception occurred at different wave heights (periods), there were no significant differences between the binned perceptions and the overall mean perceptions described by equation (4) (shown as a grey dashed line in figure 4) and equation (5). This suggests that equations (4) and (5) are sufficient in describing the average water user perception within any of the height and period bands considered.

Effect of differing experience level and preferred activity on perception:

Significantly different wave height perceptions by the different experience level (activity) groups can be identified in figures 4a and 4b (4c and 4d) where there is no overlap between the confidence bars for novice, experienced, and expert water users (surfers and non-surfers). Additionally, a group’s perception is adequately described by equations (4) or (5) if the confidence bounds of that group’s perception overlap the bounds of (4) or (5).
There were no significant differences in $P_T$ for participants of differing experience level or activity, (hence $P_T$ not being plotted), and Equation (5) adequately describes the average wave period perception of all water user groups. There were however significant differences in the perception of wave height. At small wave heights (0.5-1 m) and medium periods (8-10 s) there is disparity between the height perception of novices and experts. At these bands wave height was underestimated more by the more experienced water users, and the perception ratio in equation (4) does not sufficiently describe the various perceptions. Unsurprisingly, as they are the majority group, experienced water user’s perceptions were much better accounted for by equation (4), although at larger wave heights (1.5-2 m) the $P_H$ of experienced water users was slightly lower than that given by equation (4).

A similar result was seen for the activity groups, where at small wave heights (0.5-1 m) and short periods (6-10 s) surfers under predicted height significantly more than non-surfers. The wave height and period perception of non-surfers is sufficiently described by equation (4), whereas surfer’s perceptions were significantly different to equation (4) during short period waves (6-10 s). At measured heights of 1-1.5 m and periods of 10-12 s the perceptions of all water users were most similar to one another, and wave heights and periods were under predicted the least by surfers and more experienced water users.

**DISCUSSION**

The scatter in figure 3 (a) and (b) demonstrates the large degree of variability in people’s perception of wave heights and periods. Perception could vary due to the presence or absence of a comparison object (e.g. a person or a rock) to provide scale to the waves or a benchmark for timing wave period (Caldwell and Aucan, 2007). It might also be affected by the position and elevation of the observer or their level of observational experience (Perlin, 1984; Guedes Soares, 1986; Caldwell and Aucan, 2007). In addition the observer may have made an observation based on very few waves, whereas the wave buoy averages over 30 minutes. Further to these potential sources of observational ‘error’, bias also undoubtedly contributes to the variation in perception. Bias may be caused by differences in what each observer considers to be the trough and crest of each wave; expert water users may only consider the steeper part of the wave face, while novices the entire face from trough to crest. It has not been possible in this study to differentiate between inaccuracy and bias in each observation, but small observational errors (noise) should average out over a large number of observations, while systematic bias should remain apparent (signal).

The pronounced scatter in the wave period observations is not unusual (Battjes, 1984; Perlin, 1984; Plant and Griggs, 1992), and the relationship between $T_{1/3}$ and $T_{1/10}$ must be considered cautiously. In other studies variability has been attributed to difficulties in counting wave period, or even identifying one wave from another during mixed seas (Perlin, 1984; Plant and Griggs, 1992). It was noted that the untrained participants in this study rarely counted wave period properly, and their observations were therefore often based on a wave forecast (53% had recently seen a forecast), or were merely a quick estimate. Despite this, the mean $P_T$ found here (0.83) was not significantly different to any of the water user group’s mean perception ratios, and is similar to the $P_T$ found in other studies (0.89-0.95 (Battjes, 1984)).

The power law curves in figure 3 suggest that wave heights (periods) under 1.5 m (10 s) will be under predicted and larger heights (periods) will be over predicted, despite the fact that there is predominantly under
prediction occurring in the data. This results from the curves fitting to the bulk of the data at heights (periods) ≤1.5 m (10 s); at greater heights (periods) they fit the data poorly. The divergence of our observed scatter curve from that of Nordenstrom (1969) at heights >1 m could be a result of the difference between observing/measuring wave height in deep water (e.g. Nordenstrom, 1969) and observing/estimating breaking height with linear theory, as has been done here. However Nordenstrom’s curve is fitted over a greater range of heights, considering waves of up to 10 m. It is therefore likely that with data from larger waves, our curve would be closer to theirs, and may not show over prediction of larger waves.

The ratios in equations (4) and (5) seem to adequately describe the average perception of most water user groups. Because they indicate that water users will, on average, under predict height and period (as is apparent in the data in figure 3), and because they fit the data better at larger wave heights and periods, the ratios are deemed to be better models of wave perception than the power law curves. It should be noted however that the ratios relate to $H_s$ and $T_{ms}$ as calculated above. Linear shoaling is not infallible, and on shallow coasts usually overestimates $H_s$ because bottom friction is not considered, although this has possibly been mediated by using a conservative value for $\gamma$. There are also other methods for calculating $T_{ms}$.

For waves of 1-1.5 m or 10-12 s all water user groups had approximately the same perception of wave height, and height was under predicted the least. Interestingly, the annual mean $H_s$ and $T_{ms}$ at Perranporth fall exactly within these ranges, indicating that during average wave conditions, height and period are more accurately and consistently described by water users than during non-average conditions. Novice water users and/or non-surfers often had wave height perceptions closer to measurements, while experts and/or surfers often significantly under predicted height, especially for small waves (0.5-1 m), or short period waves (6-10 s). The perceived height of small, short period waves therefore changes through increased water use, which may be a result of these waves seeming less threatening as experience and water ability increases. There may also be a culturally bred bias in the surfing world that has not yet permeated into other water sports, which would explain the lower height perception of surfers. This may have originated from the Hawaiian scale of height perception, where $H_b \approx 0.5$, as Hawaiian surf culture has had a widespread influence on global surf culture. Machismo may be a cause of such wave height underestimation, as an observer may seek to play down the size of surf to inflate their apparent confidence. Comparison of perceptions by gender may be used to explore this further.

CONCLUSIONS

Overall, participants generally underestimated measured wave height and period at breaking, and the average perception can be approximated by $H_{ms} \approx 0.70H_b$ and $T_{ms} \approx 0.83T_{ms}$ (for waves $0.5 \leq H_b \leq 3.5$ m and $3 \leq T_{ms} \leq 15$ s). Although perceptions were highly varied, average perceptions did not change significantly under the different (aforementioned) wave conditions analyzed in the study. Perception of wave period did not change significantly between the different water user groups, but expert water users and surfers generally under predicted wave height the most, while novices and non-surfing water users made observations closer to measurements. Using specific height perception ratios for expert water users and surfers may therefore better describe their perceptions. Observations at greater wave heights and periods are needed to further explore the perception of breaking waves.

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LITERATURE CITED


Exploring Monthly To Seasonal Beach Morphodynamics Using Empirical Orthogonal Functions

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ABSTRACT


Empirical Orthogonal Function (EOF) analysis is a statistical method that can separate out the dominant modes of change in beach topographic data. Here the method is applied to four years of monthly intertidal survey data from Perranporth beach (Cornwall, UK), a predominantly dissipative site, which exhibits episodic low tide bar-rip morphology. The aim is to understand the main morphodynamic changes by studying only the dominant EOF patterns. Grided data from 48 surveys was analysed and two statistically significant EOF modes were identified. The primary EOF (EOF1) has been interpreted as a seasonal ‘beach volume function’ and shows that alongshore-uniform gains and losses of sediment, predominantly from the mid intertidal region, account for almost 50% of all the variability that occurs in the data set. This occurs with an annual periodicity, and the increasing trend in the temporal signal has been associated with the long term (+years) increase in volume that the beach is experiencing. The second EOF (EOF2), has been interpreted as the ‘dominant rip function’ and indicates that the second most dominant mode of change (~11% of the total variability) involves the development of a recurring low-tide rip channel accompanied by a steepening of the beach and an increase in 3D structure.

INTRODUCTION

The installation of a wave energy test site off the north Cornish coast (‘Wave Hub’, www.wavehub.co.uk) has instigated much research into the natural condition of the beaches and coastal processes occurring in the region. In this study, four years of intertidal survey data is analysed which was collected at a beach in the predicted shadow zone of the Wave Hub, prior to installation of wave energy devices at the site. Of particular interest is understanding the natural fluctuations in forcing conditions that lead to significant beach changes. One approach to studying beach morphodynamics is to adopt a statistical method that can concisely summarise the natural variability that occurs. The method of Empirical Orthogonal Function (EOF) analysis, has been applied widely to achieve such a purpose, and is adopted in this study. EOF analysis aims to summarise the variability in a complex phenomenon, in this case beach morphodynamics, by determining a small number of dominant ‘patterns’ of variance (herein called EOF modes or eigenfunctions). It also quantifies the magnitude of these spatial patterns through time (herein called temporal coefficients, or principal components). The data are effectively rotated by each EOF into a new coordinate base, in which the variance is maximised (Presendorfer and Mobley, 1988). Additionally, each EOF describes an orthogonal, and therefore independent, mode of change. The method is an effective data reduction tool, as normally the first few EOFs can ‘explain’ a large majority of the total beach variability. The fraction of variance explained by each EOF, given by its eigenvalue, usually reduces rapidly with increasing mode number, and therefore often only a small number of patterns are required to describe most of the variability in the data set. Higher mode EOFs explaining a small amount of the total variance (small eigenvalues) can be considered noise, and are usually disregarded.

EOF patterns can be thought of as standing oscillations whose amplitude varies over time, and can be used to show which areas of the beach co-vary about their mean position at a given moment in time. As such, standard EOFs do not describe migrating features well, and therefore their suitability must be considered for each site. Additionally, eigenfunctions are constrained by the fact that they are uncorrelated in space, while each principal component is uncorrelated in time (Presendorfer and Mobley, 1988); consideration must be given to the fact that the morphodynamics under study may not actually occur in such a way. It should also be emphasised that EOFs are a statistical decomposition of the data and the spatial patterns don’t necessarily have a physical parallel. However, An EOF can be confidently interpreted as a physically occurring mode of change, with supporting evidence from forcing parameters or other empirical observations (Miller and Dean, 2007b; Fairley et al., 2009; Loureiro et al., 2012). The method then provides a means to objectively quantify the dominant ways in which the beach varies.

The aim of this study is to understand the main morphodynamic changes at Perranporth beach (Cornwall, UK) by examining the most dominant EOF patterns. This will disentangle and quantify the dominant modes of change occurring at monthly to seasonal time scales. Observations from survey data and remotely sensed video imagery will be called upon to evidence the physical
significance of the EOF patterns, while forcing wave conditions pertinent to each mode of change will be investigated in a future paper.

**Literature**

Early studies employed EOFs to investigate profile variability, and key forms of cross-shore change were observed in the primary EOF modes (Winant, 1975; Aubrey, 1979). Winant *et al.* (1975), interpreted their first three EOFs as the mean beach profile, the bar-berm exchange, and the low tide terrace. The conclusions drawn from such studies were limited to cross-shore variability, and researchers later used EOFs to study the relative importance of longshore and cross-shore sediment exchange (Clarke and Eliot, 1982; Hsu *et al.*, 1986; Lippmann and Holman, 1990). Application of EOFs to contour lines is one such approach: cross-shore transport can be observed in modes that are alongshore uniform, and longshore transport can be observed in modes that have alongshore pivot points/nodes (Miller and Dean, 2007a), although the results from this approach are dependent on the choice of contour (Fairley *et al.*, 2009). Another approach that has been applied more recently is to perform EOF analysis on the entire gridded beach surface (Larson *et al.*, 1999; Haxel and Holman, 2004; Gómez-Pujol *et al.*, 2011). Although this cannot identify phenomena such as beach rotation (which is possible with contour EOFs) or migrating features, it can potentially identify both cross-shore and alongshore sediment exchange, producing alongshore uniform and alongshore non-uniform patterns respectively, as well as the occurrence of three dimensional (3D) features (Larson *et al.*, 1999). For these reasons, this latter approach is applied in this study.

**Research site**

Perranporth beach is situated on the north coast of Cornwall, UK. Facing west-northwest it is fully exposed to an energetic wave climate of both Atlantic swell and local wind sea, with an annual mean significant wave height of 1.6 m and peak period of 10.5 s (Austin *et al.*, 2010). It is a macrotidal beach (mean spring range 6.3 m) and although predominantly dissipative, it sits on the classification boundary between dissipative and intermediate states and regularly features low tide bar/rip morphology. The upper intertidal region has been observed to be relatively stable with little berm development, whilst the mid to low tide region is highly variable (Poate, 2011) experiencing periods of planar, featureless morphology (Figure 1, bottom panel) and rhythmic/three-dimensional morphology with rip channels (Figure 1, top panel). The beach extends 3.42 km alongshore and around 500 m cross-shore at spring low tides, though the area under study here comprises the southern-most 1.3 km stretch of the intertidal beach face.

**METHODS**

**Topographic data**

Monthly topographic surveys were conducted at Perranporth for 48 months between 2008 and 2012. The surveys were conducted using a Real-Time Kinematic Global Positioning System (RTK-GPS) giving centimetre accuracy in both the horizontal and vertical. The RTK-GPS was mounted on an all-terrain vehicle (ATV) enabling rapid collection of data over large spatial areas with relatively high accuracy. The surveys were conducted during the largest spring low tides that occurred each month, allowing the greatest possible area of the intertidal beach face to be surveyed. The data were collected in a quasi-regularly spaced grid, with alongshore transects spaced 10-15 m apart and cross-shore transects spaced 50-100 m apart. The data were automatically collected at <1 m spacing along each transect. The data were then interpolated using a loess quadratic interpolation method (Plant *et al.*, 2002), using smoothing scales of 10 m, 30 m and 60 m to resolve medium to large scale morphological features. Whilst bulk statistics were calculated from the data gridded at a 5 m resolution, the EOF analysis was performed on data gridded at 20 m resolution, as it was too computationally demanding to perform it at a higher resolution. This is deemed sufficient for resolving the larger scale morphological changes of interest here. Interpolated data for each months survey were output in a local coordinate system with increasing x axis values moving offshore. The gridded data covers an area approximately 1300 m alongshore by 450 m cross-shore, consisting of 887 data points for each month.

**EOF analysis**

In simplistic terms, EOF analysis takes a sequence of topographic data collected over time, \( z(x,t) \), and represents it as a summation of EOF patterns, \( \mathbf{E}_k(x) \), scaled by their respective temporal coefficients, \( C_k(t) \)

\[
Z(x,t) = \sum_{k=1}^{N} E_k(x) C_k(t)
\]
The spatial and temporal structure of each variability pattern respectively, at N different observations through time. Each spatial and temporal combination is orthogonal and therefore uncorrelated to any other combination, so the patterns represent independent modes of variability (Fairley et al., 2009) where the contribution to the total variability is quantified.

Bulk statistics were first calculated from the topographic data, including the mean elevation, elevation range, and standard deviation at each grid point. The data were then organised into a matrix where each column contained the data of one grid point and each row contained the data from a different temporal observation (each monthly survey). At each grid point the mean value was removed from the data, centering the data around its mean; this is beneficial as otherwise the first EOF mode tends to closely mimic the mean and can be overly dominant (Muñoz-Pérez et al., 2001). The effect of removing the mean is that each EOF represents changes relative to the mean. The covariance matrix of the mean-removed data was then calculated, and from this EOFs were computed using MATLAB's 'eig' function, which outputs the EOFs, principal components and eigenvalues. The EOFs were reshaped back into grid format for plotting and interpretation.

To objectively determine which EOFs to retain for analysis, Preisendorfer and Mobley's (1988) 'Rule N' was used, whereby a Monte Carlo approach is adopted to calculate a confidence threshold for the eigenvalues. 100 datasets consisting purely of white noise were generated and the EOF calculations were repeated with these surrogate datasets. For a real-data EOF mode to be considered as signal rather than noise, its eigenvalue must be higher than one generated from a white noise data set at the 95% confidence level. The size of each white noise data set was determined (the 6th highest eigenvalues). Any eigenvalues that are above the threshold can be considered statistically significant at the 95% confidence level as they will not be exceeded by more than 5 of the random-data eigenvalues.

RESULTS

Figure 2 shows the mean elevation, range, and standard deviation of the beach surface from the survey data. Noticeable in the middle and right panel is an increase in both variability and longshore non-uniformity from the middle to the seaward extent of the beach. Despite this tendency, the left panel indicates that the mean beach surface is almost entirely featureless and planar, indicating that there are no persistent features that are maintained throughout the year. At the low tide region approximately ~750 m alongshore there is an area of high variability that experiences twice the standard deviation compared to the rest of the domain, as well as the greatest range in elevations, representing the location of the main rip channel (further description is given below).

The EOF analysis produced two eigenfunctions which are significant at the 95% confidence level (Figure 3); the rest will be discarded as they could equally have been generated from noise. The two significant EOF modes will be analysed further, and will be referred to as EOF1 and EOF2. Together they explain the majority of the variability that occurs at the site, accounting for 49.39% and 10.69% respectively. The proceeding EOF results represent changes relative to the mean topography (shown in Figure 2, left panel).

![Figure 2. Mean elevation (left panel), elevation range (middle panel) and standard deviation (right panel) at each grid point. Calculated from 48 months of intertidal data gridded at 5m resolution.](image-url)
EOF1

EOF1 (Figure 4, top left panel) is relatively uniform, and consists almost entirely of positive variance relative to the mean, indicating that the beach face is varying in phase with itself. Most of the variance occurs around the mid-intertidal region, with lower variance at the upper beach, some small nodal areas at the low tide region to the south, and higher positive variance to the north. This EOF has a temporal signal that changes sign with an annual periodicity (Figure 4, bottom left panel), with positive variance relative to the mean in the summer months and negative variance occurring around the winter months. There appears to be a trend in the temporal signal over the period of study, as time progresses the positive variance in summer (sediment gains) becomes greater than the negative variance in winter (sediment loss).

This EOF describes seasonal gains and losses of sediment to the beach face and the eigenvalue therefore reveals the contribution that seasonal changes in beach volume make to the overall variability at Perranporth; almost 50% of all the intertidal change that occurs involves uniform gains and losses of sediment, predominantly from the mid-intertidal region. The nodal areas at the low tide mark, shown as a zero-variance contour, indicate that this EOF describes cross-shore sediment exchange between the mid intertidal region and the sub-tidal beach, as nodes divide areas of simultaneous accretion and erosion (Miller and Dean, 2007a).

Without subtidal data this can only be speculated, but it is unlikely that these changes result from longshore transport, which would more likely involve an increase in the entire profile to the depth of closure.

The seasonal periodicity of EOF1’s temporal coefficient is likely to be driven by seasonal fluctuations in incident wave energy (i.e. larger waves in winter, smaller waves in summer), which will be explored in more detail in a future article. Importantly, the trend observed in the temporal signal is an indicator that the beach experienced net accretion over this 4-year period, and correlation with wave parameters may reveal the cause of this trend. Evidence for the physical existence of EOF1 comes from a study of beach volume at Perranporth by Poate (2011), who observed a net increase in intertidal volume of 1.15 times, between the period 2008 – 2011. His time series of observed beach volume is also qualitatively well correlated with the temporal coefficients of EOF1. EOF1’s spatial structure is also supported by the higher net and gross volumetric changes that were observed in the mid-intertidal region compared to the upper (Poate, 2011).

EOF2

EOF2 (Figure 4, top right panel) accounts for ~11% of the total beach variability and displays more cross-shore and alongshore variation than EOF1. The mid to low tide region at the north of the domain has predominantly negative variance relative to the mean, whilst the upper intertidal and south end of the beach display positive variance. There is a nodal (zero) contour which divides the two areas and intersects the low tide region; this represents a band of stability in the pattern, dividing areas of opposing (out of phase) change.

Of particular interest is the presence of a large depression at ~800 m alongshore and a more minor depression at ~200 m, alongshore, which dominate the lower intertidal region and are thought to correspond to the locations of major feeder/rip channels. The out of phase response between the north and south ends of the domain indicates that at times when these dominant rips are well developed, the beach is likely to be steeper than average, with the upper intertidal and south end of the beach holding more sediment than average. An example of this beach configuration was observed at the end of January 2012 (Figure 5, top panel), when the amplitude of EOF2 is at a maximum.

Conversely, the opposing beach configuration was seen during a survey in September 2010 (Figure 5, bottom panel), when the temporal coefficient of EOF2 is negative. Prodgér (2012) employed Argus time-lapse video images to manually identify rip current locations at Perranporth, and he found that a recurring and stable low-tide rip occurred in front of the headland in the middle of the beach between ~700 and ~750 m alongshore. This represents the most frequent (19.8%) location of the 1315 rips observed during the 6 year period he studied (2006-2012). This location closely matches the large depression in EOF2 and can also be seen as the region of high elevation range and standard deviation in Figure 2 (middle and right panels respectively).

The temporal signal of EOF2 appears to have some rhythmicity, generally increasing in late autumn to a maximum around December and dropping back to a negative value rapidly in the late winter. After the winter of 2010-2011 the rhythmicity is lost; the signal becomes more erratic during the last two years, and remains positive throughout 2012. The rip occurrences on the beach displayed the same change in rhythmicity: while 2006-2010 saw consistent seasonal rip behaviour, 2011 and 2012 saw unseasonal and increased variations in rip activity (Prodgér, 2012).

DISCUSSION

Consistent with other studies, the primary modes of variability found here consist of an alongshore uniform mode and a mode with alongshore varying structure (Muñoz-Pérez et al., 2001; Miller and Dean, 2007a). These modes of beach change have been disentangled by the EOF analysis, and insight has been gained into their temporal signal and their contribution to the overall variability. EOF1 (Figure 4, top left panel) has been interpreted as a seasonal ‘beach volume function’, and while a typical study of beach volume can reveal the spatial and temporal patterns of gross and net volume change, this EOF provides additional insight as the seasonal changes in volume that it describes have been separated from shorter lived morphological events that act to temporarily change the intertidal volume (e.g. bar welding, berm building, scarping etc.).

As the dominant rip on the beach occurs in a consistent location and is spatially stable, the EOF analysis was able to represent it as an oscillating pattern (EOF2, Figure 4, top right panel). Interestingly the temporal coefficients of EOF2 suggest that development of the dominant rip and steepening of the beach face have often occurred during late autumn and winter and less often
in summer when bar-rip morphology might be expected. This is evidenced by the surveys presented in Figure 1 (upper panel) and Figure 5 (upper panel), which were both conducted during January in their respective years. Further to this, Poate (2011) observed that the morphology at Perranporth does not follow a seasonal pattern and is more event driven, being reset to a dissipative state by storm events and recovering to intermediate states in between such events. Analysis of forcing conditions is now needed to further verify the physical significance of EOF1 and EOF2 (Miller and Dean, 2007b), and reveal what hydrodynamic conditions drive these monthly to seasonal modes of beach change.

Dominant and spatially-stable forms of morphological change have been resolved well by the EOF analysis, and their physical significance has been evidenced by observations made independently of this study. Some 40% of the total variability could not be accounted for by a statistically significant EOF mode, which suggests that much of the morphodynamics at Perranporth is too complex or spatially dynamic to be represented by oscillating patterns, as EOF analysis attempts to achieve. However, as 60% of the total intertidal variability in a four year period has been summarised in just two spatial patterns, the method is deemed to have been appropriate for this site.

CONCLUSION
Alongshore uniform and alongshore non-uniform modes of morphological change have been separated through EOF analysis and their contributions to overall beach variability has been quantified. EOF1 demonstrates that almost 50% of all the intertidal change that occurs at Perranporth involves uniform gains and losses of sediment, predominantly from the mid intertidal region and is likely to result from cross-shore exchange with the subtidal beach face. This occurs with an annual periodicity, with gradual sediment gains in the spring and summer and more rapid sediment loss in the winter. The increasing trend observed in EOF1 represents the long term increase in volume that the beach is presently experiencing, and EOF1 has therefore been interpreted as a ‘beach volume function’. EOF2 has been interpreted as the ‘dominant rip function’ and indicates that the second most dominant mode of change (~11% of the total variability) involves...
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