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Modelling the Effects of Marine Energy Extraction on Non-Cohesive Sediment Transport and Morphological Change in the Pentland Firth and Orkney Waters

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Abstract

This paper considers the process of modelling sediment transport and morphological change in the Pentland Firth and Orkney Waters using coastal area models. This region is atypical of regions commonly modelled using such techniques: it is high energy with limited and highly variable regions of mobile sediment. This causes challenges with regards both model capability and availability of data. Computational time restrictions for fully coupled modelling solutions should also be recognised which limits practical duration of simulation. Impacts to modelled bed level change over test periods are noted for both wave and tidal energy extraction scenarios. In both cases the magnitude of difference is equal to the magnitude of the change itself, however, lack of data and poor validation of the morphological modelling for the wave energy test case means confidence is low in these results. Based on the difficulties faced in conducting these modelling exercises and the high cost of additional data collection, it is recommended that regulators take a pragmatic approach when requiring such modelling for environmental impact assessments at some locations where changes to morphodynamics are unlikely to be critical to key receptors. Other approaches such as conceptual modelling or consideration of bed shear stresses could be undertaken rather than fully coupled morphodynamic modelling.

1. Introduction

Marine energy extraction, both wave and tidal, can alter physical hydrodynamic conditions (e.g. Easton and Woolf, 2013; Edmunds et al., 2014), wave height, period and direction (e.g Palha et al., 2010; Smith et al., 2012) with respect to a baseline no-extraction scenario. Change occurs in both the near- and far-field and can affect sediment transport rates and pathways. This can affect the morphodynamics and the morphological state of sedimentary environments such as beaches (Abanades et al., 2014; Millar et al., 2007) and sub-tidal sandbanks (Chatzirodou and Karunarathna, 2014; Fairley et al., 2015a; Neill et al., 2012; Neill et al., 2009; Robins et al., 2014).

Non-cohesive sediment environments fulfil a range of important and economically beneficial services. In the intertidal region, beaches perform an important coastal protection function, dissipating waves before they reach the shoreline (Komar, 1997). In general, the greater the volume of sediment stored on the beach face, the greater the potential protection function the beach can perform due to the increased beach width and the larger buffer of sediment available for erosion. Beach gradient also influences the ability of a beach to protect the hinterland. Beach profiles often exhibit seasonality, with steeper profiles in summer and lower gradient profiles in winter e.g. (Winant et al., 1975). This is a beneficial mechanism as the lower gradient winter profile dissipates wave energy further offshore and over a wider area thus effectively diminishing storm waves.

Sandy beaches provide an important recreational function that can contribute towards a significant portion of a region’s economy. The amount of sand available is often considered as primary importance (Pendleton et al., 2011) but beach morphology is equally important in some regions. Morphology can impact on beach safety (Scott et al., 2014) and on suitability for certain activities, for example in the suitability of the dominant wave shape to surfing (Silva and Ferreira, 2014; Stokes et al., 2014).

Intertidal and sub-tidal ecology may also be affected by the presence or absence of sand, the stability of the substrate and the depth of mobile sediment deposit (Jumars and Nowell, 1984). Sub-tidal sandbanks can be a hazard to shipping (Medina et al., 2007) and hence changes to their position and variability could be important. Sub-tidal sandbanks can also provide a coastal protection function via the dissipation of wave energy prior to the shoreline (Dolphin et al., 2007).

In this paper, case studies are presented of energy extraction in the Pentland Firth and Orkney Waters investigated within the Terawatt project (O'Hara Murray and Gallego, 2016; Gallego et al, 2016). The Pentland Firth and Orkney waters (PFOW) are a highly energetic region with strong tidal currents in the channels and the potential of large waves from the North Atlantic (Figure 1). Much of the coastline is hard rock geology with sand beaches confined to embayment and sheltered regions. There are large areas of mobile sediment offshore in deeper water but in the energetic channels and nearshore region substrate is commonly swept bed-rock or boulders and cobbles. Tidal conditions in the Pentland Firth are forced by the hydraulic gradient between the Atlantic and the North Sea (Easton et al., 2012).

The largest beach on the west coast of Mainland Orkney is the Bay of Skaill. This beach is important both as a recreational asset and as protection to the World Heritage Site of Skara Brae, a Neolithic village. Skara Brae has experienced gradual erosion over recent years and hence any changes to beach dynamics forced by renewable energy installations must be carefully monitored.

In the Pentland Firth much of the sea floor is bedrock. Mobile sediment occurs in regions of lower flow in the form of sub-tidal sandbanks. Past research has suggested that many of these deposits are ephemeral (Farrow et al., 1984). However, several sand banks are known to be permanent features, these include the Sandy Riddle and the eastern sandbank in the inner sound (MeyGen, 2012; Moore, 2009).

In this contribution we explore the data requirements for accurate modelling of sediment transport and morphodynamics and the availability of such data in the PFOW. Subsequently we present case studies of wave and tidal energy extraction at Bay of Skaill and the Inner Sound of the Pentland Firth respectively (Figure 1). The contribution focusses on the methodological lessons learned and the implications for both regulators and developers.

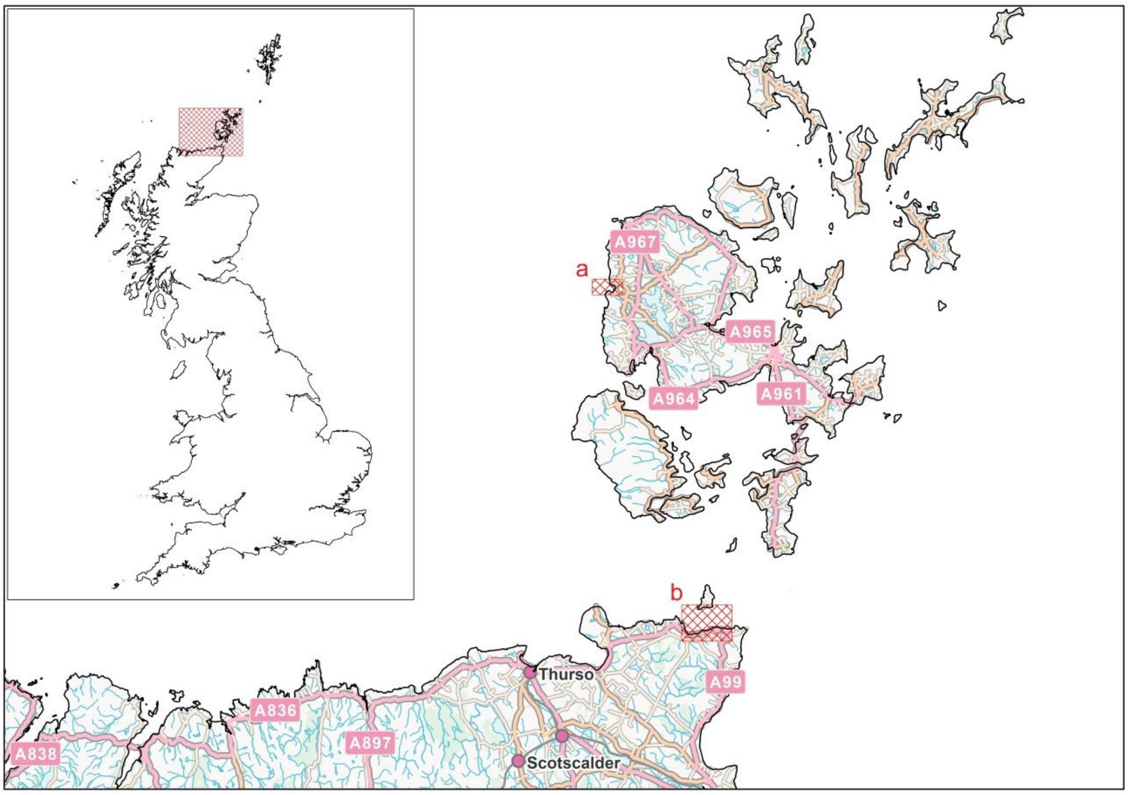

Figure 1: (inset) A map showing the location of the Pentland Firth and Orkney Waters with respect to the UK; and (main figure) the Orkney Islands showing location of the two study locations a) the Bay of Skaill and b) the Inner Sound.

2. Data for Sedimentary Research

Data availability in the Pentland Firth and Orkney Waters is limited. Routine datasets are commonly collected on populous sandy coasts with erosion problems. Coastlines with hard rock geology are often neglected in survey strategies due to the lack of risk of coastal inundation. Sutherland et al. (2004) makes distinction between an engineering approach to numerical modelling, where default parameters are used and only the minimum of data required to run the model is used, and a scientific approach whereby for data rich environments, all possible data is used in extensive calibration to assess the optimum performance of a model. In reality, the common approach is somewhere between the two with efforts made to match a limited set of measurements. Given the lack of data, an engineering rather than a scientific approach must be taken in much of the study area.

Beyond accurate bathymetry and information on hydrodynamic forcing, a range of data is required for the modelling of sediment transport and morphodynamic change. Sediment properties such as grain size, grading and relative density are key parameters in the prediction of sediment transport. These can be ascertained by analysis of point samples. In areas primarily consisting of mobile sediment with slowly varying bathymetry, wave and tidal forcing, it is viable to assume constant grain properties or interpolation between a few sparsely sampled points. For areas such as the Pentland Firth, islands and highly varying bathymetry lead to large spatial gradients in wave and tidal forcing and hence highly variable sediment properties. This means more sample points are needed which increases survey costs, possibly beyond the limits of what is appropriate or possible for marine energy developers to invest during environmental impact assessments. Interpolation between these points, while required for coverage of the model domain, is not necessarily valid. This leads to greater uncertainty in accuracy of predictions. Within the Pentland Firth data includes British Geological Society data (British Geological Survey, 2013) and data collected within marine energy projects.

In environments with varied geology, presence or absence of mobile sediment must be established across the model domain and the depth of the mobile sediment layer must be measured or estimated. Presence or absence of mobile sediment can be determined via the success of grab samples and analysis of single- or multi-beam and side-scan data. Commercially available packages such as RoxAnn can conduct discrimination based on single-beam echo-sounder data (Chivers et al., 1990; Collins and Voulgaris, 1993; Serpetti et al., 2011). If the backscatter data as well as multi-beam bathymetry are available, sophisticated classification techniques can be used to define seabed type (Ahmed and Demsar, 2013; Micallef et al., 2012). Where only bathymetry is available, manual classification can be conducted based on differences in the textural surface, this approach matched with observations from benthic video trawls when applied to the Pentland Firth (Fairley et al., 2015a). Similar discrimination approaches can be applied to side-scan sonar data (Garcia-Gil et al., 2000; Knebel, 1993; Knebel and Circe, 1995). Benthic video trawls can also give information on seabed composition. Depth to rock head can be measured using sub bottom profilers. Sub-bottom profilers measure the reflections from emitted low frequency acoustic pulse to build up a picture of the stratigraphy of the sea floor. Examples of this from the Pentland Firth and Orkney Waters is given in Leslie (2012), where a range of data from this region is presented. Survey lines are conducted and interpolation between these lines used to give spatial coverage. In intertidal regions seismic geophones can be used but there is a high cost associated with such data. Manual auguring can provide a cheaper estimate in such areas. Again it is likely that developments could not bear the cost of such surveys and hence estimation of sediment depth may be more viable. A recent paper (McIlvenny et al., 2016) has utilised side-scan sonar, grab samples and ROV video footage to better characterise the sedimentology of the Inner Sound.

Calibration of morphodynamic models can be a difficult process. Initially calibration and validation of the wave and tidal forcing are routinely undertaken using well established metrics and measurements (e.g. ADCP tidal data or directional wave buoy data). Measurement of sediment transport quantities, rates and directions is a non-trivial process (White, 1998). Beyond the difficulties in accurately measuring sediment transport, small scale spatio-temporal variations in sediment transport means that comparison with model output can be difficult given the resolution, particularly vertical, of many numerical models. Therefore, often comparison is made with morphological change. For intertidal regions, cross-shore profiles are commonly used e. g. (Masselink et al., 2014; Vousdoukas et al., 2012). Such an approach is undertaken in section three for the Bay of Skaill. Comparison with three dimensional digital terrain maps can also be conducted. Data collection for such comparisons is relatively low cost for intertidal areas whereas repeat surveys of sub-tidal sandbanks is much more expensive. Skill scores are then typically used in order to determine the success of the model (Bosboom et al., 2014; van Rijn et al., 2003)

3. Work Conducted on the Impact of Wave Energy Extraction at the Bay of Skaill

The Bay of Skaill (Figure 2) comprises of a 1 km wide, 1 km deep pocket beach with a predominantly bedrock sub-tidal, a lens of sand sized sediment in the intertidal and a cobble barrier protecting the ‘machair’ hinterland. Machair is a highly carbonate sandy soil consolidated with coarse grasses common in the north and islands of Scotland. The intertidal sediment has an average d50 of 365 µm.

Figure 2: A photograph of the bay of Skaill taken from the southern end. Beach cusps are noticeable in this photograph. The Neolithic village of Skara Brae is to the right of this photograph protected by the sea wall visible in the picture.

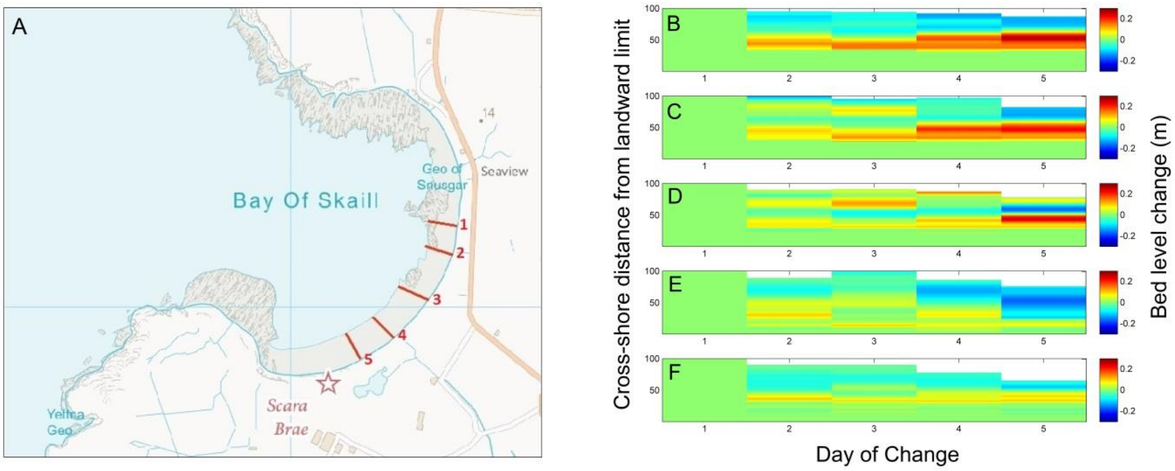

Figure 3: A map of the Bay of Skaill showing the location of the 5 measured transects (A) and cumulative bed level change for transects 1-5 (B-F).

3.1. Measurements

In order to provide model calibration data, five cross-shore beach profiles were conducted at the Bay of Skaill daily between 25/08/13 and 30/08/13. Data were collected via RTK GPS with O1 cm accuracy. Wave conditions were low to moderate energy and surf zone conditions varied between surging breakers at higher tides and spilling wave breaking on the sub-tidal rock platform with bore propagation and swash on the mobile sediment. The profile collection was planned to coincide with an AWAC deployment at the mouth of the embayment to provide concurrent wave and hydrodynamic calibration. Unfortunately, this instrument was unable to be recovered and hence there are no wave or hydrodynamic data available for calibration of models or to aid understanding of profile change. The cumulative bed level changes for the five transects are presented in Figure 3. The colour plots show the bed level change each day with respect to day one. As the week progresses there is accretion on the beach face for the northern three transects and slight erosion for the southern two transects. Changes are minimal during the model time period, this increases the difficulty of modelling this change. Equally the northern three transects are behind larger areas of rocky reef and are, therefore, slightly more sheltered than the southern two.

3.2. Modelling

Modelling was conducted using the DHI's MIKE3 suite of models (DHI, 2014). A fully coupled coastal area model incorporating hydrodynamics, a spectral wave model (Sorenson et al., 2004) and non-cohesive sediment transport was set up for the Bay of Skaill. The mesh is shown in Figure 4. A flexible triangular mesh was used with refinement in the intertidal region where profiles were measured. Vertical resolution was catered for with seven sigma levels.

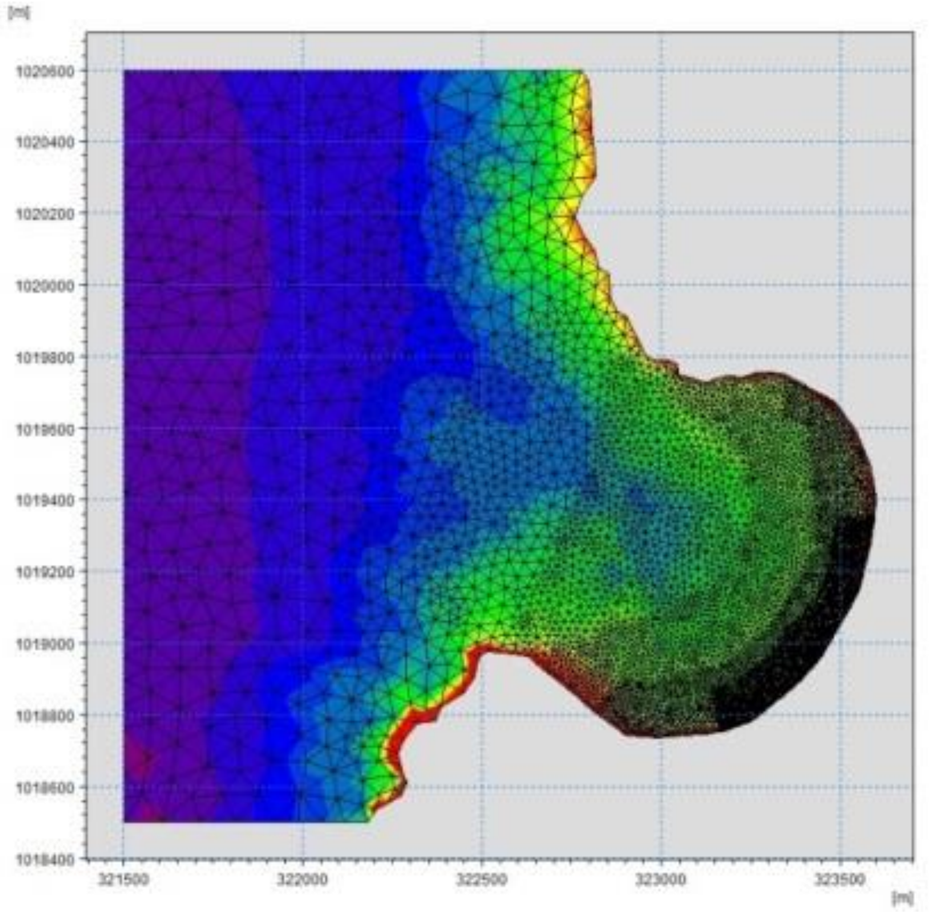

Figure 4: The mesh used at the Bay of Skaill

Hydrodynamic boundary conditions were implemented as water levels at the northern and southern boundaries with values calculated from the DHI global tidal atlas (Andersen, 1995, 1999). The offshore boundary was set to a free-slip velocity boundary. Past experience has shown this approach provides good predictions of shore parallel tidal currents such as are present on the West Coast of Orkney (Brough Head Wave Farm Ltd, 2012).

Wave conditions were implemented as parameters (H_s, T_p, Dir_p, *Directional standard deviation*) on the offshore boundary. These wave boundary conditions were extracted from simulations using the PFOW wave model created by ABPMer for The Crown Estate (Osborn et al., 2012b). The model was run with the same parameter values and wind forcing as used by ABPMer but with different offshore wave boundary conditions. Due to data availability, offshore wave boundaries were extracted from a North Atlantic model within the Terawatt consortium (Venugopal and Nemalidinne, 2015).

Areas of mobile sediment were defined using manual classification of side-scan data and with reference to Thompson and Campbell (2012). Within the sub-tidal region of the Bay of Skaill there are two small patches of mobile sediment. Thompson and Campbell (2012) used sub-bottom profiling to establish these deposits were 1 m deep. Grain size was based on samples collected in the intertidal region and a constant value of 0.365 mm implemented. Sediment samples were collected at the upper, mid and lower intertidal for all transect locations.

Default parameters were used for all three modules (DHI, 2012a, b, c) due to a lack of calibration and validation data. The lower order equations were solved due to constraints on computational power. Some model tuning was attempted by varying the bottom friction in the spectral wave model to match measured and modelled bed level change. Bottom friction was increased to a roughness length of 3 m in the offshore and sub-tidal bay in order to achieve sufficient wave dissipation to provide reasonable magnitudes of bed level change. This is an unrealistic value for roughness length; without comparison wave data it is impossible to determine why such high values are required to match morphodynamic change.

Figure 5 shows a comparison between measured and modelled profiles for the five transects over the five days. For the northernmost transects (1st and 2nd rows), modelled and measured predictions are reasonable with magnitude and location of accretion both well modelled. Predictions get progressively worse for transects to the south. For transect three the magnitude of change is correctly predicted, but the location of change is less well predicted: in particular there is an area of accretion further offshore which is not correctly modelled. For transects four and five the magnitude of modelled change is far greater than the measured change. Use of cumulative bed level change provides better comparison than daily bed level change (not shown) which was often in the wrong direction compared to measured change. Lack of wave, hydrodynamic and sediment transport data meant that further calibration of the model could not be performed. Thus confidence is low in results.

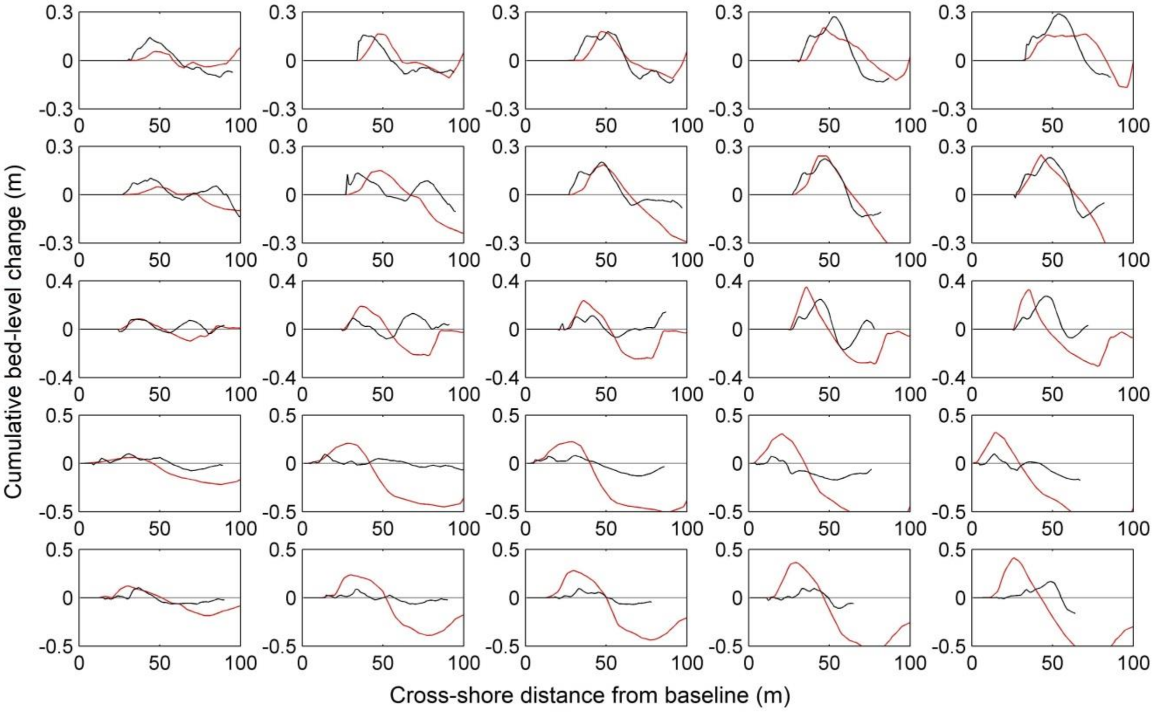

Figure 5: A comparison between modelled and measured cumulative bed level change for the five transects. The black line indicates measured change and the red line modelled change. The five rows from top-bottom are the five transects from north to south and the columns from left to right are successive days.

Despite uncertainties in model accuracy, consideration was given to the impact of wave energy extraction on beach change at the Bay of Skaill. Energy extraction was implemented into the ABPMer model used to provide boundary conditions for the local model. Array locations were based existing wave energy leases to the west of Orkney. Given the uncertainty in morphodynamic modelling a simplistic approach of introducing a line obstacle with a transmission coefficient of 0.5 was used. The coupled model was then run between 25/08/13 and 03/09/13, which incorporated a period of low energy waves when transects were taken and a storm event. A plot of the difference in wave height forced by the energy extraction is shown in Figure 6 for a location just offshore of the Bay of Skaill, the reductions in wave height are clearly visible, additionally there are small differences to the wave direction.

Differences in cumulative bed level change are presented in Figure 7 for the five transects. Differences are greatest for the southern two transects where differences are around 0.5 m which is the same magnitude as the measured changes themselves. The low confidence attributable to the current model means no firm conclusions can be drawn but it does suggest that the impact of energy extraction at the Bay of Skaill may warrant further investigation. This is especially the case since the greatest impact is predicted to occur in the south of the embayment by the Skara

Brae site. The southern end is most exposed to the north-westerly dominant wave direction which explains the greatest differences predicted in this area.

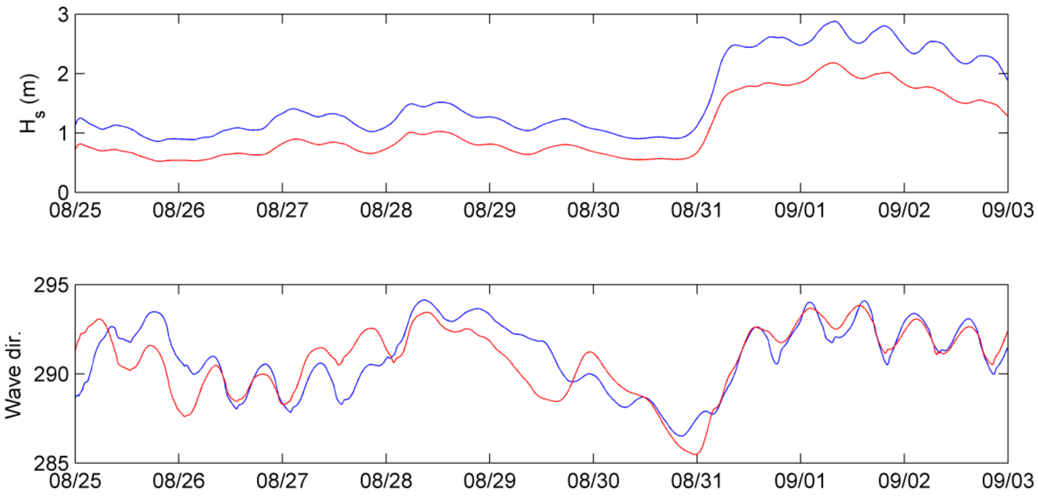

Figure 6: Time series of wave height and direction at the Bay of Skaill for the baseline (blue) and energy extraction (red) cases.

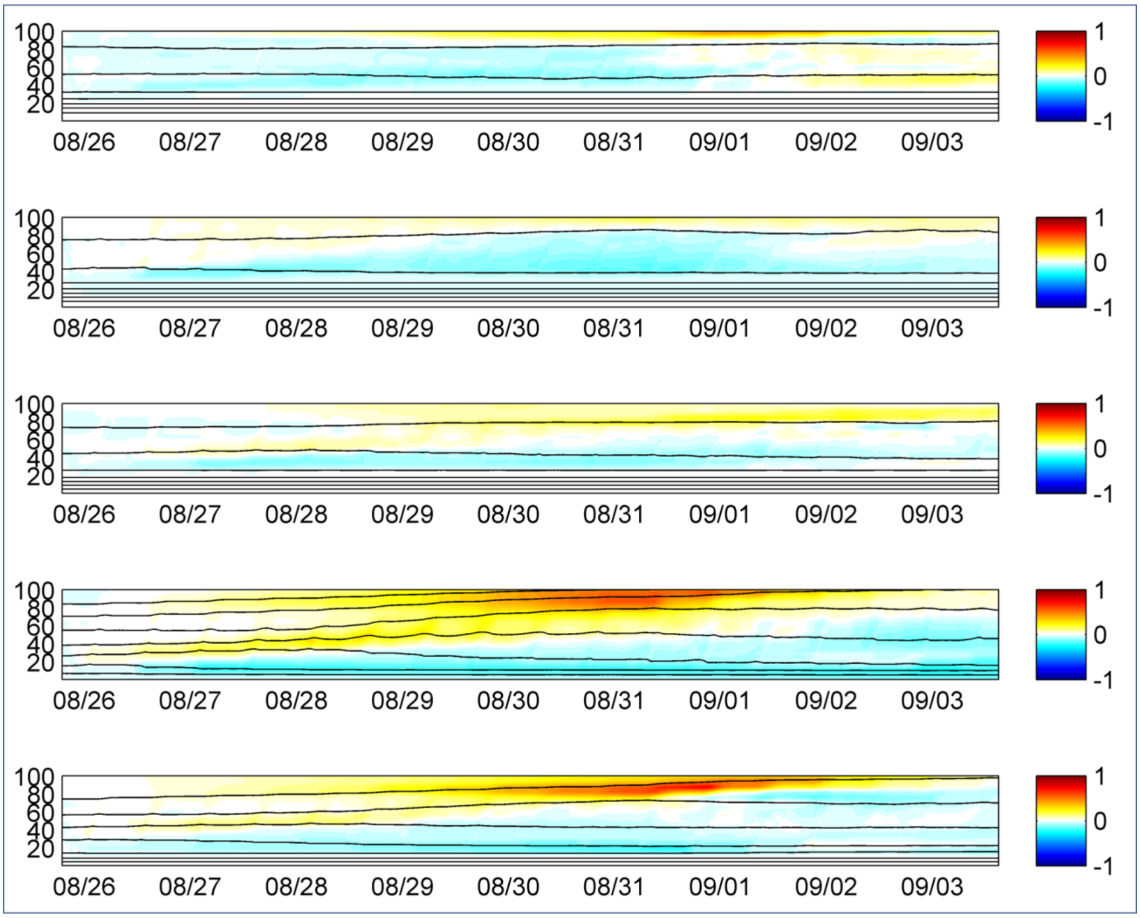

Figure 7: Differences in cumulative bed level change forced by energy extraction for the five transects from north to south (top to bottom).

3.3. Lessons Learned

Calibration data and validation data are necessary to have confidence in morphological modelling. However, instrument deployments in the nearshore of highly energetic environments have a significant risk of data loss. Measurement campaign strategies involving multiple instruments may, therefore, be necessary to avoid lack of data. In this study, lack of calibration data through instrument loss led to low confidence in the modelled forcing conditions. This meant it was difficult to determine the best strategy to improve morphological results through tuning of free parameters. At a minimum it is suggested that one nearshore wave record is obtained if modelling efforts are to be conducted. Comparison of modelled changes to measured cross shore profiles is a well-used and simple method of establishing the accuracy of morphodynamic models. Since no historical data were available at the study site, five transects were measured daily over a five day period. During this period wave conditions were low energy and hence no knowledge of the model's accuracy under high energy conditions could be gained. Therefore, it is recommended that if data collection is required either multiple, short term high frequency measurement campaigns are undertaken or an extended period of lower frequency measurements conducted. Both approaches have merits: high measurement frequencies better match to numerical model timescales whereas longer term measurements allow better consideration of seasonality.

Modelling efforts failed to accurately represent measured changes for all measured transects at the Bay of Skaill. The complexity of environments such as the Bay of Skaill means that numerical modelling may not be able to accurately represent either reality or changes forced by energy extraction to the intertidal region. This is in part due to the scarcity of sediment in the region. Morphological models have often been developed for dominantly sandy environments with the majority of change being forced by surf zone processes. At the Bay of Skaill and other exposed wave energy sites in the PFOW, much of the mobile sediment is in the lens of sediment in the intertidal with limited sediment in the nearshore. Movement of sediment over hard-rock between the intertidal and further offshore is poorly understood and, therefore, unlikely to be well modelled. Secondly much of the sediment transport, especially under lower energy conditions such as the measurement campaign, is dominated by swash zone transport which again is not well represented in numerical models. Cusp formation and evolution was present during the measurement period (Figure 2) and this process cannot be captured in coastal area model results and is may obscure other changes given the minimal changes observed during the low energy conditions of the measurement periods.

It is suggested that for many environments, with limited mobile sediment, where wave energy deployments are likely, conceptual approaches to prediction of changes in morphodynamics are explored as these may be more fruitful. Wave modelling can provide predictions for the effect of device deployment on conditions at key nearshore locations and these used to assess any possible changes to morphodynamics.

Even for locations where sand is dominant and numerical coastal area models better applicable there is a divergence between feasible timescales for morphological model simulations and requirements for consenting processes. Only short duration timescales can be successfully simulated with the computing power of standard desktop workstations, longer periods can be simulated on high performance computing clusters but these are not commonly available to device developers. Often models struggle to run much faster than real-time on a single work-station and hence modelled timescales are of episodic duration and range from a single storm event to a spring neap cycle. While these short term predictions are academically interesting, from a regulatory perspective predictions over longer time periods may be required. 2D models, either 2D horizontal of a representative shoreline or 2D vertical of a cross-shore beach profile can be run for much longer timescales and hence may be more useful for understanding of long term impacts.

4. Work Conducted on the Pentland Firth

In this section two areas of work will be summarised: morphodynamic modelling of the Inner Sound using Delft3D and morphodynamic modelling of the Pentland Firth as a whole using MIKE3. The work conducted on the inner sound with Delft3D does not include the impact of energy extraction. Further details of the Delft3D modelling are given in Chatzirodou et al. (2015) and Chatzirodou and Karunarathna (2014). Further details of the MIKE3 modelling given in Fairley et al (2015a) and Fairley et al. (2015b).

4.1. Modelling the Inner Sound using Delft 3D

4.1.1. Sand Coverage inside the Inner Sound Channel

Inside the Inner Sound channel distinct regions of sandy deposits can be observed. Regions of sand accumulation inside Inner Sound have been previously recorded (Aecom and Metoc, 2011; Easton et al., 2011; Moore, 2009). A wide range of sea bed types has been extensively identified by the Meygen EIA Quality Mark Report (MeyGen, 2012) based on a Klein 3000 side-scan sonar geophysical survey conducted by iXSurvey in 2009. The geographic extents of the survey revealed a large sandbank area (A) formed by large and medium size sand waves with maximum length (L) of 20 m and height (H) of 0.5 m, north-east inside the channel. A small-scale sandbank region (B) located westward of the island of Stroma has also been recognized. Large sandy ripples of approximately 14 m length and 0.2 m height covered the entire bank area. A less expanded bed form (C) shaped by small sandy ripples was observed southward of Mell Head in the lee of Stroma. Bedrock outcrops and discontinuous thin veneer of sandy gravel and cobbles have been further recognized in the intermediate areas bounded by the sandbank areas.

Easton et al. (2011) commented on sedimentary features found from side-scan sonar observations to the east inside the Inner Sound. Sonar surveys revealed a rippled sandy region in the lee of the island of Stroma southward and large sand waves formed on a sandbank area north – eastward. The location of the north-east sandbank was found to coincide with a convergent zone between peak ebb and flood currents from sediment transport modelling (Easton et al., 2011). Regions of sediment accretion were also formed in the observed sandy region, in the leeward side of Stroma. However, sand coverage was completely removed in areas of maximum tidal currents exceeding 2 m/sec.

In view of observations above the sea bed feature map inside the Inner Sound was re-constructed, using the Delft3D Quickin suite to identify significant regions covered by the sandbanks (Figure 8). The large, pear shaped sandbank (A), located eastwards and the smaller scale shelf bank area (B) located westwards are of particular interest to this study. Locations favoured for tidal energy extraction lie in proximity to these sandbank areas. Sandbank (A) lies in a SW-NE direction with a maximum height of ~15 m above a surrounding maximum depth of ~35 m of scoured bedrock. The axis of the bank is approximately 60^{o} from North. The sandbank is almost 3 km long and ~1 km wide. Sandbank (B) lies in NW-SE direction at maximum depth of ~ 33m.

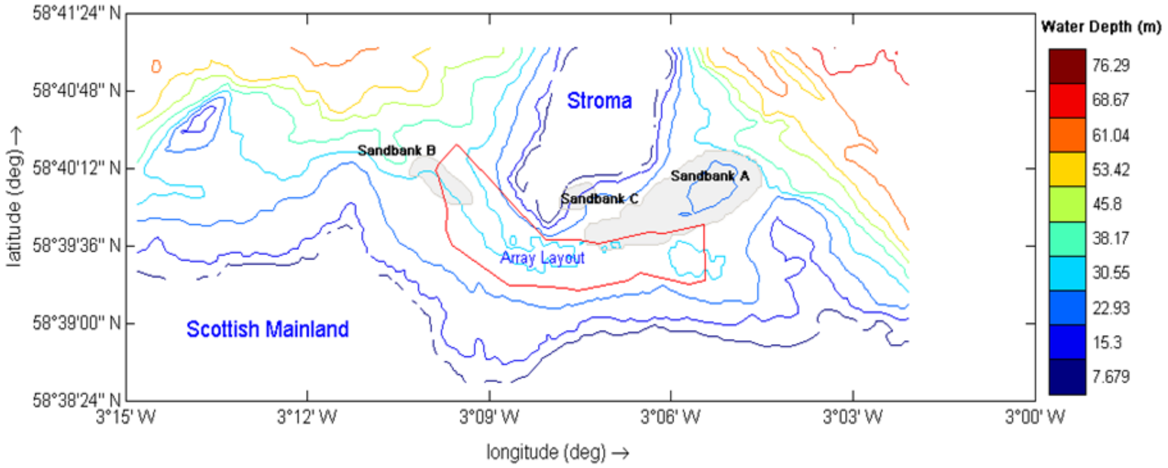

Figure 8: Sea bed features map inside Inner Sound channel has been reconstructed using Delft3D Quickin suite. Grey patches denote mobile sandbank areas. The intermediate regions are covered by non-erodible rock substratum. The red line indicates the area being considered for tidal energy extraction.

4.1.2. Morphological Model Set Up

To investigate the morphodynamic environment in the Inner Sound channel, open source Delft3D, D-Morphology modelling suite, developed by Delft Hydraulics (Lesser et al., 2004) is used. A structured grid was set up with varying resolution from 200-2000 m in deeper areas inside Pentland Firth Channel to 66 m inside Inner Sound in close proximity to the observed sandbank areas. The hydrodynamic mesh is mapped onto gridded bathymetry data available at 20 m resolution taken from The Crown Estate UK (ABPmer, 2012). In the vertical direction the modelled quantities are discretized in 10 equidistant σ- layers (Lesser et al., 2004). A constant Chezy value of $50m^{1/2}$ /sec was used to represent the regional roughness in the Delft3D computations presented in this paper. The horizontal eddy viscosity term which represents the turbulent length scales generated by the flow direction was partly approached by a constant background value varying from 10 to 1 m2/s in the higher resolution grids. In 3D simulations the horizontal eddy viscosity is eventually calculated at each σ –layer, as the sum of the constant background value and the vertical eddy viscosity computed from the k-ε turbulent closure model.

The Van Rijn (Van Rijn, 1993) deterministic sediment transport formula is applied to calculate bed load transport rates. It has been stressed that the sand availability and the sediment grain size plays a significant role only earlier at the growth stage of a sandbank region (Berthot and Pattiaratchi, 2006). At a later stage the tidal flows will mostly contribute to maintain the bank shape. Thus in the present model set up and for the sandbank (A) single D50 values of 3 mm on the north-east crest and 2 mm on the south-west flank have been used. A single D50 value of 4 mm is selected as well for sandbank (B). A common D50 value of 9 mm has been selected for non-erodible regions lying in between the sandbanks areas. It has been further assumed that the sediment grain size follows a piece-wise log uniform distribution. Bastos et al. (2004) and Berthot and Pattiaratchi (2006) argued that the bed load transport alone will dominate sand movements in shelf bank areas where sediments range from medium to mobile coarse sand. Considering that and the unavailability of any measurements, suspended sediment transport was excluded in model computations. A deterministic bed-load transport model can be less appropriate for coarse sand particles (D50> 2000μm) in flows above complex bed topography where turbulent boundary layers are developed (Lefebvre et al., 2014; Nelson et al., 1995). Inside the Inner Sound the bathymetric profile changes smoothly and results at least locally in a less complex topography. Following that it should be assumed that the Van Rijn (1993) bed load transport formula resulted in sufficiently accurate calculations of sand movements on the shelf bank areas.

4.1.3. Sandbanks Dynamics

The morphodynamic model was run for an equivalent of two spring-neap cycles between 09/09/2001 and 09/10/2001. The tidal cycle which resulted in the most significant bed level changes was further examined. It was found that sediment transport rates increased significantly in response to peak currents during the first spring tide (19/09/2001) leading to notable bed level variations. The indicated tidal asymmetry between peak ebb and flood flows inside Inner Sound generates an asymmetry in peak ebb and flood bed load transport rates on both sandbanks. It is found that the tidal flow asymmetry both in magnitude and direction, mainly contributes to the maintenance mechanisms of the enlarged sandbank (A) area located eastwards and the smaller scale sand deposit (B) observed in the westward side of the Inner Sound Channel.

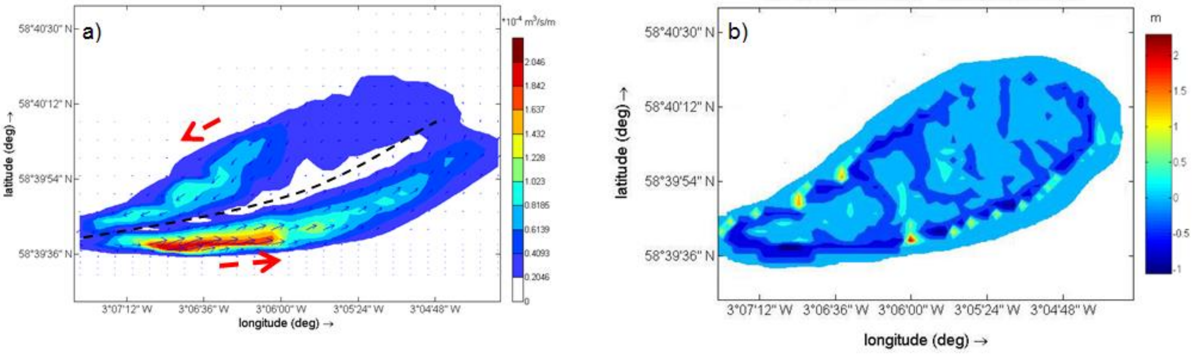

Figure 9: a) Residual sediment transport rates (m^3/s/m) covering a full spring tidal cycle (19/09/2001) at East sandbank (A in figure -) b) Cumulative erosion/accretion rate (m) on East sandbank over one month period computations (from 09/09/2001 to 09/10/2001).

4.1.3.1. East Sandbank (A)

At spring ebb phase (19/09/2001 02:40) bed-load transport rates increased towards the downstream wedge of the east sandbank (A) followed by decreasing gradients to the north-east flank. At neap ebb tide sediment transport rates are significantly weaker but still follow the same pattern. At spring flood phase (19/09/2001 08:00) bed-load transport rates increase offshore, away from the tip of the Island of Stroma on the south-west flank in response to strong flows. Low sediment transport rates exhibit a slight anti-clockwise veering closer to the sandbank crest/centre. As at ebb phase sediment transport processes mostly occur at spring flood tide in comparison to neap tide. Overall an eastward flood-dominated transport pattern is observed.

For a period covering a spring tidal cycle the residual sediment transport rates have been computed resulting in an anticlockwise circulation pattern on sandbank (A) area (Fig 9a). The net transport rates steadily decrease in magnitude towards the centre of the sandbank in a sediment transport convergent zone. The transport gradients could indicate the resultant erosion/accretion patterns (Roelvink and Reniers, 2012). Decreasing gradients on the southern flank resulted in sand accumulation whereas increasing transport rates north-westward on the sandbank revealed small regions of erosion. The sediments mostly moved and settled towards the central parts of the bank area and erosion incurs on the flanking regions (Figure 9b). Low bed level changes occurred over one month period but are likely to be bigger over long - term morphodynamic scales (decades).

4.1.3.2. West Sandbank (B)

At spring ebb tide (19/09/2001 02:40) sediments move north-westward on the west sandbank (B) in response to strong bottom velocities to the west. At spring flood tide (19/09/2001 08:00) increasing sediment transport gradients were found to the south-east on the sandbank region. At neap tide notably weaker bed load rates follow the same pattern. Overall a northward ebb transport pattern is dominant on sandbank (B). The resultant erosion/accretion patterns on the sandbank area may occur as a result of residual sediment transport computed for a period of a spring tidal cycle (Figure 10a). As can be seen in Figure 3a an inner convergent zone of decreasing transport gradients is generated. The sandbank erodes southward in response to increasing transport rates towards the sandbank centre/crest whereas sediments mostly move and accumulate at the northern part of the shelf bank area. A notable bed change can be observed in sandbank (B) (Figure 10b). Sediments travel northward and reshape the west bank in a more elongate shape.

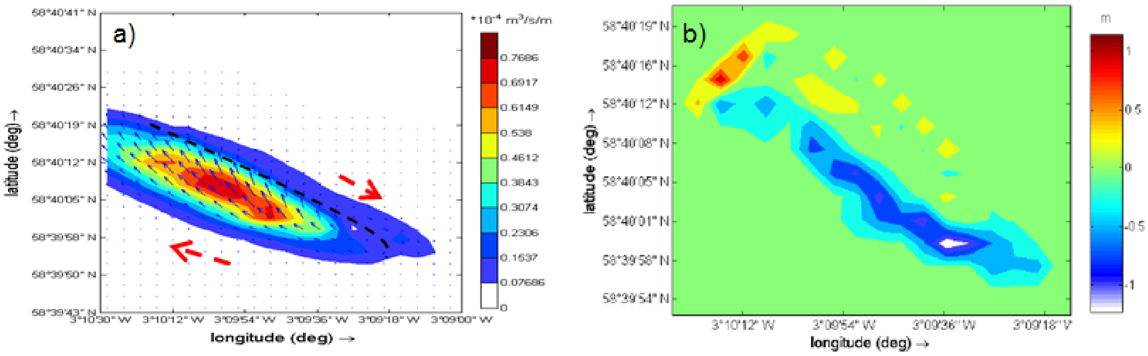

Figure 10: a) Residual sediment transport rates ($m^3/s/m$) covering a full spring tidal cycle (19/09/2001) at West sandbank (B) b) Cumulative erosion/accretion rate (m) on West sandbank (B) over one month period computations (from 09/09/2001 to 09/10/2001)

4.2. Modelling the Impact of Energy Extraction on Sandbanks in the Wider Pentland Firth using MIKE3.

The Danish Hydraulic institutes MIKE3 model has been used to investigate the impact of marine energy extraction on the wider Pentland Firth environments.

4.2.1. Establishing Sand Coverage and Grain Size.

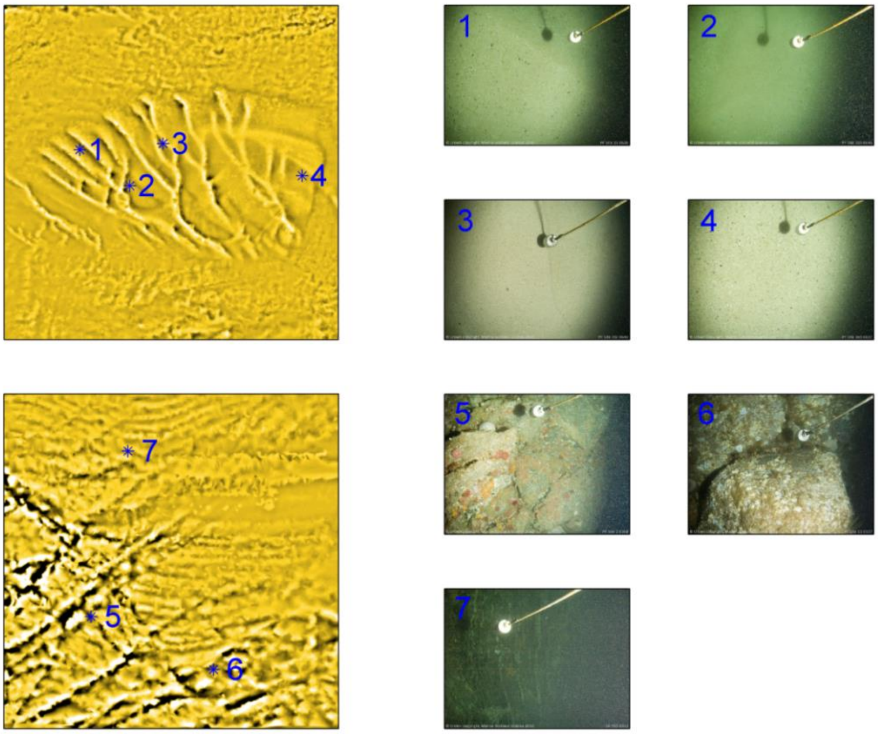

Figure 11: Ground-truthing of the textural classification, with the textural surface for a sand area in the top left, a textural surface for a rock area on the bottom left and images from Marine Scotland video trawls showing the bottom type. Reproduced from Fairley et al (2015).

In order to determine coverage of sediment, consideration was given to a textual surface created from de-trended bathymetry data. Multi-beam echo-sounder data were interpolated onto a regular grid with 3 m spacing. In areas where multi-beam data were not available a 20 m gridded bathymetry supplied by the crown estate was used (ABPmer, 2012). These gridded data could then be de-trended to provide a textural surface. Manual classification of sand areas was then conducted in a GIS package. Sand areas were visible as rippled or smooth surfaces while rock and boulder areas showed creviced irregular features. Ground-truthing of this approach is conducted against data from benthic video trawls (Figure 11). For the inner sound area, where supplementary information was available, the classification was corroborated against the Meygen Environmental statement. The de-trended surface is shown in Figure 12. Three main areas of mobile sediment were identified (Figure 12): the Sandy Riddle, a banner bank associated with the Pentland Skerries; a sandbank to the east of the inner sound associated with a residual current gyre (see section 4.1); and a large area of sand waves to the west of Stroma.

Sediment size data were taken from three sources: the Meygen Environmental statement, a dataset of analysed BGS sediment samples and from a set of Marine Scotland Science benthic video trawls. It was decided that given the spatial variation in sediment size, as great a spatial representation of sediment as possible was desirable. Therefore, while low accuracy, the use of data from benthic video trawls was deemed appropriate. Each video trawl had been given a seabed descriptor by MSS. This descriptor was used to assign a grain size for each trawl location where mobile sediment was present based on the ISO sediment scale.

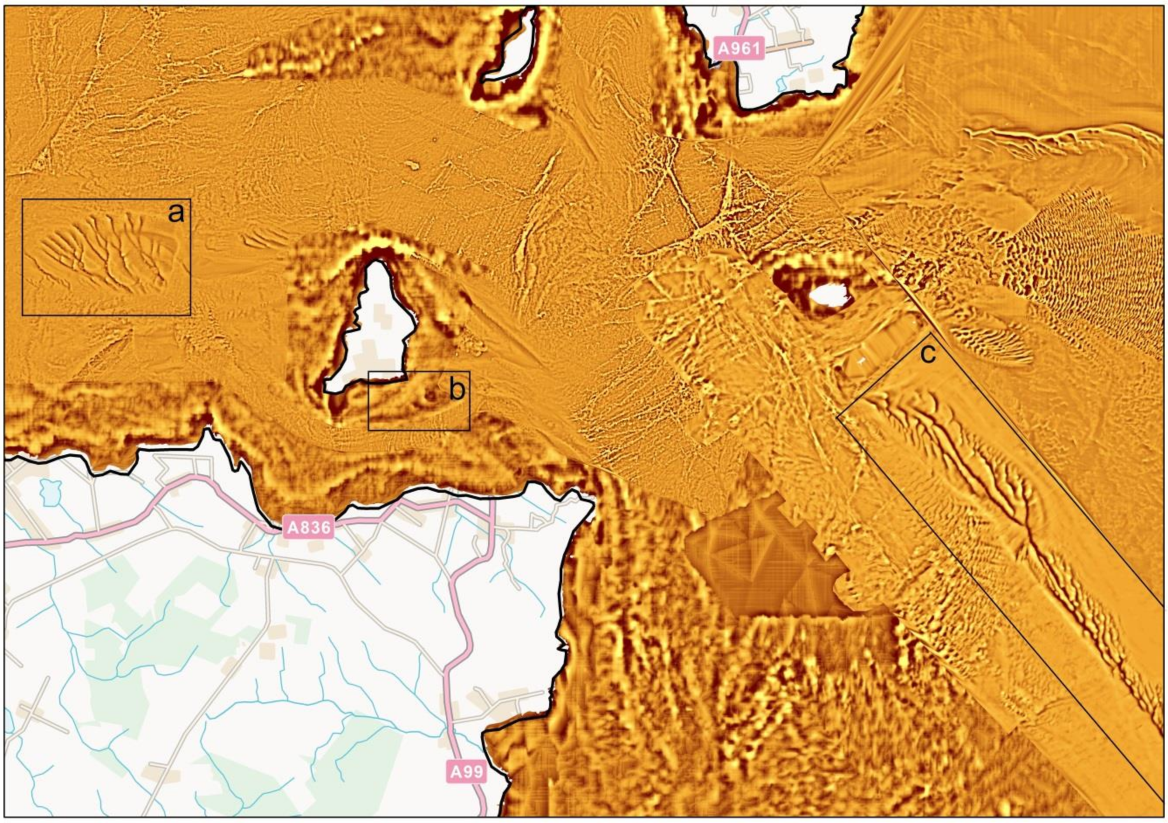

Figure 12: The de-trended surface used in identification of sand regions and the three primary mobile sediment areas identified: a) the sand wave field west of Stroma; b) the inner sound sandbank; and c) the Sandy Riddle.

4.2.2. Model Set-Up

The hydrodynamic and sand transport modules of the MIKE3 suite were used in a fully coupled mode for the simulations presented here. Simulations were conducted with and without turbines in place. A scenario where all four currently proposed sites were included and turbine number based on estimates from project reports (MeyGen, 2012; ScottishPowerRenewables, 2012; SSERenewables, 2013). It should be noted that the number of turbines implemented and array layouts are different to those given in O'Hara Murray (2016) due to the chronology in which different work packages were conducted.

For the Meygen site in the Inner Sound, the array layout presented in the environmental statement (MeyGen, 2012) was digitised. This layout comprises of a staggered grid that is slightly asymmetric to make best use of the available resource. There are fewer turbines per row in the west than the east of the array. For the other sites a regular rectangular staggered lattice layout was used. This had a lateral spacing of 2.5 turbine diameters (D) and longitudinal spacing of 10D. This spacing was informed by reports on the Ness of Duncansby site (ScottishPowerRenewables,

2012) and on academic research (Edmunds et al., 2014; Malki et al., 2014; Stallard et al., 2013).

Turbines are included within the MIKE model by specifying the *x, y,* location, the hub height, blade diameter and either a constant drag coefficient or a table of lift and drag coefficients. The implemented turbines were the same for all the tested arrays in this contribution: a constant drag of 0.6 is used, hub height is 17 m and turbine diameter is 20 m.

An unstructured triangular mesh was used which had 7642 nodes, 14619 elements and 10 sigma levels vertical resolution. The mesh was denser around areas of mobile sediment and array areas. Default values (DHI, 2012a, b) were used for all parameters in both modules apart from bed resistance for the hydrodynamic simulation. Higher order solution techniques were used for both time integration and space discretization. Hydrodynamic boundary conditions were taken from a previously validated regional model of the PFOW (Osborn et al., 2012a).

A bed resistance value of 2 m gave the best match with ADCP measurements. Simulated depth averaged currents were compared to measurements from three ADCPs in the main channel of the Pentland Firth. For all three sites the model performed well. It is believed that the high roughness length required may be due to the roughness length of the irregular bedrock in the region being much higher than that for sand and gravel areas. This does raise the question of how realistic flows are over the mobile sediment areas where bed resistance would be expected to be substantially lower. However, since ADCP data were only available for the bed-rock areas no further consideration could be given to this aspect.

For these two measurement locations, peak currents are associated with a current jet formed between the islands of Stroma and Swona. This jet is westward directed in the western half of the Pentland Firth on the ebb and manifests in the eastern half on the flood when currents are directed from west to east. It may be that the model is incorrectly representing this current jet.

Sediment transport was computed using the van Rijn equations for bed load and suspended load (van Rijn, 1984a, b). Higher order solution techniques were used for the sediment transport calculations. The forcing parameter was set to depth averaged current rather than bed shear stress in order to partially mitigate for inaccuracies caused by a constant value of bed resistance in both hydrodynamic and sediment transport modules.

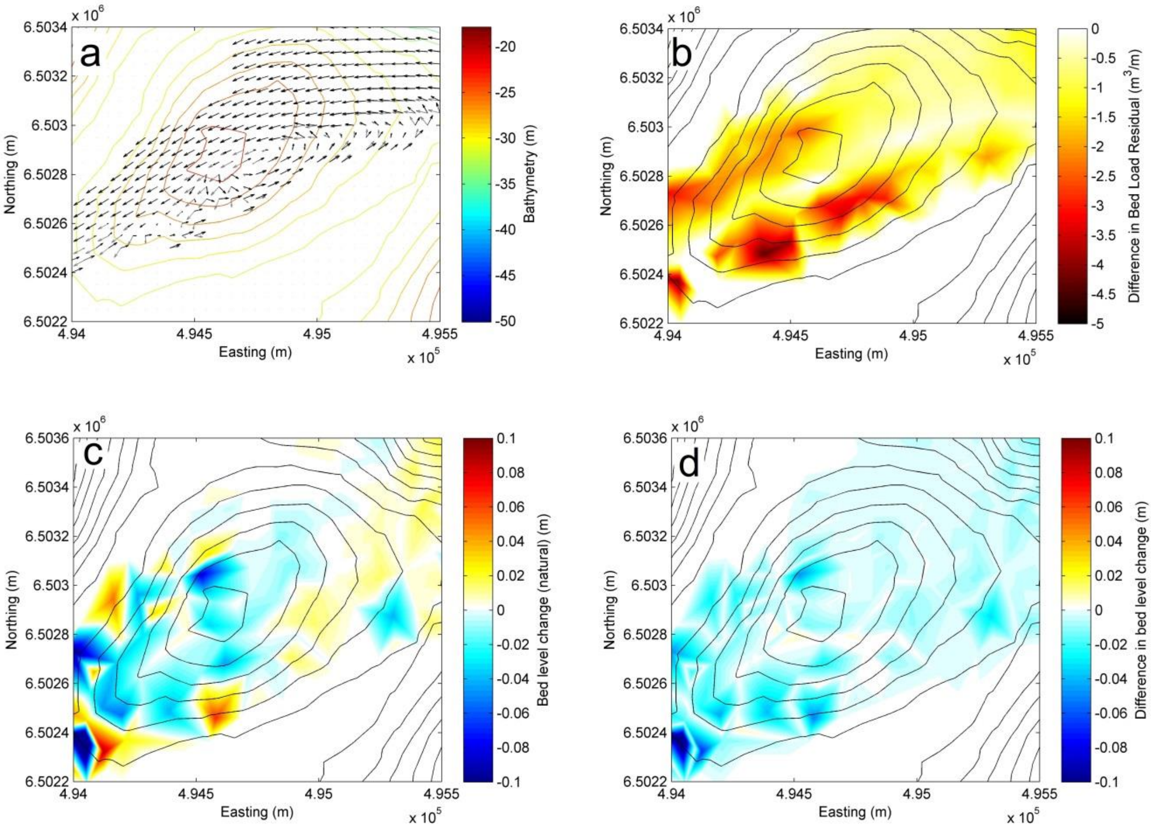

Figure 13: Maps of the inner sound sand bank showing a) differences in direction of bed load residual between natural (black arrows) energy extraction (grey arrows) scenarios; b) the difference in the magnitude of bed load residual; c) the bed level change under natural conditions and d) the difference in bed level change forced by energy extraction.

4.3.3. Morphodynamic changes predicted by MIKE3

Consideration will focus on the impact of tidal energy on the inner sound sandbanks to allow comparison with the Delft modelling and a plot of bed level change over the sand waves west of Stroma is also shown (area A in figure 12). A lunar month between 13/09/2001 and 11/10/2001 is considered in this analysis. Figure 13 shows the differences in bed load transport and morphological change for the eastern sandbank in the inner sound. Bed level change (13c) and bed-load residual direction (13a) are similar to the results presented from the Delft3D modelling. Implementation of tidal energy extraction leads to some changes to the bed-load gyre. Under natural conditions, an anti-clockwise residual gyre is present around the sandbank with minimal transport over the crest. Inclusion of energy extraction reduces the radius of the gyre and shifts the centre to the south east which leads to a SW directed current over the crest of the bank. These changes force differences in the prediction of bed level change with an overall reduction in the magnitude of change. The magnitude of the difference in predicted change is similar to the magnitude of the change itself over the modelled lunar month and, therefore, the implementation of turbines in the inner sound may have some impact on the sub-tidal sandbank.

Figure 14 shows the bed level change predicted for one lunar month over the sand waves identified in the multi-beam bathymetry. Bed level changes of up to 5 m over a lunar month are predicted. This is an unrealistic value if it is assumed that this region is a permanent feature. It is impossible to determine whether the predicted change is due to inaccurate model set up for that area, the sand wave field being an ephemeral feature, or one that is maintained by a combination of wave and tidal processes (waves were not included in this modelling exercise).

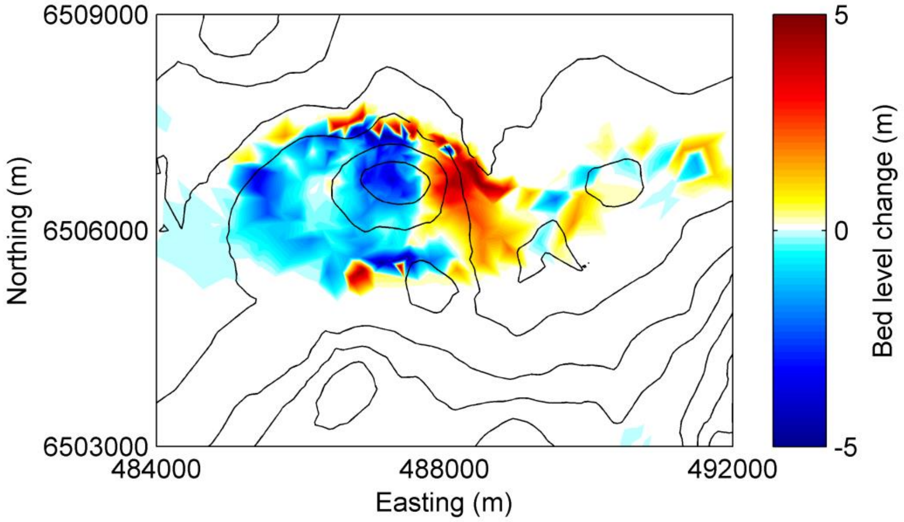

Figure 14: A plot showing bed level change for the natural condition over the sand wave area to the west of Stroma (area A).

4.4. Lessons Learnt from Modelling of Sub-Tidal Sandbanks

Two different models were set up independently using different modelling systems, different boundary conditions and different treatment of sediment sizes and areas. Nonetheless similar predictions were made for bed level change and direction of bed load transport for the inner sound sand bank. A significant body of work exists for the formation, maintenance and evolution of sub-tidal sandbanks (Bastos et al., 2004; Berthot and Pattiaratchi, 2005; Berthot and Pattiaratchi, 2006; Dolphin et al., 2007; Horrillo-Caraballo and Reeve, 2008; Neill, 2008; Pattiaratchi and Collins, 1987; Reeve et al., 2001; Scmitt et al., 2006) and the residual gyres predicted for the sandbank of the inner sound fit well with this knowledge. This gives confidence that for such sandbanks, an engineering approach of using default parameters and limited data will yield reasonable results for impacts of energy extraction. Conversely for other areas of mobile sediment such as the sand wave field, greater uncertainty remains. Without multiple bathymetric surveys it is impossible to know the permanency and natural dynamics of this region and other similar environments. If such environments are important to the environmental impact of a project, further data gathering may be required.

Other researchers (Martin-Short et al., 2015; Robins et al., 2014; Wu et al., 2011) have focused on changes to bed shear stress rather than, or in conjunction with, actually modelling sediment transport itself . Bed shear stress (τ_b) can be calculated via (1):

$$\tau_b = \rho C_d \|u\| u \tag{1}$$

Where ρ is the density of sea water, C_d is the coefficient of bottom friction, ||u||, is the velocity magnitude of the velocity vector u. This quantity predicts which size particles are initiated into motion by relating the measured bed shear stress to the critical value for a given particle size and density. Therefore, consideration of bed shear stress allows prediction of what size or particles might exist at a given location. This approach has two primary advantages: firstly data on sediment are not actually required and secondly it is much more computationally efficient to only model hydrodynamics. The first disadvantage is that the bed shear stress depends on the bottom friction which may not be known accurately over a model domain. The second disadvantage is that sediment transport and changes to morphology is not predicted and morphodynamics are often non-linear. However, if the focus is on changes to bed shear stress then the first disadvantage is not so pressing. The bed shear stress approach could be used by projects as a first step to determine whether further investigation and sediment transport modelling was required.

5. Discussion and Conclusions

This paper has highlighted research that has been conducted into the morphodynamics of sites in the Pentland Firth and Orkney Waters and the challenges that are faced in conducting such modelling. These regions are highly complex environment with large spatial gradients in wave and tidal forcing. For sub-tidal sandbanks where there is high confidence that they are permanent features, an engineering approach to modelling is believed to produce accurate results and, therefore, reasonable predictions of the impact of energy extraction. Modelling efforts for the sandbank in the inner sound suggest that turbine implementation may affect the sandbank morphodynamics. To investigate this in more detail, hydrodynamic calibration data would be needed in the inner sound and greater information on the sedimentary regime required.

Greater difficulty in determining natural dynamics and hence impact of energy extraction occurs for identified sub-tidal sediment areas that are not in typical areas for sub-tidal sandbanks and for which limited data exist. It is suggested that for such environments the approach of considering the changes to bed shear stress should be used in the first instance. If significant changes to bed shear stress are observed in sensitive areas then data collection may be required despite the expense of such campaigns.

The nature of intertidal sediment in much of the PFOW is that it is a relatively thin lens of sediment overlying the hard rock geology. Such environments are difficult to model due to both the governing dynamics (swash zone processes) and the lack of data. The second difficulty is relatively easy to rectify but the model suitability is a limiting factor. Given the limited amount of sediment in many of these environments it is reasonable to question whether accurate modelling is actually necessary. In many areas the hinterland is protected by hard rock cliffs or cobble barriers and, therefore, it is not important from a coastal protection perspective. At the study site of the Bay of Skaill, the world heritage site of Skara Brae is at risk of erosion and hence more detailed studies may be required. The Bay of Skaill is also the largest sandy beach on the west coast of Orkney and, therefore, plays an important recreational function.

Academically, it seems there would be merit in attempting a more rigorous (scientific in Sutherland (2004)’s terminology) modelling programme for the impact of energy extraction on both sub-tidal and intertidal environments in the Pentland Firth and Orkney waters. These environments are sufficiently different to the environments in which coastal area models are commonly used to model morphodynamics that determining their applicability with greater quantities of data seems worthwhile. Of particular interest is the transport of mobile sediment onshore over the sub-tidal bed-rock under calm conditions that must occur to facilitate storm recovery in areas such as the Bay of Skaill.

As wave and tidal stream energy projects become more prevalent, regulators will require evidence to support environmental impact assessments and this will include predictions of sediment transports. This work has shown that modelling of sediment transport in high energy regions is non-trivial and may not be fruitful. Collection of the level of data that is required for accurate modelling may not always be viable to individual projects and, therefore, unless high-risk receptors are present, a pragmatic approach should be taken utilising consideration of hydrodynamic parameters such as bed shear stress or conceptual modelling of the changes to morphodynamics based on modelled wave conditions.

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Requests for model or measurement data developed in this study should be addressed to the corresponding author.

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