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Data review and the development of realistic tidal and wave energy scenarios for numerical modelling of Orkney Islands waters, Scotland

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ABSTRACT

The Orkney Islands and surrounding waters (known as the Pentland Firth and Orkney Waters Strategic Area, PFOW) contain a significant portion of Scotland's tidal and wave energy resource. This paper forms part of a wider study modelling tidal and wave processes, and planned renewable energy extraction, in PFOW using 3D hydrodynamic and spectral wave numerical models. Such hydrodynamic models require a number of spatial data, i.e. high resolution bathymetry, model boundary conditions and measurements for model validation, which are hard to obtain in extreme environments such as PFOW. This paper examines the characteristics and selection criteria of the data used for the development of the models. Most of these data are freely available, and could form part of an open source marine renewable energy hydrodynamic modelling toolbox.

In order to include the planned tidal and wave energy developments in the hydrodynamic models of the wider study, realistic tidal and wave device array scenarios are required. However, there is still considerable uncertainty regarding the type of devices that will be deployed and device array layouts. Here, we describe the process undertaken, in consultation with industry, to develop a small number of generic device types and array scenarios for the PFOW, based on insight provided by documentation submitted by developers as part of the Scottish marine licensing process. For tidal developments, an algorithm was developed to determine the site specific array configuration, taking into account the number of turbines, water depth, tidal current direction and the spatial distribution of mean kinetic energy. The wave development sites did not require such detailed site specific placement of devices, and the generic layouts could simply be constructed in most cases without the need for detailed site specific resource characterisation.

It is anticipated that the renewable energy industry will be able to adopt our data selection criteria to ensure models developed for environmental impact assessments satisfy the quality requirements of the regulator. Similarly, the methodologies developed for characterising generic device types and array layouts will be useful to academia and government researchers, who do not necessarily have access to detailed device and site specific information.

1. Introduction

It is estimated that Scotland's marine area contains 25% of Europe's tidal resource, and 10% of Europe's wave resource (The Scottish Government, 2015). One area of particular interest is the Orkney Islands and surrounding waters, which contain a significant portion of Scotland's tidal and wave energy resource (Black and Veatch, 2005; Carbon Trust, 2011). For this reason, a number of sites have been granted agreement for lease by The Crown Estate (TCE) (the semi-independent, incorporated public body which manages the UK's seabed from mean low water to the 12-nautical-mile limit) as areas for commercial renewable energy development within the region known as the Pentland Firth and Orkney Waters Strategic Area (PFOW) (The Crown Estate, 2013). In 2010 TCE granted lease agreements to five tidal and six wave development sites, forming the *PFOW Round One Development Sites* (Fig. 1). Each designated site had a nominal maximum power rating (or energy generating capacity) assigned to it, with a total of 1 and 0.6 GW for the tidal and wave sites, respectively.

The Scottish Government is committed to the sustainable development of the tidal and wave energy sector, as incorporated in

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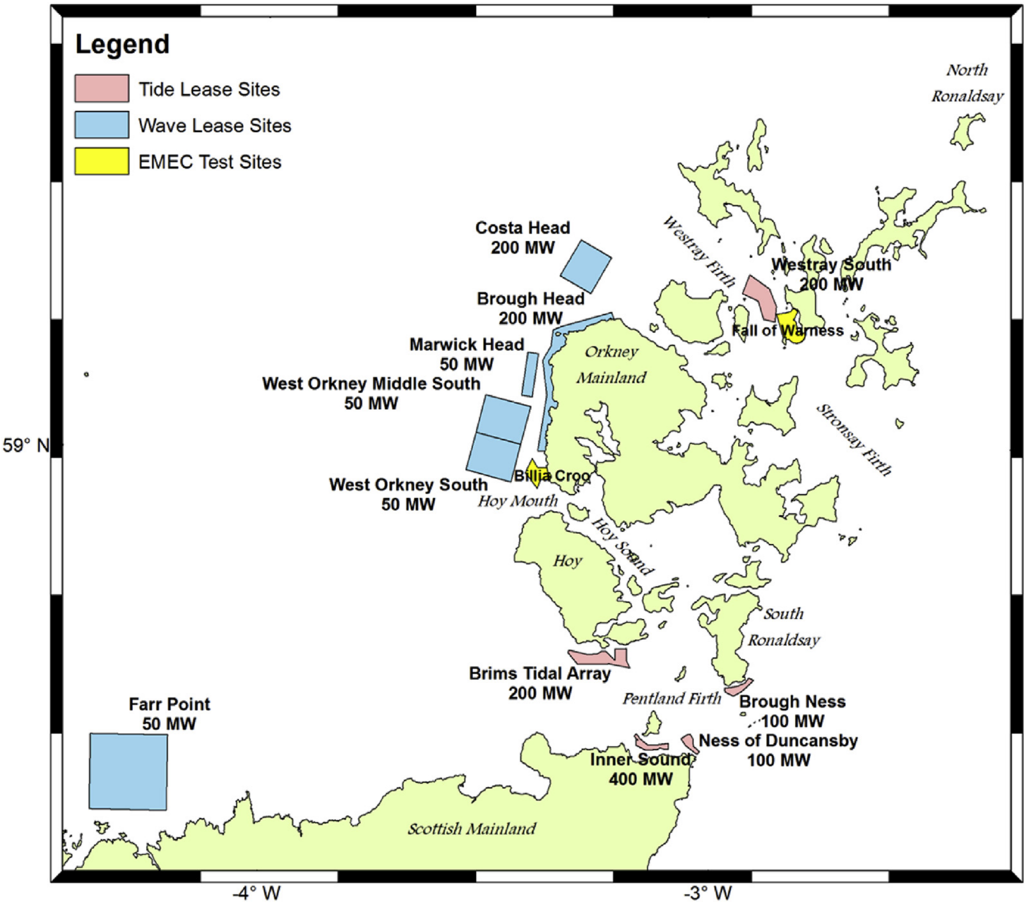

Fig. 1. Map showing the Pentland Firth and Orkney Waters Round One Development Sites, their nominal capacity, and the European Marine Energy Centre (EMEC) test sites. Modified from The Crown Estate (2013).

the National Marine Plan (The Scottish Government, 2015). There is, however, some degree of uncertainty regarding the potential physical and ecological environmental impact of large scale developments. One approach to understand the potential impact on the physical environment is hydrodynamic modelling of both the baseline, or undisturbed, state and a state which includes marine renewable energy (MRE) extraction. This is an emerging field and a number of methods for representing tidal and wave energy extraction in hydrodynamic models are being developed. For example Rennau et al. (2012) introduced an additional friction sink term in the momentum equations of the 3D hydrodynamic General Estuarine Transport Model (GETM) to represent tidal turbines at a sub-grid scale. van der Molen et al. (2016) have since modelled tidal energy extraction the Pentland Firth to explore the impact on both the physical and biological environments using GETM coupled with the European Regional Seas Ecosystem Model-Biogeochemical Flux Model (ERSEM-BFM).

The work we present here forms part of a wider project (the *TeraWatt* project, Side et al., 2016). The primary aims of the wider study were to model the tidal flow and wave fields in the PFOW, to include wave and tidal energy extraction in the models, and to assess the impact of wave and tidal energy extraction on the physical and biological environment. In this paper, we describe the PFOW region, including details of recent tidal and wave energy resource assessments (Section 2). In order to develop three dimensional hydrodynamic and spectral wave models of this complex region, a number of datasets are required. Section 3 describes the data used in the wider modelling study and examines the characteristics, and selection criteria, of the data used for the development of the models, such as their spatial resolution and the types of forcing data used. The wider study used two main hydrodynamic and spectral wave modelling packages, (1) MIKE by DHI, including MIKE 3 Flexible Mesh Hydrodynamic module (MIKE 3 FM HD, hereafter referred to as MIKE 3) and MIKE 21 Flexible Mesh Spectral Wave module (MIKE 21 FM SW) (https://www.mikepoweredbydhi.com/download/product-documentation) to model currents and waves, respectively, and (2) DELFT 3D (Deltares, 2014) and SWAN to model currents and waves, respectively. Based on the outputs of those models, realistic tidal stream (Section 4) and wave (Section 5) array scenarios for the PFOW Round One Development Sites have been developed. Such scenarios were used by the wider project to investigate how large scale tidal and wave energy development in the PFOW may change the physical and ecological processes in the region. It is anticipated that the renewable energy industry will be able use the principles explored in this paper to ensure models developed for environmental impact assessments are likely to satisfy the quality requirements of the regulator. Similarly, the applicability of the generic device types and layouts to future model development by academia and government, who do not necessarily have access to detailed device and site specific information, is discussed.

2. The Pentland Firth and Orkney Waters

The Orkney Islands lie off the north coast of the Scottish mainland, and are separated from the mainland by a narrow channel, the

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Pentland Firth, which provides one link between the North Atlantic and the northern North Sea. The M_2 Semidiurnal tidal wave propagates clockwise around the UK, swinging east and then south around the northern Orkney Islands and travelling down the east coast of Orkney and along the eastern Scottish mainland. This leads to an approximate 2 h phase difference between each end of the Pentland Firth (Easton et al., 2012), setting up a hydraulic gradient along its length. A dynamic and energetic tidal regime is the result, and the Pentland Firth has some of the fastest tidal stream currents in the world, exceeding 5 m s^{-1} during spring tides. The tide flows eastward from the North Atlantic into the North Sea during the flood and westward during the ebb tide. In addition to fast tidal races, there are highly turbulent areas throughout the Firth, which are especially turbulent during times of strong westerly winds being opposed by the westward ebb tide. The tidal races in the PFOW are not just confined to the Pentland Firth; the narrow tidal straits between the islands, e.g. Westray and Stronsay Firths, and headlands, e.g. North Ronaldsay, also have strong and dynamic tidal flows. These strong tidal flows have received significant attention in relation to tidal stream energy, with 4/5 of the tidal PFOW Round One Development Sites being in the Pentland Firth and 1/5 being in the Westray Firth. It is likely, however, that other areas around the islands will be targeted for tidal energy exploitation in the future (The Scottish Government, 2015).

It is difficult to put an exact figure on the tidal resource potential of the PFOW. There have been a number of studies quantifying the potential of the extractable tidal energy resource in the Pentland Firth, from approximately 1 GW (Black and Veatch, 2005) to approximately 18 GW (Salter and Taylor, 2007). The lower estimate of approximately 1 GW (Black and Veatch, 2005) is based on the kinetic energy flux method where the energy of a tidal channel is taken as the flux of the kinetic energy through the channel (based on the channel cross section at one point and average flow speeds). This method has been shown to underestimate the resource and should only be used for narrow tidal channels connected by two large basins (Garrett and Cummins, 2005; MacKay, 2008). Some of the more recent estimates of the power potential of the Pentland Firth are based on 2D hydrodynamic models with energy extraction from tidal turbines included in the model. Draper et al. (2014) concluded that the maximum extractable power of the Pentland Firth is 4.2 GW averaged over the spring-neap cycle. This estimate was based on a 2D hydrodynamic model with M_2 and S_2 tidal forcing, and with tidal energy extraction represented using enhanced bed roughness in a 1.5 km strip across the whole width of the Pentland Firth. Another recent estimate of 1.9 GW (Adcock et al., 2013) is based on rows of tidal turbines modelled using actuator disk theory in a 2D hydrodynamic model. More recently, O'Hara Murray and Gallego (2017) have used a 3D hydrodynamic model to estimate the maximum extractable power to be 5.3 GW averaged over the spring-neap cycle.

The Orkney Islands wave regime is dominated by the passage of low pressure systems and swell waves from the North Atlantic. The west of the Orkney Islands therefore has a significantly higher wave resource than the east. Neill et al. (2014) report that the highest wave resource is found to the north and west of Orkney, but that there is significant seasonal variability with a resource of up to 30–50 kW m^{-1} during winter months and <10 kW m^{-1} during summer months.

3. Data for hydrodynamic models

The models developed as part of the wider study, and which are of primary interest here, are regional scale, three dimensional, hydrodynamic and spectral wave models using structured or unstructured grids with minimum node spacing of the order of 100–250 m (collectively referred to as *hydrodynamic models* from now on). Hydrodynamic models require a number of datasets describing the characteristics of the area being modelled, namely coastline, bathymetry and seabed sediment data. To an extent, the resolution and accuracy requirements of these data depend on the resolution and scale of the model. Forcing datasets are also required along model boundaries (boundary conditions) and across the whole domain, such as atmospheric forcing. Such forcing data are often taken from other, coarser, atmospheric and hydrodynamic models. Other requirements for the development of accurate hydrodynamic models are measurements of water elevations, currents and waves in order to (a) calibrate the model through the adjustment of parameters (within physically defined limits) to force the model to better represent reality, and (b) validate the model using different data. There should always be an awareness of the constraints and uncertainty of all these datasets, both for modelled data and physical measurements.

This section describes the data ultimately used to model the hydrodynamics of the PFOW region in the wider project, and reports where these data can be found and whether they are subject to any licensing constraints. The wider project compiled a vast amount of data and metadata, of which only a small fraction were ultimately used. This section presents those data, while O'Hara Murray (2015) provides a more detailed, and complete, description of all the data available to the wider project. Often multiple datasets were identified and, in these cases, the criteria used to select any specific dataset are described. Table 2 in the Appendix categorises and lists all the datasets described in this section.

3.1. *Bathymetry data*

It is important for the model grid to have sufficient horizontal spatial resolution to resolve relevant bathymetric features such as mega-ripples, trenches, sand bars and banks, which influence the hydrodynamics. The water depth, relative to a common datum, needs to be specified at specific points on the computational grid, which is made up of elements sharing common nodes/vertices. This is usually at the position of each computational grid node, or at the centre of each element. The approach taken is often to interpolate point depth measurements, which are not necessarily on an ordered grid, to the computational grid. This interpolation will generally smooth the bathymetry to some extent. The underlying bathymetry data is required to have at least as high a horizontal resolution as the model grid. Ideally the horizontal resolution of the underlying bathymetry will be greater than the model grid, in order to maximise the accuracy of the interpolation.

The output from Multi Beam Echo Sounder (MBES) systems can typically resolve seabed features to a horizontal resolution of less than 1 m, and is typically binned at a horizontal resolution of 1–10 m. Such high resolution results in large datasets being generated for relatively small areas of the seabed, and is significantly higher than what is required for hydrodynamic models, which are likely to have a mesh resolution 1–3 orders of magnitude smaller. MBES data are therefore ideal for hydrodynamic model development; in fact the horizontal resolution of such data may need to be reduced before being interpolated to the model grid.

Much of the coastal waters in the UK have been surveyed by either MBES or Single Beam Echo Sounders (SBES). These data can be obtained from the UK Hydrographic Office (UKHO) Infrastructure for Spatial Information in Europe (INSPIRE) data archive centre (https://www.gov.uk/inspire-portal-and-medin-bathymetry-data-archive-centre) under open government license. This dataset has a number of contributors including the UKHO, the Maritime and Coastguard Agency (MCA) and Marine Scotland Science (MSS, the Science division of the Marine Scotland directorate of the Scottish

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Government). Whilst these data cover much of the PFOW, there are at the time of writing some gaps.

As part of the wider project, a number of sources of data were reviewed to fill the bathymetry gaps, such as measurements taken by ship echo sounders (Smith and Sandwell, 1997) and Admiralty Chart data, which have a lower horizontal resolution than MBES. The Crown Estate made the results from a similar data review exercise available to the project (The Crown Estate, 2012), which included a bathymetry dataset for the PFOW region derived from a number of high resolution sources interpolated to a regular 20 m horizontal grid. Much of the underlying data were from hydrographic survey data held by the UKHO, but the gaps were filled using the Digital Elevation Model (DEM) (Astrium OceanWise, 2011) made available by the Department of Environment, Food and Rural Affairs (DEFRA). The 20 m horizontal resolution was a good balance between file size, limited by the computational facilities available, and high enough resolution to resolve all the relevant bathymetric features at the scale of the model grid, typically of the order of 100 m. For this reason these 20 m gridded data were used by the wider study and in this paper.

3.2. Seabed sediments data

Important sediment transport processes operate over a wide range of length scales, some of which are very small. Sediment transport modelling requires detailed bed sediment distribution maps in addition to high resolution and accurate bathymetry data. Small scale processes are not resolved in coupled hydrodynamic – sediment transport models but are often parameterised using empirical formulations. Knowledge of the typical grain size and the grain size distribution is of particular importance because it determines whether the sediment can be lifted from the bed and transported by currents, waves and other, potentially turbulent, processes.

The British Geological Society (BGS) have a large dataset of seabed sediment samples available via their Web Map Services under the Open Government Licence (http://www.bgs.ac.uk/GeoIndex/offshore.htm). These data include some detailed particle size and size distribution data which were used by the wider study (Fairley and Karunarathna, 2014).

3.3. Currents measurements

Measurements of the tidal currents are crucial for the calibration and validation of hydrodynamic models. For three dimensional models it is important to use measurements throughout the water column, to determine whether the model is reproducing the current profile adequately. Presently, current speeds and directions are typically measured using Acoustic Doppler Current Profilers (ADCP) that can profile through the water column. These are typically deployed on a frame or mooring for a period of time to produce a time series at a single location, or used from a moving vessel to measure how currents vary spatially (e.g. Goddijn-Murphy et al., 2013). Single point time series are often easier to interpret, as there is no need to separate spatial and temporal effects, as well as to account for the effect of the motion of the ship. There is some inherent uncertainty related to ADCP data, as they have diverging acoustic beams and therefore assume that the water column is horizontally homogeneous within the measurement volume (e.g. RD Instruments, 1996). Usually a temporal *ensemble average* is taken over a fixed number of backscatter returns (*pings*) (Trump, 1991). ADCP data requires some level of processing to assess the quality of each ensemble average and to make appropriate adjustments to the compass. Brumley et al. (1990) detail the performance of broadband ADCPs. The deployment methodology should be chosen with the application of the data in mind. For example, many tidal site developers choose to deploy ADCPs on ridged bottom frames to eliminate any movement as much as possible, enabling higher frequency measurements to be made. The principal currents dataset used by the wider study consisted of three 30-day fixed upward looking ADCP deployments, starting on 14 September 2001. These data were collected by Gardline Marine Sciences, under contract to the MCA to make a number of tidal stream measurements in and around the Pentland Firth in September 2001 (Gardline Surveys, 2001), and were made available to the wider study (David Woolf, Personal Communication). In addition to these static ADCP deployments, four vessel-mounted ADCP transects, between 17–23 September 2001, were made along the boundaries of the Pentland Firth. Fig. 2 shows the location of these instrument deployments and vessel-mounted transects. The moored ADCP data were processed by Gardline Surveys (2001) who applied a number of quality control procedures including range checking the velocity time series, and examining the velocity time series for sharp changes between ensemble averages (spikes) and unusual plateaus in the speed. The tidal and non-tidal components of the velocity time series were also examined using a tidal harmonic analysis technique.

Another source of data used by the wider study was a 12 week ADCP dataset from the Fall of Warness, where the European Marine Energy Centre (EMEC) has a tidal test area (Fig. 1). The ADCP was deployed at 59° 9.360′ N, 002° 49.860′ W on 14 July 2010 (Fig. 2). These data were purchased from EMEC and are not publically available.

During the course of this project, MSS deployed an ADCP in Stronsay Firth, 59° 00.17′ N, 002° 38.52′ W, for an M_2 tidal cycle on 21/05/2014. In addition to this, MSS conducted vessel mounted ADCP transects over M_2 tidal cycles in Hoy mouth and Hoy sound, Stronsay Firth, and across the east end of the Pentland Firth in 2014. Fig. 2 shows the location of the MSS ADCP measurements. MSS also made available current meter time series from the Fair Isle channel from 2008 and a number of historical current meter data off the Scottish east coast for the sediment transport studies of the wider study. All these data are available from the British Oceanographic Data Centre (BODC) or MSS. MSS quality control all ADCP data by reviewing a number of parameters to assess the quality of each ensemble average, including the error velocity, percentage good pings and correlation.

3.4. Waves measurements

Measurements of wave parameters are required for the calibration and validation of spectral waves models. Relevant wave statistics are the significant wave height and the wave period where the energy spectrum peaks. The waves data used by the wider study were obtained from Wave Rider buoys. The Centre for Environment, Fisheries and Aquaculture Science (Cefas) have a strategic UK wave monitoring network, WaveNet, consisting of a network of Wave Rider buoys primarily sited close to coastal areas at risk of flooding (https://www.cefas.co.uk/publications-data/wavenet). Most of the data are freely available under an Open Government Licence, although some are restricted to non-commercial government and academic use (http://cefasmapping.defra.gov.uk). Some of the data can be downloaded for commercial use subject to an extraction fee. The quality assurance and quality control procedures adopted by Cefas are detailed on the WaveNet website and include range checking and de-spiking the wave parameters.

In addition to the Cefas WaveNet data, the wider study purchased EMEC data from a Wave Rider buoy deployed at Billia Croo, 58° 58.214′ N, 003° 23.454′ W, where EMEC have a wave energy test

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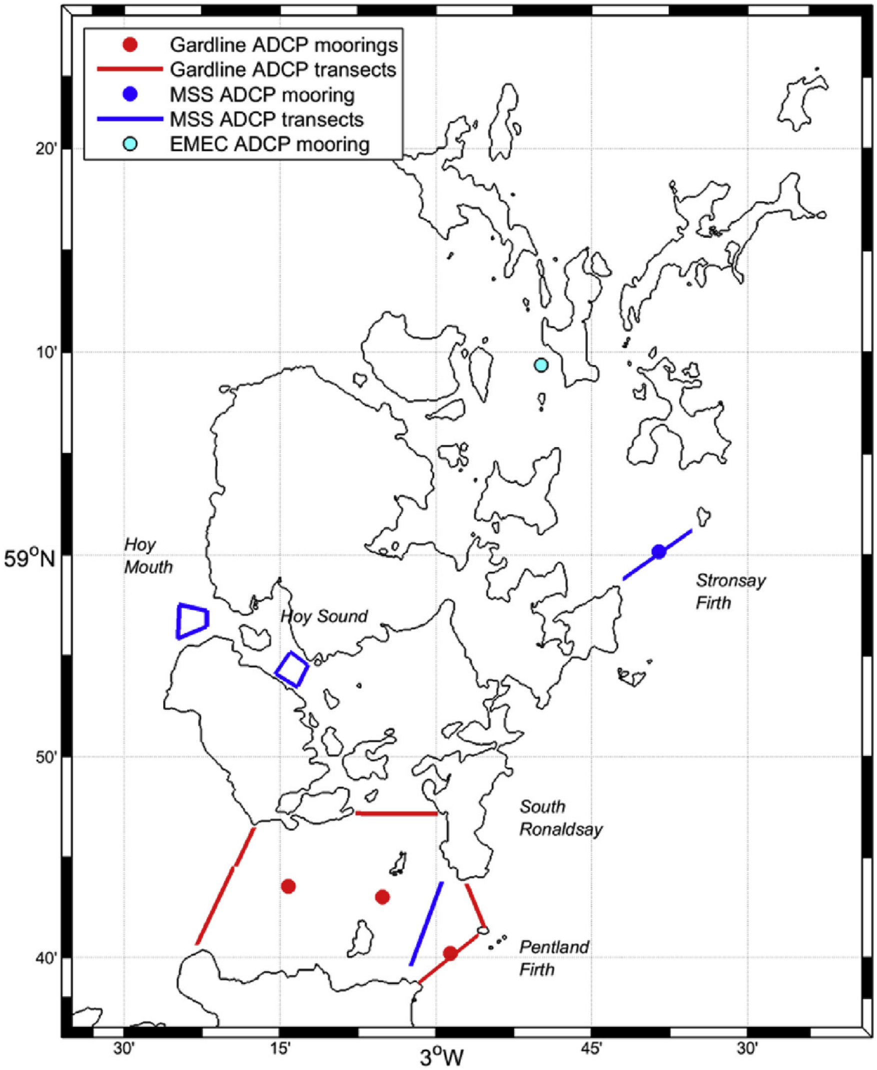

Fig. 2. The location of the Gardline Marine Sciences, Marine Scotland Science (MSS) and European Marine Energy Centre (EMEC) Acoustic Doppler Current Profiler (ADCP) measurements.

centre (Fig. 1). These data consisted of 30 min binned wave statistics for two complete years, 2010 and 2012. As with the EMEC ADCP data, these data were purchased by the project and are not publically available. The wider study also used data from a Wave Rider buoy deployed off Bragar, west coast of the Isle of Lewis, Scotland as part of the Hebridean Marine Energy Future project (Vögler and Venugopal, 2012).

3.5. Model data

Hydrodynamic models require forcing data and initial conditions across the model domain and at the open boundaries. Because forcing data are required over a range of spatial scales and time periods, output from other models is often used. For tidal boundary conditions, the wider study used output from the Oregon State University Tidal Prediction Software (OTPS), an open source barotropic tidal model based on the Oregon State University tidal inversion of TOPEX/POSEIDON altimeter and tide gauge data (Egbert et al., 2010). The model can be obtained from http://volkov.oce.orst.edu/tides/otps.html and there is also a Matlab implementation available from http://polaris.esr.org/ptm_index.html. Wind forcing data for the wave models were obtained from the European Centre for Medium Range Weather Forecast (ECMWF) ERA-40 atmospheric model (Dee et al., 2011), available from http://www.ecmwf.int/en/research/climate-reanalysis/browse-reanalysis-datasets.

In addition to model forcing data, the wider study used the UKHO Vertical Offshore Reference Frame (VORF) model to convert between the various vertical datums used in the different datasets, such as chart datum, mean sea level and lowest astronomic tide. The model output consisted of surfaces specifying the difference in height between different datums, and was gridded at 0.008° intervals. Output from the VORF model was made available to the wider study by the UKHO under an Open Government Licence.

3.6. Additional datasets

The previous sections describe the main datasets compiled for the hydrodynamic model development as part of the wider project, many of which are specific to the region of interest (PFOW) or are not considered to be widely used. For completeness, two further datasets are described here. Coastline data are often crucial for defining the coastal boundary of hydrodynamic models. A common choice is the Global Self-consistent, Hierarchical, High resolution

Geography Database (GSHHG) available from the NOAA National Centers for Environmental Information (https://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html). These data are based on the World Vector Shorelines (WVS) and CIA World Data Bank II (WDBII) datasets. Long time series of accurate water elevation measurements are crucial for monitoring sea level change but also for measuring the contribution from the tide and non-tidal factors, such as storm surges. Such measurements are also needed to validate modelled water elevations. The UK National Tide Gauge Network consists of 44 coastal locations recording tidal elevations. These data are available from the British Oceanographic Data Centre, http://www.bodc.ac.uk/projects/uk/ntslf.

4. Tidal stream arrays scenario development

The PFOW Round One Development Sites leased within the PFOW by TCE provide a broad indication of where the first tidal arrays in the PFOW will be located. However, these sites will be used as initial areas of search, within which actual arrays will be placed. A number of factors will determine the exact positioning of MRE devices within these leased zones. One of the major constraints is the availability of tidal resource and, whilst TCE have targeted areas with fast tidal currents, these currents vary within the sites in both the horizontal and vertical dimension, as well as temporally through the spring-neap tidal cycle. The tidal resources assessment undertaken is described in Section 4.1. As the placement of devices will change the characteristics of the resource (Vennell et al., 2015), interference between devices will also need to be taken into consideration. Another constraint on the positioning of devices designed to be mounted on the seabed is its suitability, both in terms of substrate and relief. Finally, an important consideration will be water depth. This is to ensure that the tidal turbines do not extend beyond the water surface, but also potentially so that they are sufficiently deep to allow the safe navigation of vessels above them (which could be a licensing constraint), unless navigational restrictions are imposed in the area. Where the tidal arrays and devices will be eventually located within the leased zones is unknown until the projects are fully licensed and detailed planning by the developers begins. It was therefore necessary to develop a method for determining the position of the arrays in order to develop realistic scenarios for tidal and wave MRE developments in the PFOW for the wider study.

Some work has been conducted by treating array layouts as an optimization problem (Funke et al., 2014; Kramer et al., 2015). There is great merit in this approach as it takes the changes resulting from tidal energy extraction into account, but requires a large number of model runs to find an optimal solution. Large regional scale hydrodynamic models cannot therefore be used with these methods, due to the high computational resource that would be required, and this paper takes a much simpler approach by purely taking the undisturbed resource into account, along with a number of other constraints.

One of the factors that will determine the ultimate spatial extent of an array of tidal devices is the number of tidal devices and their spacing within the array. As stated above, the exact layout of tidal turbines within an array is something that will ultimately effect the performance of individual turbines and the tidal array as a whole, and has been investigated by a number of authors (e.g. Myers and Bahaj, 2012). Vennell et al. (2015) distinguish between micro and macro design of arrays, with the so-called micro design focussing on the inter array layout of tidal devices, and the macro design focusing on the position of an array as a whole. The macro design is, to an extent, defined here by the locations of the development sites and does not, therefore, need to be considered in this paper. However, the development sites are potentially large enough to accommodate what could be considered to be more than one distinct array. The device spacing does, however, need to be considered specifically here for two reasons, (i) it will ultimately define the spatial extent of the array, and (ii) the tidal turbine module within MIKE 3, one of the hydrodynamic models used in the wider study (see below), requires the exact placement of devices to be specified. It was decided that each tidal array within the PFOW should, as far as possible, be composed of the same generic devices and have the same generic underlying array layout. The development of a generic tidal turbine type is outlined in Section 4.2. The methodologies adopted for the design and placement of generic arrays are outlined in Sections 4.3 and 4.4, respectively. Section 4.5 presents the tidal stream array layout results.

4.1. Tidal resource assessment

As part of the wider study, MIKE 3 and DELFT 3D models of the PFOW were developed (Baston et al., 2014; Waldman et al., this issue). The MIKE 3 model used for this study had an unstructured grid with a typical node spacing in the region of interest of 125 m, and was run for one month to generate the output required for this study. This model used the bathymetry interpolated to a 20 m grid described in Section 3.1, and was calibrated and validated using the currents measurements presented in Section 3.3. Waldman et al. (this issue) reported in detail on the development and validation of the MIKE 3 model for this region. Tidal current velocities output from the model were used as one of the constraints for the placement of arrays of tidal turbines within the development sites (Section 4.4). A full quantitative resource assessment was not necessary, as all that was required for the present exercise was the broad spatial distribution of tidal resource. The kinetic energy (*K.E.*) of the tidal stream is proportional to the cube of the instantaneous tidal current speed. We used the temporal mean of the cube of the instantaneous depth mean current speed (U), calculated over one spring-neap tidal cycle (14.765 days) for each grid point within the model domain:

$$K.E. \sim mean\left(U^3\right)$$

A principal component analysis was performed on the time series of depth mean velocity from each element in the MIKE 3 model. This enabled the principal current direction and the spatial distribution of temporal mean speeds to be calculated across each of the sites. The spatial mean and standard deviation of the principal direction for each development site are presented in Table 1, along with the area of each site, and the average and maximum current speed of each site. The Inner sound development site had the highest variance of current directions, as it occupies a large proportion of the full length of the Inner Sound of Stroma channel. For this reason the site was sub divided into three areas and the mean direction was calculated for each of these sub-sites using a principal component analysis on the modelled data from each sub-site. The results are included in Table 1.

4.2. Generic tidal turbine and device types

There are different tidal stream turbine technologies under development and the PFOW is likely to see a range of different types of devices deployed. In order to simplify the specification of the tidal array scenario, a single generic tidal stream turbine design was used. Baston et al. (2014). provide the characteristics of this turbine and the rationale behind them. Briefly, the generic horizontal axis tidal stream turbine has a rated maximum power output (or capacity) of 1–1.5 MW, a 20 m diameter rotor, and a current speed dependent thrust coefficient with a cut-in and cut-out speed

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Table 1
The mean direction and standard deviation of the principal component of tidal currents from the MIKE 3 tidal model for each of the tidal development sites in the PFOW, and the three sub-sites of the Inner Sound. The area of each site, the designated capacity, and the spatial mean and maximum (the spatial mean and maximum of the temporal mean of the depth mean) current speeds are also listed.

Site name	Designated capacity (MW)	Mean direction (degrees)	Standard deviation (degrees)	Area (km^2)	Mean speed ($m\ s^{-1}$)	Maximum speed ($m\ s^{-1}$)
Ness of Duncansby	100	120	8	9	1.5	3.7
Brough Ness	100	75	16	11	1.3	3.8
Brims Tidal Array	200	93	7	41	1.6	4.1
Westray South	200	144	12	48	1.3	3.1
Inner Sound (whole site)	400	101	23	12	1.6	4.3
Inner Sound sub-site 1		124	11		1.6	4.3
Inner Sound sub-site 2		99	4		1.8	3.8
Inner Sound sub-site 3		80	5		1.7	4.1

of 1 m s^{-1} and 5 m s^{-1}, respectively. A constant power output for each turbine of 1 MW was assumed for this paper, in order to determine the number of devices required to reach the energy generating capacity of each leased site.

Most of the planned PFOW tidal developments are likely to use 1 MW single axis tidal stream devices. The one exception is the Brough Ness development which is most likely to use the Marine Current Turbines 2 MW device, which has two horizontal axis turbines with a hub to hub spacing of approximately 30 m. Therefore, two different generic devices were defined for this study, each using the above generic turbine: a 1 MW device with a single turbine, and a 2 MW device with two turbines with a hub to hub spacing of 30 m.

4.3. Generic array layouts

A simple array layout considered by a number of studies is a grid of turbines aligned with the flow and with a constant across stream and downstream spacing. This spacing is often defined in terms of the rotor diameter, D, of the turbine. Across stream and downstream spacing of $3D$ and 10–15 D, respectively, are common choices (Lewis et al., 2015; Myers and Bahaj, 2005, 2012). Another logical array feature is to have the rows of devices offset, such that the turbines in one row are aligned to the gaps between the turbines in the adjacent rows (Myers and Bahaj, 2012). This feature takes advantage of the anticipated acceleration of the flow around individual turbines.

The approach taken here to design a generic array layout was to review the available licensing documentation for the planned developments in the PFOW held by Marine Scotland, the Directorate of the Scottish Government responsible for the licensing of MRE developments in Scottish Waters. These documents are available from www.gov.scot/Topics/marine/Licensing/marine/scoping. The aim was to develop a generic array layout that could be used for all the PFOW sites but which would also be a realistic possibility. Within the licensing documentation, limited information was available regarding the exact final array layouts. This was due to uncertainties in the final technologies, that the projects are still under development and that many projects will be adopting a phased deployment and are therefore only initially seeking consent for a small proportion of the final development. Still, there was sufficient information available to construct a coherent array scenario. The approach taken by developers for their Environmental Impact Assessments (EIA), leading to the Environmental Statements (ES) required for licensing, is to consider an envelope, often termed a Rochdale envelope, of possibilities. Out of all the available licensing documentation the MeyGen phase 1 ES (MeyGen, 2014) and supporting literature (www.gov.scot/Topics/marine/Licensing/marine/scoping/MeyGen) provided the most comprehensive array layout information and, for this reason, was used primarily for this work. The ES used an example array layout for the proposed 86 devices, forming the Phase 1 Development. The spacing used in the ES was 45 m across stream and 160 m downstream, with staggered rows of turbines.

The final generic tidal array layout for the 1 MW horizontal axis devices was chosen to have a spacing 45 m (2.25 D) across stream and 160 m (8 D) downstream, with staggered rows. For the 2 MW twin turbine device, the above spacing was simply doubled with 90 m (4.5 D) across stream hub to hub spacing between each 2 MW device and 320 m (16 D) downstream, staggered, spacing. The across stream spacing of 90 m equated to 120 m spacing between the centre of each 2 MW device.

4.4. Generic array positioning

The factors considered here to determine the position of the arrays were (a) the number of devices, (b) the water depth, (c) the principal current direction, and (d) the spatial distribution of mean cubed current speeds. The bathymetry data used was the interpolated bathymetry on a 20 m grid described in Section 3.1. The analysis of the MIKE 3 model output described in Section 4.1 was used to characterise the spatial distribution of tidal resource.

A generic array layout algorithm was developed to position devices in a standard way in each of the PFOW tidal sites. Fig. 3 shows the evolution of the Ness of Duncansby array layout as the generic array layout algorithm progressed. For each development site, or sub-site in the case of the Inner Sound, a grid of devices was initially created with the designated generic device layout, centred over the site, or sub-site. The grids were then rotated so that they were correctly aligned with the mean current direction for the site, or sub-site. Fig. 3a shows the position of individual turbines after this first stage of the process for the Ness of Duncansby site. The bathymetry data were interpolated to the device locations, and the devices placed in depths of less than 27.5 m relative to mean sea level were removed. This was to ensure that the 20 m diameter blades of the devices were always below the water surface. Fig. 3b shows the turbine positions after this second stage of the process for the Ness of Duncansby site. The last stage involved removing the devices within each site that were in the poorest tidal energy resource, and only keeping enough devices to reach the energy generating capacity of each site. As discussed in Section 4.1, the resource was assessed by interpolating the temporal mean of the cube of the depth mean current speeds from the MIKE 3 hydrodynamic model to the device locations. This last stage was performed iteratively, ensuring that there were no isolated turbines. It was considered unlikely that isolated turbines, many 100s of meters away from the main array, would be located on account of a very small patch of (potentially marginally) higher current speeds. Fig. 3c shows the resulting Ness of Duncansby array after this last stage of the array layout process.

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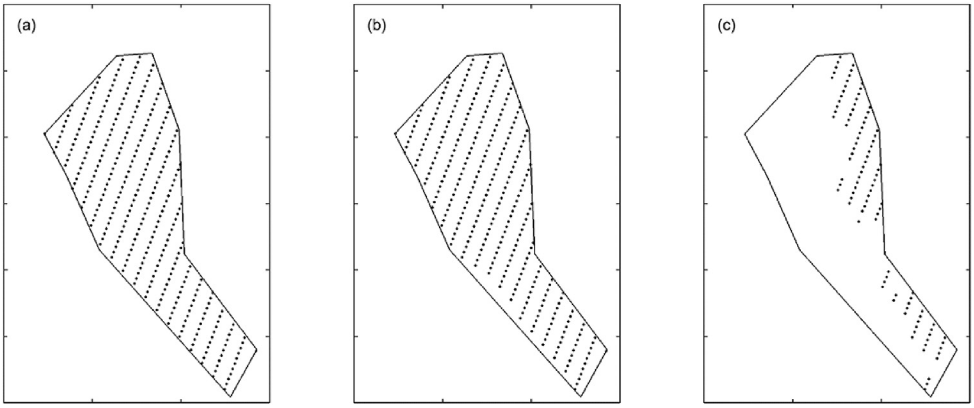

Fig. 3. The evolution of the Ness of Duncansby tidal stream array layout using the generic layout algorithm, showing the array layout after (a) the alignment of the turbine grid with the main flow direction, (b) the removal of devices in shallow water regions, and (c) the retaining of devices in the highest resource areas.

4.5. *Tidal stream array layout results*

Figs. 4–7 show the final array layouts for the Inner Sound, Ness of Duncasby, Brims Tidal Array and Westray South, respectively, overlaying the mean depth average current speed from the MIKE 3 output for the region around each development site at each grid element. The projection used for these figures is UTM 30 N, and the MIKE 3 modelled depth average current speed at the resolution of the model grid is shown. The array layouts for these developments all have 45 × 160 m (across stream x downstream) offset spacing of 1 MW devices. There Inner Sound array (Fig. 4) fills most of the lease site, with the majority of the gaps due to too shallow water depth. Only three devices were removed from areas of poor tidal resource. Most of the tidal devices within the Ness of Duncansby array (Fig. 5) are positioned on the north and east side of the lease site. The area of the site is more than sufficient to accommodate the generic tidal devices with the generic spacing, and the highest resource in the area is found in the most offshore region of the site, where the devices were positioned. The majority of the tidal turbines within the Brims tidal array (Fig. 6) are positioned within the centre of the lease site, where there is higher resource. As for the Ness of Duncansby, the area of the tidal site is more than sufficient to accommodate the 200 turbines proposed here, and the water depth is more than sufficient throughout the site for the generic turbine we have used in our study. There is therefore ample space to arrange the turbines to fully optimise the power output. The turbines within the Westray south array (Fig. 7) are mainly positioned in the centre of the channel, towards the south east side of

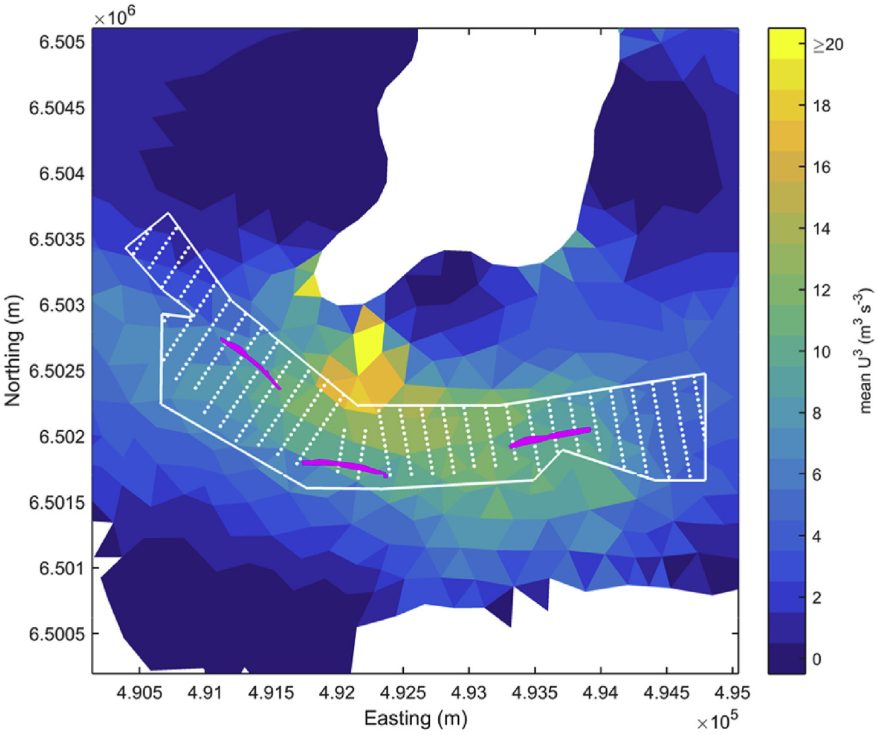

Fig. 4. The final array layout for the 400 MW Inner Sound development overlaying the mean of the cubed depth average current speed (mean U^3) from the MIKE 3 output. The tidal ellipses for the three sub-sites are indicated by the magenta lines.

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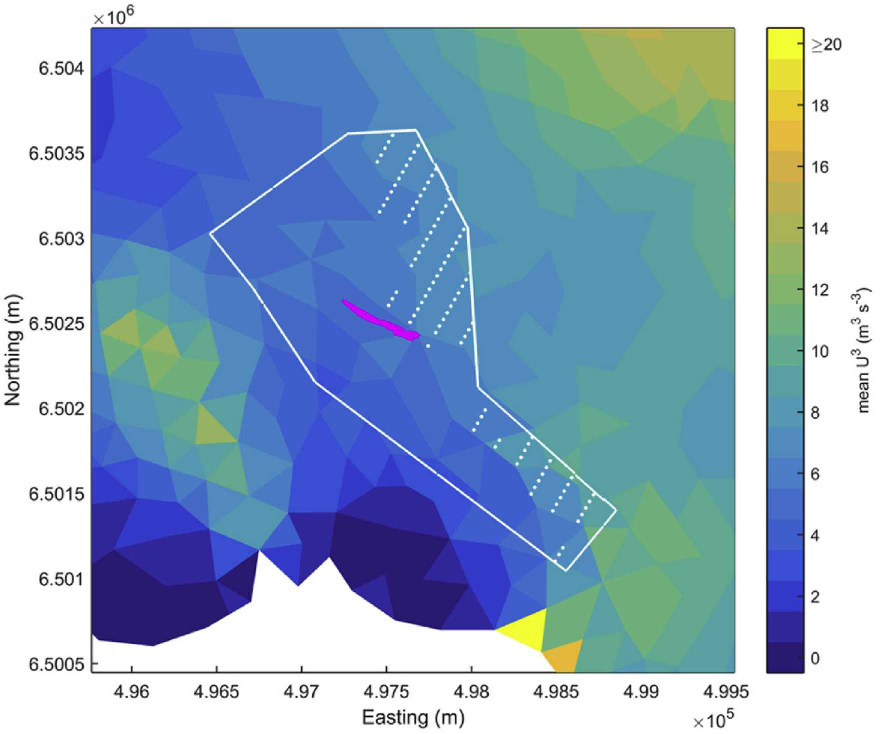

Fig. 5. The final array layout for the 100 MW Ness of Duncansby development overlaying the mean of the cubed depth average current speed (mean U^3) from the MIKE 3 output. The tidal ellipse for the site is indicated by the magenta line.

the tidal site. There are a number of devices further north and closer to the channel headland, located within a patch of high tidal resource.

Fig. 8 shows the final Brough Ness development, which has 50, 2 MW, devices, each made up of two 20 m diameter turbines, with an offset array spacing of 90 × 320 m (across stream

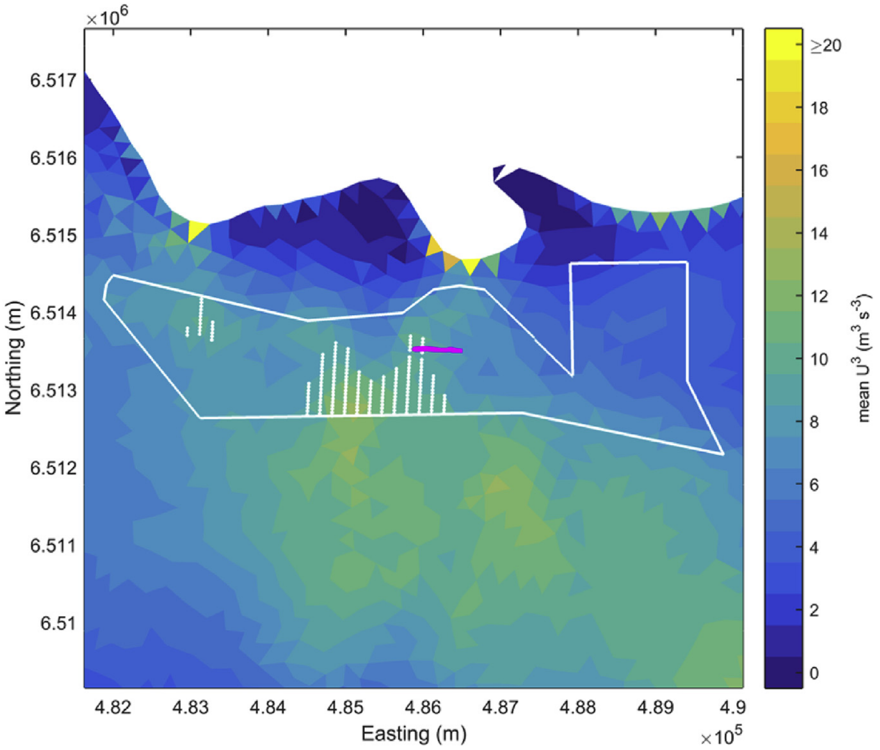

Fig. 6. The final array layout for the 200 MW Brims Tidal Array development overlaying the mean of the cubed depth average current speed (mean U^3) from the MIKE 3 output. The tidal ellipse for the site is indicated by the magenta line.

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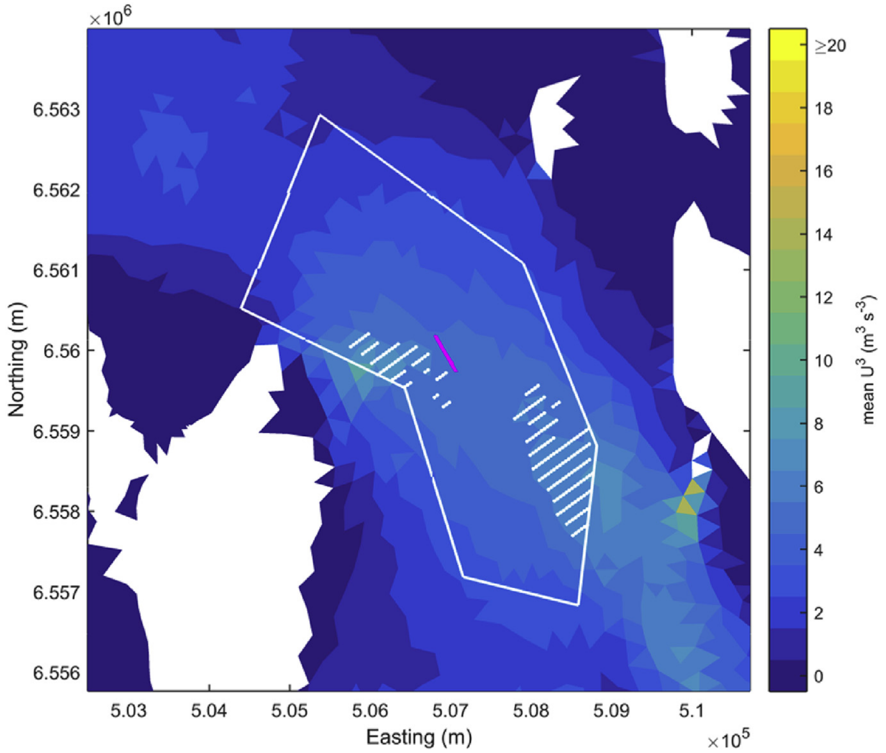

Fig. 7. The final array layout for the 200 MW Westray South development overlaying the mean of the cubed depth average current speed (mean U^3) from the MIKE 3 output. The tidal ellipse for the site is indicated by the magenta line.

x downstream). The position of each 20 m diameter turbine, with two turbines per device, is shown in Fig. 8. In this tidal site the resource is significantly higher towards the south west corner, and this is where the tidal devices were positioned, avoiding the resource-poor area towards the north of the site.

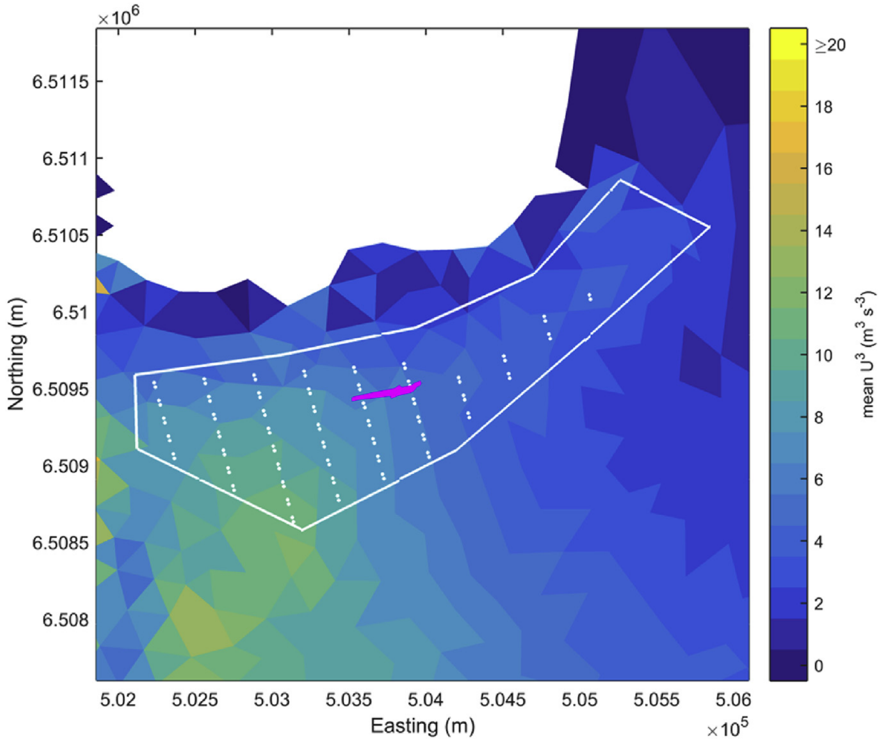

Fig. 8. The final array layout for the 100 MW Brough Ness development overlaying the mean of the cubed depth average current speed (mean U^3) from the MIKE 3 output. The tidal ellipse for the site is indicated by the magenta line.

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5. Wave arrays scenario

As in the case of tidal arrays, the wave PFOW Round One Development Sites provide broad areas of search in which to place wave energy devices. However, unlike tidal sites, there are not as many constraints on where many of the types of wave energy devices can be placed. For this reason, it makes sense for wave energy developers to space out devices, or arrays of devices, to occupy the whole of the development sites. As far as possible, generic devices and array layouts were developed for wave energy sites.

5.1. Generic device type

MacIver et al. (2014) reviewed how wave energy extraction can be incorporated in the spectral wave models of the wider study, and presented a set of generalized characteristics based on numerical modelling. Because of the variety of fundamentally different types of wave energy devices likely to be deployed in PFOW, it was impossible to develop a single generic device. This paper therefore considers the three broad device types currently being considered by developers; (a) a 750 kW wave attenuator, (b) a 2.5 MW wave absorber, and (c) a 1 MW oscillating wave surge converter. Wave attenuators are floating devices with a number of different sections that capture energy from the relative motion between adjacent sections (Drew et al., 2009). Wave absorbers float on the surface and capture energy from the vertical displacement due to the motion of waves. Oscillating wave surge converters tend to operate in shallow water and extract energy from the horizontal movement of water particles due to the wave surge.

5.2. Wave array layouts results

Four out of the six wave development sites within the PFOW plan to use a 750 kW wave attenuator device. The scoping report for the West Orkney South development site (RSK, 2012) indicated that the devices would most likely be deployed in arrays of 22 devices, in two staggered rows, with a space of 10 times the device length between arrays (1800 m). The most efficient way to fill the proposed West Orkney South and West Orkney Middle South development areas with arrays of this size, in order to reach the 50 MW energy generating capacity of each site, was to use a 400 × 400 m (centre to centre) spacing of devices. Fig. 9 shows the array layout for the West Orkney South development. This configuration was also used for the adjacent West Orkney Middle South development. This generic array layout also worked well for the Farr Point development, which has a larger area but the same 50 MW energy generating capacity (Fig. 10). This array layout was, however, not feasible within the Marwick Head development site, due to its somewhat smaller area, while having the same 50 MW energy generating capacity, so an array of 66 devices with a 350 × 400 m (cross stream x downstream) staggered spacing across 4 rows was developed (Fig. 11). It is likely that the devices within this site will experience more interactions and wave effects than in the other (larger) areas.

The Costa Head development plans to use a 2.5 MW flexible membrane wave absorber (Xodus group, 2012). In order to fit 80 of these devices within the development area and to reach the energy generating capacity of 200 MW, a 550 × 600 m (cross stream x downstream) staggered array design was used to completely fill the site (Fig. 12).

The Brough Head development site plans to use a 1 MW oscillating wave surge converter (Xodus group, 2011). The example array provided in the Brough Head coastal processes impact assessment report suggested that the devices should have a spacing of 25–65 m. A spacing of 45 m was chosen for this study. The devices are 26 m wide, which gave a centre to centre spacing of 71 m. The licensing documentation revealed that the devices should be in 10–15 m water depth. Therefore, for this study the devices were distributed in approximately 5 arrays of 40 devices, in order to reach the 200 MW generating capacity along the 12.5 m depth contour (Fig. 13). The 20 m gridded bathymetry data were used to determine the location of the 12.5 m contour.

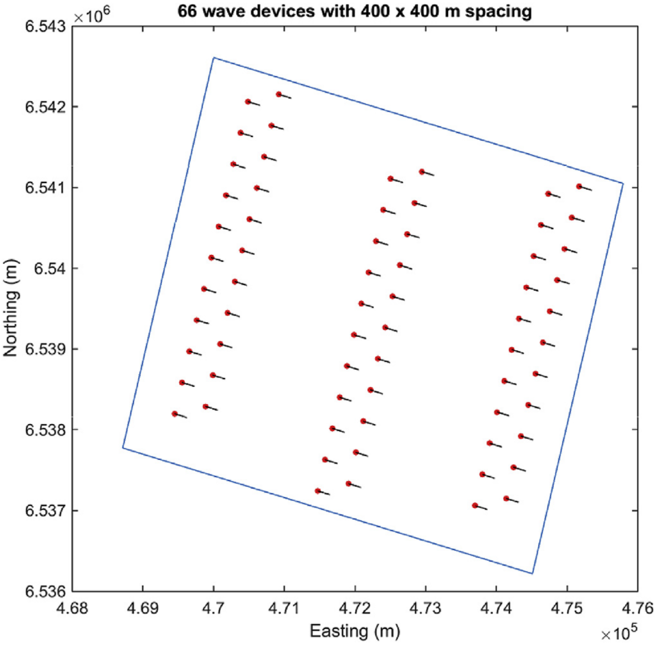

Fig. 9. The West Orkney South wave farm array layout with 66 wave devices, in three groups of 22, using the 400 × 400 m generic device spacing.

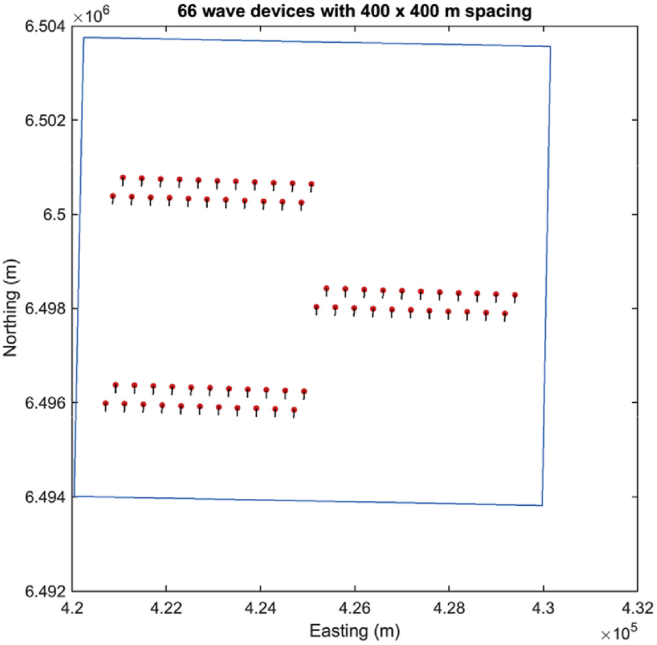

Fig. 10. The Farr Point wave farm array layout with 66 wave devices, in three groups of 22, using the 400 × 400 m generic device spacing.

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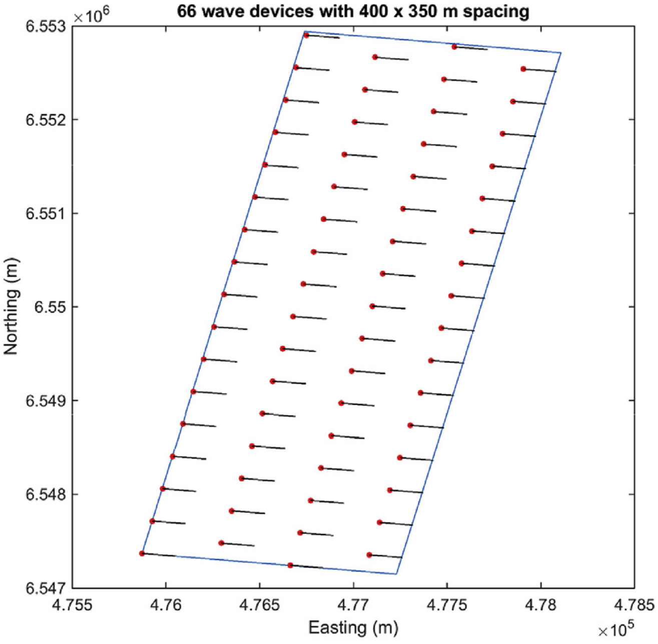

Fig. 11. The Marwick Head wave farm array layout with 66 wave devices using 400 × 350 m device spacing.

6. Discussion

The first part of this paper outlines the data used during the wider hydrodynamic modelling project and explores some of the selection criteria. Perhaps the most challenging aspect of the data review and preparation work was selecting a common bathymetry data source for all the models to use. The bathymetry dataset, provided by TCE for the PFOW region (The Crown Estate, 2012) proved to be ideal for the modelling work. These data were derived from a number of high resolution sources, interpolated to a regular 20 m horizontal grid, and were ideal for model development as they had more than sufficient horizontal resolution. It is also crucial to validate hydrodynamic models using measured data and, because the PFOW is a dynamic and complex area, it was important to use measurements of currents and waves from a variety of locations within the region. The main dataset used for the validation of the tidal models was the ADCP data obtained by Gardline Marine Sciences in the Pentland Firth. These measurements were, however, confined to a relatively small area of the PFOW, albeit arguably the most complex area. It was therefore important to supplement these data with data from the EMEC test sites and the locations surveyed by MSS during the project (Stronsey Firth, Pentland Firth and Hoy Sound). All the data collected for the wider study are listed in Table 2 in the Appendix.

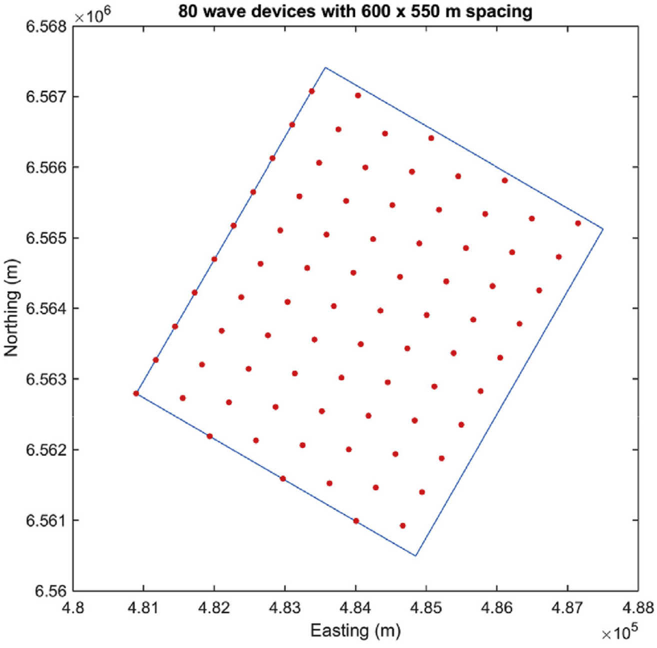

Fig. 12. The Costa Head wave farm array layout with 80 wave devices using 600 × 550 m device spacing.

The second part of this paper describes the development of a tidal stream and wave arrays scenario for the PFOW Round One Development Sites. Whilst the designated sites provide an approximate guide to the location of the arrays, it was important to investigate how the energy extraction will be distributed within these sites, i.e. where devices may be placed within the sites. This work shows that for the Inner Sound, the placement of all the devices will be fairly uniform throughout the area, assuming the maximum capacity is reached and 400 × 1 MW turbines are placed in the site. In fact, the designated capacity for the Inner Sound (based purely on the number of 1 MW turbines) can only just be achieved using the proposed spacing of the turbines. All the other tidal energy sites could easily accommodate the proposed number of tidal stream devices. For these sites the spatial variability of the resource played a more important role in the device positioning. This spatial variability was determined from the MIKE 3 model output and is therefore subject to the uncertainty and limitations inherent in hydrodynamic and ocean modelling. The model was calibrated using measurements and the validity of the model was tested against a number of other measurements, as described in Waldman et al. (this issue). Still there is inherent uncertainty relating to (1) there being no available data from the lease sites to further calibrate and validate the model in those areas, (2) uncertainty in the model input data such as bathymetry, bed roughness, and boundary forcing data, and (3) uncertainty related to assumptions made in the model formulation.

The positioning of the wave arrays did not have the same level of resource related constraints as the tidal arrays. There will still be site specific and inter array issues that need to be addressed when positioning wave devices, but this was beyond the scope of this paper.

It was assumed for this work that the designated energy generating capacity for each tidal array will be achieved by summing the rated maximum power output of each individual device in the array. It is recognised that, in practice, wave and tidal devices will only reach this power rating during optimum conditions and that the individual devices in an array will not necessarily simultaneously operate at their rated output due to the spatial and temporal variation in tidal resource, and the interaction between devices (Vennell et al., 2015). Still, this approach was adopted to avoid having to consider the complexities of inter array device performance assessment, which is beyond the scope of this paper. It is acknowledged that developers will have to consider the inter array turbine spacing in order to maximise the efficiency of the array (Vennell et al., 2015), especially as arrays get larger. Our work does not go beyond a broad spacing assessment based on the available Scottish licensing literature. This was considered to be sufficient for the development of scenarios suitable for impact studies as part of the wider project.

This work provided locations for individual wave and tidal devices. Such exact positioning is essential for the incorporation of the

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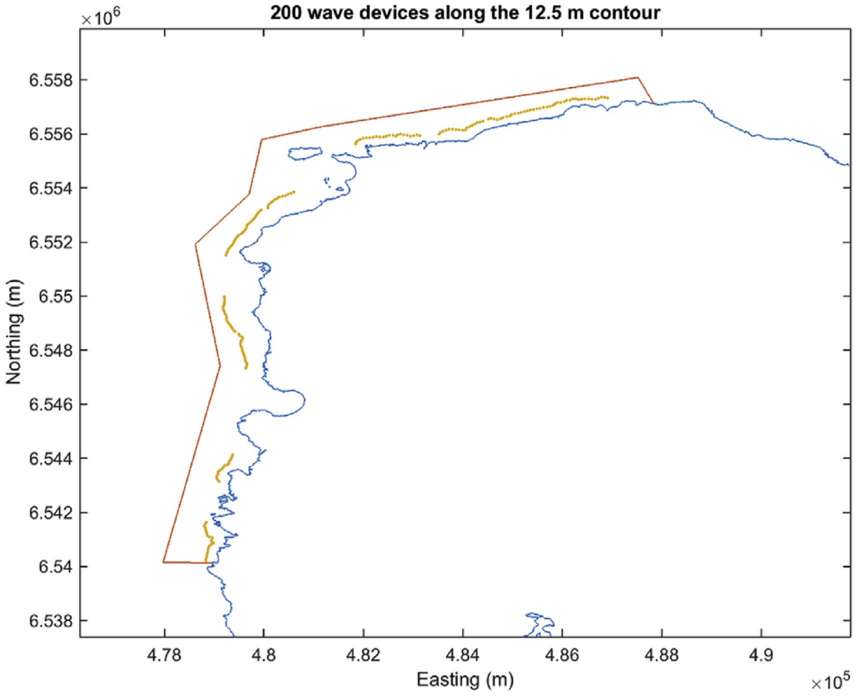

Fig. 13. The Brough Head wave farm array layout with 200 wave devices positioned in groups along the 12.5 m depth contour.

devices into the MIKE 3 hydrodynamic software (Baston et al., 2014; Waldman et al., this issue). The representation of the tidal stream devices in MIKE 3 was achieved using a sub-grid scale parameterisation, and as such the number of turbines within each grid element is ultimately all that is required. However the MIKE 3 software requires the location of individual devices to be specified as MRE developers would have such detailed information available, and this method provides a good way to distribute devices across model elements. Other hydrodynamic modelling software would not necessarily have such input format requirements, and only the number of turbines per grid element would be required for similar sub-grid scale parameterisation. In addition to the input format requirements of the MIKE 3 software, it was decided to locate individual devices in order to ensure the resulting arrays were based on realistic layouts of turbines, with appropriate spacing for example. The layouts produced could also be used in higher resolution, turbine resolving, computational fluid dynamic models.

The data reviewed here are an example of data types and characteristics appropriate for the development of hydrodynamic models suitable for MRE impact assessments and marine spatial planning. It is recognised that the array scenarios developed here provide merely a first pass scenario for the PFOW Round One Development Sites. In practice, MRE developers will have to consider a wide range of other constraints on where to place individual devices. MRE developers will also be able to model their development(s) in greater detail as they decide on the specifics of the array. The scenarios developed here, however, enable those without array specific information to perform quantitative cumulative impact assessments (e.g. Fairley et al., 2015). Individual MRE developers are required to assess the cumulative impact of their development(s) in combination with other developments in the region, as part of the licensing process (The Scottish Government, 2012). Cumulative impact assessments also form an important component of marine spatial planning, and the array scenarios and the methodology developed here are suitable for such exercises.

Four of the five PFOW Round One Development Sites considered here lie within the Pentland Firth region. The sites are situated on headlands within the Firth and within the Inner Sound, one of the sub channels of the Pentland Firth. These sites target the high resource areas in water depth of less than 50 m. In order to fully exploit the tidal resource within the Pentland Firth region it may be necessary to extract tidal energy from the full width of the tidal channel, either across the whole channel (e.g. between Hoy and the Scottish mainland) or from all the *parallel* sub channels (Draper et al., 2014; Woolf, 2013). There is therefore potential for the further exploitation of the Pentland Firth region beyond the Round One Development Sites. Indeed, it is possible that further development will be necessary in order to achieve the maximum power output that is implied by the designated capacity, i.e. so that the Inner Sound resource is not diverted into the main Pentland Firth by the ‘400 MW’ Inner Sound development. Draper et al. (2014), Adcock et al. (2013) and O'Hara Murray and Gallego (2017) used hypothetical tidal energy scenarios, designed to fully exploit the tidal energy resource in the Pentland Firth, incorporated in hydrodynamic models. Their results suggest that the Pentland Firth as a whole can only provide approximately 2–5 GW on average. It is therefore unlikely for the Round One Development Sites in the Pentland Firth, covering only a small fraction of the channel, to achieve their combined 0.8 GW capacity rating. Further work is clearly required, using realistic tidal energy scenarios and 3D hydrodynamic models, to understand the full MRE potential for this tidally energetic region, and how it can be realistically and sustainably achieved.

7. Conclusions

Datasets of appropriate characteristics, in terms of quality, coverage and resolution, are critical for the development and validation of accurate hydrodynamic models to be used by the MRE industry, stakeholders and regulators in order to quantify and evaluate the potential environmental impact of the removal of energy from the marine environment. Here, we assemble the most

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appropriate datasets to model the physical environment and the extraction of MRE (wave and tidal) in our focus study area, the Pentland Firth and Orkney Waters, and we describe the availability of such data to the modelling community.

A methodology is presented to arrange generic but plausible tidal and wave MRE devices into array layouts consistent with those likely to be deployed commercially, as evidenced by the available licensing applications thus far submitted by commercial developers. These data and methodologies will facilitate future model development by academia and government researchers, who do not necessarily have access to the detailed device and site specific information available to commercial operators, while providing industry with assurances that the methods developed will satisfy the quality requirements of regulators and stakeholders.

The future development of the PFOW beyond the PFOW Round One Development Sites will require careful planning, and output from hydrodynamic models will need to be considered. This is due to the nature of the high tidal resource in the region, and the potential for individual developments to interact with the resource, changing the resource, and with each other. It is likely that in order to determine the most suitable location for future sustainable developments, maximising the tidal resource, a number of scenarios will need to be explored using hydrodynamic models.

Acknowledgements

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Appendix

Table 2
List of data, grouped by type, and their location on Internet. Type codes: B=Bathymetry, S=Sediments, E = Water Elevations, CL=CoastLine, C=Currents, W=Waves, M = Model

Name	Type	Description	Web URL/email	Reference
Smith and Sandwell	B	Gridded bathymetry (900 m) derived from Satellite Altimetry and Ship Depth Soundings	http://gcmd.nasa.gov/records/GCMD_SIO_NOAA_SEAFLOORTOPO.html	Smith and Sandwell (1997)
TCE 20 m bathymetry	B	20 m gridded bathymetry for the PFOW region derived from a number of data	Made available to the wider project by TCE: https://www.thecrownestate.co.uk	The Crown Estate (2012)
UKHO	B	High resolution MBES bathymetry data obtained directly from the UKHO, including data from MCA	https://www.gov.uk/inspire-portal-and-medin-bathymetry-data-archive-centre	
MSS BMES	B	High resolution MBES bathymetry data from MSS	http://www.scotland.gov.uk/Topics/marine/science/MSInteractive	
BGS sediments	S	Seabed sediment samples including the fraction of mud, sand, gravel and results from a particle size analysis	http://www.bgs.ac.uk/GeoIndex/offshore.htm	British Geological Survey (2013)
UK National Tidal Gauge Network	E	Water elevation measurements at 44 locations around the UK coastline	http://www.bodc.ac.uk/projects/uk/ntslf	
GSHHG	CL	NOAA Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG)	https://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html	
Gardline ADCP	C	ADCP and VM ADCP data made available by MCA from 2001 58° 43.567′ N, 003° 14.183′ W 58° 43.017′ N, 003° 05.150′ W 58° 40.217′ N, 002° 58.583′ W	Made available to the wider project by Gardline Surveys http://www.gardlinemarinesciences.com	Gardline Surveys (2001)
EMEC ADCP	C	ADCP data from the Fall of Warness, 12 weeks starting 12 July 2010, purchased from EMEC for TeraWatt. 59° 9.360′ N, 002° 49.860′ W	Purchased for the project from EMEC: http://www.emec.org.uk	
MSS current meter	C	Fair Isle channel (2008) and Scottish east coast current meter data	https://www.bodc.ac.uk/data/online_delivery/currents/	
MSS ADCP	C	12 h stationary ADCP data measurements in Stronsay Firth, 21/05/2014. 59° 0.17′ N, 002° 38.52′ W	Available on request: oceanography@marlab.ac.uk	
MSS VM ADCP	C	Vessel mounted ADCP data gathered in 2014 from the East Pentland Firth and Stronsay Firth	Available on request: oceanography@marlab.ac.uk	
EMEC Waves	W	Wave rider buoy data, Billia Croo, for complete years 2010 and 2012, purchased from EMEC for TeraWatt. 58° 58.214′ N, 003° 23.454′ W	Purchased for the project from EMEC: http://www.emec.org.uk	
Cefas WaveNet	W	A network or wave rider buoys around the UK	http://cefasmapping.defra.gov.uk	
VORF	M	Vertical Offshore Reference Frame model for converting between vertical datums	UK Hydrographic Office: bdc@ukho.gov.uk	(Turner et al., 2010)
ERA-40	M	ECMWF atmospheric model	http://www.ecmwf.int/en/research/climate-reanalysis/browse-reanalysis-datasets	Dee et al. (2011)
OTPS and TMD	M	Tidal model based on an inversion of TOPEX/POSEIDON altimeter data and tide gauge data	http://volkov.oce.orst.edu/tides/otps.html http://polaris.esr.org/ptm_index.html	Egbert et al. (2010)

References

Adcock, T.A.A., Draper, S., Houlsby, G.T., Borthwick, A.G.L., Serhadlioğlu, S., 2013. The available power from tidal stream turbines in the Pentland Firth. Proc. R. Soc. A Math. Phys. Eng. Sci. http://dx.doi.org/10.1098/rspa.2013.0072.

Astrium OceanWise, 2011. Creation of a High Resolution Digital Elevation Model (DEM) of the British Isles Continental Shelf. Prepared for Defra, Contract Reference: 13820.

Baston, S., Waldman, S., Side, J., 2014. Modelling energy extraction in tidal flows. In: TeraWatt Position Papers: a “Toolbox” of Methods to Better Understand and Assess the Effects of Tidal and Wave Energy Arrays on the Marine Environment, pp. 75–107. MASTS: Company Number - SC485726; Charity Number - SC045259. http://www.masts.ac.uk/about/masts-publications/terawatt-publications/.

Black & Veatch, 2005. Phase II UK Tidal Stream Energy Resource Assessment. Prepard for Carbon Trust. Report Submission 107799/D/2200/03 [WWW Document]. https://www.carbontrust.com/media/174041/phaseiitidalstreamresourcereport2005.pdf (Accessed 22 February 2017).

British Geological Survey, 2013. BGS Legacy Particle Size Analysis Uncontrolled Data Export. British Geological Survey.

Brumley, B.H., Cabrera, R.G., Deines, K.L., Terray, E.A., 1990. Performance of a broadband acoustic Doppler current profiler. In: Proceedings of the IEEE Fourth Working Conference on Current Measurement.

Carbon Trust, 2011. Accelerating Marine Energy. The Potential for Cost Reduction - Insights from the Carbon Trust Marine Energy Accelerator. CTC797.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., Vitart, F., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 137, 553–597. http://dx.doi.org/10.1002/qj.828.

Deltares, 2014. Delft3D-FLOW User Manual, Hydro-morphodynamics. Version 3.15.34158 [WWW Document]. http://oss.deltares.nl/documents/183920/185723/Delft3D-FLOW_User_Manual.pdf (Accessed 22 February 2017).

Draper, S., Adcock, T.A.A., Borthwick, A.G.L., Houlsby, G.T., 2014. Estimate of the tidal stream power resource of the Pentland Firth. Renew. Energy 63, 650–657. http://dx.doi.org/10.1016/j.renene.2013.10.015.

Drew, B., Plummer, A., Sahinkaya, M.N., 2009. A review of wave energy converter technology. J. Power Energy. http://dx.doi.org/10.1243/09576509JPE782.

Easton, M.C., Woolf, D.K., Bowyer, P.A., 2012. The dynamics of an energetic tidal channel, the Pentland Firth, Scotland. Cont. Shelf Res. 48, 50–60. http://dx.doi.org/10.1016/j.csr.2012.08.009.

Egbert, G.D., Erofeeva, S.Y., Ray, R.D., 2010. Assimilation of altimetry data for nonlinear shallow-water tides: quarter-diurnal tides of the Northwest European Shelf. Cont. Shelf Res. 30, 668–679. http://dx.doi.org/10.1016/j.csr.2009.10.011.

Fairley, I., Karunarathna, H., 2014. Modelling the impacts of marine energy extraction on non-cohesive sediment transport and morphodynamics. In: TeraWatt Position Papers: a “Toolbox” of Methods to Better Understand and Assess the Effects of Tidal and Wave Energy Arrays on the Marine Environment, pp. 109–127. MASTS: Company Number - SC485726; Charity Number - SC045259. http://www.masts.ac.uk/about/masts-publications/terawatt-publications/.

Fairley, I., Masters, I., Karunarathna, H., 2015. The cumulative impact of tidal stream turbine arrays on sediment transport in the Pentland Firth. Renew. Energy 80, 755–769. http://dx.doi.org/10.1016/j.renene.2015.03.004.

Funke, S.W., Farrell, P.E., Piggott, M.D., 2014. Tidal turbine array optimisation using the adjoint approach. Renew. Energy 63, 658–673. http://dx.doi.org/10.1016/j.renene.2013.09.031.

Gardline Surveys, 2001. Pentland Firth Tidal Stream Observations.

Garrett, C., Cummins, P., 2005. The power potential of tidal currents in channels. Proc. R. Soc. A Math. Phys. Eng. Sci. 461, 2563–2572. http://dx.doi.org/10.1098/rspa.2005.1494.

Goddijn-Murphy, L., Woolf, D.K., Easton, M.C., 2013. Current patterns in the inner sound (Pentland Firth) from underway ADCP data. J. Atmos. Ocean. Technol. 30, 96–111. http://dx.doi.org/10.1175/JTECH-D-11-00223.1.

Kramer, S.C., Funke, S.W., Piggott, M.D., 2015. A continuous approach for the optimisation of tidal turbine farms. In: Proc. 11th Eur. Wave Tidal Energy Conf, pp. 1–8.

Lewis, M., Neill, S.P., Robins, P.E., Hashemi, M.R., 2015. Resource assessment for future generations of tidal-stream energy arrays. Energy 83, 403–415. http://dx.doi.org/10.1016/j.energy.2015.02.038.

MacIver, R., Reddy, N.T., Venugopal, V., 2014. Representing wave energy extraction in regional scale numerical models. In: TeraWatt Position Papers: a “Toolbox” of Methods to Better Understand and Assess the Effects of Tidal and Wave Energy Arrays on the Marine Environment, pp. 49–73. MASTS: Company Number - SC485726; Charity Number - SC045259. http://www.masts.ac.uk/about/masts-publications/terawatt-publications/.

MacKay, D.J.C., 2008. Sustainable Energy — without the Hot Air. Energy. UIT Cambridge Ltd. http://dx.doi.org/10.1109/PES.2004.1373296.

MeyGen, 2014. MeyGen Tidal Energy Project Phase 1 Environmental Statement [WWW Document]. www.gov.scot/Topics/marine/Licensing/marine/scoping/MeyGen.

Myers, L., Bahaj, A.S., 2005. Simulated electrical power potential harnessed by marine current turbine arrays in the Alderney Race. Renew. Energy 30, 1713–1731. http://dx.doi.org/10.1016/j.renene.2005.02.008.

Myers, L.E., Bahaj, A.S., 2012. An experimental investigation simulating flow effects in first generation marine current energy converter arrays. Renew. Energy 37, 28–36. http://dx.doi.org/10.1016/j.renene.2011.03.043.

Neill, S.P., Lewis, M.J., Hashemi, M.R., Slater, E., Lawrence, J., Spall, S.A., 2014. Inter-annual and inter-seasonal variability of the Orkney wave power resource. Appl. Energy 132, 339–348. http://dx.doi.org/10.1016/j.apenergy.2014.07.023.

O'Hara Murray, R.B., 2015. Data acquisition and processing for TeraWatt. In: TeraWatt Position Papers: a “Toolbox” of Methods to Better Understand and Assess the Effects of Tidal and Wave Energy Arrays on the Marine Environment. MASTS: Company Number - SC485726; Charity Number - SC045259. http://www.masts.ac.uk/about/masts-publications/terawatt-publications/.

O'Hara Murray, R.B., Gallego, A., 2017. A modelling study of the tidal stream resource of the Pentland Firth, Scotland. Renew. Energy 102, 326–340. http://dx.doi.org/10.1016/j.renene.2016.10.053.

RD Instruments, 1996. Acoustic Doppler Current Profiler Principle of Operation a Practical Primer, second ed.

Rennau, H., Schimmels, S., Burchard, H., 2012. On the effect of structure-induced resistance and mixing on inflows into the Baltic Sea: a numerical model study. Coast. Eng. 60, 53–68. http://dx.doi.org/10.1016/j.coastaleng.2011.08.002.

RSK, 2012. West Orkney South Wave Energy Site - Environmental Scoping Report [WWW Document]. http://www.gov.scot/Topics/marine/Licensing/marine/scoping/WestOrkneySouthWaveEnergySite/scoping-report.

Salter, S.H., Taylor, J.R.M., 2007. Vertical-axis tidal-current generators and the Pentland Firth. Proc. Inst. Mech. Eng. Part A J. Power Energy 221, 181–199. http://dx.doi.org/10.1243/09576509JPE295.

Side, J., Gallego, A., James, M., Davies, I., Heath, M., Karunarathna, H., Venugopal, V., Vögler, A., Burrows, M., 2016. Developing methodologies for large scale wave and tidal stream marine renewable energy extraction and its environmental impact: an overview of the TeraWatt project. Ocean Coast. Manag. http://dx.doi.org/10.1016/j.ocecoaman.2016.11.015.

Smith, W.H.F., Sandwell, D.T., 1997. Global sea floor topography from satellite altimetry and ship depth soundings. Science 277, 1956–1962. http://dx.doi.org/10.1126/science.277.5334.1956.

The Crown Estate, 2013. Pentland Firth and Orkney Waters Strategic Area Review Project [WWW Document]. http://www.thecrownestate.co.uk/media/5446/pfow-strategic-area-review-project-2012.pdf (Accessed 22 February 2017).

The Crown Estate, 2012. Pentland Firth and Orkney Waters Strategic Area: Preparation of Bathymetry to Support Modelling Studies. R.1963.

The Scottish Government, 2015. Scotland's National Marine Plan [WWW Document]. http://www.gov.scot/Publications/2015/03/6517 (Accessed 22 February 2017).

The Scottish Government, 2012. Marine Scotland Licensing and Consents Manual [WWW Document]. R. 1957. http://www.gov.scot/Topics/marine/Licensing/marine/LicensingManual (Accessed 22 February 2017).

Trump, C.L., 1991. Single ping ADCP data. IEEE J. Ocean. Eng. 16, 382–389. http://dx.doi.org/10.1109/48.90902.

Turner, J.F., Iliffe, J.C., Ziebart, M.K., Wilson, C., Horsburgh, K.J., 2010. Interpolation of tidal levels in the coastal zone for the creation of a hydrographic datum. J. Atmos. Ocean. Technol. 27 http://dx.doi.org/10.1175/2009JTECHO645.1.

van der Molen, J., Ruardij, P., Greenwood, N., 2016. Potential environmental impact of tidal energy extraction in the Pentland Firth at large spatial scales: results of a biogeochemical model. Biogeosciences 13, 2593–2609. http://dx.doi.org/10.5194/bg-13-2593-2016.

Vennell, R., Funke, S.W., Draper, S., Stevens, C., Divett, T., 2015. Designing large arrays of tidal turbines: a synthesis and review. Renew. Sustain. Energy Rev. 41, 454–472. http://dx.doi.org/10.1016/j.rser.2014.08.022.

Vögler, A., Venugopal, V., 2012. Hebridean marine energy resources: wave-power characterisation using a buoy network. In: Proceedings of the ASME 31st International Conference on Ocean, Offshore and Arctic Engineering, pp. 477–488. http://dx.doi.org/10.1115/OMAE2012-83658.

Waldman, S., Baston, S., Side, J., Nemalidinne, R., Venugopal, V., Chatzirodou, A., 2017. Implementation of tidal turbines in MIKE3 and Delft3D models of Pentland Firth & Orkney Waters. Ocean Coast. Manag. (in this issue).

Woolf, D.K., 2013. The strength and phase of the tidal stream. Int. J. Mar. Energy 3–4, 3–13. http://dx.doi.org/10.1016/j.ijome.2013.11.001.

Xodus group, 2012. Costa Head Wave Farm Limited - Scoping Report [WWW Document]. http://www.gov.scot/Topics/marine/Licensing/marine/scoping/costa/scoping-report (Accessed 22 February 2017).

Xodus group, 2011. Brough Head Wave Farm - Scoping Report [WWW Document]. http://www.gov.scot/Topics/marine/Licensing/marine/scoping/broughhead/scoping-report (Accessed 22 February 2017).

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