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Large scale three-dimensional modelling for wave and tidal energy resource and environmental impact: Methodologies for quantifying acceptable thresholds for sustainable exploitation

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1. Introduction

1.1. Background

In the context of increasing societal concerns about the effect of traditional energy sources based on the combustion of fossil fuels on the earth's climate, Marine Renewable Energy (MRE) is a relatively new sector showing considerable promise, particularly in highly populated areas of northern Europe where other (e.g. some terrestrial) renewable energy sources have either fulfilled their potential or are likely to encounter significant challenges as a result of lack of free/available resource, environmental or socio-economic impact, etc.

The MRE sector comprises a number of different technologies (see Magagna and Uihlein, 2015). In order of degree of readiness, these include offshore wind, tidal energy, wave energy and a few emerging technologies such as salinity gradient and thermal energy conversion. The latter have been piloted already (in some cases, for quite some time) but their current technology readiness level (see review by Magagna and Uihlein, 2015) suggests that they are still some way off becoming commercially viable.

Offshore wind is the most mature offshore MRE sub-sector, building upon the widespread deployment of onshore wind farms. By 2015, offshore wind had reached a generating capacity of >5 GW in United Kingdom waters. Across Europe, the total adds up to >10 GW and some 700 MW in the rest of the world (source: Offshore Wind Factsheet 2015; http://www.renewableuk.com/en/publications/index.cfm/offshore-wind-factsheet). The potential effects of offshore wind farms on the physical environment are relatively straight-forward to measure and model. The main effects on the physical environment relate to the effect of energy extraction on the wind field, which reduces e.g. the amount of energy available to mix the water column, and the physical effect of the turbine support structures on the flow and wave fields. Their main direct biological effect during the operational phase is their potential interaction with birds, although other effects have been proposed (e.g. support structures can serve as artificial reefs for native or invasive species). Some construction methods produce levels of underwater noise that can be of concern regarding marine mammals and, potentially, fish.

The tidal MRE sector includes a number of different technologies that exploit tides to generate electricity. They include tidal stream devices, where turbines placed within the tidal stream exploit the

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kinetic energy of the tidal flow to generate electricity, and dam-like structures with turbines, such tidal lagoons and barrages (closed dams) or turbines in open dams perpendicular to the tidal flow. Most Tidal Energy Converters (TECs), e.g. for tidal stream developments, are typically horizontal axis bladed turbines (although other designs exist) and therefore share some similarities with wind turbines. However, TECs are yet to reach the required level of technical maturity for routine large scale commercial deployment, although they show promise, particularly in areas where the resource is most abundant, such as parts of the coastal waters west and north of Scotland (The Scottish Government, 2013).

Wave energy converters (WECs), in contrast to TECs, are diverse in design, although they all share the same source of energy to generate power: the combined wind seas and ocean-swells as they approach coastal areas, where their potential for exploitation is currently concentrated (for economic reasons). The lack of convergence towards a preferred design has been identified as an obstacle to the commercial development of the waves sub-sector and poses some practical challenges when it comes to investigate its potential environmental impact.

1.2. Study area

The main geographic focus of this work is the Pentland Firth and Orkney Waters (PFOW) area (Fig. 1), comprising waters around the Orkney Islands off the north Scottish coast and the 10–12 km wide channel (the Pentland Firth) that separates this archipelago from the Scottish mainland. The Pentland Firth is significantly deeper than the bays and channels among the islands, which are generally less than 25 m and rarely exceed 40 m. Depths in the main Pentland Firth channel typically reach 60–80 m and even >90 m on the western side. The Inner Sound, south of the Island of Stroma in the Pentland Firth, is somewhat shallower (ca. 35 m). The M_2 tide that propagates clockwise around the British Isles results in an approximately 2 h phase difference between the west and east ends of the Pentland Firth and sets up a hydraulic gradient that generates strong tidal currents which can reach 5 m s^{-1}. Tidal currents are also forced around headlands and through other channels within the Orkney Islands, where spring flows can exceed 3.5 m s^{-1}. The amount of extractable tidal stream power in the area has been the subject of a number of studies with wide-ranging estimates. For the Pentland Firth, the higher limit has been estimated as 4.2 GW averaged over the spring-neap cycle (Draper et al., 2014) but more recent work reports a more realistic scenario of around 1.5 GW (O'Hara Murray and Gallego, 2016a,b).

The wave regime in PFOW is dominated by Atlantic swells and the influence of low pressure systems that travel primarily from west to east across the North Atlantic. Therefore, wave conditions are most severe in the exposed coastal areas to the west. The seasonal range of average wave resource in the area has been estimated between <10 (summer) and 50 kW (winter, top range of the estimate) (Neill et al., 2014).

The PFOW area is rich in geological features, coastal landscapes and seascapes that collectively support diverse habitats and species, many of which are considered rare and/or vulnerable. There are four designated Special Areas of Conservation (SAC; European Union designation) in Orkney and three SACs on the adjacent north coast of the Scottish mainland, for the protection of marine and coastal habitats. Another 29 sites (some with marine elements) have been designed as Sites of Special Scientific Interest (SSSI; national designation) and three nature conservation Marine Protected Areas (MPA) were formally designated in the area in 2014 (Pilot Pentland Firth and Orkney Waters Working Group, 2016).

The marine environment also has great social and economic importance for the Orkney Islands and adjacent areas of the north of Scotland. Fishing is a long-established industry in the area, targeting a wide range of pelagic (herring, mackerel), demersal (including cod, haddock, whiting, saithe, monkfish) and shellfish (including prawn, *Nephrops*, lobster, brown and velvet crab, whelk and scallop) species. The Scottish Sea Fisheries Statistics 2015 (The Scottish Government, 2016) indicates that there were 132 Scottish based active fishing vessels in the Orkney area and a further 93 in the adjacent north Scottish mainland area of Scrabster (all vessel sizes). The combined value of landings in 2015 by Scottish based vessels in the area was in excess of £39M. Fishing is an integral part of coastal and island communities as a source of employment and as an important link to maintaining associated services, thus contributing to community sustainability. The PFOW area is utilised by a variety of other vessels with various cargoes, passenger ferries and recreation. Aquaculture is also relatively important, although aquaculture sites have so far been located largely in sheltered waters of no primary interest for MRE exploitation. The marine and coastal area in the PFOW supports a wide range of activities associated with recreation, sport, leisure and tourism that make a significant contribution to the local economy and the sustainability of remote communities. Many of these activities are based on the wildlife, the scenery or are water-based, and rely on a clean, safe and diverse marine environment. Key interactions are expected to take place between the MRE sector and the fishing industry, shipping and navigation and the natural environment, and to be key elements of environmental impact assessments and the licensing/consenting process. There may be interactions with other sectors but these are anticipated to be minor.

1.3. Legislative framework

The Scottish Government has set a target of a largely decarbonised electricity generation sector by 2030, with a renewable electricity target of 100% of the Scottish consumption equivalent by 2020. MRE developments in Scottish waters are subject to licensing conditions. Part Four of the Marine (Scotland) Act 2010 gives Scottish Ministers responsibility for licensing activities within inshore Scottish waters (up to 12 nm), as well as for offshore waters (12–200 nm) under the Marine and Coastal Access Act 2009 for non-reserved activities such as MRE developments. Developers in Scotland need to apply for licences or consents under a number of regulations which include the Electricity Act (S36) 1989, the Coast Protection Act 1949 and the Food and Environment Protection Act 1985. The licensing landscape in Scotland has been simplified recently to provide a largely one-stop-shop that allows simultaneous application for the relevant consents. In addition to a marine licence, a project will require approvals or consents from other authorities such as The Crown Estate, a landed estate under The Crown Estate Act 1961, which leases the seabed within the UK 12 nm limit and the rights to non-fossil-fuel natural resources on the UK continental shelf.

Although the specific details will vary between countries, most applicable national environmental legislation in Europe is directly transposed from European Union legislation and it is often similar to other international legislation, commonly based on international conventions, so the information we present here will be of wider applicability beyond the Scottish context. The primary instrument for monitoring and managing the quality of Scotland's coastal waters out to 3 nm from the coast is based on the European Union (EU) Water Framework Directive (WFD; EC (2000)). The PFOW area is largely classified as 'good' status under the WFD. The waters on the eastern portion of the Pentland Firth are of 'high' status, as well as several "transitional waters" in the PFOW area (Pilot Pentland Firth and Orkney Waters Working Group (2016)).

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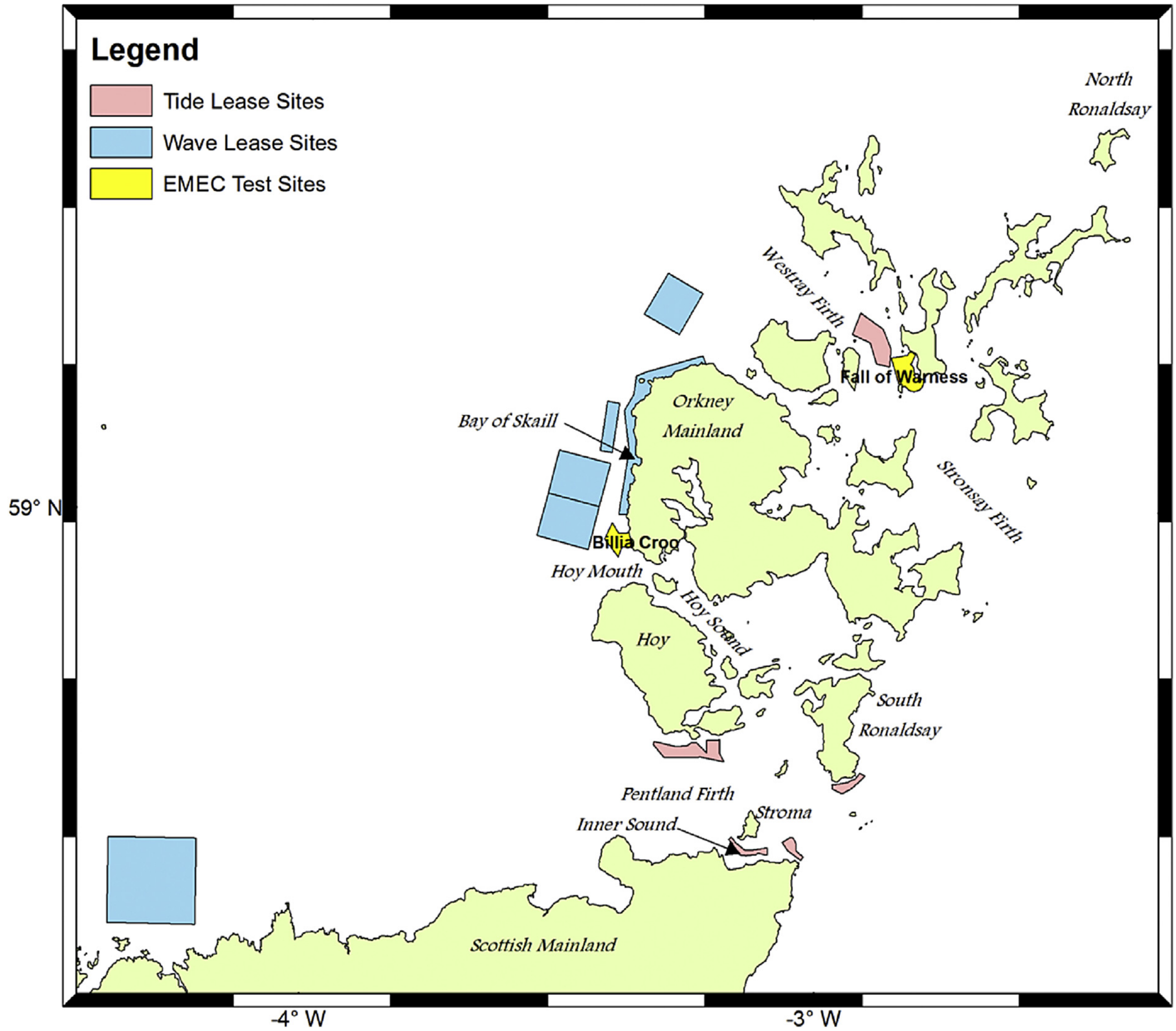

Fig. 1. Map showing the Pentland Firth and Orkney Waters area and the location of the wave and tidal stream MRE development sites considered in the project.

The Marine Strategy Framework Directive (MSFD; EC (2008)) is the piece of European legislation which establishes a common framework and objectives for the prevention, protection and conservation of the marine environment against damaging human activities beyond the spatial domain of the WFD. EU countries must assess the environmental status of their marine waters and set environmental targets, develop monitoring networks, prepare programmes of measures and set specific objectives towards reaching a “Good Environmental Status (GES)” by 2020. The MSFD sets out, in its Annex I, eleven qualitative Descriptors of GES. The main Descriptors that may be directly impacted by MRE developments are D6 (“The sea floor integrity ensures functioning of the ecosystem”), D11 (“Introduction of energy (including underwater noise) does not adversely affect the ecosystem”) and, in particular, D7 (“Permanent alteration of hydrographical conditions does not adversely affect the ecosystem”). Hydrographical conditions play a critical role in the dynamics of marine ecosystems, particularly in coastal areas, and can be altered by human activities. One of the main pressures on D7 explicitly identified refers to MRE installations (http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-7/index_en.htm).

In practice, experience has shown that the dominant pieces of environmental legislation influencing licensing/consenting of MRE developments are Council Directive 92/43/EEC (the “Habitats Directive” (EC, 1992),) and Directive 2009/147/EC (the “Birds Directive” (EC, 2009)). The Habitats Directive aims to promote the maintenance of biodiversity, protecting a wide range of rare, threatened or endemic animal and plant species and some 200 rare and characteristic habitat types, taking account of economic, social, cultural and regional requirements. The Birds Directive aims to protect all of the 500 wild bird species naturally occurring in the European Union and, through national legislation, it establishes a network of Special Protection Areas (SPAs) that include all the most suitable territories for these species. In Scotland, there are a number of coastal SPAs protecting the breeding sites of, particularly, migratory seabirds species that visit Scotland during the breeding season. In parallel, Special Areas of Conservation (SACs) are established under the Habitats Directive to protect habitats and species of conservation value. In marine systems, these include distinctive habitats such as sandbanks, sea caves and cliffs etc., and key species such as bottlenose dolphin and seal species. SPAs and SACs are included in the Natura 2000 ecological network set up under the Habitats Directive.

The potential impact of wave or tidal stream Marine Energy Converters (MECs) has been discussed in the scientific literature. Pelc and Fujita (2002) considered wave devices to be relatively

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environmentally benign and tidal stream turbines to be the most environmentally friendly tidal power option. A review of the ecological impact of MRE (Gill, 2005) showed that, despite a growth in publications on renewable energy, only a fraction at the time (<1%; none on coastal ecology) considered its potential environmental risks. Theoretical risks of the extensive subsurface structures introduced by MRE into the coastal environment outlined by Gill (2005) identified changes to water circulation and to the transport and deposition of sediment, noise and vibration during the construction and operational phases, changes to the electrical and electromagnetic fields, and degradation and/or removal of habitats. Gill (2005) also warned against an undue focus on rare species of high intrinsic appeal to the detriment of impacts on the ecosystem structure, processes and key functional species. The effects of near- and far-field changes to the flow and wave fields, and sedimentation patterns have been identified by subsequent publications (e.g. Shields et al., 2011) including specifically in the Pentland Firth area (Shields et al., 2009). These effects are not just negative: a number of potentially beneficial effects has also been proposed (Inger et al., 2009), such as the creation of artificial reefs, *de-facto* marine protected areas and fish aggregation devices. Interactions between positive and negative effects, as well as cumulative effects (Inger et al., 2009) requiring a different scale of management actions (Boehlert and Gill, 2010). Shields et al. (2011) identified the PFOW area as a particular case study to provide essential industry standards and environmental guidelines of worldwide applicability. However, because of the relative lack of empirical data on how marine habitats and wildlife will interact with wave and tidal stream MECs and their distinct nature relative to other forms of marine developments, understanding their potential environmental impact is particularly challenging and important. Smaller-scale demonstrator devices have been studied in depth but there is a clear need to monitor carefully the quantitative and qualitative nature of the effects of early commercial-scale developments against the natural baseline. Environmental impact assessment procedures are covered by European legislation such as Directives 2011/92/EU (the “Environmental Impact Assessment, EIA” Directive) and 2001/42/EC (the “Strategic Environmental Assessment, SEA” Directive) and their relevant national transposition (in Scotland, the Environmental Assessment (Scotland) Act 2005), to ensure that the potential environmental implications are taken into account before plans and projects are formally adopted and licences/consents are granted. Where a project has the potential to have a significant effect on a Natura site, a Habitats Regulation Appraisal (HRA) is required under the Habitats Directive. This process progresses from qualitative assessment to a more detailed Appropriate Assessment (AA). Projects can only be consented if the AA concludes that the development will not affect the integrity of the relevant protected (Natura 2000) sites.

This paper summarises the output of a collaborative modelling project (the TeraWatt project; Side et al. (2016)). In the absence of comprehensive observational data, modelling projects like the present one are fundamental to estimate the potential effects of MRE developments on the physical environment and, consequently, on the marine ecosystem. This paper draws on the project outputs and presents potential methodologies for quantifying acceptable thresholds for sustainable MRE exploitation within the context of the existing planning, regulatory and environmental legislative framework. In the following sections, we describe the modelling methodologies to represent the hydrodynamics and the implementation of energy extraction, and their effect on the physical environment, followed by a description of the regulatory framework in Scotland and a discussion on the acceptability criteria for sustainable exploitation.

2. Modelling methodologies: hydrodynamics and energy extraction

2.1. Data

In order to develop three dimensional hydrodynamic and spectral wave models, a number of datasets was required for model initialisation, forcing, calibration and validation. In addition, seabed sediment data were needed for sediment transport modelling. A comprehensive description of the data used in the project is presented by O'Hara Murray and Gallego (2016a,b) and O'Hara Murray (2015) so only a summary will be presented here.

Bathymetry data are needed at the appropriate resolution for the model grids (typically below 100 m). The bathymetric dataset used in the study (The Crown Estate, 2012) was derived from a variety of high resolution sources interpolated to a regular 20 m horizontal grid. Much of the underlying data were UK Hydrographic Office (UKHO) survey data, with gaps filled from the Digital Elevation Model (DEM) (Astrium OceanWise, 2011).

Bed sediment distribution data, including particle size and particle size distribution data, were obtained from the British Geological Survey (BGS) Web Map Services (http://www.bgs.ac.uk/GeoIndex/offshore.htm). At specific sediment dynamics modelling sites, such as the Bay of Skaill, targeted survey work was carried out within the project, such as beach profiles (Fairley et al., 2016) or site-specific datasets were identified (Inner Sound: MeyGen (2012) and Marine Scotland Science multibeam echosounder data groundtruthed by video trawls).

The main sets of data on currents used in the project consisted of 3 moored ADCP 30-day deployments in the Pentland Firth collected by Gardline Marine Sciences for the Maritime and Coastguard Agency (MCA) and 4 vessel-mounted ADCP (VMADCP) transects along its boundaries, as well as moored ADCP data purchased from the European Marine Energy Centre (EMEC) at their Fall of Warness site, a short moored ADCP deployment in Stronsay Firth, and two VMADCP surveys across the Hoy Mouth and Hoy Sound (see Fig. 2 in O'Hara Murray and Gallego (2016a,b) for the location of these surveys).

Waves data were obtained from WaveNet, the Cefas-operated Datawell Directional Waverider buoy network (https://www.cefas.co.uk/cefas-data-hub/wavenet), as well as Waverider data purchased from EMEC's Billia Croo site and data from a Waverider buoy deployed off Bragar (west coast of the Isle of Lewis, Scotland; Vögler and Venugopal (2012)).

Tidal boundary forcing used the output of the barotropic Oregon State University Tidal Prediction Software (OTPS; Egbert et al., 2010) and the DHI Global Tidal Model Database (Cheng and Andersen, 2010). Wind forcing data for waves modelling were obtained from the European Centre for Medium Range Weather Forecast (ECMWF) ERA-40 re-analysis dataset.

2.2. Numerical models – flow

Following consultation with MRE project developers, it was clear that the industry places considerably greater confidence in what are perceived to be tried-and-tested commercial models in preference to others generally employed by the academic community in research contexts. The project team was advised that, in order to engage fully with the renewables industry, we would need to use models they would trust and be familiar with. Therefore, MIKE3 (Danish Hydraulic Institute, DHI) and Delft3D-Flow (Deltares) were selected for tidal modelling, and MIKE21 SW (DHI) for waves modelling.

MIKE3 is a free-surface hydrostatic model that uses a cell-centred finite volume method to solve the three-dimensional

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incompressible Reynolds-averaged Navier-Stokes equations, with the Boussinesq approximation and a k-ε turbulence closure scheme in the vertical and the Smagorinsky horizontal eddy viscosity formulation. In the vertical, we used sigma coordinates and, in the horizontal, triangular elements allowing for an unstructured grid that provides enhanced flexibility to represent complex geometries (e.g. coastline and bathymetric features) in areas where more detail is required, with greater computational efficiency. A description of the MIKE3 implementation in our study area is given by Waldman et al. (2016) but, briefly, a model domain was set up covering the whole of the Orkney Islands, the Pentland Firth and adjacent waters off the north and northeastern Scottish mainland, with a horizontal resolution that varied between 4000 and 50–200 m (in high tidal velocity areas) and 10 equidistant vertical sigma layers. The flow model was calibrated against the 3 moored ADCP current profile datasets referred to above.

Delft3D-Flow is a finite difference hydrostatic model that solves the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations, with the Boussinesq assumptions. We chose a sigma vertical coordinate system and the model's rectangular (structured) staggered Arakawa-C grid in the horizontal. To achieve the degree of horizontal resolution required in the focus area while covering a wide enough domain to minimise boundary effects, within computational constraints, two grids of different resolution were bi-directionally coupled: a coarser resolution (1×1 km) grid in 2-dimensions covering an area slightly larger than the full MIKE3 domain and a higher resolution (200×200 m), 3-dimensional (10 sigma layers), grid covering the Pentland Firth and the Orkney Islands (see Waldman et al., 2016). The turbulence closure scheme selected was the same as for the MIKE3 model (k-ε). The outer domain model was calibrated against water level data and the inner domain model against the Fall of Warness ADCP dataset, using the 3 moored Pentland Firth ADCP datasets for validation.

The two flow models predicted very similar relative changes in all parameters of interest over their spatial domain. Depth-averaged current speeds showed very similar absolute values but both models had been calibrated against this variable. This was achieved by using different values for bed resistance (Waldman et al., 2016). Bed resistance is often used as a tuning parameter and is therefore not necessarily representative of the actual seabed resistance. It also influences the modelled vertical velocity profiles and, consequently, parameters of relevance to sediment transport and ecological processes such as bottom velocity and near-bed stress. However, in our study, relative changes (spatially and as a result of energy extraction) in these variables are more important than absolute values (Waldman et al., 2016), so the relative similarities between the two flow models are reassuring.

2.3. Numerical models – waves

We used MIKE21 SW for wave modelling. This is an unstructured grid, finite volume, spectral wind-wave model that simulates the growth, decay and transformation of wind-generated waves and swell. The model offers two alternative formulations: fully spectral or a directional decoupled parametric formulation. The fully spectral version incorporates wave growth due to wind effects, non-linear wave-wave interactions, dissipation due to bottom friction, white-capping and wave breaking, effect of time-varying depth and bathymetric effects on wave refraction and shoaling, and wave-current interactions. The model domain used in this project spanned the whole of the North Atlantic (Venugopal and Nemalidinne, 2015). The model resolution was coarser in the open North Atlantic (element area approx. 2.5 km^2) and finer in the Pentland Firth and Orkney waters, and in the Hebrides and northwest Scotland (approx. 1700 m^2). The detailed model setup is described in Venugopal and Nemalidinne (2015) and Venugopal et al. (2016). The model was calibrated for significant wave height, peak wave period and peak wave direction against four Waverider data locations from the WaveNet network and the Isle of Lewis Waverider dataset, and successfully validated against three 2010 datasets, as described by Venugopal et al. (2016).

2.4. Simulating tidal stream MECs

One of the objectives of the project was to characterise sufficiently realistic generic devices for tidal stream and wave MECs that could be used by scientists without access to the technical details of such devices available to MRE developers. The characteristics of these devices were developed from information in the public domain, including that provided in licence applications, and was substantiated by consultation with developers. The most common design at present for tidal steam converters is a horizontal axis turbine and this was the device we aimed to represent in the models. Single 1.0–1.5 MW capacity rated tidal turbines were characterised by monopiles with a single 20 m diameter rotor, cut-in/cut-out speeds of 1 and 4 m s^{-1}, respectively, 2.5 m s^{-1} rated speed and current speed-dependent thrust coefficient (Baston et al., 2015). The types of wave energy devices likely to be deployed in PFOW were more variable than tidal stream devices and so three broad device types were used, representing those currently under consideration by developers; (i) a 750 kW wave attenuator, a floating device oriented in parallel to the direction of wave propagation, which captures energy from the relative motion between two sections of the device as the wave passes; (ii) a 2.5 MW wave point absorber, a fully- or partially-submerged device that captures energy from the heave motion of the waves; and (iii) a 1 MW oscillating wave surge converter or terminator, where a buoyant hinged flap attached to the seabed moves backwards and forwards, pushing hydraulic pistons to drive a turbine.

With the exception of experimental demonstrator devices, commercial-scale MRE developments will consist of arrays of individual devices. The sites with agreement for lease for MRE developments were used as initial general target areas for the location of arrays of devices. Their precise exact positioning within these areas will be based on a number of factors: 1) the availability of the resource; 2) potential interference between devices; 3) water depth; and 4) seabed suitability, in terms of substrate and/or relief. Most of these constraints will influence the location of all types of devices (tidal stream and waves) and designs, although their relative importance will differ.

Based on licence application documentation, two types of tidal stream turbines were considered: i) a 1 MW single axis turbine with a 20 m diameter rotor; and ii) a 2 MW device with two horizontal axis turbines with 20 m diameter rotors and a hub-to-hub spacing of 30 m. Their layout within an array assumed a constant across- and downstream spacing, aligned to the main direction of the flow and with staggered (offset) rows which takes advantage of the expected flow acceleration around individual devices (e.g. see Rao et al., 2016). Individual devices were also located within each general area on the basis of a) number of devices as a function of the licensed total capacity of each development; b) main current direction; c) distribution of the tidal resource within the development area; and d) water depth ($\geq$27.5 m below mean sea level, to ensure that the turbine blades would be constantly submerged). O'Hara Murray and Gallego (2016a,b) provide greater detail of the array design process and present the final layout of the hypothetical arrays in the licensed sites used in the energy extraction simulations.

2.5. Simulating wave MECs

In the case of WEC arrays, there were fewer constraints on where many of the types of devices could be placed so the general principle was to space out individual devices to occupy the whole of the licensed areas, giving consideration to the necessary operational depths for each device type. Four out of six wave development project sites within the PFOW stated that they intended to use the wave attenuator device. The number and spacing of attenuators in staggered rows was based on information provided by developers in their licence applications, the intended electricity generating capacity of each site and any spatial constraints. The one development planning to use point absorber devices required a 550 m (cross-stream) and 600 m (downstream) staggered design over the full development site, while the oscillating wave surge converters planned for one development were spaced by 45 m (71 m centre-to-centre, as they are 26 m wide), which is within the spacing window reported in the licensing documentation. The appropriate number to achieve the intended energy generating capacity was spaced out along the 12.5 m depth contour, which is within their operational target depth range of 10–15 m. See O'Hara Murray and Gallego (2016a,b) for full details.

Tidal stream arrays were implemented in the MIKE3 model of the study area (Waldman et al., 2016) using the “Turbine” facility within the software, parameterising the device as a sub-grid scale process using an actuator disk model with a user-defined thrust coefficient (Baston et al., 2015). Turbine parameters and locations, as defined above, were input into the model while supporting structures (2.5 m diameter cylindrical monopiles between the seabed and hub height) were also represented using the built-in “Pier” facility. There was no equivalent facility to model turbines in Delft3D and we were advised against customising the standard software, e.g. to parameterise the devices as momentum sinks, so tidal stream turbines were parameterised within the standard code as porous plates. Waldman et al. (2016) detail how this was implemented in the model and the limitations of the approach in terms of e.g. vertical positioning, constant thrust coefficient and fixed orientation.

WECs were implemented in the MIKE21 SW model for only 3 of the proposed development sites, two with wave attenuators and one with an oscillating wave surge converter. The model has no built-in facility to simulate WECs and so the arrays were represented by sub-grid scale parameterisation (Venugopal et al., 2016). In a separate numerical modelling exercise, the WAMIT model (www.wamit.com) was run to provide values of wave energy transmission factors (energy absorption, reflection and transmission characteristics) which were input into MIKE21 SW. WEC arrays were represented as a line structure where energy transmission is characterised by the energy balance equation. MIKE21 SW can then be used to model wave propagation over the model domain, incorporating the effect of wave energy extraction. Some of the simplifying assumptions made in this approach require further work to fully estimate the sensitivity of the results to the frequency-dependent behaviour and dynamic response characteristics of the absorption, transmission and reflection coefficients.

3. Modelling methodologies: physical environmental effects

3.1. Tidal stream modelling

Both MIKE3 and Deltf3D produced similar results on the effect of tidal stream arrays on depth-averaged current speeds, showing decreased velocities in tidal streams in line with the arrays and increased velocities to either side, as flow is partly diverted around the array (Waldman et al., 2016). These effects were particularly evident in the Inner Sound development, where the flow is constrained by coastline on both sides (Fig. 4 of O'Hara Murray and Gallego, 2016a,b) and the turbines occupy a high proportion of the total water depth. The relative effects of tidal energy extraction on bed stress were similar between the two models. The results showed decreases of bed stress of 45% and increases of up to 100% in some areas (Waldman et al., 2016). However, some spatial differences between the models were observed. These are believed to be the effect of differences in the computational grid, which result in small differences in the exact locations of simulated eddies which may affect individual devices in slightly different ways (Waldman et al., 2016).

At the time this work was carried out, MIKE3 provided a superior capability to represent the type of tidal stream device under consideration, as the limitations of the approach implemented in Delft3D resulted in a constant thrust coefficient, fixed orientation and spatially variable vertical position of the devices (Waldman et al., 2016). An error in the calculation of turbine thrust in a high resolution model, of the type identified by Kramer et al. (2014), was noted and a correction implemented (Waldman et al., 2015). A similar correction has been incorporated into the latest version of MIKE.

The observed spatial differences in model results demonstrate the importance of validating model output with field data in order to achieve the level of detail required for the precise positioning of individual devices in any given area. Our results also underline the importance of developing means of characterising bed resistance (empirically or theoretically) instead of using it as a tuning parameter. Used as such, the use of the models to obtain absolute values for variables of relevance to sediment transport and benthic ecological processes such as bottom velocity and near-bed stress is limited. It is also critical to obtain good quality velocity data (relatively rare in these operationally difficult areas outside a commercially sensitive context) for model validation outside the calibration areas/periods, in order to test the predictive power of these models. The quadratic relationship between velocity and bed stress implies that increases in velocity have greater effects on bed stress than decreases in velocity and, consequently, in some circumstances the greatest environmental impact may not be caused by TECs slowing down the flow but the increased velocities resulting from flow deflection (Waldman et al., 2016).

3.2. Waves modelling

The extraction of wave energy by WEC arrays resulted in a clear reduction in incident wave height behind the arrays, with the greatest effect clearly in the area immediately behind. At the point of maximum impact (immediately behind the array, close to the coastline), a large decrease relative to average conditions was observed: approximately 1 m difference from annual mean baseline conditions (Venugopal et al., 2016). The effect is reduced with increased distance as a result of diffracted wave energy penetrating into the lee of the array from the sides. For the proposed array off the Bay of Skaill, the results of Venugopal et al., (2016) suggested that reduced wave height and (relatively less affected) wave period and direction may result in relatively minor changes to sediments and coastal morphology (beach erosion). An important finding of these simulations was the potential cumulative effect of multiple developments. This is dependent on array layout and number of developments (Venugopal et al., 2016) and needs to be studied both in the near- and far-field. In the present work we generally constrained the spatial domain of our models to investigate potential effects in our focal area (PFOW). Far-field effects can be significant in some scenarios (e.g. van der Molen et al., 2015) and are being currently investigated by project partners in a follow-up project.

3.3. Seabed sediment modelling

Fairley et al. (2016) simulated the effect of MRE extraction on sediment processes (bedload sediment transport and morphological change) in two case study areas within the area of interest: the largest beach on the west coast of Mainland Orkney (the Bay of Skaill) and the Inner Sound of the Pentland Firth. The Bay of Skaill is close to proposed wave developments (Brough Head, West Orkney and Marwick Head). The Brough Head development site includes the Bay of Skaill within the area but the indicative device layout available to us shows the nearest WEC devices >1 km from the bay. There is a proposed development in the Inner Sound which, being constrained by Stroma and the Scottish Mainland and using the criteria applied by O'Hara Murray and Gallego (2016a,b), would occupy a significant proportion of the channel.

The Bay of Skaill is an important recreational asset and protects the Skara Brae Neolithic village, which is part of a UNESCO World Heritage Site. Modelling for this site was carried out using MIKE3, fully coupled with a spectral wave model and the non-cohesive sediment transport module of the modelling suite (Fairley et al., 2016) and validated against the only field data available on the site (5 beach profile transects), in the absence of concurrent waves and current profile data. Differences between the baseline scenario and that with wave energy extraction were observed, in the context of relatively lower confidence in the modelling output, due to the lack of calibration data and the unavoidable use of default model parameters as a result. These differences were greatest (approx. 0.5 m) on the southernmost transects and are of the magnitude of the changes measured in the field. These results need further investigation, particularly given the location of the Skara Brae archaeological site on the south end of the bay. Other valuable lessons derived from the exercise include the need for a longer period of field measurements that capture a range of conditions; the data used in this project were acquired over a low wave energy period when most sediment transport would have been dominated by swash zone transport (not generally well represented in numerical models), plus it is not possible to evaluate the model's suitability under high energy conditions. Also, in practical terms, this work highlighted the heavy computational requirements of the type of simulations needed to adequately model seabed morphology beyond the short term. For consent applications, where longer term predictions may be required, the accuracy of three-dimensional modelling may need to be sacrificed in favour of computationally cheaper two-dimensional models (Fairley et al., 2016).

To study the effect of tidal stream energy extraction on sediment dynamics in the Pentland Firth, two commercial models were used. Delft3D with D-Morphology was used to study the morphodynamic sediment environment in the Inner Sound and its results showed that the currently observed sandbank dynamics are largely maintained by tidal flow asymmetries in magnitude and direction (Fairley et al., 2016). MIKE3D was used to investigate the effect of tidal stream energy extraction on the sandbanks in the wider Pentland Firth (see Fig. 6 of Fairley et al., 2015). An anti-clockwise persistent eddy around the eastern sandbank in the Inner Sound, with minimal transport over the crest, was shown in the baseline simulations and explained the persistence of the feature. Energy extraction resulted in the reduction of the eddy and the displacement of its centre, with a directional flow over the crest of the bank. The magnitude of these changes was similar to the simulated baseline temporal variability, suggesting that energy extraction in the Inner Sound may affect the sediment dynamics in these subtidal banks (Fairley et al., 2016). However, considerable uncertainty remains. For example, the predicted natural variability in some other features such as a sandwave field to the west of Stroma is very high and, intuitively, inconsistent with their perceived permanency. At present, it is not possible to rule out model shortcomings, real sandwave variability or the combined effect of waves (not modelled here) and tide. Therefore, Fairley et al. (2016) concluded that, in some cases such as the persistent eddy-influenced sandbanks, a relatively data-light modelling approach, using default model settings, may be adequate to assess the impact of energy extraction. In other areas of mobile sediments like the sandwave fields, additional field data may be required to gain further confidence in the model results. Sediment transport modelling is computationally complex and expensive, and the acquisition of suitable field data is challenging and costly in these operationally and conceptually difficult environments. Therefore, it may be more realistic and efficient to focus detailed efforts on areas where high-risk receptors are present, using a more generic, pragmatic approach elsewhere, as illustrated by our work.

3.4. Suspended particulate material modelling

Another example of a generic modelling approach to study the potential effects of wave and tidal energy extraction was presented by Heath et al. (2016). A one-dimensional model was developed to investigate suspended particulate material (SPM) dynamics. SPM characterises the light environment in the water column and is therefore critical for many ecological processes, and it has been postulated that hydrodynamic changes to the marine environment as a result of MRE extraction have the potential to affect SPM dynamics. Numerical simulation modelling of SPM dynamics is a particularly challenging task, as discussed by Heath et al. (2016), but the parsimonious approach they developed was sufficient to capture the observed natural temporal variability (seasonal, tidal, sub-tidal and storm events), although high turbidity extremes were not fully replicated, probably due to the nature of the forcing flow data (purely tidal, excluding wind and surge effects). The extraction of wave and tidal energy of the magnitude expected of a large scale tidal or wave array resulted in a reduction of water column turbidity within measurable detection variability levels. With the caveat that this may need to be qualified by the likely non-linear relationship between the energy extraction by MRE devices and wave or current variability, Heath et al. (2016) concluded that detectable levels of change in turbidity would require some 50% attenuation of current speed, something unlikely beyond the immediate vicinity of devices at current scales of development, where processes not represented in the model are likely to dominate.

4. Regulatory framework and acceptability criteria for sustainable exploitation

As outlined in the Introduction, the regulatory framework for MRE developments we describe in this paper will be of general applicability beyond the Scottish context due to its foundation in European and other international legislation, although aspects may vary through differences in details of the transposition of those regulations into national legislation.

In Scottish waters, activities covered by the Marine (Scotland) Act 2010 with the potential to have a significant effect on the environment, local communities and other users need to undergo a pre-application consultation (Marine Scotland, 2015), to inform all potentially interested parties. MRE developments with a total area exceeding 10,000 m^2 fall within this category. Not all licensable projects require an EIA as part of their application. Whether an EIA must be undertaken for the provision of the Environmental Statement (ES) which reports the findings of the EIA is dependent on whether the project features within Annex I (mandatory EIA) or Annex II (EIA only necessary if the project exceeds certain limits or

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thresholds) of the European Commission EIA Directive. MRE projects are likely to fall within Annex II and the decision about EIA requirement will be made during the “EIA Screening” stage (Marine Scotland, 2015). However, a statutory EIA is generally required. The next stage in the process is termed “EIA Scoping” and involves preparing a preliminary analysis of impact (Scoping Report) based on existing information, allowing the opportunity to identify any issues that need further exploration or inclusion in the EIA. This occurs through formal response to the Scoping Report from the consenting authority. These preliminary steps define the structure and scope of the EIA and its reporting document, the ES. The EIA must (BSI, 2015) i) describe the project; ii) outline the main alternative methods (e.g. pile foundation types, construction methodologies, etc.) and the reasons for choosing any given one; iii) describe in detail the environmental (physical, biological and human) baseline regarding any aspects that could potentially be affected and the methodology used to characterise it; and iv) present any mitigation measures that will be put in place to prevent, reduce and offset adverse environmental effects, and how these will be monitored. Once the impact pathways and receptor sensitivities have been established, receptor vulnerability is evaluated. Both beneficial and adverse impacts are assessed on a scale of negligible to major. Moderate or major adverse impacts require some form of impact reduction or mitigation measure. EIA regulations specify that cumulative effects need to be accounted for within an EIA. Guidance on the assessment of cumulative effects is available on EC (1999).

If a proposed development has the potential to have a significant impact on a Natura site, an HRA needs to be carried out. This is a consenting procedure that states that the competent authority (normally the licensing/consenting authority) needs to carry out an Appropriate Assessment (AA) of the plan or project. The AA needs to address whether the integrity of the Natura site is likely to be adversely affected, considering closely the nature conservation objectives of the site, based on, and supported by, evidence that is capable of standing up to scientific scrutiny.

On a broader scale, under the MSFD, EU Member States are required to undertake an initial assessment of the state of their seas (Article 8), determine a set of characteristics for GES (Article 9), and establish relevant targets (Article 10), based on the 11 descriptors set out in Annex I, the elements set out in Annex III (characteristics, pressures and impacts), and a series of relevant Descriptors defined in the Commission Decision on criteria and methodological standards for Good Environmental Status (EC, 2010). Regarding D7, changes in the tidal regime, sediment transport, currents and wave action are explicitly mentioned.

The reporting scale for MSFD does not apply to small scale, near-field effects (although those may fall under other environmental legislation, as discussed above) but rather those that may “affect marine ecosystems at a broader scale” (EC, 2010). Two D7 criteria are defined: 7.1, spatial characterisation of permanent alterations; and 7.2, impact of permanent hydrographical changes, with their respective indicators (7.1.1: Extent of area affected by permanent alterations; 7.2.1: Spatial extent of habitats affected by the permanent alteration; 7.2.2: Changes in habitats, in particular the functions provided, due to altered hydrographical conditions). At the time of writing, no standard methodology has been defined for assessment of GES for this Descriptor. Due to the nature of this descriptor and its current state of development, D7 is not a quantitative descriptor at present and it is not possible to define objective thresholds for its GES indicators.

A review of the Commission Decision for D7 (Stolk et al., 2015), recommended the use of models to quantify the effects from permanent alterations to the hydrographic regime. Modelling, applying a common methodology, should be used to reduce uncertainties in the assessment of impacts. In order to understand the effect of D7-related impacts on other descriptors such as D1 (“Biodiversity is maintained”) and D6 (“The sea floor integrity ensures functioning of the ecosystem”), as well, additional research is needed on habitat modelling, pressure mapping and cumulative impacts, along with monitoring of potentially affected areas (Stolk et al., 2015). Models used within methodologies such as EIA, SEA, HRA and marine spatial planning will contribute to evaluating and assessing the extent and the cumulative aspects of impacts from MRE activities. The quantitative assessment of indirect, combined and cumulative effects would still benefit from the development of suitable quantitative methods and tools, which would be the next logical step from the work presented here, although some advances have already been made (e.g. the TRaC-MImAS tool assessing potential hydromorphological alterations in WFD “transitional and coastal (TraC)”waters; UKTAG (2013). See Appendix A).

MRE developments also need to be compatible with their general planning context. In Scotland, the marine planning framework is made up of the National Marine Plan (adopted in March 2015 with the publication of the Strategic Environmental Assessment Post-Adoption Statement), the ongoing roll-out of the Regional Marine Plans for the identified 11 Scottish Marine Regions and sectoral plans such as those prepared for offshore renewable energy (wind, wave and tidal). Marine spatial planning, particularly at the broader geographical level, makes uses of instruments such as The Crown Estate's MaRS (Marine Resource System), a GIS-based tool with hundreds of spatial datasets that allow spatial analyses to identify areas of opportunity and potential constraint for development (e.g. by MRE projects) by weighing combinations of technical constraints, sensitivities, competing interests and other uses of the marine environment.

Current experience indicates that establishing compliance with the need to protect Natura 2000 sites is the key environmental element in determining whether licences/consent for development should be granted. It is clear that changes to the hydrodynamic environment from the current scale of development of MRE projects and those conceivable over the next few years (such as the scenarios considered in the *Terawatt* project) should be measurable. However, it is unlikely that they will be sufficient to cause projects to be rejected through failure to meet WFD requirements (see Appendix A), or to lead to permanent hydrographic changes of a magnitude that would cause failure to attain GES under Descriptor 7 of the MSFD. It is much less clear whether we can be confident that this scale of development does not have the potential to adversely affect the integrity of Natura 2000 sites. We have demonstrated that changes in the tidal current speeds resulting from MRE developments are sufficient to cause alterations to sediment dynamics in some locations. Impact assessments, therefore, will need to take account of the potential for impacts on protected sites that relay on sediment characteristics. These include sites such as designated sandbanks, or sites designated for the protection of benthic species with particular substrate requirements.

Similarly, our understanding of the feeding ecology of a range of protected species, including marine mammals and seabirds, is indicating that species have particular preferred feeding habitats, characterised by factors such as current speed, turbulence and primary production rates (Waggitt et al., 2016a, 2016b), influenced by the presence/absence of oceanographic fronts. There will be an increasing need to take account of the changes to the physical environment in assessments of effects on foraging success and efficiency, and consequences for reproductive success, mortality rates and the dynamics of protected populations associated with Natura 2000 sites.

We can predict that there will be a continuing and intensifying need for specific quantitative information on the individual and cumulative effects of MRE developments on the physical and biological aspects of the marine environment. The EIA and, where appropriate, HRA processes that underpin the planning and legislative framework will remain reliant on best current science, together with qualitative judgement and expert opinion. We believe that work such as that presented here makes a critical contribution to filling the existing gaps and reducing the uncertainties in impact assessments.

5. Conclusions, further work and recommendations

This paper summarises the output of a collaborative modelling project to estimate the potential effects of MRE developments on the marine environment.

At the basis of all modelling work lies the most appropriate and best quality data. Here, various datasets for model initialisation, forcing, calibration and validation were compiled. Most of these data will be freely available to developers, academia and regulators (O'Hara Murray and Gallego, 2016a,b) and will facilitate a common data framework for EIA modelling.

Two commercially-developed numerical modelling suites were used primarily in this work, following industry advice. The two flow models used produced a similar description of the hydrodynamics of the study area and predicted very consistent relative changes to the physical environment as a result of tidal energy extraction. However, bed resistance was used as a tuning parameter for model calibration in both models and that influenced velocity profiles and derived parameters of relevance to sediment dynamics and ecological processes. Our results underline the importance of developing means of characterising bed resistance adequately (empirically or theoretically) to circumvent this limitation. Our work also highlighted the need for the appropriate facilities to characterise MRE devices within the software suites, as technical approximations required in their absence can bring about their own errors and inaccuracies. It could be argued that the most up to date non-commercial models often favoured by the academic community may allow greater flexibility and, eventually, provide more powerful and accurate modelling tools. However, open and comprehensive cross-validation against commercial software will be required in order to gain the confidence of industry and regulators.

The project succeeded in characterising sufficiently realistic generic devices for tidal stream and wave MECs that could be used by scientists without access to the technical details available to MRE developers. This was easier in the case of TECs than WECs, largely due to the lack of design convergence of the latter, but also due to the technical limitations of the modelling software used, which forced us to represent WEC arrays by sub-grid scale parameterisation. We have high confidence in the way the tidal arrays were represented in the models (in particular in MIKE3) and also the wave arrays but further work will be desirable for the latter to fully estimate the sensitivity of the results to the frequency-dependent behaviour and dynamic response characteristics implemented in the model.

The model results showed localised sea bed effects at the level of the proposed MRE developments in the PFOW area, with large-scale effects on water column characteristics such as the turbidity field unlikely. Tidal stream developments decreased velocities in line with the arrays and increased velocities to either side, as flow is diverted, more noticeably in sites where the flow is particularly constrained by coastline. Sea bed dynamics (e.g. sand banks and sand wave fields) in the Pentland Firth are maintained by the characteristics of the flow. The results of simulations with energy extraction suggested that hydrological changes may affect the sediment dynamics of these subtidal features, although observed differences between the models demonstrate the importance of model validation with field data in order to achieve the level of accuracy required for array positioning for commercially viable and sustainable exploitation. The extraction of wave energy by arrays of WECs also suggested localised effects behind the developments but reduced with increased distance. Tentative results (pending further validation) at specific sites (e.g. Bay of Skaill) suggest potential localised effects on coastal morphology that require further investigation. A recommendation from sediment modelling was to focus this computationally-intensive and potentially expensive (in terms of difficulty and cost of field data acquisition) work on areas where high-risk receptors are identified, applying a more generic approach elsewhere.

In the current absence of quantitative targets, the achievement of Good Environmental Status in European waters regarding the more directly relevant Descriptors to MRE developments (D6, D11 and, in particular, D7) is currently heavily reliant on the adequacy of the marine planning and EIA (including HRA, where appropriate) framework. To that effect, large scale three-dimensional modelling is critical for being able to understand and quantify the direct, indirect and cumulative effects of MRE extraction. We are confident that the methodologies presented here and future work incorporating other environmental (e.g. climate change) factors and the downstream effect of physical changes on the marine ecosystem will make a critical contribution to this process.

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Appendix A. Example of an assessment of the potential hydromorphological alterations in WFD transitional and coastal waters of the Pentland Firth by TEC arrays using the TRaC-MImAS tool

The Transitional and Coastal Water Morphological Impact Assessment System (TRaC-MImAS; UKTAG (2013)) was developed as a risk based regulatory decision-support tool. TRAC-MImAS is designed to help regulators determine whether new projects likely to alter hydromorphological features could risk the ecological objectives of the Water Framework Directive (WFD).

The tool uses a concept of capacity and assumes that new projects "consume" that capacity, causing a degradation of ecological conditions. The tool uses simplified area/footprints to measure the change in capacity for WFD water-bodies and provides a guide to regulators. Expert advice would always be sought for larger or more complex projects.

In this exercise, two TRaC-MImAS assessments were carried out for the water-bodies covering the Pentland Firth: one for the water-body named "Dunnet Head to Duncansby Head" (including the Ness of Duncansby and Inner Sound proposed developments, as shown in Fig. 1 of O'Hara Murray and Gallego (2016a,b)) and another for the water body "Old Head to Tor Ness" (including the Brough Ness and Brims developments). These water-bodies contained 500 and 300 devices respectively.

The assessment would be initially conducted at a small scale (Stage 1) over an area of 0.5 km^2. This would involve plotting out the assessment area, calculating intertidal and subtidal areas and

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building a baseline of existing modifications to the area in question. Any modification, such as piers and shoreline reinforcement, must be included. Due to the size of the tidal arrays under consideration, this stage was not applicable and a full water-body assessment was conducted (Stage 2). This involves building a baseline at the whole water-body scale.

The intertidal area is plotted and that total is removed from the total water-body area to provide the subtidal value. All existing structures are mapped and added to the assessment baseline. These are categorised under various types of obstructions or modifications. In most cases a simple area is calculated for structures but in more complex scenarios footprint rules are used. Once the baseline has been calculated the new project is then added and any change in the water-body status is recorded. The tool presents changes as a deterioration from the baseline status through categories that range from High, through Good, Moderate, Poor and Bad. Any change in category would provide an indication to the regulator that a given project should be reviewed further and, if necessary, expert guidance should be requested.

For both assessments conducted in this exercise, a footprint rule was required to provide an area for the tidal devices. This footprint was based on the spacing between devices. The devices here were aligned in rows, but each row was sufficiently spaced from each other that overlap was not a factor. A perimeter was drawn around the devices using the spacing between each device (45 m) as a guide. It is acknowledged in the TRaC-MImAS technical guidance that this footprint overestimates the actual footprint in order to include the downcurrent effects of the devices.

In the Dunnet Head to Duncansby Head assessment, 500 devices were placed in 52 rows with three individual devices each. The total footprint for these devices was 2.24 km^2. The total subtidal area for the water-body was 175.85 km^2. The footprint would be 1.2% of the subtidal area. This was input to the tool under the category "Tidal Devices (high impact)". This addition did not cause the capacity to degrade into a new classification. In a real scenario, the ensuing advice to the regulator would be that there would be no objection to this project.

In the Old Head to Tor Ness assessment, 300 devices were placed in 71 rows. Following the above footprint rules, the footprint for these devices was 1.5 km^2. The total subtidal area for the water-body was 195.10 km^2. The footprint would be 0.7% of the subtidal area. As above, this was input to the tool under the category "Tidal Devices (high impact)". The addition did not cause the capacity to degrade into a new classification. As with the previous assessment, this did not result in a change in capacity category and the same advice would be provided to the regulator.

Both scenarios were applied in relatively unmodified water-bodies (High status). Several piers and jetties were present along the coastline but no major modification has taken place in these areas. A High classification water body degrades to a Good classification at 5% capacity, which was quite far from the assessed impact of these developments. However, although the assessments indicated that no degradation would take place, it should be noted that the TRaC-MImAS tool has not been tested thoroughly for tidal devices and, in this situation, expert advice would still be sought and appropriate Environmental Impact Assessments based on measurements and the type of modelling carried out in this project would be required in support of licence applications.

In addition, TRaC-MImAS is not designed to assess the effect of floating devices. This means that projects such as marine farms, some pontoons and, crucially, floating WECs could not be assessed with this tool. An assessment could still be conducted using the same footprint rules as for tidal devices but any decisions would be deferred to expert advice.

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