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# 1 Large scale three-dimensional modelling for wave and tidal energy resource and 2 environmental impact: methodologies for quantifying acceptable thresholds for 3 sustainable exploitation

4  
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- 19
- 20 • We describe a modelling project to estimate the potential effects of wave & tidal stream
- 21 renewables on the marine environment
- 22 • Realistic generic devices to be used by those without access to the technical details available
- 23 to developers are described
- 24 • Results show largely local sea bed effects at the level of the currently proposed renewables
- 25 developments in our study area
- 26 • Large scale 3D modelling is critical to quantify the direct, indirect and cumulative effects of
- 27 renewable energy extraction
- 28 • This is critical to comply with planning & environmental impact assessment regulations and
- 29 achieve Good Environmental Status

## 30 31 **1 Introduction**

### 32 33 **1.1 Background**

34  
35 In the context of increasing societal concerns about the effect of traditional energy sources  
36 based on the combustion of fossil fuels on the earth's climate, Marine Renewable Energy  
37 (MRE) is a relatively new sector showing considerable promise, particularly in highly  
38 populated areas of northern Europe where other (e.g. some terrestrial) renewable energy  
39 sources have either fulfilled their potential or are likely to encounter significant challenges as  
40 a result of lack of free/available resource, environmental or socio-economic impact, etc.

41  
42 The MRE sector comprises a number of different technologies (see Magagna and Uihlein,  
43 2015). In order of degree of readiness, these include offshore wind, tidal energy, wave energy  
44 and a few emerging technologies such as salinity gradient and thermal energy conversion.  
45 The latter have been piloted already (in some cases, for quite some time) but their current

46 technology readiness level (see review by Magagna and Uihlein, 2015) suggests that they are  
47 still some way off becoming commercially viable.

48

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

63

64 The tidal MRE sector includes a number of different technologies that exploit tides to  
65 generate electricity. They include tidal stream devices, where turbines placed within the tidal  
66 stream exploit the kinetic energy of the tidal flow to generate electricity, and dam-like  
67 structures with turbines, such tidal lagoons and barrages (closed dams) or turbines in open  
68 dams perpendicular to the tidal flow. Most Tidal Energy Converters (TECs), e.g. for tidal  
69 stream developments, are typically horizontal axis bladed turbines (although other designs  
70 exist) and therefore share some similarities with wind turbines. However, TECs are yet to  
71 reach the required level of technical maturity for routine large scale commercial deployment,  
72 although they show promise, particularly in areas where the resource is most abundant, such  
73 as parts of the coastal waters west and north of Scotland (The Scottish Government, 2013).

74

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

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83

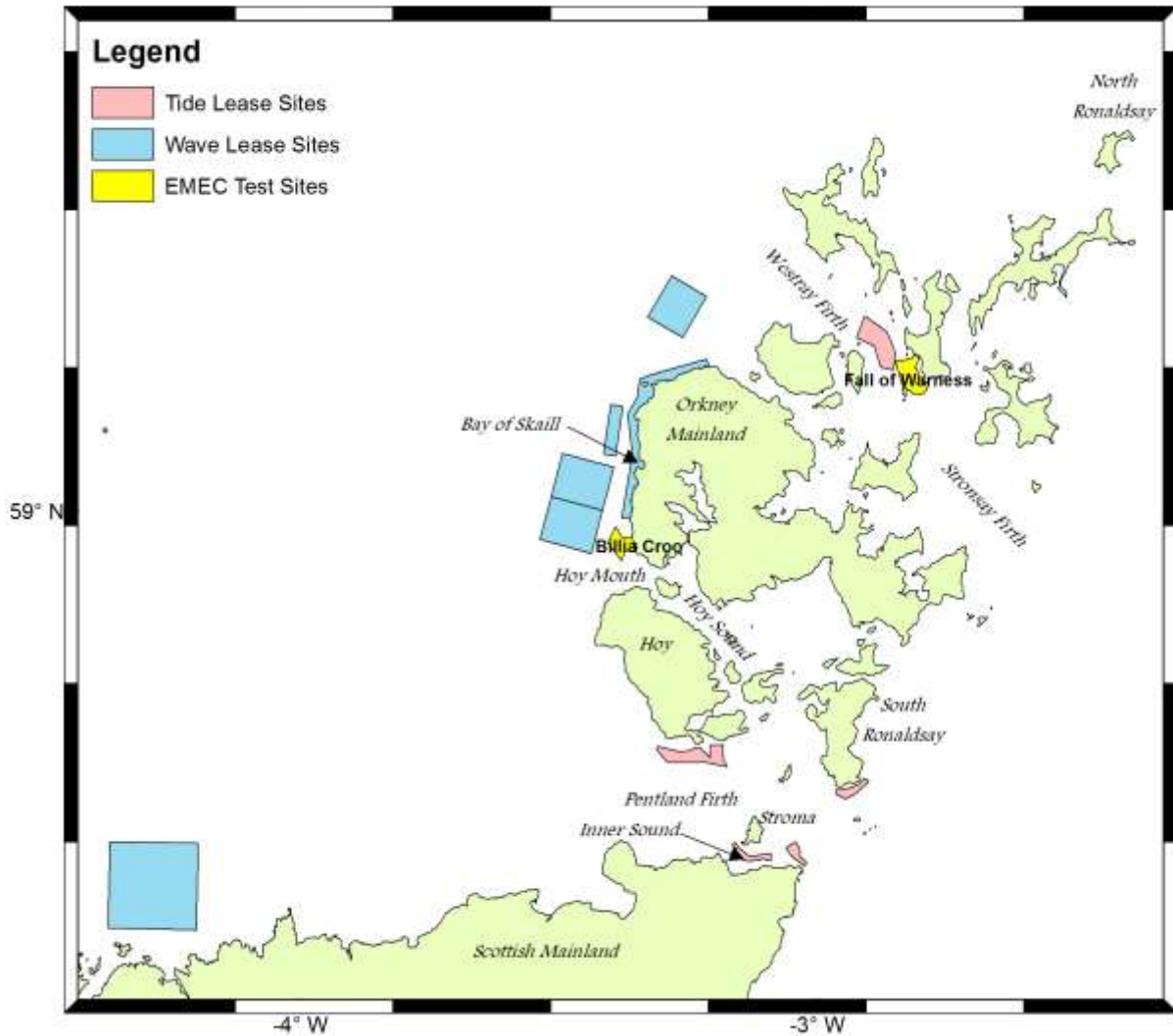
## 84 **1.2 Study area**

85

86 The main geographic focus of this work is the Pentland Firth and Orkney Waters (PFOW) area  
87 (Fig. 1), comprising waters around the Orkney Islands off the north Scottish coast and the 10-  
88 12 km wide channel (the Pentland Firth) that separates this archipelago from the Scottish  
89 mainland. The Pentland Firth is significantly deeper than the bays and channels among the  
90 islands, which are generally less than 25 m and rarely exceed 40 m. Depths in the main  
91 Pentland Firth channel typically reach 60-80 m and even >90m on the western side. The Inner  
92 Sound, south of the Island of Stroma in the Pentland Firth, is somewhat shallower (ca. 35 m).

93 The M<sub>2</sub> tide that propagates clockwise around the British Isles results in an approximately 2 h  
 94 phase difference between the west and east ends of the Pentland Firth and sets up a hydraulic  
 95 gradient that generates strong tidal currents which can reach 5 m s<sup>-1</sup>. Tidal currents are also  
 96 forced around headlands and through other channels within the Orkney Islands, where spring  
 97 flows can exceed 3.5 m s<sup>-1</sup>. The amount of extractable tidal stream power in the area has  
 98 been the subject of a number of studies with wide-ranging estimates. For the Pentland Firth,  
 99 the higher limit has been estimated as 4.2 GW averaged over the spring-neap cycle (Draper  
 100 *et al.*, 2014) but more recent work reports a more realistic scenario of around 1.5 GW (O’Hara  
 101 Murray and Gallego, submitted).

102



103  
 104 Figure 1: Map showing the Pentland Firth and Orkney Waters area and the location of the  
 105 wave and tidal stream MRE development sites considered in the project.

106  
 107 The wave regime in PFOW is dominated by Atlantic swells and the influence of low pressure  
 108 systems that travel primarily from west to east across the North Atlantic. Therefore, wave  
 109 conditions are most severe in the exposed coastal areas to the west. The seasonal range of  
 110 average wave resource in the area has been estimated between <10 (summer) and 50 kW  
 111 (winter, top range of the estimate) (Neill *et al.*, 2014).

112

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

121

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

143

### 144 **1.3 Legislative framework**

145

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

160

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

171  
172 The Marine Strategy Framework Directive (MSFD; EC (2008)) is the piece of European  
173 legislation which establishes a common framework and objectives for the prevention,  
174 protection and conservation of the marine environment against damaging human activities  
175 beyond the spatial domain of the WFD. EU countries must assess the environmental status  
176 of their marine waters and set environmental targets, develop monitoring networks, prepare  
177 programmes of measures and set specific objectives towards reaching a “Good Environmental  
178 Status (GES)” by 2020. The MSFD sets out, in its Annex I, eleven qualitative Descriptors of  
179 GES. The main Descriptors that may be directly impacted by MRE developments are D6 (“The  
180 sea floor integrity ensures functioning of the ecosystem”), D11 (“Introduction of energy  
181 (including underwater noise) does not adversely affect the ecosystem”) and, in particular, D7  
182 (“Permanent alteration of hydrographical conditions does not adversely affect the  
183 ecosystem”). Hydrographical conditions play a critical role in the dynamics of marine  
184 ecosystems, particularly in coastal areas, and can be altered by human activities. One of the  
185 main pressures on D7 explicitly identified refers to MRE installations  
186 ([http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-  
187 7/index\\_en.htm](http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-7/index_en.htm)).

188  
189 In practice, experience has shown that the dominant pieces of environmental legislation  
190 influencing licensing/consenting of MRE developments are Council Directive 92/43/EEC (the  
191 “Habitats Directive”, (EC, 1992)) and Directive 2009/147/EC (the “Birds Directive” (EC, 2009)).  
192 The Habitats Directive aims to promote the maintenance of biodiversity, protecting a wide  
193 range of rare, threatened or endemic animal and plant species and some 200 rare and  
194 characteristic habitat types, taking account of economic, social, cultural and regional  
195 requirements. The Birds Directive aims to protect all of the 500 wild bird species naturally  
196 occurring in the European Union and, through national legislation, it establishes a network of  
197 Special Protection Areas (SPAs) that include all the most suitable territories for these species.  
198 In Scotland, there are a number of coastal SPAs protecting the breeding sites of, particularly,  
199 migratory seabirds species that visit Scotland during the breeding season. In parallel, Special  
200 Areas of Conservation (SACs) are established under the Habitats Directive to protect habitats  
201 and species of conservation value. In marine systems, these include distinctive habitats such  
202 as sandbanks, sea caves and cliffs etc., and key species such as bottlenose dolphin and seal  
203 species. SPAs and SACs are included in the Natura 2000 ecological network set up under the  
204 Habitats Directive.

205  
206 The potential impact of wave or tidal stream Marine Energy Converters (MECs) has been  
207 discussed in the scientific literature. Pelc and Fujita (2002) considered wave devices to be

208 relatively environmentally benign and tidal stream turbines to be the most environmentally  
209 friendly tidal power option. A review of the ecological impact of MRE (Gill, 2005) showed  
210 that, despite a growth in publications on renewable energy, only a fraction at the time (<1%;  
211 none on coastal ecology) considered its potential environmental risks. Theoretical risks of the  
212 extensive subsurface structures introduced by MRE into the coastal environment outlined by  
213 Gill (2005) identified changes to water circulation and to the transport and deposition of  
214 sediment, noise and vibration during the construction and operational phases, changes to the  
215 electrical and electromagnetic fields, and degradation and/or removal of habitats. Gill (2005)  
216 also warned against an undue focus on rare species of high intrinsic appeal to the detriment  
217 of impacts on the ecosystem structure, processes and key functional species. The effects of  
218 near- and far-field changes to the flow and wave fields, and sedimentation patterns have been  
219 identified by subsequent publications (e.g. Shields *et al.*, 2011) including specifically in the  
220 Pentland Firth area (Shields *et al.*, 2009). These effects are not just negative: a number of  
221 potentially beneficial effects has also been proposed (Inger *et al.*, 2009), such as the creation  
222 of artificial reefs, *de-facto* marine protected areas and fish aggregation devices. Interactions  
223 between positive and negative effects, as well as cumulative effects (Inger *et al.*, 2009)  
224 requiring a different scale of management actions (Boehlert and Gill, 2010). Shields *et al.*  
225 (2011) identified the PFOW area as a particular case study to provide essential industry  
226 standards and environmental guidelines of worldwide applicability. However, because of the  
227 relative lack of empirical data on how marine habitats and wildlife will interact with wave and  
228 tidal stream MECs and their distinct nature relative to other forms of marine developments,  
229 understanding their potential environmental impact is particularly challenging and important.  
230 Smaller-scale demonstrator devices have been studied in depth but there is a clear need to  
231 monitor carefully the quantitative and qualitative nature of the effects of early commercial-  
232 scale developments against the natural baseline. Environmental impact assessment  
233 procedures are covered by European legislation such as Directives 2011/92/EU (the  
234 “Environmental Impact Assessment, EIA” Directive) and 2001/42/EC (the “Strategic  
235 Environmental Assessment, SEA” Directive) and their relevant national transposition (in  
236 Scotland, the Environmental Assessment (Scotland) Act 2005), to ensure that the potential  
237 environmental implications are taken into account before plans and projects are formally  
238 adopted and licences/consents are granted. Where a project has the potential to have a  
239 significant effect on a Natura site, a Habitats Regulation Appraisal (HRA) is required under the  
240 Habitats Directive. This process progresses from qualitative assessment to a more detailed  
241 Appropriate Assessment (AA). Projects can only be consented if the AA concludes that the  
242 development will not affect the integrity of the relevant protected (Natura 2000) sites.

243  
244 This paper summarises the output of a collaborative modelling project (the TeraWatt project;  
245 Side *et al.* (this issue)). In the absence of comprehensive observational data, modelling  
246 projects like the present one are fundamental to estimate the potential effects of MRE  
247 developments on the physical environment and, consequently, on the marine ecosystem. This  
248 paper draws on the project outputs and presents potential methodologies for quantifying  
249 acceptable thresholds for sustainable MRE exploitation within the context of the existing  
250 planning, regulatory and environmental legislative framework. In the following sections, we  
251 describe the modelling methodologies to represent the hydrodynamics and the  
252 implementation of energy extraction, and their effect on the physical environment, followed  
253 by a description of the regulatory framework in Scotland and a discussion on the acceptability  
254 criteria for sustainable exploitation.

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## **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 (this issue) 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 Skail, targeted survey work was carried out within the project, such as beach profiles (Fairley *et al.*, this issue) or site-specific datasets were identified (Inner Sound: MeyGen (2012) and Marine Scotland Science multibeam echosounder data ground-truthed 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 (this issue) 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**



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

309  
310 MIKE3 is a free-surface hydrostatic model that uses a cell-centred finite volume method to  
311 solve the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations,  
312 with the Boussinesq approximation and a  $k-\epsilon$  turbulence closure scheme in the vertical and  
313 the Smagorinsky horizontal eddy viscosity formulation. In the vertical, we used sigma  
314 coordinates and, in the horizontal, triangular elements allowing for an unstructured grid that  
315 provides enhanced flexibility to represent complex geometries (e.g. coastline and  
316 bathymetric features) in areas where more detail is required, with greater computational  
317 efficiency. A description of the MIKE3 implementation in our study area is given by Waldman  
318 *et al.* (this issue) but, briefly, a model domain was set up covering the whole of the Orkney  
319 Islands, the Pentland Firth and adjacent waters off the north and northeastern Scottish  
320 mainland, with a horizontal resolution that varied between 4000 and 50-200 m (in high tidal  
321 velocity areas) and 10 equidistant vertical sigma layers. The flow model was calibrated against  
322 the 3 moored ADCP current profile datasets referred to above.

323  
324 Delft3D-Flow is a finite difference hydrostatic model that solves the three-dimensional  
325 incompressible Reynolds-averaged Navier-Stokes equations, with the Boussinesq  
326 assumptions. We chose a sigma vertical coordinate system and the model's rectangular  
327 (structured) staggered Arakawa-C grid in the horizontal. To achieve the degree of horizontal  
328 resolution required in the focus area while covering a wide enough domain to minimise  
329 boundary effects, within computational constraints, two grids of different resolution were bi-  
330 directionally coupled: a coarser resolution (1 x 1 km) grid in 2-dimensions covering an area  
331 slightly larger than the full MIKE3 domain and a higher resolution (200 x 200 m), 3-  
332 dimensional (10 sigma layers), grid covering the Pentland Firth and the Orkney Islands (see  
333 Waldman *et al.*, this issue). The turbulence closure scheme selected was the same as for the  
334 MIKE3 model ( $k-\epsilon$ ). The outer domain model was calibrated against water level data and the  
335 inner domain model against the Fall of Warness ADCP dataset, using the 3 moored Pentland  
336 Firth ADCP datasets for validation.

337  
338 The two flow models predicted very similar relative changes in all parameters of interest over  
339 their spatial domain. Depth-averaged current speeds showed very similar absolute values but  
340 both models had been calibrated against this variable. This was achieved by using different  
341 values for bed resistance (Waldman *et al.*, this issue). Bed resistance is often used as a tuning  
342 parameter and is therefore not necessarily representative of the actual seabed resistance. It  
343 also influences the modelled vertical velocity profiles and, consequently, parameters of  
344 relevance to sediment transport and ecological processes such as bottom velocity and near-  
345 bed stress. However, in our study, relative changes (spatially and as a result of energy  
346 extraction) in these variables are more important than absolute values (Waldman *et al.*, this  
347 issue), so the relative similarities between the two flow models are reassuring.

348

349

### 350 **2.3 Numerical models – waves**

351

352 We used MIKE21 SW for wave modelling. This is an unstructured grid, finite volume, spectral  
353 wind-wave model that simulates the growth, decay and transformation of wind-generated  
354 waves and swell. The model offers two alternative formulations: fully spectral or a directional  
355 decoupled parametric formulation. The fully spectral version incorporates wave growth due  
356 to wind effects, non-linear wave-wave interactions, dissipation due to bottom friction, white-  
357 capping and wave breaking, effect of time-varying depth and bathymetric effects on wave  
358 refraction and shoaling, and wave-current interactions. The model domain used in this  
359 project spanned the whole of the North Atlantic (Venugopal and Nimalidinne, 2015). The  
360 model resolution was coarser in the open North Atlantic (element area approx. 2.5 km<sup>2</sup>) and  
361 finer in the Pentland Firth and Orkney waters, and in the Hebrides and northwest Scotland  
362 (approx. 1700 m<sup>2</sup>). The detailed model setup is described in Venugopal and Nimalidinne  
363 (2015) and Venugopal *et al.* (this issue). The model was calibrated for significant wave height,  
364 peak wave period and peak wave direction against four Waverider data locations from the  
365 WaveNet network and the Isle of Lewis Waverider dataset, and successfully validated against  
366 three 2010 datasets, as described by Venugopal *et al.* (this issue).

367

### 368 **2.4 Simulating tidal stream MECs**

369

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

388

389 With the exception of experimental demonstrator devices, commercial-scale MRE  
390 developments will consist of arrays of individual devices. The sites with agreement for lease  
391 for MRE developments were used as initial general target areas for the location of arrays of  
392 devices. Their precise exact positioning within these areas will be based on a number of  
393 factors: 1) the availability of the resource; 2) potential interference between devices; 3) water  
394 depth; and 4) seabed suitability, in terms of substrate and/or relief. Most of these constraints

395 will influence the location of all types of devices (tidal stream and waves) and designs,  
396 although their relative importance will differ.

397

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

411

412

## 413 **2.5 Simulating wave MECs**

414

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

430

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

442

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

455

456

### 457 **3 Modelling methodologies: physical environmental effects**

458

#### 459 **3.1 Tidal stream modelling**

460

461 Both MIKE3 and Delft3D produced similar results on the effect of tidal stream arrays on depth-  
462 averaged current speeds, showing decreased velocities in tidal streams in line with the arrays  
463 and increased velocities to either side, as flow is partly diverted around the array (Waldman  
464 *et al.*, this issue). These effects were particularly evident in the Inner Sound development,  
465 where the flow is constrained by coastline on both sides (Fig. 4 of O'Hara Murray and Gallego,  
466 this issue) and the turbines occupy a high proportion of the total water depth. The relative  
467 effects of tidal energy extraction on bed stress were similar between the two models. The  
468 results showed decreases of bed stress of 45% and increases of up to 100% in some areas  
469 (Waldman *et al.*, this issue). However, some spatial differences between the models were  
470 observed. These are believed to be the effect of differences in the computational grid, which  
471 result in small differences in the exact locations of simulated eddies which may affect  
472 individual devices in slightly different ways (Waldman *et al.*, this issue).

473

474 At the time this work was carried out, MIKE3 provided a superior capability to represent the  
475 type of tidal stream device under consideration, as the limitations of the approach  
476 implemented in Delft3D resulted in a constant thrust coefficient, fixed orientation and  
477 spatially variable vertical position of the devices (Waldman *et al.*, this issue). An error in the  
478 calculation of turbine thrust in a high resolution model, of the type identified by Kramer *et al.*  
479 (2014), was noted and a correction implemented (Waldman *et al.*, 2015). A similar correction  
480 has been incorporated into the latest version of MIKE.

481

482 The observed spatial differences in model results demonstrate the importance of validating  
483 model output with field data in order to achieve the level of detail required for the precise  
484 positioning of individual devices in any given area. Our results also underline the importance  
485 of developing means of characterising bed resistance (empirically or theoretically) instead of  
486 using it as a tuning parameter. Used as such, the use of the models to obtain absolute values  
487 for variables of relevance to sediment transport and benthic ecological processes such as  
488 bottom velocity and near-bed stress is limited. It is also critical to obtain good quality velocity

489 data (relatively rare in these operationally difficult areas outside a commercially sensitive  
490 context) for model validation outside the calibration areas/periods, in order to test the  
491 predictive power of these models. The quadratic relationship between velocity and bed stress  
492 implies that increases in velocity have greater effects on bed stress than decreases in velocity  
493 and, consequently, in some circumstances the greatest environmental impact may not be  
494 caused by TECs slowing down the flow but the increased velocities resulting from flow  
495 deflection (Waldman *et al.*, this issue).

496  
497

### 498 **3.2 Waves modelling**

499

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

516

### 517 **3.3 Seabed sediment modelling**

518

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

529

530 The Bay of Skail is an important recreational asset and protects the Skara Brae Neolithic  
531 village, which is part of a UNESCO World Heritage Site. Modelling for this site was carried out  
532 using MIKE3, fully coupled with a spectral wave model and the non-cohesive sediment  
533 transport module of the modelling suite (Fairley *et al.*, this issue) and validated against the  
534 only field data available on the site (5 beach profile transects), in the absence of concurrent  
535 waves and current profile data. Differences between the baseline scenario and that with

536 wave energy extraction were observed, in the context of relatively lower confidence in the  
537 modelling output, due to the lack of calibration data and the unavoidable use of default model  
538 parameters as a result. These differences were greatest (approx. 0.5 m) on the southernmost  
539 transects and are of the magnitude of the changes measured in the field. These results need  
540 further investigation, particularly given the location of the Skara Brae archaeological site on  
541 the south end of the bay. Other valuable lessons derived from the exercise include the need  
542 for a longer period of field measurements that capture a range of conditions; the data used  
543 in this project were acquired over a low wave energy period when most sediment transport  
544 would have been dominated by swash zone transport (not generally well represented in  
545 numerical models), plus it is not possible to evaluate the model's suitability under high energy  
546 conditions. Also, in practical terms, this work highlighted the heavy computational  
547 requirements of the type of simulations needed to adequately model seabed morphology  
548 beyond the short term. For consent applications, where longer term predictions may be  
549 required, the accuracy of three-dimensional modelling may need to be sacrificed in favour of  
550 computationally cheaper two-dimensional models (Fairley *et al.*, this issue).

551  
552 To study the effect of tidal stream energy extraction on sediment dynamics in the Pentland  
553 Firth, two commercial models were used. Delft3D with D-Morphology was used to study the  
554 morphodynamic sediment environment in the Inner Sound and its results showed that the  
555 currently observed sandbank dynamics are largely maintained by tidal flow asymmetries in  
556 magnitude and direction (Fairley *et al.*, this issue). MIKE3D was used to investigate the effect  
557 of tidal stream energy extraction on the sandbanks in the wider Pentland Firth (see Fig. 6 of  
558 Fairley *et al.*, 2015). An anti-clockwise persistent eddy around the eastern sandbank in the  
559 Inner Sound, with minimal transport over the crest, was shown in the baseline simulations  
560 and explained the persistence of the feature. Energy extraction resulted in the reduction of  
561 the eddy and the displacement of its centre, with a directional flow over the crest of the bank.  
562 The magnitude of these changes was similar to the simulated baseline temporal variability,  
563 suggesting that energy extraction in the Inner Sound may affect the sediment dynamics in  
564 these subtidal banks (Fairley *et al.*, this issue). However, considerable uncertainty remains.  
565 For example, the predicted natural variability in some other features such as a sandwave field  
566 to the west of Stroma is very high and, intuitively, inconsistent with their perceived  
567 permanency. At present, it is not possible to rule out model shortcomings, real sandwave  
568 variability or the combined effect of waves (not modelled here) and tide. Therefore, Fairley  
569 *et al.*, (this issue) concluded that, in some cases such as the persistent eddy-influenced  
570 sandbanks, a relatively data-light modelling approach, using default model settings, may be  
571 adequate to assess the impact of energy extraction. In other areas of mobile sediments like  
572 the sandwave fields, additional field data may be required to gain further confidence in the  
573 model results. Sediment transport modelling is computationally complex and expensive, and  
574 the acquisition of suitable field data is challenging and costly in these operationally and  
575 conceptually difficult environments. Therefore, it may be more realistic and efficient to focus  
576 detailed efforts on areas where high-risk receptors are present, using a more generic,  
577 pragmatic approach elsewhere, as illustrated by our work.

### 578 579 **3.4 Suspended particulate material modelling**

580  
581 Another example of a generic modelling approach to study the potential effects of wave and  
582 tidal energy extraction was presented by Heath *et al.* (this issue). A one-dimensional model

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

600

601

#### 602 **4 Regulatory framework and acceptability criteria for sustainable exploitation**

603

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

608

609 In Scottish waters, activities covered by the Marine (Scotland) Act 2010 with the potential to  
610 have a significant effect on the environment, local communities and other users need to  
611 undergo a pre-application consultation (Marine Scotland, 2015), to inform all potentially  
612 interested parties. MRE developments with a total area exceeding 10,000 m<sup>2</sup> fall within this  
613 category. Not all licensable projects require an EIA as part of their application. Whether an  
614 EIA must be undertaken for the provision of the Environmental Statement (ES) which reports  
615 the findings of the EIA is dependent on whether the project features within Annex I  
616 (mandatory EIA) or Annex II (EIA only necessary if the project exceeds certain limits or  
617 thresholds) of the European Commission EIA Directive. MRE projects are likely to fall within  
618 Annex II and the decision about EIA requirement will be made during the “EIA Screening”  
619 stage (Marine Scotland, 2015). However, a statutory EIA is generally required. The next stage  
620 in the process is termed “EIA Scoping” and involves preparing a preliminary analysis of impact  
621 (Scoping Report) based on existing information, allowing the opportunity to identify any  
622 issues that need further exploration or inclusion in the EIA. This occurs through formal  
623 response to the Scoping Report from the consenting authority. These preliminary steps  
624 define the structure and scope of the EIA and its reporting document, the ES. The EIA must  
625 (BSI, 2015) i) describe the project; ii) outline the main alternative methods (e.g. pile  
626 foundation types, construction methodologies, etc.) and the reasons for choosing any given  
627 one; iii) describe in detail the environmental (physical, biological and human) baseline  
628 regarding any aspects that could potentially be affected and the methodology used to  
629 characterise it; and iv) present any mitigation measures that will be put in place to prevent,

630 reduce and offset adverse environmental effects, and how these will be monitored. Once the  
631 impact pathways and receptor sensitivities have been established, receptor vulnerability is  
632 evaluated. Both beneficial and adverse impacts are assessed on a scale of negligible to major.  
633 Moderate or major adverse impacts require some form of impact reduction or mitigation  
634 measure. EIA regulations specify that cumulative effects need to be accounted for within an  
635 EIA. Guidance on the assessment of cumulative effects is available on EC (2001).

636  
637 If a proposed development has the potential to have a significant impact on a Natura site, an  
638 HRA needs to be carried out. This is a consenting procedure that states that the competent  
639 authority (normally the licensing/consenting authority) needs to carry out an Appropriate  
640 Assessment (AA) of the plan or project. The AA needs to address whether the integrity of the  
641 Natura site is likely to be adversely affected, considering closely the nature conservation  
642 objectives of the site, based on, and supported by, evidence that is capable of standing up to  
643 scientific scrutiny.

644  
645 On a broader scale, under the MSFD, EU Member States are required to undertake an  
646 initial assessment of the state of their seas (Article 8), determine a set of characteristics for  
647 GES (Article 9), and establish relevant targets (Article 10), based on the 11 descriptors set out  
648 in Annex I, the elements set out in Annex III (characteristics, pressures and impacts), and a  
649 series of relevant Descriptors defined in the Commission Decision on criteria and  
650 methodological standards for Good Environmental Status (EC, 2010). Regarding D7, changes  
651 in the tidal regime, sediment transport, currents and wave action are explicitly mentioned.

652  
653 The reporting scale for MSFD does not apply to small scale, near-field effects (although those  
654 may fall under other environmental legislation, as discussed above) but rather those that may  
655 “affect marine ecosystems at a broader scale” (EC, 2010). Two D7 criteria are defined: 7.1,  
656 spatial characterisation of permanent alterations; and 7.2, impact of permanent  
657 hydrographical changes, with their respective indicators (7.1.1: Extent of area affected by  
658 permanent alterations; 7.2.1: Spatial extent of habitats affected by the permanent alteration;  
659 7.2.2: Changes in habitats, in particular the functions provided, due to altered hydrographical  
660 conditions). At the time of writing, no standard methodology has been defined for  
661 assessment of GES for this Descriptor. Due to the nature of this descriptor and its current  
662 state of development, D7 is not a quantitative descriptor at present and it is not possible to  
663 define objective thresholds for its GES indicators.

664  
665 A review of the Commission Decision for D7 (Stolk *et al.*, 2015), recommended the use of  
666 models to quantify the effects from permanent alterations to the hydrographic regime.  
667 Modelling, applying a common methodology, should be used to reduce uncertainties in the  
668 assessment of impacts. In order to understand the effect of D7-related impacts on other  
669 descriptors such as D1 (“Biodiversity is maintained”) and D6 (“The sea floor integrity ensures  
670 functioning of the ecosystem”), as well, additional research is needed on habitat modelling,  
671 pressure mapping and cumulative impacts, along with monitoring of potentially affected  
672 areas (Stolk *et al.*, 2015). Models used within methodologies such as EIA, SEA, HRA and  
673 marine spatial planning will contribute to evaluating and assessing the extent and the  
674 cumulative aspects of impacts from MRE activities. The quantitative assessment of indirect,  
675 combined and cumulative effects would still benefit from the development of suitable  
676 quantitative methods and tools, which would be the next logical step from the work



677 presented here, although some advances have already been made (e.g. the TRaC-MImAS tool  
678 assessing potential hydromorphological alterations in WFD “transitional and coastal  
679 (TraC)”waters; UKTAG (2013). See Appendix A).

680

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

692

693 Current experience indicates that establishing compliance with the need to protect Natura  
694 2000 sites is the key environmental element in determining whether licences/consent for  
695 development should be granted. It is clear that changes to the hydrodynamic environment  
696 from the current scale of development of MRE projects and those conceivable over the next  
697 few years (such as the scenarios considered in the *Terawatt* project) should be measurable.  
698 However, it is unlikely that they will be sufficient to cause projects to be rejected through  
699 failure to meet WFD requirements (see Appendix A), or to lead to permanent hydrographic  
700 changes of a magnitude that would cause failure to attain GES under Descriptor 7 of the  
701 MSFD. It is much less clear whether we can be confident that this scale of development does  
702 not have the potential to adversely affect the integrity of Natura 2000 sites. We have  
703 demonstrated that changes in the tidal current speeds resulting from MRE developments are  
704 sufficient to cause alterations to sediment dynamics in some locations. Impact assessments,  
705 therefore, will need to take account of the potential for impacts on protected sites that rely  
706 on sediment characteristics. These include sites such as designated sandbanks, or sites  
707 designated for the protection of benthic species with particular substrate requirements.

708

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

717

718 We can predict that there will be a continuing and intensifying need for specific quantitative  
719 information on the individual and cumulative effects of MRE developments on the physical  
720 and biological aspects of the marine environment. The EIA and, where appropriate, HRA  
721 processes that underpin the planning and legislative framework will remain reliant on best  
722 current science, together with qualitative judgement and expert opinion. We believe that

723 work such as that presented here makes a critical contribution to filling the existing gaps and  
724 reducing the uncertainties in impact assessments.

725

726

## 727 **5 Conclusions, further work and recommendations**

728

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

731

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

737

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

753

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

763

764 The model results showed localised sea bed effects at the level of the proposed MRE  
765 developments in the PFOW area, with large-scale effects on water column characteristics  
766 such as the turbidity field unlikely. Tidal stream developments decreased velocities in line  
767 with the arrays and increased velocities to either side, as flow is diverted, more noticeably in  
768 sites where the flow is particularly constrained by coastline. Sea bed dynamics (e.g. sand  
769 banks and sand wave fields) in the Pentland Firth are maintained by the characteristics of the

770 flow. The results of simulations with energy extraction suggested that hydrological changes  
771 may affect the sediment dynamics of these subtidal features, although observed differences  
772 between the models demonstrate the importance of model validation with field data in order  
773 to achieve the level of accuracy required for array positioning for commercially viable and  
774 sustainable exploitation. The extraction of wave energy by arrays of WECs also suggested  
775 localised effects behind the developments but reduced with increased distance. Tentative  
776 results (pending further validation) at specific sites (e.g. Bay of Skail) suggest potential  
777 localised effects on coastal morphology that require further investigation. A  
778 recommendation from sediment modelling was to focus this computationally-intensive and  
779 potentially expensive (in terms of difficulty and cost of field data acquisition) work on areas  
780 where high-risk receptors are identified, applying a more generic approach elsewhere.

781  
782 In the current absence of quantitative targets, the achievement of Good Environmental Status  
783 in European waters regarding the more directly relevant Descriptors to MRE developments  
784 (D6, D11 and, in particular, D7) is currently heavily reliant on the adequacy of the marine  
785 planning and EIA (including HRA, where appropriate) framework. To that effect, large scale  
786 three-dimensional modelling is critical for being able to understand and quantify the direct,  
787 indirect and cumulative effects of MRE extraction. We are confident that the methodologies  
788 presented here and future work incorporating other environmental (e.g. climate change)  
789 factors and the downstream effect of physical changes on the marine ecosystem will make a  
790 critical contribution to this process.

791

792

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794

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799 assessment presented in Appendix A.

800

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

988

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

994

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

999

1000 In this exercise, two TRaC-MImAS assessments were carried out for the water-bodies covering  
1001 the Pentland Firth: one for the water-body named "Dunnet Head to Duncansby Head"  
1002 (including the Ness of Duncansby and Inner Sound proposed developments, as shown in Fig.  
1003 1 of O’Hara Murray and Gallego (this issue)) and another for the water body "Old Head to Tor  
1004 Ness" (including the Brough Ness and Brims developments). These water-bodies contained  
1005 500 and 300 devices respectively.

1006

1007 The assessment would be initially conducted at a small scale (Stage 1) over an area of 0.5 km<sup>2</sup>.  
1008 This would involve plotting out the assessment area, calculating intertidal and subtidal areas  
1009 and building a baseline of existing modifications to the area in question. Any modification,  
1010 such as piers and shoreline reinforcement, must be included. Due to the size of the tidal arrays  
1011 under consideration, this stage was not applicable and a full water-body assessment was  
1012 conducted (Stage 2). This involves building a baseline at the whole water-body scale.

1013

1014 The intertidal area is plotted and that total is removed from the total water-body area to  
1015 provide the subtidal value. All existing structures are mapped and added to the assessment  
1016 baseline. These are categorised under various types of obstructions or modifications. In most  
1017 cases a simple area is calculated for structures but in more complex scenarios footprint rules  
1018 are used. Once the baseline has been calculated the new project is then added and any  
1019 change in the water-body status is recorded. The tool presents changes as a deterioration  
1020 from the baseline status through categories that range from High, through Good, Moderate,  
1021 Poor and Bad. Any change in category would provide an indication to the regulator that a  
1022 given project should be reviewed further and, if necessary, expert guidance should be  
1023 requested.

1024

1025 For both assessments conducted in this exercise, a footprint rule was required to provide an  
1026 area for the tidal devices. This footprint was based on the spacing between devices. The  
1027 devices here were aligned in rows, but each row was sufficiently spaced from each other that  
1028 overlap was not a factor. A perimeter was drawn around the devices using the spacing  
1029 between each device (45 m) as a guide. It is acknowledged in the TRaC-MImAS technical  
1030 guidance that this footprint overestimates the actual footprint in order to include the  
1031 downcurrent effects of the devices.



1032

1033 In the Dunnet Head to Duncansby Head assessment, 500 devices were placed in 52 rows with  
1034 three individual devices each. The total footprint for these devices was 2.24 km<sup>2</sup>. The total  
1035 subtidal area for the water-body was 175.85 km<sup>2</sup>. The footprint would be 1.2% of the subtidal  
1036 area. This was input to the tool under the category "Tidal Devices (high impact)". This addition  
1037 did not cause the capacity to degrade into a new classification. In a real scenario, the ensuing  
1038 advice to the regulator would be that there would be no objection to this project.

1039

1040 In the Old Head to Tor Ness assessment, 300 devices were placed in 71 rows. Following the  
1041 above footprint rules, the footprint for these devices was 1.5 km<sup>2</sup>. The total subtidal area for  
1042 the water-body was 195.10 km<sup>2</sup>. The footprint would be 0.7% of the subtidal area. As above,  
1043 this was input to the tool under the category "Tidal Devices (high impact)". The addition did  
1044 not cause the capacity to degrade into a new classification. As with the previous assessment,  
1045 this did not result in a change in capacity category and the same advice would be provided to  
1046 the regulator.

1047

1048 Both scenarios were applied in relatively unmodified water-bodies (High status). Several piers  
1049 and jetties were present along the coastline but no major modification has taken place in  
1050 these areas. A High classification water body degrades to a Good classification at 5% capacity,  
1051 which was quite far from the assessed impact of these developments. However, although the  
1052 assessments indicated that no degradation would take place, it should be noted that the  
1053 TRaC-MImAS tool has not been tested thoroughly for tidal devices and, in this situation,  
1054 expert advice would still be sought and appropriate Environmental Impact Assessments based  
1055 on measurements and the type of modelling carried out in this project would be required in  
1056 support of licence applications.

1057

1058 In addition, TRaC-MImAS is not designed to assess the effect of floating devices. This means  
1059 that projects such as marine farms, some pontoons and, crucially, floating WECs could not be  
1060 assessed with this tool. An assessment could still be conducted using the same footprint rules  
1061 as for tidal devices but any decisions would be deferred to expert advice.