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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
40 as 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
44 energy and a few emerging technologies such as salinity gradient and thermal energy
45 conversion. The latter have been piloted already (in some cases, for quite some time) but

46 their current technology readiness level (see review by Magagna and Uihlein, 2015) suggests
47 that they are 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
66 tidal 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
72 deployment, although they show promise, particularly in areas where the resource is most
73 abundant, such as parts of the coastal waters west and north of Scotland (The Scottish
74 Government, 2013).

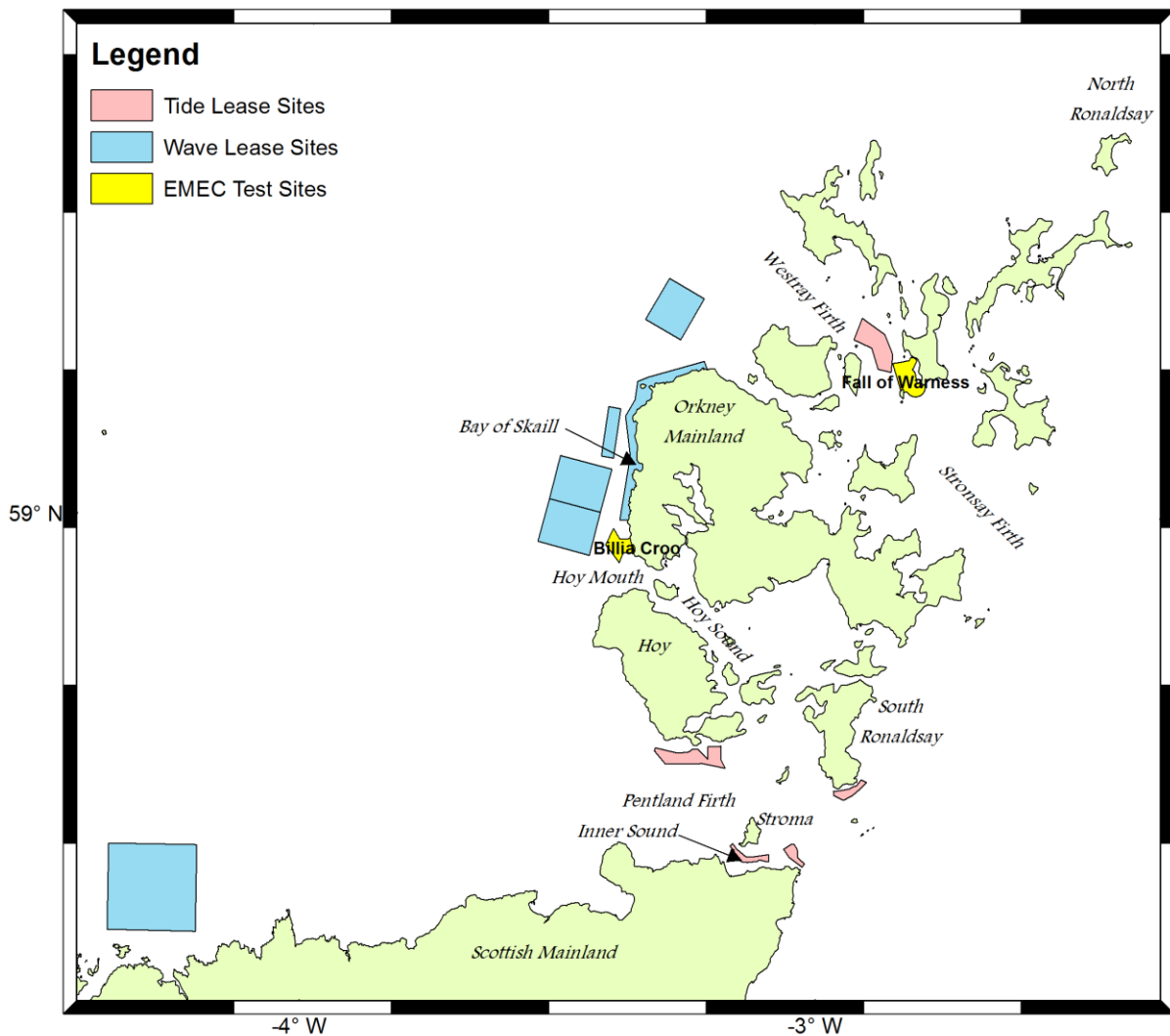
75
76 Wave energy converters (WECs), in contrast to TECs, are diverse in design, although they all
77 share the same source of energy to generate power: the combined wind seas and ocean-
78 swells as they approach coastal areas, where their potential for exploitation is currently
79 concentrated (for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

83
84

85 **1.2 Study area**

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

93 side. The Inner Sound, south of the Island of Stroma in the Pentland Firth, is somewhat
 94 shallower (ca. 35 m). The M_2 tide that propagates clockwise around the British Isles results
 95 in an approximately 2 h phase difference between the west and east ends of the Pentland
 96 Firth and sets up a hydraulic gradient that generates strong tidal currents which can reach 5
 97 $m\ s^{-1}$. Tidal currents are also forced around headlands and through other channels within
 98 the Orkney Islands, where spring flows can exceed $3.5\ m\ s^{-1}$. The amount of extractable
 99 tidal stream power in the area has been the subject of a number of studies with wide-
 100 ranging estimates. For the Pentland Firth, the higher limit has been estimated as 4.2 GW
 101 averaged over the spring-neap cycle (Draper *et al.*, 2014) but more recent work reports a
 102 more realistic scenario of around 1.5 GW (O'Hara Murray and Gallego, submitted).
 103



104
 105 Figure 1: Map showing the Pentland Firth and Orkney Waters area and the location of the
 106 wave and tidal stream MRE development sites considered in the project.
 107

108 The wave regime in PFOW is dominated by Atlantic swells and the influence of low pressure
 109 systems that travel primarily from west to east across the North Atlantic. Therefore, wave
 110 conditions are most severe in the exposed coastal areas to the west. The seasonal range of
 111 average wave resource in the area has been estimated between <10 (summer) and 50 kW
 112 (winter, top range of the estimate) (Neill *et al.*, 2014).
 113

114 The PFOW area is rich in geological features, coastal landscapes and seascapes that
115 collectively support diverse habitats and species, many of which are considered rare and/or
116 vulnerable. There are four designated Special Areas of Conservation (SAC; European Union
117 designation) in Orkney and three SACs on the adjacent north coast of the Scottish mainland,
118 for the protection of marine and coastal habitats. Another 29 sites (some with marine
119 elements) have been designed as Sites of Special Scientific Interest (SSSI; national
120 designation) and three nature conservation Marine Protected Areas (MPA) were formally
121 designated in the area in 2014 (Pilot Pentland Firth and Orkney Waters Working Group,
122 2016).

123

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

146

147 **1.3 Legislative framework**

148

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

162 seabed within the UK 12 nm limit and the rights to non-fossil-fuel natural resources on the
163 UK continental shelf.

164

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

175

176 The Marine Strategy Framework Directive (MSFD; EC (2008)) is the piece of European
177 legislation which establishes a common framework and objectives for the prevention,
178 protection and conservation of the marine environment against damaging human activities
179 beyond the spatial domain of the WFD. EU countries must assess the environmental status
180 of their marine waters and set environmental targets, develop monitoring networks,
181 prepare programmes of measures and set specific objectives towards reaching a “Good
182 Environmental Status (GES)” by 2020. The MSFD sets out, in its Annex I, eleven qualitative
183 Descriptors of GES. The main Descriptors that may be directly impacted by MRE
184 developments are D6 (“The sea floor integrity ensures functioning of the ecosystem”), D11
185 (“Introduction of energy (including underwater noise) does not adversely affect the
186 ecosystem”) and, in particular, D7 (“Permanent alteration of hydrographical conditions does
187 not adversely affect the ecosystem”). Hydrographical conditions play a critical role in the
188 dynamics of marine ecosystems, particularly in coastal areas, and can be altered by human
189 activities. One of the main pressures on D7 explicitly identified refers to MRE installations
190 ([http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-](http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-7/index_en.htm)
191 [7/index_en.htm](http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-7/index_en.htm)).

192

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

209

210 The potential impact of wave or tidal stream Marine Energy Converters (MECs) has been
211 discussed in the scientific literature. Pelc and Fujita (2002) considered wave devices to be
212 relatively environmentally benign and tidal stream turbines to be the most environmentally
213 friendly tidal power option. A review of the ecological impact of MRE (Gill, 2005) showed
214 that, despite a growth in publications on renewable energy, only a fraction at the time (<1%;
215 none on coastal ecology) considered its potential environmental risks. Theoretical risks of
216 the extensive subsurface structures introduced by MRE into the coastal environment
217 outlined by Gill (2005) identified changes to water circulation and to the transport and
218 deposition of sediment, noise and vibration during the construction and operational phases,
219 changes to the electrical and electromagnetic fields, and degradation and/or removal of
220 habitats. Gill (2005) also warned against an undue focus on rare species of high intrinsic
221 appeal to the detriment of impacts on the ecosystem structure, processes and key
222 functional species. The effects of near- and far-field changes to the flow and wave fields,
223 and sedimentation patterns have been identified by subsequent publications (e.g. Shields *et al.*,
224 2011) including specifically in the Pentland Firth area (Shields *et al.*, 2009). These effects
225 are not just negative: a number of potentially beneficial effects has also been proposed
226 (Inger *et al.*, 2009), such as the creation of artificial reefs, *de-facto* marine protected areas
227 and fish aggregation devices. Interactions between positive and negative effects, as well as
228 cumulative effects (Inger *et al.*, 2009) requiring a different scale of management actions
229 (Boehlert and Gill, 2010). Shields *et al.* (2011) identified the PFOW area as a particular case
230 study to provide essential industry standards and environmental guidelines of worldwide
231 applicability. However, because of the relative lack of empirical data on how marine
232 habitats and wildlife will interact with wave and tidal stream MECs and their distinct nature
233 relative to other forms of marine developments, understanding their potential
234 environmental impact is particularly challenging and important. Smaller-scale demonstrator
235 devices have been studied in depth but there is a clear need to monitor carefully the
236 quantitative and qualitative nature of the effects of early commercial-scale developments
237 against the natural baseline. Environmental impact assessment procedures are covered by
238 European legislation such as Directives 2011/92/EU (the “Environmental Impact
239 Assessment, EIA” Directive) and 2001/42/EC (the “Strategic Environmental Assessment,
240 SEA” Directive) and their relevant national transposition (in Scotland, the Environmental
241 Assessment (Scotland) Act 2005), to ensure that the potential environmental implications
242 are taken into account before plans and projects are formally adopted and
243 licences/consents are granted. Where a project has the potential to have a significant effect
244 on a Natura site, a Habitats Regulation Appraisal (HRA) is required under the Habitats
245 Directive. This process progresses from qualitative assessment to a more detailed
246 Appropriate Assessment (AA). Projects can only be consented if the AA concludes that the
247 development will not affect the integrity of the relevant protected (Natura 2000) sites.

248

249 This paper summarises the output of a collaborative modelling project (the TeraWatt
250 project; Side *et al.* (this issue)). In the absence of comprehensive observational data,
251 modelling projects like the present one are fundamental to estimate the potential effects of
252 MRE developments on the physical environment and, consequently, on the marine
253 ecosystem. This paper draws on the project outputs and presents potential methodologies
254 for quantifying acceptable thresholds for sustainable MRE exploitation within the context of
255 the existing planning, regulatory and environmental legislative framework. In the following

256 sections, we describe the modelling methodologies to represent the hydrodynamics and the
257 implementation of energy extraction, and their effect on the physical environment, followed
258 by a description of the regulatory framework in Scotland and a discussion on the
259 acceptability criteria for sustainable exploitation.

260

261

262 **2 Modelling methodologies: hydrodynamics and energy extraction**

263

264 **2.1 Data**

265

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

272

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

278

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

286

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

294

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

299

300 Tidal boundary forcing used the output of the barotropic Oregon State University Tidal
301 Prediction Software (OTPS; Egbert *et al.*, 2010) and the DHI Global Tidal Model Database
302 (Cheng and Andersen, 2010). Wind forcing data for waves modelling were obtained from

303 the European Centre for Medium Range Weather Forecast (ECMWF) ERA-40 re-analysis
304 dataset.

305
306

307 **2.2 Numerical models – flow**

308

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

316

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

330

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

344

345 The two flow models predicted very similar relative changes in all parameters of interest
346 over their spatial domain. Depth-averaged current speeds showed very similar absolute
347 values but both models had been calibrated against this variable. This was achieved by
348 using different values for bed resistance (Waldman *et al.*, this issue). Bed resistance is often
349 used as a tuning parameter and is therefore not necessarily representative of the actual

350 seabed resistance. It also influences the modelled vertical velocity profiles and,
351 consequently, parameters of relevance to sediment transport and ecological processes such
352 as bottom velocity and near-bed stress. However, in our study, relative changes (spatially
353 and as a result of energy extraction) in these variables are more important than absolute
354 values (Waldman *et al.*, this issue), so the relative similarities between the two flow models
355 are reassuring.

356
357

358 **2.3 Numerical models – waves**

359

360 We used MIKE21 SW for wave modelling. This is an unstructured grid, finite volume,
361 spectral wind-wave model that simulates the growth, decay and transformation of wind-
362 generated waves and swell. The model offers two alternative formulations: fully spectral or
363 a directional decoupled parametric formulation. The fully spectral version incorporates
364 wave growth due to wind effects, non-linear wave-wave interactions, dissipation due to
365 bottom friction, white-capping and wave breaking, effect of time-varying depth and
366 bathymetric effects on wave refraction and shoaling, and wave-current interactions. The
367 model domain used in this project spanned the whole of the North Atlantic (Venugopal and
368 Nimalidinne, 2015). The model resolution was coarser in the open North Atlantic (element
369 area approx. 2.5 km²) and finer in the Pentland Firth and Orkney waters, and in the Hebrides
370 and northwest Scotland (approx. 1700 m²). The detailed model setup is described in
371 Venugopal and Nimalidinne (2015) and Venugopal *et al.* (this issue). The model was
372 calibrated for significant wave height, peak wave period and peak wave direction against
373 four Waverider data locations from the WaveNet network and the Isle of Lewis Waverider
374 dataset, and successfully validated against three 2010 datasets, as described by Venugopal
375 *et al.* (this issue).

376

377 **2.4 Simulating tidal stream MECs**

378

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

397

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

406

407 Based on licence application documentation, two types of tidal stream turbines were
408 considered: i) a 1 MW single axis turbine with a 20 m diameter rotor; and ii) a 2 MW device
409 with two horizontal axis turbines with 20 m diameter rotors and a hub-to-hub spacing of 30
410 m. Their layout within an array assumed a constant across- and downstream spacing,
411 aligned to the main direction of the flow and with staggered (offset) rows which takes
412 advantage of the expected flow acceleration around individual devices (e.g. see Rao *et al.*,
413 2016). Individual devices were also located within each general area on the basis of a)
414 number of devices as a function of the licensed total capacity of each development; b) main
415 current direction; c) distribution of the tidal resource within the development area; and d)
416 water depth (≥ 27.5 m below mean sea level, to ensure that the turbine blades would be
417 constantly submerged). O'Hara Murray and Gallego (this issue) provide greater detail of the
418 array design process and present the final layout of the hypothetical arrays in the licensed
419 sites used in the energy extraction simulations.

420

421

422 **2.5 Simulating wave MECs**

423

424 In the case of WEC arrays, there were fewer constraints on where many of the types of
425 devices could be placed so the general principle was to space out individual devices to
426 occupy the whole of the licensed areas, giving consideration to the necessary operational
427 depths for each device type. Four out of six wave development project sites within the
428 PFOW stated that they intended to use the wave attenuator device. The number and
429 spacing of attenuators in staggered rows was based on information provided by developers
430 in their licence applications, the intended electricity generating capacity of each site and any
431 spatial constraints. The one development planning to use point absorber devices required a
432 550 m (cross-stream) and 600 m (downstream) staggered design over the full development
433 site, while the oscillating wave surge converters planned for one development were spaced
434 by 45 m (71 m centre-to-centre, as they are 26 m wide), which is within the spacing window
435 reported in the licensing documentation. The appropriate number to achieve the intended
436 energy generating capacity was spaced out along the 12.5 m depth contour, which is within
437 their operational target depth range of 10-15 m. See O'Hara Murray and Gallego (this issue)
438 for full details.

439

440 Tidal stream arrays were implemented in the MIKE3 model of the study area (Waldman *et al.*
441 *et al.*, this issue) using the "Turbine" facility within the software, parameterising the device as
442 a sub-grid scale process using an actuator disk model with a user-defined thrust coefficient
443 (Baston *et al.*, 2015). Turbine parameters and locations, as defined above, were input into

444 the model while supporting structures (2.5 m diameter cylindrical monopiles between the
445 seabed and hub height) were also represented using the built-in “Pier” facility. There was
446 no equivalent facility to model turbines in Delft3D and we were advised against customising
447 the standard software, e.g. to parameterise the devices as momentum sinks, so tidal stream
448 turbines were parameterised within the standard code as porous plates. Waldman *et al.*
449 (this issue) detail how this was implemented in the model and the limitations of the
450 approach in terms of e.g. vertical positioning, constant thrust coefficient and fixed
451 orientation.

452

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

465

466

467 **3 Modelling methodologies: physical environmental effects**

468

469 **3.1 Tidal stream modelling**

470

471 Both MIKE3 and Delft3D produced similar results on the effect of tidal stream arrays on
472 depth-averaged current speeds, showing decreased velocities in tidal streams in line with
473 the arrays and increased velocities to either side, as flow is partly diverted around the array
474 (Waldman *et al.*, this issue). These effects were particularly evident in the Inner Sound
475 development, where the flow is constrained by coastline on both sides (Fig. 4 of O’Hara
476 Murray and Gallego, this issue) and the turbines occupy a high proportion of the total water
477 depth. The relative effects of tidal energy extraction on bed stress were similar between
478 the two models. The results showed decreases of bed stress of 45% and increases of up to
479 100% in some areas (Waldman *et al.*, this issue). However, some spatial differences
480 between the models were observed. These are believed to be the effect of differences in
481 the computational grid, which result in small differences in the exact locations of simulated
482 eddies which may affect individual devices in slightly different ways (Waldman *et al.*, this
483 issue).

484

485 At the time this work was carried out, MIKE3 provided a superior capability to represent the
486 type of tidal stream device under consideration, as the limitations of the approach
487 implemented in Delft3D resulted in a constant thrust coefficient, fixed orientation and
488 spatially variable vertical position of the devices (Waldman *et al.*, this issue). An error in the
489 calculation of turbine thrust in a high resolution model, of the type identified by Kramer *et*

490 *al.* (2014), was noted and a correction implemented (Waldman *et al.*, 2015). A similar
491 correction has been incorporated into the latest version of MIKE.

492

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

507

508

509 **3.2 Waves modelling**

510

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

527

528 **3.3 Seabed sediment modelling**

529

530 Fairley *et al.* (this issue) simulated the effect of MRE extraction on sediment processes
531 (bedload sediment transport and morphological change) in two case study areas within the
532 area of interest: the largest beach on the west coast of Mainland Orkney (the Bay of Skail)
533 and the Inner Sound of the Pentland Firth. The Bay of Skail is close to proposed wave
534 developments (Brough Head, West Orkney and Marwick Head). The Brough Head
535 development site includes the Bay of Skail within the area but the indicative device layout
536 available to us shows the nearest WEC devices > 1 km from the bay. There is a proposed

537 development in the Inner Sound which, being constrained by Stroma and the Scottish
538 Mainland and using the criteria applied by O'Hara Murray and Gallego (this issue), would
539 occupy a significant proportion of the channel.

540

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

563

564 To study the effect of tidal stream energy extraction on sediment dynamics in the Pentland
565 Firth, two commercial models were used. Delft3D with D-Morphology was used to study
566 the morphodynamic sediment environment in the Inner Sound and its results showed that
567 the currently observed sandbank dynamics are largely maintained by tidal flow asymmetries
568 in magnitude and direction (Fairley *et al.*, this issue). MIKE3D was used to investigate the
569 effect of tidal stream energy extraction on the sandbanks in the wider Pentland Firth (see
570 Fig. 6 of Fairley *et al.*, 2015). An anti-clockwise persistent eddy around the eastern
571 sandbank in the Inner Sound, with minimal transport over the crest, was shown in the
572 baseline simulations and explained the persistence of the feature. Energy extraction
573 resulted in the reduction of the eddy and the displacement of its centre, with a directional
574 flow over the crest of the bank. The magnitude of these changes was similar to the
575 simulated baseline temporal variability, suggesting that energy extraction in the Inner Sound
576 may affect the sediment dynamics in these subtidal banks (Fairley *et al.*, this issue).
577 However, considerable uncertainty remains. For example, the predicted natural variability
578 in some other features such as a sandwave field to the west of Stroma is very high and,
579 intuitively, inconsistent with their perceived permanency. At present, it is not possible to
580 rule out model shortcomings, real sandwave variability or the combined effect of waves (not
581 modelled here) and tide. Therefore, Fairley *et al.*, (this issue) concluded that, in some cases
582 such as the persistent eddy-influenced sandbanks, a relatively data-light modelling
583 approach, using default model settings, may be adequate to assess the impact of energy

584 extraction. In other areas of mobile sediments like the sandwave fields, additional field data
585 may be required to gain further confidence in the model results. Sediment transport
586 modelling is computationally complex and expensive, and the acquisition of suitable field
587 data is challenging and costly in these operationally and conceptually difficult environments.
588 Therefore, it may be more realistic and efficient to focus detailed efforts on areas where
589 high-risk receptors are present, using a more generic, pragmatic approach elsewhere, as
590 illustrated by our work.

591

592 **3.4 Suspended particulate material modelling**

593

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

613

614

615 **4 Regulatory framework and acceptability criteria for sustainable exploitation**

616

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

622

623 In Scottish waters, activities covered by the Marine (Scotland) Act 2010 with the potential to
624 have a significant effect on the environment, local communities and other users need to
625 undergo a pre-application consultation (Marine Scotland, 2015), to inform all potentially
626 interested parties. MRE developments with a total area exceeding 10,000 m² fall within this
627 category. Not all licensable projects require an EIA as part of their application. Whether an
628 EIA must be undertaken for the provision of the Environmental Statement (ES) which
629 reports the findings of the EIA is dependent on whether the project features within Annex I
630 (mandatory EIA) or Annex II (EIA only necessary if the project exceeds certain limits or

631 thresholds) of the European Commission EIA Directive. MRE projects are likely to fall within
632 Annex II and the decision about EIA requirement will be made during the “EIA Screening”
633 stage (Marine Scotland, 2015). However, a statutory EIA is generally required. The next
634 stage in the process is termed “EIA Scoping” and involves preparing a preliminary analysis of
635 impact (Scoping Report) based on existing information, allowing the opportunity to identify
636 any issues that need further exploration or inclusion in the EIA. This occurs through formal
637 response to the Scoping Report from the consenting authority. These preliminary steps
638 define the structure and scope of the EIA and its reporting document, the ES. The EIA must
639 (BSI, 2015) i) describe the project; ii) outline the main alternative methods (e.g. pile
640 foundation types, construction methodologies, etc.) and the reasons for choosing any given
641 one; iii) describe in detail the environmental (physical, biological and human) baseline
642 regarding any aspects that could potentially be affected and the methodology used to
643 characterise it; and iv) present any mitigation measures that will be put in place to prevent,
644 reduce and offset adverse environmental effects, and how these will be monitored. Once
645 the impact pathways and receptor sensitivities have been established, receptor vulnerability
646 is evaluated. Both beneficial and adverse impacts are assessed on a scale of negligible to
647 major. Moderate or major adverse impacts require some form of impact reduction or
648 mitigation measure. EIA regulations specify that cumulative effects need to be accounted
649 for within an EIA. Guidance on the assessment of cumulative effects is available on EC
650 (2001).

651
652 If a proposed development has the potential to have a significant impact on a Natura site,
653 an HRA needs to be carried out. This is a consenting procedure that states that the
654 competent authority (normally the licensing/consenting authority) needs to carry out an
655 Appropriate Assessment (AA) of the plan or project. The AA needs to address whether the
656 integrity of the Natura site is likely to be adversely affected, considering closely the nature
657 conservation objectives of the site, based on, and supported by, evidence that is capable of
658 standing up to scientific scrutiny.

659
660 On a broader scale, under the MSFD, EU Member States are required to undertake an
661 initial assessment of the state of their seas (Article 8), determine a set of characteristics for
662 GES (Article 9), and establish relevant targets (Article 10), based on the 11 descriptors set
663 out in Annex I, the elements set out in Annex III (characteristics, pressures and impacts), and
664 a series of relevant Descriptors defined in the Commission Decision on criteria and
665 methodological standards for Good Environmental Status (EC, 2010). Regarding D7,
666 changes in the tidal regime, sediment transport, currents and wave action are explicitly
667 mentioned.

668
669 The reporting scale for MSFD does not apply to small scale, near-field effects (although
670 those may fall under other environmental legislation, as discussed above) but rather those
671 that may “affect marine ecosystems at a broader scale” (EC, 2010). Two D7 criteria are
672 defined: 7.1, spatial characterisation of permanent alterations; and 7.2, impact of
673 permanent hydrographical changes, with their respective indicators (7.1.1: Extent of area
674 affected by permanent alterations; 7.2.1: Spatial extent of habitats affected by the
675 permanent alteration; 7.2.2: Changes in habitats, in particular the functions provided, due
676 to altered hydrographical conditions). At the time of writing, no standard methodology has
677 been defined for assessment of GES for this Descriptor. Due to the nature of this descriptor

678 and its current state of development, D7 is not a quantitative descriptor at present and it is
679 not possible to define objective thresholds for its GES indicators.

680

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

696

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

708

709 Current experience indicates that establishing compliance with the need to protect Natura
710 2000 sites is the key environmental element in determining whether licences/consent for
711 development should be granted. It is clear that changes to the hydrodynamic environment
712 from the current scale of development of MRE projects and those conceivable over the next
713 few years (such as the scenarios considered in the *Terawatt* project) should be measurable.
714 However, it is unlikely that they will be sufficient to cause projects to be rejected through
715 failure to meet WFD requirements (see Appendix A), or to lead to permanent hydrographic
716 changes of a magnitude that would cause failure to attain GES under Descriptor 7 of the
717 MSFD. It is much less clear whether we can be confident that this scale of development
718 does not have the potential to adversely affect the integrity of Natura 2000 sites. We have
719 demonstrated that changes in the tidal current speeds resulting from MRE developments
720 are sufficient to cause alterations to sediment dynamics in some locations. Impact
721 assessments, therefore, will need to take account of the potential for impacts on protected
722 sites that rely on sediment characteristics. These include sites such as designated
723 sandbanks, or sites designated for the protection of benthic species with particular
724 substrate requirements.

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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, this issue) 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.

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

780

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

798

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

808

809

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811

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817

818

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1002

1003 **Appendix A:** *Example of an assessment of the potential hydromorphological alterations in*
1004 *WFD transitional and coastal waters of the Pentland Firth by TEC arrays using the TRaC-*
1005 *MImAS tool*

1006
1007 The Transitional and Coastal Water Morphological Impact Assessment System (TRaC-
1008 MImAS; UKTAG (2013)) was developed as a risk based regulatory decision-support tool.
1009 TRaC-MImAS is designed to help regulators determine whether new projects likely to alter
1010 hydromorphological features could risk the ecological objectives of the Water Framework
1011 Directive (WFD).

1012
1013 The tool uses a concept of capacity and assumes that new projects “consume” that capacity,
1014 causing a degradation of ecological conditions. The tool uses simplified area/footprints to
1015 measure the change in capacity for WFD water-bodies and provides a guide to regulators.
1016 Expert advice would always be sought for larger or more complex projects.

1017
1018 In this exercise, two TRaC-MImAS assessments were carried out for the water-bodies
1019 covering the Pentland Firth: one for the water-body named "Dunnet Head to Duncansby
1020 Head" (including the Ness of Duncansby and Inner Sound proposed developments, as shown
1021 in Fig. 1 of O’Hara Murray and Gallego (this issue)) and another for the water body "Old
1022 Head to Tor Ness" (including the Brough Ness and Brims developments). These water-
1023 bodies contained 500 and 300 devices respectively.

1024
1025 The assessment would be initially conducted at a small scale (Stage 1) over an area of 0.5
1026 km². This would involve plotting out the assessment area, calculating intertidal and subtidal
1027 areas and building a baseline of existing modifications to the area in question. Any
1028 modification, such as piers and shoreline reinforcement, must be included. Due to the size
1029 of the tidal arrays under consideration, this stage was not applicable and a full water-body
1030 assessment was conducted (Stage 2). This involves building a baseline at the whole water-
1031 body scale.

1032
1033 The intertidal area is plotted and that total is removed from the total water-body area to
1034 provide the subtidal value. All existing structures are mapped and added to the assessment
1035 baseline. These are categorised under various types of obstructions or modifications. In
1036 most cases a simple area is calculated for structures but in more complex scenarios
1037 footprint rules are used. Once the baseline has been calculated the new project is then
1038 added and any change in the water-body status is recorded. The tool presents changes as a
1039 deterioration from the baseline status through categories that range from High, through
1040 Good, Moderate, Poor and Bad. Any change in category would provide an indication to the
1041 regulator that a given project should be reviewed further and, if necessary, expert guidance
1042 should be requested.

1043
1044 For both assessments conducted in this exercise, a footprint rule was required to provide an
1045 area for the tidal devices. This footprint was based on the spacing between devices. The
1046 devices here were aligned in rows, but each row was sufficiently spaced from each other
1047 that overlap was not a factor. A perimeter was drawn around the devices using the spacing
1048 between each device (45 m) as a guide. It is acknowledged in the TRaC-MImAS technical

1049 guidance that this footprint overestimates the actual footprint in order to include the
1050 downcurrent effects of the devices.

1051

1052 In the Dunnet Head to Duncansby Head assessment, 500 devices were placed in 52 rows
1053 with three individual devices each. The total footprint for these devices was 2.24 km². The
1054 total subtidal area for the water-body was 175.85 km². The footprint would be 1.2% of the
1055 subtidal area. This was input to the tool under the category "Tidal Devices (high impact)".
1056 This addition did not cause the capacity to degrade into a new classification. In a real
1057 scenario, the ensuing advice to the regulator would be that there would be no objection to
1058 this project.

1059

1060 In the Old Head to Tor Ness assessment, 300 devices were placed in 71 rows. Following the
1061 above footprint rules, the footprint for these devices was 1.5 km². The total subtidal area
1062 for the water-body was 195.10 km². The footprint would be 0.7% of the subtidal area. As
1063 above, this was input to the tool under the category "Tidal Devices (high impact)". The
1064 addition did not cause the capacity to degrade into a new classification. As with the previous
1065 assessment, this did not result in a change in capacity category and the same advice would
1066 be provided to the regulator.

1067

1068 Both scenarios were applied in relatively unmodified water-bodies (High status). Several
1069 piers and jetties were present along the coastline but no major modification has taken place
1070 in these areas. A High classification water body degrades to a Good classification at 5%
1071 capacity, which was quite far from the assessed impact of these developments. However,
1072 although the assessments indicated that no degradation would take place, it should be
1073 noted that the TRaC-MImAS tool has not been tested thoroughly for tidal devices and, in
1074 this situation, expert advice would still be sought and appropriate Environmental Impact
1075 Assessments based on measurements and the type of modelling carried out in this project
1076 would be required in support of licence applications.

1077

1078 In addition, TRaC-MImAS is not designed to assess the effect of floating devices. This means
1079 that projects such as marine farms, some pontoons and, crucially, floating WECs could not
1080 be assessed with this tool. An assessment could still be conducted using the same footprint
1081 rules as for tidal devices but any decisions would be deferred to expert advice.