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1 **CHALLENGES AND OPPORTUNITIES IN MONITORING THE IMPACTS OF**
2 **TIDAL-STREAM ENERGY DEVICES ON MARINE VERTEBRATES**

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9 **ABSTRACT**

10 Marine tidal-stream renewable energy devices (MREDs) are beginning to move from the
11 demonstration to early commercial deployment phase. However, the ecological impacts which
12 may result when large arrays of these devices are deployed are unknown. This uncertainty is
13 placing a considerable burden on developers who must collect biological data through baseline
14 and post-deployment monitoring programs under the Environmental Impact Assessment
15 process. Regulators and other stakeholders are often particularly concerned about impacts on
16 marine vertebrates (fish, seabirds and mammals) because many of these receptors are of high
17 conservation and public concern. Unfortunately monitoring for most marine vertebrates is
18 challenging and expensive, especially in the tidally-energetic waters where tidal-stream
19 MREDs will be deployed. Surveys for marine vertebrates often have low statistical power and
20 so are likely to fail to detect all but substantial changes in abundance. Furthermore, many
21 marine vertebrate species have large geographical ranges so that even if local changes in
22 abundance are detected, they cannot usually be related to the wider populations. Much of the
23 monitoring currently being undertaken at tidal-stream MRED development sites is thus leading
24 to a ‘data-rich but information-poor’ (DRIP) situation. Such an approach adds to development
25 costs whilst contributing little to wider ecosystem-based understanding. In the present article
26 we discuss the issues surrounding the impacts of tidal-stream MREDs on marine vertebrates in
27 order to address the questions regulators, developers and other stakeholders need to ask when
28 designing monitoring programs for these receptors.

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29 *Keywords:* Environmental Impact Assessment, Renewable energy, Strategic Environmental
30 Assessment, Tidal-stream power, Vertebrates.

31 *Abbreviations:*

32 CBD – (United Nations) Convention on Biodiversity

33 CI – Cumulative Impacts

34 DRIP – Data-rich, information-poor

35 EIA – Environmental Impact Assessment

36 EMF – Electromagnetic field

37 EMMP – Environmental Monitoring and Management Plan

38 ES – Environmental Statement

39 EU – European Union

40 MRE – Marine renewable energy

41 MRED – Marine renewable energy device

42 NGO – Non-governmental organisation

43 PCoD – Population Consequences of Disturbance

44 SDM – Survey, deploy and monitor

45 SEA – Strategic Environmental Assessment

46 **1. Introduction**

47 *1.1. The present state of marine tidal-stream energy extraction*

48 Marine renewable energy (MRE) has the potential to provide up to approximately 7% of global
49 electricity demand [1-3]. Whilst most of this potential comes from offshore wind, tidal-stream
50 energy could yield around 0.75% of global demand [4]. Extracting energy from tidal-streams
51 is attractive because the energy source is more predictable compared with offshore wind and
52 wave [4-6] but, on the other hand, there are fewer sites which are suitable for tidal-stream
53 MRE [4, 5].

54 A large number of designs of tidal-stream devices are presently in development
55 although they cluster into three main categories (i) horizontal axis turbines (ii) vertical axis
56 turbines and (iii) reciprocating devices (Fig. 1). To date axis-mounted systems have dominated
57 the industry. In contrast, oscillating devices extract energy using a reciprocal vertical motion
58 but, according to Rourke et al. [7], these designs are not as efficient as rotational devices. Most
59 tidal-stream MREs are mounted on frames placed on the seabed but hanging devices from
60 floating structures is also being trialled. The main environmental concerns are likely to be
61 broadly similar across devices and include physical disturbance, collision risk, hydrographic
62 modification and the production of noise and electromagnetic fields. It has generally been
63 concluded that pollution risks from such devices should be low since they only contain small
64 quantities of chemicals, such as lubricants and coolants. However, the impact of biofouling has
65 probably been underestimated and there is little information on the degree to which anti-fouling
66 coatings will have to be used to protect turbines, transformers and switch gear.

67 To date, test deployments of tidal-stream MREs have taken place at a number of sites
68 including the Pentland Firth, Strangford Lough and Ramsay Sound (UK), the Bay of Fundy
69 (Canada), Cobscook Bay, Maine (USA) and Raz Blanchard (France). Several companies are
70 currently developing commercial-scale projects but before consents are granted they will have
71 to satisfy regulators with regard to the likely environmental impacts. National environmental
72 legislation is often driven by high-level agreements, such as the 1992 UN Convention on
73 Biodiversity (CBD), which calls for sustainable development and provides a framework for
74 halting and reversing losses in biodiversity [8]. However, this raises the question of how
75 negative environmental impacts should be balanced against wider positive outcomes. For
76 example, the renewables industry and some researchers have argued that the local disruption

77 associated with projects needs to be offset against the wider global benefits of reducing
78 anthropogenic greenhouse gas emissions [9, 10]. Regulators on-the-other-hand usually take a
79 ‘precautionary approach’ and focus almost exclusively on the potential negative impacts [11].
80 Some stakeholders have therefore argued for a more risk-based approach as exemplified by the
81 Scottish Government’s ‘Survey, Deploy and Monitor’ (SDM) strategy [12]. However, the
82 SDM guidance was designed for initial, prototype-scale projects and may be less applicable as
83 developments scale-up [13]. Another alternative could be to adopt an adaptive management
84 strategy, taking advantage of lessons learned from a gradual increase in deployment [12,14].
85 Whichever approach is chosen the debates around balancing ‘local impacts’ against ‘global
86 benefits’ are heavily culturally contextualised and, despite international conventions such as
87 the CBD, specific outcomes tend to depend on the relative values that societies place on
88 ‘ecosystem’ versus ‘economic’ services at the local level [12,15-17]. The role of science is to
89 provide the data on, and analysis of, the potential impacts so that decisions are well-informed,
90 positive ecological benefits maximised and negative impacts minimised. Acceptable levels of
91 impact therefore need to be defined by regulators (with scientific input and wider stakeholder
92 consent) before new technologies, such as tidal-stream energy, enter the commercial “valley of
93 death” which is the critical period between technology demonstration and market pull to full
94 commercialisation [18]. Where such agreement is lacking, the large financial investments
95 needed to move from ‘demonstration’ to ‘commercial’ scale may be adversely affected [11,19-
96 21]. In a review of UK investors, Leete at al. [22] identified the predictability of regulations as
97 being critical. Although the investors quoted in Leete at al. [22] were referring mainly to
98 uncertainty around guaranteed pricing, further uncertainty and unpredictability in
99 environmental consenting is also likely to lead to reduced investor confidence as tidal-stream
100 MRE moves beyond the testing phase [14].

101 *1.2. Requirements for environmental impact assessments*

102 As in most other countries, developers in Europe are required to produce an
103 Environmental Statement (ES) based on an Environmental Impact Assessment (EIA) before
104 any project which might have significant impacts on the environment can commence [23]. The
105 production of the ES/EIA typically involves collecting physical, biological and socio-economic
106 data to establish baseline conditions, followed by consideration of the stressors the project will
107 generate and their likely impacts on sensitive receptors¹ [24]. Regulators in Europe also

¹Following Innovate UK [24] Innovate UK. Environmental impact assessment for offshore renewable energy projects - Guide. British Standards Institution; 2015. p. 64. we define “impact” as implicitly meaning the

108 generally require evidence of low impact across all stressors, or that unavoidable impacts are
109 suitably reduced, offset, or mitigated [25]. However, the whole EIA process has been criticised
110 as “quasi-scientific”, over-reliant on expert judgement, and its value in delivering effective
111 environmental protection has been questioned [12]. In relation to MREDs, concerns have been
112 raised that the process places an unnecessary burden on a nascent, environmentally-friendly
113 industry because the costs of producing EIA/ESs are normally borne by the developer [9-
114 11,18].

115 Assuming a licence to deploy is granted, post-deployment monitoring (via an
116 Environmental Management and Monitoring Plan (EMMP) is normally required, especially for
117 novel technologies where the ecological impacts are not well understood [9,12,24]. The EMMP
118 is supposed to be capable of evaluating whether compliance with the conditions of the
119 development licence is occurring and, if problems are detected, to trigger appropriate action
120 [26-28]. However, because it is unreasonable to expect all receptors to be monitored, regulators
121 normally agree to the EMMP being focused on a subset thought to be most at risk [24,28,29].
122 For MREDs, this subset of receptors is often dominated by marine vertebrates because of their
123 frequent listing under conservation legislation, potential for interactions with the devices and
124 typically-high public profile.

125 Although marine impact assessment protocols and post-deployment monitoring are
126 well established for some industries, such as offshore oil and gas, the MRE sector is still
127 developing this experience and there are few agreed standards [14,27]. The offshore wind
128 industry does have a longer track-record compared with tidal-stream and the impacts associated
129 with windfarms have been studied across a range of receptors, sites and timeframes [28,30-34].
130 Despite this experience, several recent papers have identified significant shortcomings with the
131 majority of environmental monitoring undertaken at these sites [27,28,35-44]. Weak statistical
132 power [45], problems with relating local impacts to wider populations and evaluation of
133 cumulative impacts have been highlighted as being of particular concern.

vulnerability of the “receptor” to a “stressor” resulting from a combination of its “sensitivity” and “exposure” to that “stressor”. The “significance” of the impact then results from a combination of the “importance” of the feature and its “vulnerability to impact”. In the context of this review the “receptors” discussed are all biological but the term can also include non-living elements, such as monuments, archaeological sites and landscapes.

134 *1.3. Purpose*

135 In this article the focus is on the potential challenges of monitoring the impacts of tidal-
136 stream MREs on marine vertebrates (fish, seabirds and marine mammals). The analysis
137 presented is based mainly on European Union (EU) environmental legislation but the
138 conclusions will apply more widely. It is essential that regulators, developers and other
139 stakeholders properly understand the challenges involved in monitoring marine vertebrates
140 because a lack of understanding is likely to lead to monitoring programs which are
141 economically expensive but also statistically weak. This combination will not only contribute
142 to the ‘technology valley of death’ by increasing cost [10,20,21] but potentially could result in
143 failures to detect serious impacts on marine vertebrate populations as arrays of tidal-stream
144 MREs become operational [6]. Ineffective monitoring and a failure to properly account for
145 the cumulative and wider-scale ecosystem-impacts will also exacerbate the ‘data-rich,
146 information-poor’ (DRIP) situation in which, it has been argued, the scientific community now
147 find ourselves with regard to environmental monitoring for MRE [26]. Development of more
148 rational ecological monitoring programs in relation to tidal-stream MRE developments will
149 also require a re-evaluation of the balance between what society can expect individual
150 developers to fund and the responsibilities of national and regional authorities. Underlying
151 these issues is a growing recognition that the present ‘one-size fits all’ EIA approach is not fit
152 for purpose and needs to be more proportionate to the likely ecological impacts of MREs
153 [9,12,13,46].

154 **2. Legislative requirements for baseline assessment and monitoring**

155 *2.1. Global requirements for impact assessment and monitoring associated with MRE*
156 *developments*

157 In most jurisdictions which are actively pursuing MRE developers are required to
158 undertake some form of EIA before deployment [47]. Broadly, an EIA presents evidence
159 (baseline data gathered through site characterisation surveys, modelling, evaluation etc.) of
160 likely environmental impacts following four steps: (1) Identification of the environmental
161 changes which may result from the development and the features which may be affected; (2)
162 Evaluation of the exposure risk and sensitivity of the receptors; (3) Evaluation of the impact
163 significance in relation to the vulnerability and exposure risk of the features; (4) Identification
164 of mitigation measures for any significant impacts identified and evaluation of the likely

165 residual impacts [12,18,24]. In the EU, EIA is mandatory for large-scale developments, such
166 as power stations, motorways, and bridges [23,48] but member states have discretion as to
167 whether a full EIA is required for smaller developments (Annex II of the Directive)². A further
168 complication is that EU Directives have to be transposed into national law and implemented
169 through national regulations. This process has led to differences in how the EIA Directive has
170 been implemented between member states [25,49,50]. For example, in the UK any MRE
171 project more than 1MW requires an EIA [24] whilst, in Germany there are no specific
172 procedures to obtain consent for tidal energy projects and they are considered under the
173 legislation developed for the offshore wind sector [47]. Globally there is also variation in the
174 scale of projects which trigger mandatory EIA. For example, in Canada EIAs are only required
175 for tidal energy projects more than 50 MW whilst in South Korea the threshold is even higher
176 at 100 MW [47].

177 In the EU, authorities are also obligated to undertake Strategic Environmental Impact
178 Assessments (SEA) in relation to large-scale plans and programs [51]. This is generally
179 undertaken before the EIAs associated with individual projects are submitted and provides a
180 high-level over-view of potential impacts, usually at a regional level [52].

181 **3. Potential impacts of tidal-stream devices on marine vertebrates**

182 As mentioned previously a large range of potential tidal-stream MRED designs are in
183 development (Fig. 1) and the ecological impacts of these devices on marine vertebrates will
184 vary with both their design and the size of arrays [11,53].

185 *3.1. Pre-deployment and deployment impacts*

186 Pre-deployment and deployment of MREDs will involve increased vessel movements
187 and activities such as seismic surveys and drilling of anchor points. These activities will
188 inevitably cause some physical disturbance, noise and increased turbidity but the construction
189 phase will normally be quite short. Underwater noise is often identified as the main
190 environmental concern during this phase with seismic surveys and pile driving being
191 particularly noisy. Whilst many tidal-stream device designs will not require pile driving,
192 drilling of anchor points and armouring of cables using concrete mats or rock-dumping are also

² Developments are subject to an additional, but complementary consent process [24, 49] if the development is associated with protected areas or species covered by the Habitats and Birds Directives [50].

193 potentially noisy activities [54]. Slow start-ups for operations generating substantial noise are
194 often used as mitigation because this is assumed to allow time for sensitive animals, such as
195 fish and cetaceans, to move away. Other mitigation measures which have been applied in
196 windfarm developments have included avoiding construction during sensitive times of the year,
197 for example during the spawning season of Atlantic herring *Clupea harengus* [42]. Increased
198 shipping, for example moving of components from overseas ports, also brings about an
199 increased risk of introduction of invasive species. Biosecurity planning therefore needs to be
200 implemented to mitigate this risk.

201 3.1. Operational impacts

202 The operational life for MREDs is often quoted as being up to 25 years so this phase is
203 likely to lead to the longest risk exposure times. Although there is much uncertainty regarding
204 the potential impacts on marine vertebrates of operating large arrays of tidal-stream MREDs
205 [53], collisions between animals and moving components are expected to be the main risk [6,
206 55-57]. Considering the speed of turbine rotation, Frid et al. [9] felt that the risks of collisions
207 were quite low, although they acknowledged that how animals will actually behave around
208 devices was, and remains, largely unknown [6]. The risks of direct collision will also vary
209 according to device design, the speed of moving components and tidal state as well as the
210 species involved [58], their distribution and how readily the animals detect and avoid the
211 devices [46]. Evaluating collision risks is definitely not straight-forward and may further be
212 altered through indirect effects. For example, some MRED designs include structures above
213 sea-level and this could encourage seabirds to roost at the sites. Whilst this could have positive
214 impacts for the birds, it might also expose a larger number to collision with the moving
215 underwater components thus altering the overall collision risk outcome [6].

216 In evaluating such risks consultants also need to be careful of making naïve biological
217 assumptions. For example, tracking studies have shown that fish such as plaice (*Pleuronectes*
218 *platessa*) and flapper skate (*Dipturus cf intermedia*) move up into the water column at certain
219 times. Such vertical movements may be associated with feeding, spawning or the use of tidal
220 streams for efficient horizontal movement [59,60]. Such species, which are normally assumed
221 to be benthic, could therefore become exposed to moving device components operating above
222 the seabed at certain times [61]. Entanglement in mooring lines may present an additional
223 hazard for larger marine vertebrates although the risk was considered to be relatively low by
224 Benjamins et al. [62].

225 While the additional noise from operating MREDs may alert animals to the presence of
226 the devices and reduce collisions, excessive noise could result in the displacement of fish or
227 marine mammals, potentially excluding them from important foraging areas [6,64]. However,
228 tidally energetic sites often have high levels of ambient noise which may mask device-
229 generated sound and vibrations [63]. All MREDs also generate electromagnetic fields (EMF),
230 principally around the sub-surface transformers and transmission cabling [9]. EMF radiation
231 may potentially impact chondrichthyan fishes in particular [65,66]. Although the strength of
232 the EMF falls rapidly with distance from the emitter [67], the impacts of large cabling arrays
233 have not yet been well characterised [6]. Large numbers of tidal-stream MREDs could also
234 alter the local and medium-field hydrodynamics at the site [6,68] potentially affecting the
235 foraging success of seabirds and marine mammals [9,66,69]. Although fluid dynamics models
236 have been applied to individual devices, scaling such studies up to array levels presents
237 significant computational challenges.

238 The introduction of new underwater structures to the marine environment undoubtedly
239 has the potential to modify local predator-prey interactions. Existing underwater structures
240 frequently attract fish from the surrounding area [70-72] and such local increases in potential
241 prey can then attract larger predators. Such changes could modify the likelihood of collisions
242 between the predators and the MREDs, likelihoods which are normally calculated using the
243 baseline data collected before any MREDs have been deployed. Alternatively the turbulence
244 in high-energy environments may, under natural conditions, make prey more vulnerable to
245 capture by predators and extracting some of this tidal energy might reduce predation feeding
246 success. However, although there is convincing evidence that seabirds and mammals, such as
247 the harbour porpoise (*Phocoena phocoena*), exploit high-energy sites for foraging [73], very
248 little is known about how these predators or their prey behave in such high-energy
249 environments. The potential impacts of tidal-stream MREDs on predator-prey dynamics thus
250 remain largely speculative although some changes have been observed around offshore wind-
251 farms [32,33,74]. Unfortunately the differences between both the devices and the site
252 characteristics mean that conclusions from windfarms cannot be readily extrapolated to tidal-
253 stream MREDs [9,75].

254 3.2. *Impacts during decommissioning*

255 Environmental impacts during decommissioning are likely to be similar to those during
256 construction and deployment and are thus usually evaluated under a common heading. One

257 difference between the phases relates to biofouling where the handling and disposal of
258 potentially large amounts of biological material needs to be taken into account. Furthermore,
259 the environmental issues around decommissioning are rarely properly addressed during project
260 planning because an operational life of 20-30 years is envisaged. This lack of forward-planning
261 is well illustrated by the present situation with regard to decommissioning of redundant oil and
262 gas structures [76].

263 **4. Overarching challenges of monitoring marine vertebrates**

264 A number of the challenges of monitoring marine vertebrates are common across the
265 main groups: fish, seabirds and marine mammals. Abundances of these animals (excepting
266 some fish) are often low and aggregation further results in observations typically being
267 dominated by zero counts. Unless surveys are carefully designed this zero-inflation leads to
268 low precision and statistical power. For example, using the English North Sea International
269 Bottom Trawl Survey data, which comprise around 40-50 trawl tows per year, Maxwell and
270 Jennings [77] demonstrated that 5 to 10 years of monitoring would be required to detect a
271 change in abundance of even the most common fish species consistent with the IUCN A1
272 criteria for critically endangered and vulnerable groups. For rarer species the time required to
273 detect such abundance changes would be substantially longer. A further problem is that
274 catchability (or observability) varies between species and often between different sizes and
275 sexes of the same species. This variability is usually poorly estimated or unknown. It is
276 therefore often impossible to produce accurate estimates of absolute population numbers within
277 an area (although with careful standardisation relative indices over time can often be
278 generated). Animal abundance within a site will also change on multiple time-scales (including
279 diurnal, tidal and seasonal) so that repeated surveys will usually be required [78]. Finally the
280 physical nature of most tidally-energetic sites, often combined with poor weather conditions,
281 presents many challenges to the collection of observational data, including risks of lost
282 equipment, significant down-time and health and safety hazards.

283 *4.1. The specific challenges of monitoring the abundance and behaviour of marine fish in*
284 *relation to MRE developments*

285 Marine fish are highly diverse in their size and behaviour complicating attempts at
286 designing comprehensive monitoring strategies. Relating local to population impacts is
287 complicated by the fact that reliable estimates of population sizes are generally only available
288 for a limited number of commercially important species, species which also tend to be more
289 numerically abundant. Although these stock assessments often suggest that the populations are
290 composed of many millions of individuals, these apparently large population sizes may obscure
291 fine-scale structuring. Recent genetic analyses of marine fish have often suggested surprisingly
292 low effective population sizes and meta-population structuring and local adaptations may be
293 more common than often assumed [79-81].

294 Physical sampling using modified commercial gears, such as trawls, long-lines and set-
295 nets, remains the main tool for monitoring fish. Active acoustics are also widely used but
296 mainly for assessing the abundance of pelagic species. Even here a certain amount of net-based
297 sampling is usually required to corroborate the acoustic identifications. Crucially, deployment
298 of most standard towed or fixed fishing gears at tidal-stream MRE sites is likely to be
299 challenging due to the high current speeds and rocky terrain [82]. Studies using stationary
300 cameras and/or active acoustic equipment are beginning to be successfully used in these
301 locations and can provide insights into how fish behave around MREs as well as generating
302 estimates of local abundance [61,83-85]. Even when the identity of the organisms cannot be
303 established, acoustic data may be useful for assessing the risk of extreme events, such as the
304 occurrence of unusually high biomasses in the vicinity of MREs [14, 86].

305 A wide variety of spatial behaviours, ranging from semi-permanent residency to basin-
306 scale migrations, have been observed in the limited number of fish species whose movements
307 have been studied in any detail in the wild [59,60,87-89]. Despite these insights, the spatial
308 responses of fish to artificial structures remain poorly understood and there is continuing debate
309 over whether such structures enhance fish productivity, or merely attract animals from
310 surrounding areas [71,84,90]. Tagging has been widely used to study the dispersal and
311 behaviour of fish and, under assumptions regarding differential mortality between tagged and
312 un-tagged animals, rates of migration and tag losses, the technique can yield estimates of
313 population abundance and mortality [91]. However, in the marine environment the underlying
314 assumptions are often hard to meet unless the tagging program is well designed and covers a

315 very large spatial area [92]. Inert plastic or metal tags are the cheapest to deploy but obtaining
316 reliable data relies on the recaptures being accurately reported. Inert tags also only yield
317 information on the initial and final dates and locations of capture (unless the fish are subject to
318 catch and release angling). The problem of continuous monitoring and low tag return rates can
319 be reduced by using satellite transmitting (pop-up) data storage tags but these are much more
320 expensive than inert tags and can only be deployed on larger fish [87]. Very small data-storage
321 tags capable of recording depth, temperature and light are now available and have been
322 successfully used to study the movements and vertical behaviour of medium-sized fish, such
323 as plaice and cod (*Gadus morhua*) [60,93-95]. These tags are expensive and data recovery
324 relies on the tags being returned in sufficient numbers when the fish are caught either by
325 commercial or recreational fishers. Larger fish can also be implanted with coded acoustic tags
326 which can be detected using fixed telemetry stations. This technique is especially suited to
327 monitoring residency and behaviour of fish within limited spatial areas [60,96,97].

328 *4.2. The specific challenges of monitoring the abundance and behaviour of seabirds and*
329 *marine mammals in relation to MRE developments*

330 Methodological and statistical approaches to estimating seabird and marine mammal
331 abundance from observational data have received considerable attention in recent years [98-
332 100]. For MRE sites close to land both seabirds and marine mammals may be observed from
333 suitable vantage points onshore. The ability of land-based observers to detect seabirds and
334 marine mammals at sea does, however, decrease substantially with distance and with poor
335 meteorological conditions and sea-state [101]. Furthermore, detectability can also be affected
336 by tidal state due to the generation of surface turbulence. Aerial or vessel-based surveys are
337 often used for monitoring seabirds and marine mammals further offshore but these approaches
338 are costly and similarly affected by observing conditions. Recent improvements include the
339 application of digital-still and video photography [102] and the use of un-manned aerial
340 vehicles [103-108]. Techniques for the automated detection and counting of animals in video
341 or still images are also improving but rigorous ground-truthing is required to estimate false-
342 positive rates [109]. Although these high-tech approaches should eventually lead to reduced
343 costs for collecting observations of seabirds and marine mammals such surveys remain
344 expensive and logistically challenging at present [109,110].

345 Another widely used method to detect the presence of cetaceans is passive acoustic
346 monitoring [111]. Hydrophones are deployed either from ships or special moorings or drifters

347 to record acoustic data [112]. Cetacean vocalisations are then isolated from the data, usually
348 with the aid of software, such as PAMGUARD. Compared with visual monitoring the
349 technique can produce information on species presence, relative abundance and distribution
350 under a far wider range of sea conditions and over much longer time periods [111]. With more
351 sophisticated hydrophone configurations information on the diving behaviour and movements
352 of animals can also be inferred. However, only vocalising animals can be detected and
353 accurately distinguishing different individuals, or even closely related species, can be difficult
354 if not impossible. Tidal-stream MRE sites also tend to be naturally noisy which can mask
355 cetacean vocalisations, particularly at times of peak flow [112]. It can therefore be challenging
356 to use PAM to estimate the total number of cetaceans within such areas.

357 As well as presence/absence the movements of marine vertebrates in relation to MRED
358 sites are often of interest. Data recording tags have been widely used on seabirds (Fig. 2) and
359 pinnipeds for his purpose. Compared with tagging fish, such studies are made easier because
360 the animals breed onshore where they can be captured, tagged and subsequently recovered
361 [33,113,114], or the data remotely downloaded [115]. However, this can lead to a bias towards
362 mature animals and such studies tend to generate short-term data. Much less is therefore known
363 about seabird and pinniped movements outside of the breeding season [115]. Data storage and
364 transmitting tags have also been used to track the movements of cetaceans but tagging these
365 animals is more difficult as they do not haul out on land [116]. As with fish, large numbers of
366 animals may need to be tagged to obtain robust results so that the costs of gathering such data
367 can be high.

368 *4.3. The challenges of monitoring marine vertebrates due to the spatial and temporal* 369 *scales over which the animals range*

370 Many marine vertebrates exhibit large spatial ranges and this complicates the evaluation
371 of MRE development impacts on populations. The spawning, nursery and adult feeding areas
372 of many species of fish are often spatially separated resulting in extensive seasonal migrations
373 [87,117] whilst the largest species, such as basking sharks (*Cetorhinus maximus*), can range
374 over thousands of kilometres [118]. Despite these large overall ranges, meta-population
375 structuring may be relatively common in fish so that genetically distinct groups of adults will
376 show more limited dispersal [119]. When stock abundance has been strongly reduced, for
377 example by commercial fishing, the species range also usually contracts into a limited number
378 of hot-spots [60]. Under these conditions mixing between sub-populations may be further

379 reduced [120,121] so that present realised habitat distributions may only represent a fraction of
380 potential habitat [122]. The high mobility of the majority of marine fish must also be considered
381 in relation to potentially positive benefits which are sometimes claimed in relation to fisheries
382 exclusions around MRE sites [128-130]. Research on no-take zones clearly suggests a strong
383 negative relationship between benefits (measured as increases in fish abundance, average size
384 or reproductive output) and mobility [131,132]. Most tidal-stream MRE development sites are
385 thus likely to be too small to generate significant positive benefits. In addition, most of the
386 energetic sites proposed for tidal-stream MRE development are not heavily fished using towed
387 gear, in contrast to the larger-scale offshore wind-farms in areas such as the North Sea, where
388 exclusion of fishing effort may have some positive impact [129].

389 Seabirds are often widely dispersed during most of the year but aggregate at breeding
390 sites which provide protection from predators and the resources to feed the offspring [123]. It
391 is thought that tidally-energetic locations may provide improved foraging compared with less
392 energetic areas. Seabird breeding colonies may therefore be associated with many tidal-stream
393 MRE development sites [124]. Interference with foraging has the potential to impact these
394 populations [123] since seabird populations are sensitive to even small, long-term declines in
395 breeding success [125].

396 Tidally-energetic sites may also provide favoured foraging areas for marine mammals,
397 such as the harbour porpoise and harbour seal (*Phoca vitulina*) [73]. Whilst other marine
398 mammals are wide-ranging, from regional [126] to basin-scales [127], they may still pass
399 through coastal MRED sites at certain times of the year.

400 Several specific issues arise as a consequence of these marine vertebrate movement
401 patterns:

- 402 • Animals may travel considerable distances to take advantage of resources at tidally-
403 energetic locations. Although most current developments are small (typically less than
404 10 km²), the spatial scale of the impact may be much larger, and thus beyond the means
405 of individual developers to monitor adequately.
- 406 • The scales of movement exhibited by many marine vertebrates mean that trans-national
407 boundary impacts must often be taken into account [24].
- 408 • Use of a site may be critical for breeding success. Both direct increases in adult
409 mortality from device interactions and indirect reductions in foraging success could

410 lead to population declines over time. This issue may be especially important for some
411 seabird species.

- 412 • Animals may only be attracted to sites for limited periods of time. The intensity of use
413 of high-energy sites by seabirds and marine mammals not only varies seasonally but
414 with the tidal cycle [103]. Monitoring activities taking place at fixed times, such as
415 during slack water around neap tides, run the risk of missing important changes in the
416 abundance or behaviour of animals.
- 417 • For most marine vertebrates MRE development sites will only comprise a small
418 proportion of their geographical range. The consequences of impacts occurring within
419 the site need to be considered in the context of all the other impacts the animals are
420 exposed to throughout their range.

421 *4.4. Implications of vertebrate movements for the definition of appropriate assessment* 422 *units*

423 At present the burden for monitoring impacts within and around development sites
424 typically rests with the developer [47]. However, regulators and other stakeholders are actually
425 interested in impacts at the population-unit level. Whilst a development might cause alteration
426 of a local community, this may not necessarily be of wider consequence if the impacted
427 individuals form part of a much larger population. Local effects may, however, be important if
428 the receptor is associated with a depleted population, or forms part of a sub-population.
429 Unfortunately for most marine vertebrates detailed understanding of their population structure
430 is lacking. For fish, fine-scale population structuring has only been studied in a few marine
431 species and these are mostly ones of commercial interest [81,119,133]. For seabirds, it is often
432 impossible to know which breeding colony birds have come from unless large-scale ringing
433 programs are undertaken [144]. Data on fine-scale population structuring in marine mammals
434 is also often lacking, even for comparatively well-studied species [134].

435 The dynamics of marine vertebrate populations are also affected by multiple large-scale
436 factors. Fluctuating recruitment success is well documented for many commercial fish species
437 as a result of long time-series of stock assessments. In some cases it has been possible to link
438 these fluctuations with regional-scale environmental factors [135-137]. Long-term climate
439 change has also emerged as the most likely driver for shifts in the spatial and depth distribution
440 of many fish species [138-140]. In the north-eastern Atlantic, the breeding success of some
441 species of seabird and the body condition of harbour porpoises have both been linked with

442 changes in their sandeel (*Ammodytidae*) prey, changes which in turn have been linked with
443 large-scale, climate-related effects on the plankton [141,142]. Reduced breeding success in
444 cetaceans has similarly been linked to large-scale factors, such as the accumulation of persistent
445 organic pollutants biomagnified through the food-web [143]. Monitoring the abundance of
446 vertebrates within small MRE sites (even using statistically robust designs) is therefore
447 unlikely to shed much light on the specific causes of any observed changes in abundance at the
448 population level, especially when the wider population is affected by other stressors operating
449 outside of the development site [28].

450 The mechanisms by which acute impacts on individual animals contribute to
451 population-level impacts are thus often poorly understood and difficult to quantify [145].
452 Recently developed modelling approaches such as Population Consequences of Disturbance
453 (Interim-PCoD) have attempted to integrate the effects of behavioural changes in individuals,
454 especially in response to noise, to the population level [146-148]. However, the approach relies
455 heavily on assumptions regarding the size of the relevant management units and that all animals
456 will respond in a similar manner to the stressor. The technique also relies on expert elicitation
457 to address knowledge gaps so it is unlikely to be a satisfactory substitute for dedicated
458 biological studies [149]. Nonetheless, this approach does provide a methodology for assessing
459 potential population-level outcomes resulting from MRE (and other) marine developments.
460 The role of fundamental research is clear because improvements in basic knowledge of marine
461 vertebrate population structure, reproductive rates and long-term effects of anthropogenic
462 impacts on individual fitness should improve the reliability of population level predictions.

463 Taken overall, the patterns and scales of movement typical of marine vertebrates mean
464 that more consideration needs to be given to whether EIA monitoring approaches, as currently
465 practised, are appropriate. Because of costs it is unreasonable to expect individual developers
466 to undertake population-scale monitoring for such wide-ranging receptors so such data
467 collection can probably only be undertaken by government bodies, or other relevant authorities.
468 There is, however, a need for developers to be asked to produce site-specific data which can
469 more usefully contribute to analyses at ecologically relevant scales [26]. This will generally
470 require much more effort during the discussion, planning and co-ordination stages of
471 monitoring programs than has been achieved to date.

472 *4.5. Implications of vertebrate movements for assessing cumulative impacts*

473 Environmental legislation typically demands that the cumulative impacts (CI) of human
474 activity are also considered [48, 150]. However, cumulative impacts are likely to be complex
475 with potentially nonlinear synergism and thus evaluation of CI within EIAs has been
476 recognised as a specific weakness [24]. As discussed above, large marine vertebrates are
477 frequently wide-ranging and long-lived so individuals could be impacted by multiple MRE
478 developments over decadal timescales. Tidal-stream energy generation is also only one of the
479 numerous anthropogenic activities with potential to impact marine vertebrate populations and
480 integrating multiple MRE-associated impacts, against the background of other, often poorly-
481 quantified impacts, is extremely challenging. In a similar manner to population level impacts,
482 CI for marine vertebrates may be more sensibly dealt with during SEA, but this has rarely been
483 undertaken in a rigorous manner [151].

484 The ability to monitor CI across MRE developments will also depend on effective
485 collection and integration of comparable metrics across different sites over appropriate
486 timescales [27]. Currently, data gathering by industry is not generally consistent or comparable
487 between development areas and/or jurisdictions or companies, resulting in data gaps and other
488 problems that further complicate any assessments of cumulative impacts [43,134]. There may
489 therefore be considerable benefits to taking a more integrated approach in terms of
490 methodological approach, frequency of sampling and data resolution among all the
491 developments in a region.

492 *4.6. Implications of the characteristics of marine vertebrates for the statistical power and*
493 *precision of monitoring*

494 Before embarking on a potentially expensive monitoring programme, it is crucially
495 important to agree on the required detection thresholds [14,27,152]. If the required detection
496 thresholds³ are not explicitly defined at the outset there is an immediate danger that sampling
497 effort will be reduced to that which has been budgeted for, and below that needed to provide
498 sufficient statistical power [45]. On the other hand, demands to detect unreasonably small
499 levels of change in marine vertebrate populations will lead to un-affordable monitoring
500 programmes. Computer simulations should be used to help design field surveys which meet

³ A threshold is defined as “a target level or state based on the avoidance of unacceptable outcomes, or an ecologically defined shift in system status [153].

501 statistical power requirements and to assess the relative costs and benefits of different designs
502 [125,151,154]. The results of such simulations may indicate that the resulting statistical power
503 will be so low that the surveys are not justified. In these cases other approaches, such as
504 integrating across different receptors [77] or across adjacent developments covering larger
505 areas, may lead to more statistically robust outcomes. Alternative monitoring strategies
506 generating different metrics (e.g. relative rather than absolute abundance, habitat usage) should
507 also be explored. In-depth discussions with regulators, their science advisors and the academic
508 community are needed to determine appropriate levels of monitoring effort in proportion to the
509 likely impacts expected from the development [46]. Guidance on how to develop a monitoring
510 programme for marine vertebrates in relation to tidal-stream MRE is still relatively limited
511 [155-157] but one overall approach could be to follow the flow diagram shown in Fig. 3.

512 **5. Discussion**

513 Based on the European experience, assessment of the impacts of tidal-stream MRE
514 developments appears to be progressing according to regulatory requirements but there are
515 concerns that the current approach risks both repeating some of the short-comings of
516 monitoring the impacts of offshore wind-farms [27,28,151] and damaging the development of
517 tidal-stream MRE due to excessive demands on individual developers [11].

518 Many populations of marine vertebrates are presently at reduced levels of abundance
519 due to historic over-exploitation, accidental mortality, pollution and other pressures [158-162].
520 For larger marine vertebrates this can combine with naturally low population growth rates
521 making these species particularly vulnerable to additional mortality or reductions in
522 reproductive success. Against this background regulators have often been reluctant to specify
523 acceptable impacts and thus what detection thresholds are appropriate. There has also been a
524 failure to insist that site-scale monitoring be integrated into wider ecosystem-scale monitoring,
525 either by forcing companies to collaborate with each other [24] or by encouraging closer
526 working with national and international monitoring programs. Data sharing could be an
527 effective way of reducing EIA costs but companies are often reluctant to put their data into the
528 public domain because they view it as offering advantages to their competitors [24]. As well
529 as opening up EIA-associated data, the MRE infrastructure itself could make a valuable societal
530 contribution by transmitting environmental data ashore from sub-sea sensors [26,28].
531 Regulators need to encourage such engagement by, for example, recycling part of the site lease
532 fees to support the collection and analysis of environmental and biological data collected at

533 MRE sites for wider use. In Europe, such analyses could make a valuable contribution to the
534 Ecosystem-scale assessments required under the Marine Strategy Framework Directive [150].

535 A wide range of tidal-stream MRED designs are currently being developed which will
536 all require research into their likely ecological impacts [9]. This situation is likely to improve
537 over time through design consolidation and accumulation of knowledge regarding impacts
538 [12,20,163] but, even after 25 years of development⁴, significant problems have been identified
539 in relation to environmental monitoring around wind-farms [27,28]. In theory post-deployment
540 monitoring is supposed to (i) validate predictions made in the EIA or HRA (ii) to detect any
541 unforeseen impacts and (iii) ensure compliance with agreed residual impacts following
542 mitigation measures. Monitoring programmes therefore clearly need to be designed with
543 specific pre-agreed detection thresholds, but this is often not the case [27,151]. Setting
544 appropriate thresholds often requires a great deal of negotiation/consultation and potentially
545 additional research including modelling of receptor population dynamics. Because of this
546 developers cannot realistically be expected to decide on appropriate thresholds themselves,
547 although this often seems to happen under present EIA arrangements [151]. To achieve more
548 rational threshold setting will require a much greater focus on SEA [27] to allow strategic
549 assessment of population level sensitivities and impacts (including cumulative impacts) and to
550 trigger the research required to fill knowledge gaps [12,151]. This seems to be a particularly
551 appropriate suggestion in relation to many marine vertebrate receptors where the impacts of
552 MREs potentially extend well beyond the local spatial scale, and the populations are likely
553 to be affected by multiple developments and stressors. Having agreed thresholds, a clearer
554 process for the design of baseline and post-deployment monitoring is needed that takes into
555 consideration both the statistical power required [26,27,45], the economic costs of collecting
556 the data, and how those costs should be partitioned between developers and the wider tax-base
557 [12].

558 Based on observations from offshore wind-farms, complex interactions involving
559 multiple trophic levels should be expected around and within tidal-stream MRED arrays.
560 Effective monitoring will therefore need to be multi-disciplinary and such an integrated
561 approach would also be consistent with ecosystem-based management, as opposed to a purely
562 conservation approach focussing on the abundance of iconic and charismatic species
563 [26,28,164]. Unfortunately this also means establishing clear causal linkages between impacts

⁴ The first commercial offshore wind farm was installed in Vindeby, Denmark in 1991.

564 at specific tidal-stream MRE sites and population level changes which for marine vertebrates
565 may be particularly challenging [165].

566 It has been widely recognised that monitoring methods need to remain as consistent as
567 possible throughout the lifetime of a project [24,27]. In practice, pre-consent surveys are rarely
568 designed with proper consideration that the data needs to act as a base-line for evaluating post-
569 deployment changes and attempts to align the two datasets *post-hoc* have usually had limited
570 success. Similarly, while local conditions at certain sites may favour particular assessment
571 methods, it is important to consider how differences in monitoring approaches across adjacent
572 development sites may hinder the assessment of cumulative impacts. Such considerations are
573 particularly important with regard to marine vertebrates given their dispersal ranges. Overall
574 there is an urgent need to develop more open, transparent and reproducible assessment methods
575 which are supported by peer-reviewed research [166].

576 As novel monitoring methods are increasingly deployed around MREs, these new
577 techniques need to be sufficiently described and tested to ensure reproducibility. For example,
578 combining time-depth-accelerometer tags with global positioning satellite fixing has already
579 provided valuable insights into the diving behaviour of various species in tidal-stream sites
580 [170,171]. Platforms equipped with active acoustics are also being developed to allow tracking
581 of diving seabirds and marine mammals (as well as large fish or other targets) around devices
582 in order to investigate diving behaviour and collision risk under natural conditions [85,172]. It
583 is especially important that information from these new sources is shared and disseminated
584 among regulators, industry, the academic community and other stakeholders, and that
585 assessment priorities are reviewed in light of advances in monitoring techniques [12,28].

586 Although much of the present effort in EIA is spent on trying to quantify the origin and
587 extent to which marine vertebrates use or transit a tidal-stream MRE development site, we
588 argue that it is probably more important to understand how the animals will interact with the
589 MREs [123]. There are numerous examples from marine natural resource management
590 demonstrating the difficulties in moving from observed correlations between population
591 dynamics and other factors. Such correlations can be spurious and are prone to breakdown
592 unexpectedly unless they are supported by causal mechanisms [167-169]. In relation to tidal-
593 stream MRE impacts the causal mechanisms can probably only be addressed through direct
594 evidence and so much more research is required into how animals and devices actually interact
595 [28]. Although pre-deployment modelling can provide some insights, direct observations using

596 full-scale MREDs operating in the natural environment will be required. As long as there is
597 some consolidation in device designs, results from such intensive studies should be more
598 widely applicable, even if such studies are only conducted at a limited number of test sites.
599 Because the benefits of such knowledge may accrue to other competing developers, it may be
600 more reasonable to expect these fundamental studies to be funded at national or international
601 level. Alternatively, tidal-stream MRE developers could collaborate to create research pools
602 which would ultimately benefit the industry as whole, an example being the UK Offshore
603 Renewables Joint Industry Programme (ORJIP).

604 Fig. 4 suggests an approach towards EIA which differentiates between the site-specific
605 monitoring which might reasonably be expected to be undertaken by a developer, and
606 monitoring which, because of its scale, needs to be undertaken at national and international
607 levels. As discussed in this article, marine vertebrates, especially the larger species, are
608 typically wide-ranging and long-lived so that individual tidal-stream MRE development sites
609 only represent a small fraction of their ecologically relevant habitat (although the site may be
610 highly relevant to critical life-stages). Moreover, many marine vertebrates are difficult to detect
611 and monitoring will require considerable amounts of effort in challenging environments to
612 achieve results with sufficient statistical power. Given these considerations, we suggest that
613 population-level impacts will have to be addressed at regional and basin-level scales through
614 more strategic assessments. This implies that more attention must be paid to the likely
615 cumulative impacts across MRE developments, and that developers will have to work more
616 closely with each other, and with regulators and the research community, so that data collection
617 is more appropriate to these goals [27]. Developers might then be able to focus their resources
618 on supporting process studies *sensu* Lindeboom *et al.* [28] and on the detection of actual
619 interactions between organisms and their devices. For example, collision risk is generally
620 viewed as one of the more serious potential risks, and turbines are routinely equipped with
621 built-in accelerometers and strain gauges to measure performance. With more research these
622 data might be used to directly monitor collision events, or show that they are not occurring or
623 are extremely rare [173]. Emerging techniques, such as active acoustic imaging sonar, may
624 allow collisions and near-misses to be directly observed close to devices, although assessing
625 whether any non-fatal collision injuries have impacted longer-term survival will be challenging
626 [174]. As well as focussed studies to investigate how marine vertebrates behave around tidal-
627 stream MREDs, continuous monitoring may be required for receptor populations judged to be
628 in imminent danger of extinction and where each mortality event needs to be recorded.

629 However, making such judgements requires population-based assessments of long-term
630 susceptibility, and we have already argued that this should not be the responsibility of
631 individual developers. Achieving a better balance of responsibilities between developers and
632 regulators would represent an improvement over the present situation where developers are
633 often required to undertake expensive, localised abundance monitoring which has limited
634 relevance for the management of the wider populations [175] and merely leads to the
635 accumulation of more DRIPy data [26].

636 **6. Conclusions**

637 Tidal-stream MREDs are now beginning to move from the testing to the commercial
638 deployment phase but undertaking biological studies in tidally-energetic sites is challenging
639 [103]. Many traditional biological sampling techniques are poorly suited to such environments
640 and new approaches for observing, monitoring and modelling animals will be required [103].
641 Furthermore, many of the marine vertebrates utilising these sites range over much larger spatial
642 areas or belong to much larger populations. This raises numerous challenges for developers,
643 researchers and regulators who must find ways to integrate results from local-scale monitoring
644 with population level assessments. Partitioning causes for any observed population-level shifts
645 in marine vertebrate abundances or distributions between tidal-stream MREDs and other
646 factors, including changes in ecosystem productivity, pollutants and fisheries interactions, will
647 be extremely challenging. The scale of these challenges raises the question of whether EIAs
648 are the appropriate place for assessing such population-scale impacts. We suggest a sequence
649 of issues which should be considered to avoid implementing MRE site-based monitoring which
650 proves to be either extremely costly, statistically ineffective, or both, and which only results in
651 the production of yet more DRIPy data [26]. Where statistical power analysis suggests that
652 cost-effective monitoring cannot be undertaken, we recommend that the emphasis should be
653 shifted towards understanding device-animal interactions. From available observations it is
654 known that fish, seabirds and marine mammals are attracted to tidally-energetic sites at certain
655 states of the tide, and that this is probably linked to improved opportunities for foraging [73,83].
656 However, we know little about the actual behavioural interactions taking place between the
657 predators and prey in such turbulent waters, or how these behaviours may be affected by arrays
658 of MREDs. Finally, we suggest that there is a need to re-visit the balance of responsibilities
659 between developers and regulators, as set out under current EIA approaches, in order to make

660 better use of the limited resources available for biological research and monitoring in relation
661 to tidal-stream MRE developments.

662

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1139 **Figure legends**

1140 Fig 1. Generalised examples of tidal-stream MRE technologies currently in development: (a)
1141 Horizontal axis turbines; (b) Reciprocating hydrofoil; (c) Vertical axis turbines; (d) Venturi-
1142 effect device. Images re-used with kind permission of the Aquatic Renewable Energy
1143 Technologies project (Aqua-RET co-ordinated by AquaTT, www.aquaret.com).

1144 Fig 2. Foraging paths of adult great skuas (*Stercorarius skua*) tagged with GPS tracking devices
1145 on Hoy (Orkney Islands) and Foula (Shetland Islands) demonstrating the range of individual
1146 movements versus the scale of the Scottish Government's inshore and offshore marine
1147 planning regions. Seabird tracking data were kindly provided by the Environmental Research
1148 Institute and the British Trust for Ornithology jointly funded by the Marine Renewable Energy
1149 and the Environment (MaREE) project (Highlands and Islands Enterprise, the European
1150 Regional Development Fund, and the Scottish Funding Council) and the UK Department of
1151 Energy and Climate Change (DECC).

1152 Fig. 3. Suggested approach to developing post-deployment monitoring for marine vertebrates
1153 in relation to tidal-stream MREs. The approach assumes that the pre-consent EIA has been
1154 largely completed and that the potential impacts have been assessed. The boxes shaded light
1155 grey are essential but often seemed to be missed out in developing EMMPs.

1156 Fig. 4. Schema for how the environmental monitoring associated with tidal-stream MRE (and
1157 other marine) developments could be better integrated into ecosystem-scale assessments.
1158 Arrows indicate general flows of information. The lack of hard boundaries graduating from
1159 national to regional policy frameworks illustrates the fact that the impacts of individual projects
1160 on marine vertebrates will frequently be transboundary in nature.

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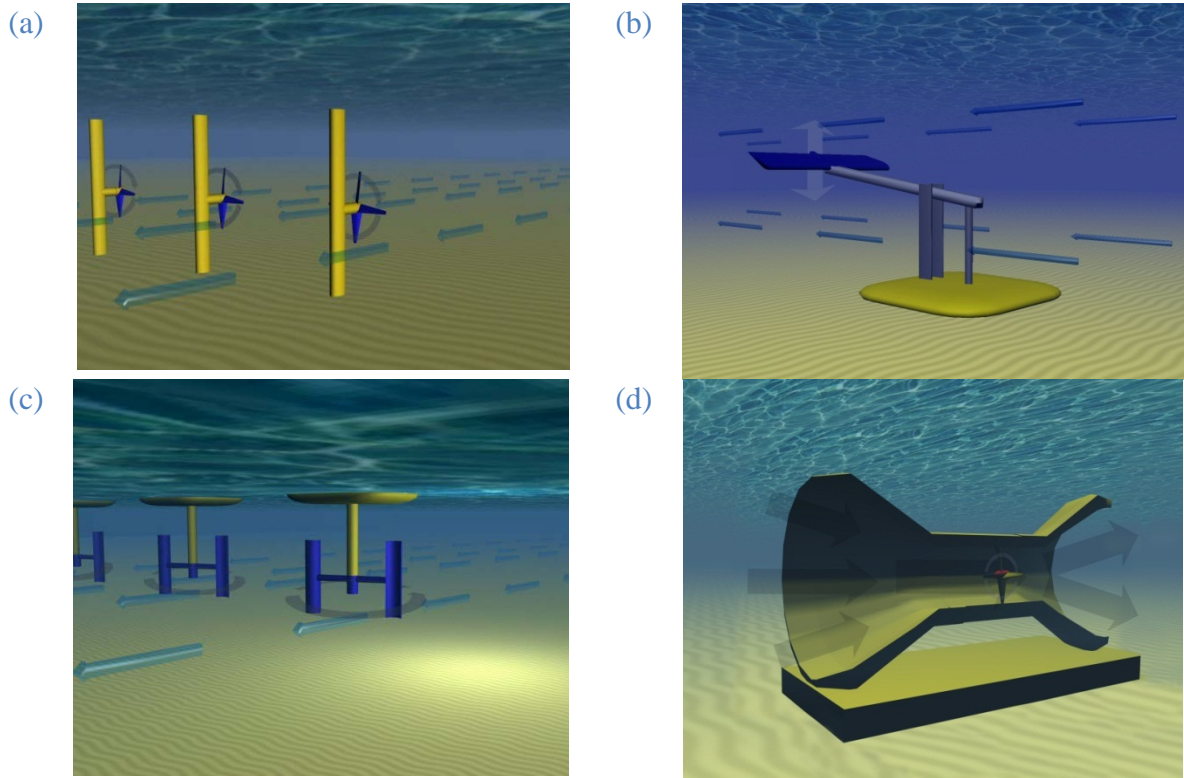
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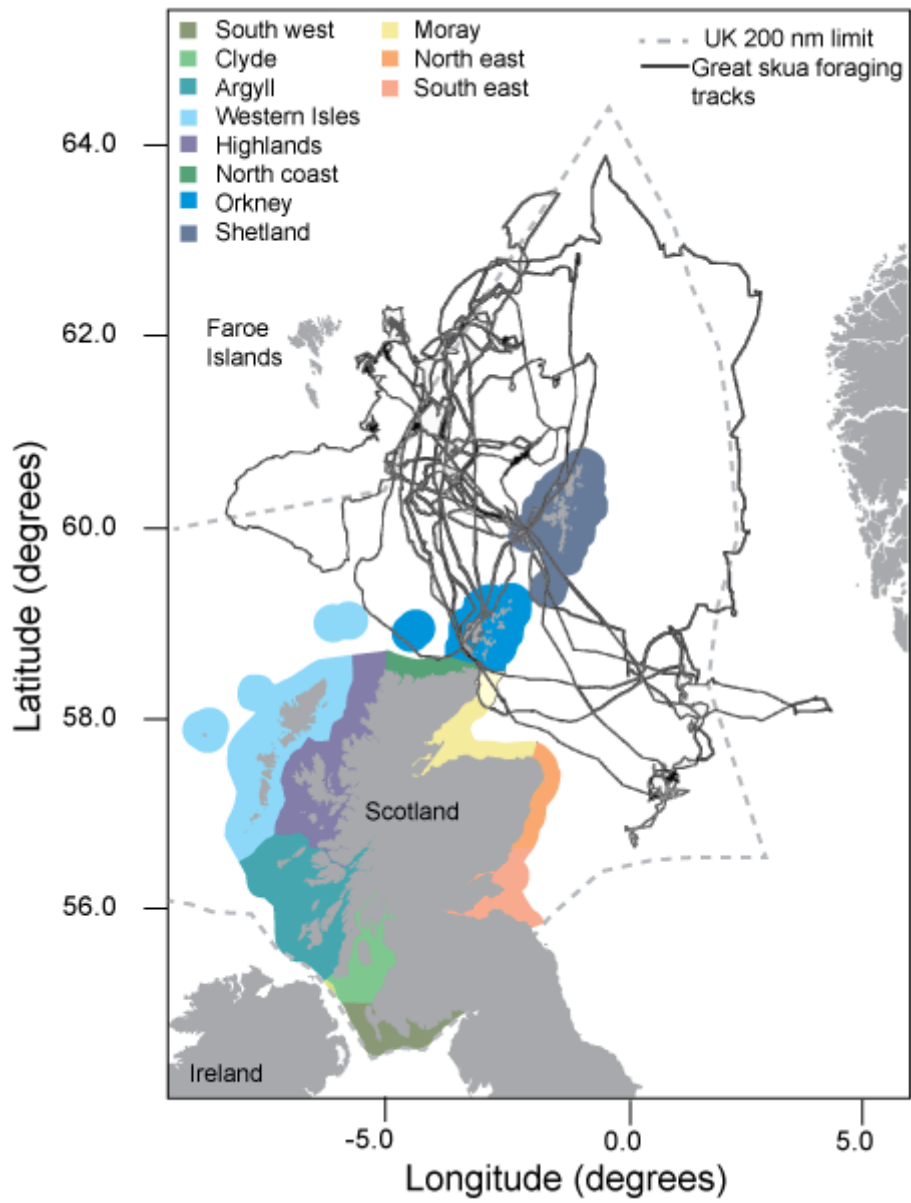
Fig 1.



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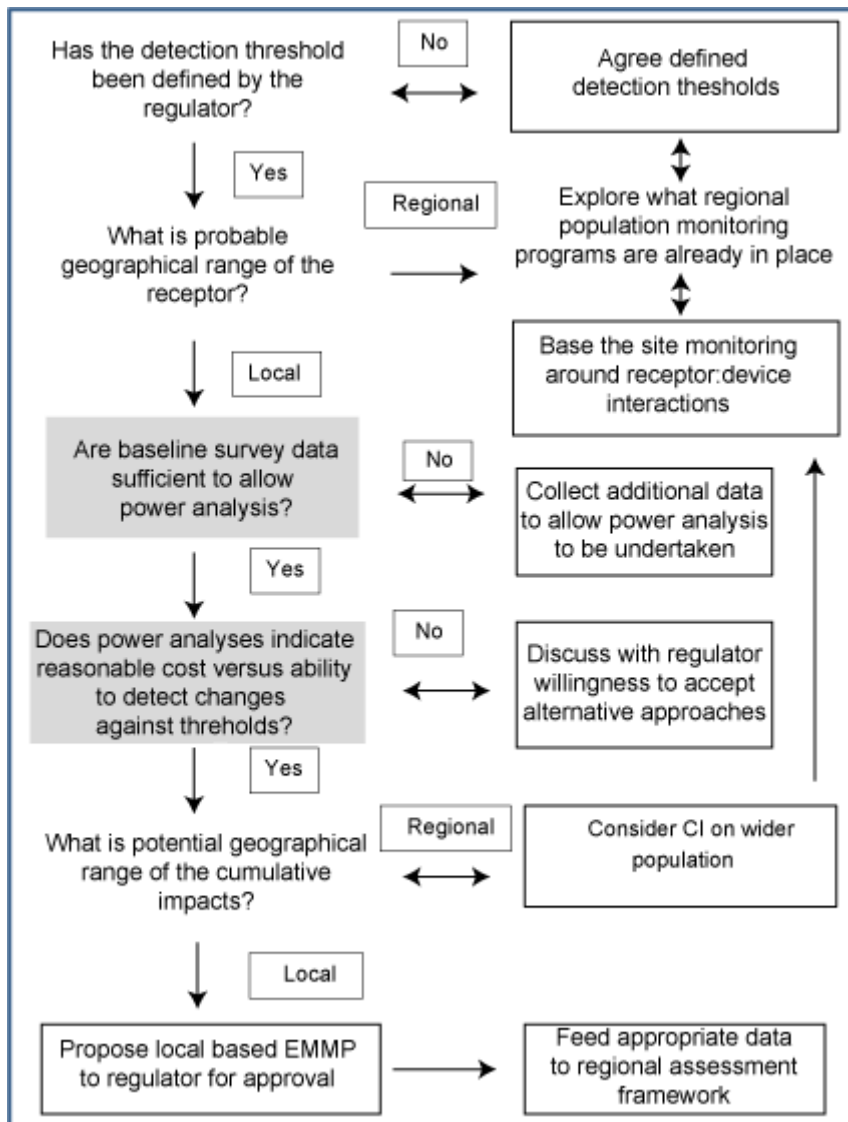
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Fig 2.



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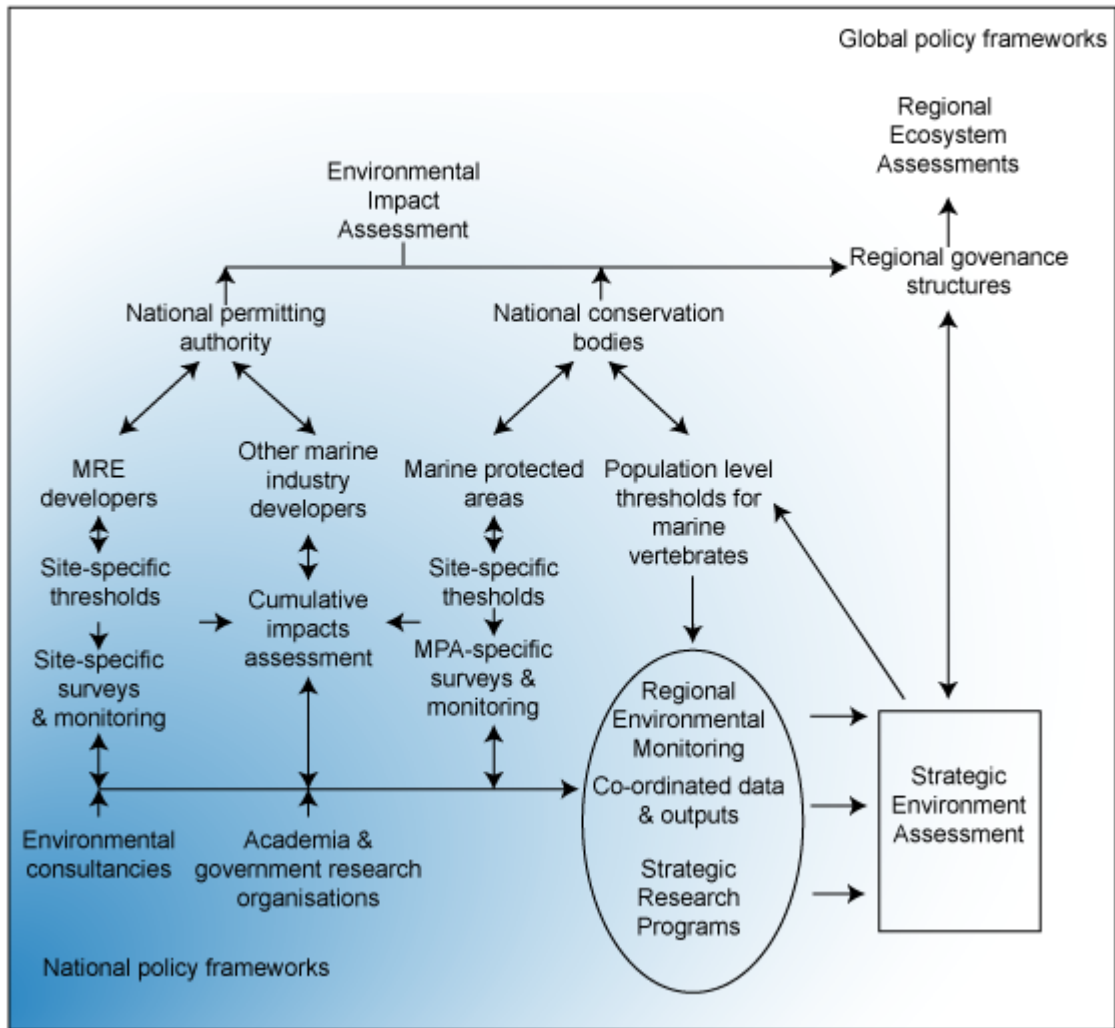
Fig 3.



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Fig 4.



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