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

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ABSTRACT

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

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Abbreviations:

CBD – (United Nations) Convention on Biodiversity

CI – Cumulative Impacts

DRIP – Data-rich, information-poor

EIA – Environmental Impact Assessment

EMF – Electromagnetic field

EMMP – Environmental Monitoring and Management Plan

ES – Environmental Statement

EU – European Union

MRE – Marine renewable energy

MRED – Marine renewable energy device

NGO – Non-governmental organisation

PCoD – Population Consequences of Disturbance

SDM – Survey, deploy and monitor

SEA – Strategic Environmental Assessment

1. Introduction

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

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

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

To date, test deployments of tidal-stream MREDs have taken place at a number of sites including the Pentland Firth, Strangford Lough and Ramsay Sound (UK), the Bay of Fundy (Canada), Cobscook Bay, Maine (USA) and Raz Blanchard (France). Several companies are currently developing commercial-scale projects but before consents are granted they will have to satisfy regulators with regard to the likely environmental impacts. National environmental legislation is often driven by high-level agreements, such as the 1992 UN Convention on Biodiversity (CBD), which calls for sustainable development and provides a framework for halting and reversing losses in biodiversity [8]. However, this raises the question of how negative environmental impacts should be balanced against wider positive outcomes. For example, the renewables industry and some researchers have argued that the local disruption associated with projects needs to be offset against the wider global benefits of reducing anthropogenic greenhouse gas emissions [9, 10]. Regulators on-the-other-hand usually take a ‘precautionary approach’ and focus almost exclusively on the potential negative impacts [11]. Some stakeholders have therefore argued for a more risk-based approach as exemplified by the Scottish Government’s ‘Survey, Deploy and Monitor’ (SDM) strategy [12]. However, the SDM guidance was designed for initial, prototype-scale projects and may be less applicable as developments scale-up [13]. Another alternative could be to adopt an adaptive management strategy, taking advantage of lessons learned from a gradual increase in deployment [12,14]. Whichever approach is chosen the debates around balancing ‘local impacts’ against ‘global benefits’ are heavily culturally contextualised and, despite international conventions such as the CBD, specific outcomes tend to depend on the relative values that societies place on ‘ecosystem’ versus ‘economic’ services at the local level [12,15-17]. The role of science is to provide the data on, and analysis of, the potential impacts so that decisions are well-informed, positive ecological benefits maximised and negative impacts minimised. Acceptable levels of impact therefore need to be defined by regulators (with scientific input and wider stakeholder consent) before new technologies, such as tidal-stream energy, enter the commercial “valley of death” which is the critical period between technology demonstration and market pull to full commercialisation [18]. Where such agreement is lacking, the large financial investments needed to move from ‘demonstration’ to ‘commercial’ scale may be adversely affected [11,19-21]. In a review of UK investors, Leete at al. [22] identified the predictability of regulations as being critical. Although the investors quoted in Leete at al. [22] were referring mainly to uncertainty around guaranteed pricing, further uncertainty and unpredictability in environmental consenting is also likely to lead to reduced investor confidence as tidal-stream MRE moves beyond the testing phase [14].

1.2. Requirements for environmental impact assessments

As in most other countries, developers in Europe are required to produce an Environmental Statement (ES) based on an Environmental Impact Assessment (EIA) before any project which might have significant impacts on the environment can commence [23]. The production of the ES/EIA typically involves collecting physical, biological and socio-economic data to establish baseline conditions, followed by consideration of the stressors the project will generate and their likely impacts on sensitive receptors[1] [24]. Regulators in Europe also

[1]Following 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

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

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

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

1.3. Purpose

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

2. Legislative requirements for baseline assessment and monitoring

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

In most jurisdictions which are actively pursuing MRE developers are required to undertake some form of EIA before deployment [47]. Broadly, an EIA presents evidence (baseline data gathered through site characterisation surveys, modelling, evaluation etc.) of likely environmental impacts following four steps: (1) Identification of the environmental changes which may result from the development and the features which may be affected; (2) Evaluation of the exposure risk and sensitivity of the receptors; (3) Evaluation of the impact significance in relation to the vulnerability and exposure risk of the features; (4) Identification of mitigation measures for any significant impacts identified and evaluation of the likely residual impacts [12,18,24]. In the EU, EIA is mandatory for large-scale developments, such as power stations, motorways, and bridges [23,48] but member states have discretion as to whether a full EIA is required for smaller developments (Annex II of the Directive)[2]. A further complication is that EU Directives have to be transposed into national law and implemented through national regulations. This process has led to differences in how the EIA Directive has been implemented between member states [25,49,50]. For example, in the UK any MRE project more than 1MW requires an EIA [24] whilst, in Germany there are no specific procedures to obtain consent for tidal energy projects and they are considered under the legislation developed for the offshore wind sector [47]. Globally there is also variation in the scale of projects which trigger mandatory EIA. For example, in Canada EIAs are only required for tidal energy projects more than 50 MW whilst in South Korea the threshold is even higher at 100 MW [47].

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

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

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

3.1. Pre-deployment and deployment impacts

Pre-deployment and deployment of MREDs will involve increased vessel movements and activities such as seismic surveys and drilling of anchor points. These activities will inevitably cause some physical disturbance, noise and increased turbidity but the construction phase will normally be quite short. Underwater noise is often identified as the main environmental concern during this phase with seismic surveys and pile driving being particularly noisy. Whilst many tidal-stream device designs will not require pile driving, 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].

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

3.1. Operational impacts

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

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

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

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

3.2. Impacts during decommissioning

Environmental impacts during decommissioning are likely to be similar to those during construction and deployment and are thus usually evaluated under a common heading. One difference between the phases relates to biofouling where the handling and disposal of potentially large amounts of biological material needs to be taken into account. Furthermore, the environmental issues around decommissioning are rarely properly addressed during project planning because an operational life of 20-30 years is envisaged. This lack of forward-planning is well illustrated by the present situation with regard to decommissioning of redundant oil and gas structures [76].

4. Overarching challenges of monitoring marine vertebrates

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

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

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

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

A wide variety of spatial behaviours, ranging from semi-permanent residency to basin-scale migrations, have been observed in the limited number of fish species whose movements have been studied in any detail in the wild [59,60,87-89]. Despite these insights, the spatial responses of fish to artificial structures remain poorly understood and there is continuing debate over whether such structures enhance fish productivity, or merely attract animals from surrounding areas [71,84,90]. Tagging has been widely used to study the dispersal and behaviour of fish and, under assumptions regarding differential mortality between tagged and un-tagged animals, rates of migration and tag losses, the technique can yield estimates of population abundance and mortality [91]. However, in the marine environment the underlying assumptions are often hard to meet unless the tagging program is well designed and covers a very large spatial area [92]. Inert plastic or metal tags are the cheapest to deploy but obtaining reliable data relies on the recaptures being accurately reported. Inert tags also only yield information on the initial and final dates and locations of capture (unless the fish are subject to catch and release angling). The problem of continuous monitoring and low tag return rates can be reduced by using satellite transmitting (pop-up) data storage tags but these are much more expensive than inert tags and can only be deployed on larger fish [87]. Very small data-storage tags capable of recording depth, temperature and light are now available and have been successfully used to study the movements and vertical behaviour of medium-sized fish, such as plaice and cod (*Gadus morhua*) [60,93-95]. These tags are expensive and data recovery relies on the tags being returned in sufficient numbers when the fish are caught either by commercial or recreational fishers. Larger fish can also be implanted with coded acoustic tags which can be detected using fixed telemetry stations. This technique is especially suited to monitoring residency and behaviour of fish within limited spatial areas [60,96,97].

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

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

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

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

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

Many marine vertebrates exhibit large spatial ranges and this complicates the evaluation of MRE development impacts on populations. The spawning, nursery and adult feeding areas of many species of fish are often spatially separated resulting in extensive seasonal migrations [87,117] whilst the largest species, such as basking sharks (*Cetorhinus maximus*), can range over thousands of kilometres [118]. Despite these large overall ranges, meta-population structuring may be relatively common in fish so that genetically distinct groups of adults will show more limited dispersal [119]. When stock abundance has been strongly reduced, for example by commercial fishing, the species range also usually contracts into a limited number of hot-spots [60]. Under these conditions mixing between sub-populations may be further reduced [120,121] so that present realised habitat distributions may only represent a fraction of potential habitat [122]. The high mobility of the majority of marine fish must also be considered in relation to potentially positive benefits which are sometimes claimed in relation to fisheries exclusions around MRE sites [128-130]. Research on no-take zones clearly suggests a strong negative relationship between benefits (measured as increases in fish abundance, average size or reproductive output) and mobility [131,132]. Most tidal-stream MRE development sites are thus likely to be too small to generate significant positive benefits. In addition, most of the energetic sites proposed for tidal-stream MRE development are not heavily fished using towed gear, in contrast to the larger-scale offshore wind-farms in areas such as the North Sea, where exclusion of fishing effort may have some positive impact [129].

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

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

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

- Animals may travel considerable distances to take advantage of resources at tidally-energetic locations. Although most current developments are small (typically less than 10 km^2), the spatial scale of the impact may be much larger, and thus beyond the means of individual developers to monitor adequately.
- The scales of movement exhibited by many marine vertebrates mean that trans-national boundary impacts must often be taken into account [24].
- Use of a site may be critical for breeding success. Both direct increases in adult mortality from device interactions and indirect reductions in foraging success could

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

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

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

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

The dynamics of marine vertebrate populations are also affected by multiple large-scale factors. Fluctuating recruitment success is well documented for many commercial fish species as a result of long time-series of stock assessments. In some cases it has been possible to link these fluctuations with regional–scale environmental factors [135-137]. Long-term climate change has also emerged as the most likely driver for shifts in the spatial and depth distribution of many fish species [138-140]. In the north-eastern Atlantic, the breeding success of some species of seabird and the body condition of harbour porpoises have both been linked with changes in their sandeel (Ammodytidae) prey, changes which in turn have been linked with large-scale, climate-related effects on the plankton [141,142]. Reduced breeding success in cetaceans has similarly been linked to large-scale factors, such as the accumulation of persistent organic pollutants biomagnified through the food-web [143]. Monitoring the abundance of vertebrates within small MRE sites (even using statistically robust designs) is therefore unlikely to shed much light on the specific causes of any observed changes in abundance at the population level, especially when the wider population is affected by other stressors operating outside of the development site [28].

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

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

4.5. Implications of vertebrate movements for assessing cumulative impacts

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

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

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

Before embarking on a potentially expensive monitoring programme, it is crucially important to agree on the required detection thresholds [14,27,152]. If the required detection thresholds[3] are not explicitly defined at the outset there is an immediate danger that sampling effort will be reduced to that which has been budgeted for, and below that needed to provide sufficient statistical power [45]. On the other hand, demands to detect unreasonably small levels of change in marine vertebrate populations will lead to un-affordable monitoring 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].

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

5. Discussion

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

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

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

A wide range of tidal-stream MRED designs are currently being developed which will all require research into their likely ecological impacts [9]. This situation is likely to improve over time through design consolidation and accumulation of knowledge regarding impacts [12,20,163] but, even after 25 years of development[4], significant problems have been identified in relation to environmental monitoring around wind-farms [27,28]. In theory post-deployment monitoring is supposed to (i) validate predictions made in the EIA or HRA (ii) to detect any unforeseen impacts and (iii) ensure compliance with agreed residual impacts following mitigation measures. Monitoring programmes therefore clearly need to be designed with specific pre-agreed detection thresholds, but this is often not the case [27,151]. Setting appropriate thresholds often requires a great deal of negotiation/consultation and potentially additional research including modelling of receptor population dynamics. Because of this developers cannot realistically be expected to decide on appropriate thresholds themselves, although this often seems to happen under present EIA arrangements [151]. To achieve more rational threshold setting will require a much greater focus on SEA [27] to allow strategic assessment of population level sensitivities and impacts (including cumulative impacts) and to trigger the research required to fill knowledge gaps [12,151]. This seems to be a particularly appropriate suggestion in relation to many marine vertebrate receptors where the impacts of MREDs potentially extend well beyond the local spatial scale, and the populations are likely to be affected by multiple developments and stressors. Having agreed thresholds, a clearer process for the design of baseline and post-deployment monitoring is needed that takes into consideration both the statistical power required [26,27,45], the economic costs of collecting the data, and how those costs should be partitioned between developers and the wider tax-base [12].

Based on observations from offshore wind-farms, complex interactions involving multiple trophic levels should be expected around and within tidal-stream MRED arrays. Effective monitoring will therefore need to be multi-disciplinary and such an integrated approach would also be consistent with ecosystem-based management, as opposed to a purely conservation approach focussing on the abundance of iconic and charismatic species [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.

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

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

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

Although much of the present effort in EIA is spent on trying to quantify the origin and extent to which marine vertebrates use or transit a tidal-stream MRE development site, we argue that it is probably more important to understand how the animals will interact with the MREDs [123]. There are numerous examples from marine natural resource management demonstrating the difficulties in moving from observed correlations between population dynamics and other factors. Such correlations can be spurious and are prone to breakdown unexpectedly unless they are supported by causal mechanisms [167-169]. In relation to tidal-stream MRE impacts the causal mechanisms can probably only be addressed through direct evidence and so much more research is required into how animals and devices actually interact [28]. Although pre-deployment modelling can provide some insights, direct observations using full-scale MREDs operating in the natural environment will be required. As long as there is some consolidation in device designs, results from such intensive studies should be more widely applicable, even if such studies are only conducted at a limited number of test sites. Because the benefits of such knowledge may accrue to other competing developers, it may be more reasonable to expect these fundamental studies to be funded at national or international level. Alternatively, tidal-stream MRE developers could collaborate to create research pools which would ultimately benefit the industry as whole, an example being the UK Offshore Renewables Joint Industry Programme (ORJIP).

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

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

6. Conclusions

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

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Figure legends

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

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

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

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

Fig 1.

(a) (b) (c) (d)

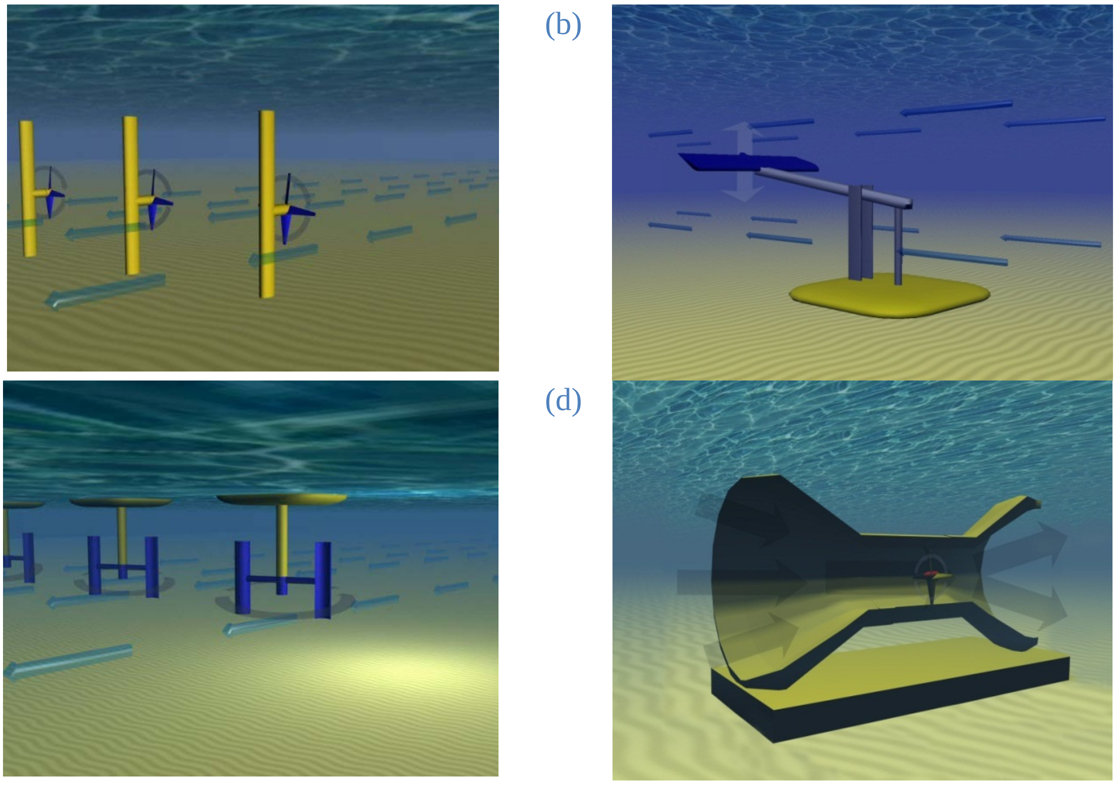
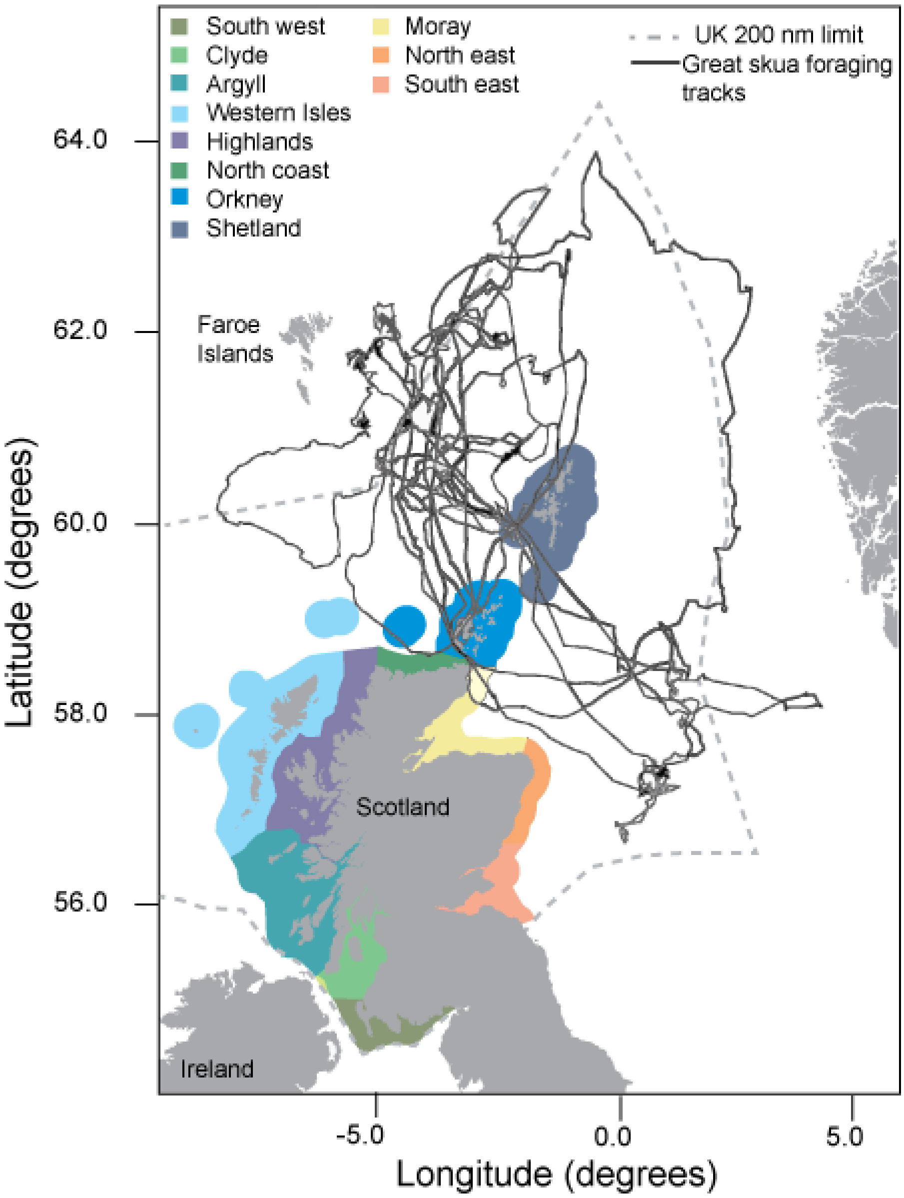


Fig 2.



South west
Clyde
Argyll
Western Isles
Highlands
North coast
Orkney
Shetland
Moray
North east
South east
UK 200 nm limit
Great skua foraging tracks
Faroe Islands
Scotland
Ireland
64.0
62.0
60.0
58.0
56.0
Latitude (degrees)
-5.0
0.0
5.0
Longitude (degrees)

1170

Fig 3.

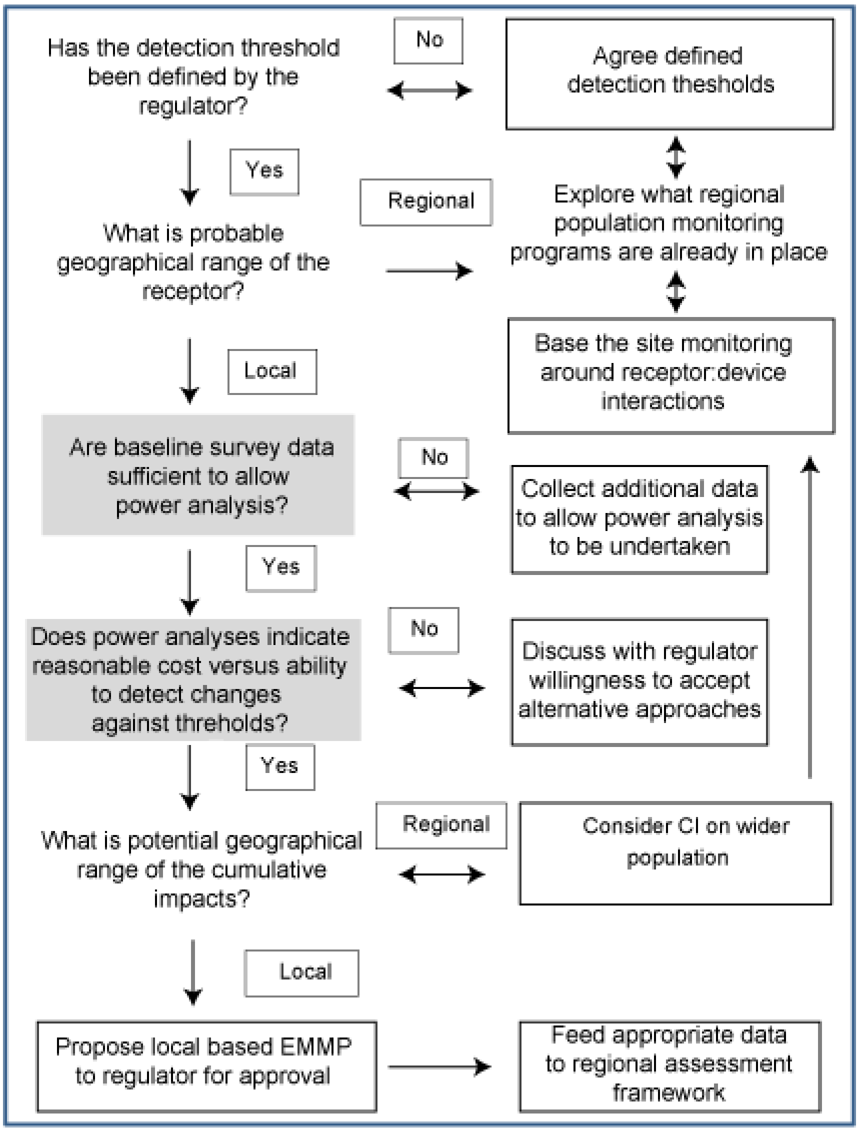


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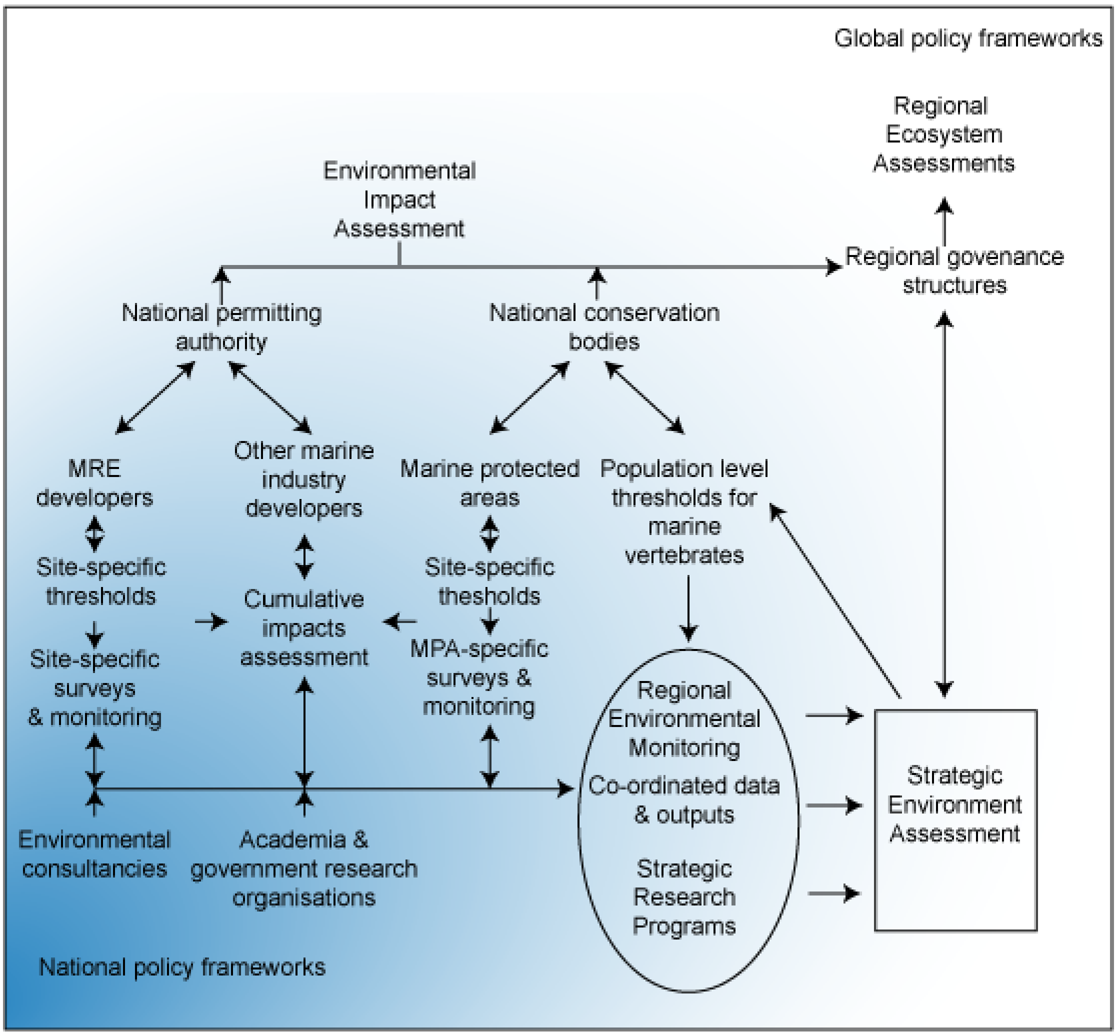
Fig 4.


Global policy frameworks
Regional Ecosystem Assessments
Environmental Impact Assessment
Regional govenance structures
National permitting authority
National conservation bodies
MRE developers
Other marine industry developers
Marine protected areas
Population level thresholds for marine vertebrates
Site-specific thresholds
Cumulative impacts assessment
Site-specific thesholds
Site-specific surveys & monitoring
MPA-specific surveys & monitoring
Regional Environmental Monitoring
Co-ordinated data & outputs
Strategic Research Programs
Strategic Environment Assessment
Environmental consultancies
Academia & government research organisations
National policy frameworks