Chapter S12. Adaptive Management Related to Marine Renewable Energy

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As the marine renewable energy (MRE) industry is rapidly ramped up from single devices to commercial-scale MRE deployments, developers and regulators will need evidence of the environmental effects of MRE to inform project development and consenting/permitting (hereafter consenting) processes. Uncertainty surrounding the potential impacts of novel MRE technologies on sensitive marine animals, habitats, and ecosystem processes means that even robust baseline environmental information cannot comprehensively address all pre-deployment knowledge gaps (Copping 2018). Tools and practical approaches are needed to help with the sustainable development of the industry. Adaptive management (AM), also referred to as learning by/while doing, enables projects to be deployed incrementally, despite uncertainty, in a way that prevents unacceptable harm to the marine environment. This chapter explores and suggests a pathway for applying a passive approach to AM for the consenting of single devices and array-scale MRE projects.

S12.1. INTRODUCTION TO ADAPTIVE MANAGEMENT

AM is best defined as an iterative management process that seeks to reduce scientific uncertainty and improve management through rigorous monitoring and periodic review of management decisions in response to growing knowledge gained from monitoring data (Copping et al. 2019, Williams et al. 2009). Monitoring is designed to address specific scientific questions and hence contribute to the wider scientific knowledge base, which can be used to amend decisions, refine policy, and improve consenting processes in light of new information (Le Lièvre 2019).

AM finds its origins in conservation and natural resources management (Holling 1978). It has been applied in a wide range of environmental contexts including biodiversity conservation (Cooney and Dickson 2005; Keith et al. 2011), water resource management (Pahl-Wostl 2007), commercial fishing (Walters 2007), and forestry and harvest management (Nichols et al. 2015). A recent review of AM practices in the wind energy sector reveals that despite the absence of a commonly accepted definition of AM, its conceptual attributes are progressively emerging to address onshore wind-wildlife interactions, especially impacts on bats and birds (Copping et al. 2016; Hanna et al. 2016).

From a procedural perspective, AM is a six-step cycle (Figure S12.1):

1) **Assess problem.** Conduct baseline monitoring and environmental assessment to assess the problem and define management objectives.
2) **Design management actions.** In the context of MRE, this refers to the design of the project proposals and mitigation plans, compensation, habitat enhancement measures, and monitoring – all which are informed by the environmental assessment.

3) **Implement the project.**
4) **Monitor.** Conduct follow-up monitoring to collect data after the project has been deployed.
5) **Evaluate.** Evaluate the monitoring results.
6) **Adjust.** Adapt management and monitoring methods and scope in light of what has been learned from observations. (Williams et al. 2009).

AM learning outcomes can be applied to a particular project (changes in monitoring design, mitigation, or compensatory measures), and the learning should provide information that supports planning policies and regulation of future MRE proposals—a learning process called “double-loop” or “institutional” learning (Figure S12.1).

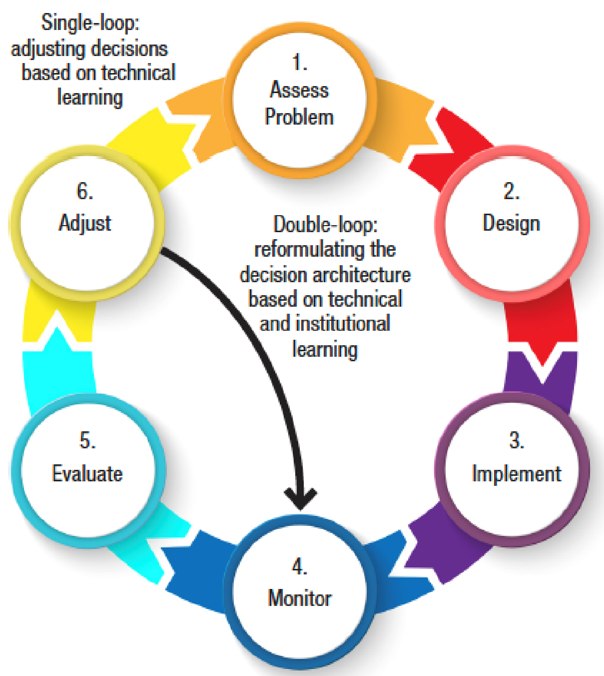

Figure S12.1. The adaptive management (AM) cycle. The original concept of AM concerned single loop learning, while later additions recognize the value of double loop learning, particularly to inform planning and siting for future MRE installations in a region. (Graphic by Robyn Rick. Adapted from Williams 2011a; Williams and Brown 2018)

These six steps occur in an iterative decision-making process based on a deliberative/set-up phase and an iterative phase (Williams 2011b). The set-up phase entails conducting an initial environmental assessment and preparing an AM plan. An AM plan should clearly frame the environmental problem in terms of impact predictions, choice of scientific models and identification of data gaps and uncertainties. An AM plan should be detailed, practical and be explicit on how uncertainty is to be responded to at all development stages. The key elements of an AM plan include measurable management objectives (e.g. conservation or mitigation goals), detailed monitoring programs and pre-defined management measures (i.e. mitigation, compensation or habitat enhancement). It is during the iterative phase that the project and associated management measures are implemented, monitored and evaluated against specified management objectives.

Monitoring in AM serves the purpose of validating impact predictions and evaluating the efficacy of management measures in achieving conservation or mitigation goals. Simply monitoring and adjusting monitoring/management measures in light of up-dated information is not sufficient to do AM. Under the DOI Technical Guide, AM entails exploring a range of management alternatives prior to development and operation to meet specific mitigation and conservation goals, predicting their outcomes based on available scientific knowledge, carefully implementing one or more of these alternatives, monitoring their effects and using the results to update knowledge and adjust management on this basis of monitoring feedbacks (Williams et al. 2009). Management interventions are to be adjusted until monitoring shows that the specified mitigation or conservation objectives are achieved.

Stakeholder involvement is a crucial element of adaptive management. Participative decision-making generates learning outcomes that extend beyond the scope of science (Fujitani et al. 2017). Stakeholders should be involved early in the AM cycle to help assess environmental problems, contribute to the collection of local knowledge, design management actions in terms of mitigation and monitoring activities, and participate in the evaluation of monitoring results (Williams and Brown 2013).

A distinction is made between active and passive AM (Williams 2011a). Active AM designs and applies management actions as experiments or "testable hypotheses" (Walters 1986) to reduce uncertainty and accelerate understanding of ecological processes. This means that certain management decisions may be put at risk in order to learn about receptors' responses to particular actions. Conversely, passive AM lacks testable hypotheses and focuses on monitoring the effects of management measures to reduce uncertainty and determine whether adjustments are needed to achieve specific mitigation objectives. In most jurisdictions, environmental legislation and regulations may not allow experiments involving the deliberate risk of causing mortalities, physical injury, or disturbance of marine animals for the purpose of learning. While passive AM may have a more limited capacity for reducing uncertainty about the mechanisms that cause impacts, at larger deployment scales passive AM may provide a more balanced approach to understanding risk, particularly in relation to protected species where AM needs to be reconciled with the precautionary principle. Passive AM accounts for scientific uncertainty and provides new observational data to learn about the effects of management and generate informative approaches and methods for future MRE projects. As such, it may be particularly useful for increasing global understanding of the effects of MRE technologies and evaluating the effectiveness of monitoring and mitigation actions, thereby allowing for feedback loops and learning for the subsequent deployment phases of specific projects or decision-making for future developments.

S12.2. IMPLEMENTING ADAPTIVE MANAGEMENT IN AN MRE CONTEXT

Not a new concept, AM has been used in other natural resource management situations (Copping et al. 2019; Williams 2011a, 2011b; Williams and Brown 2014) and holds promise as a useful tool to support the consenting of MRE projects when the environmental effects are not well understood. It can be used to avoid unacceptable effects through its systematic and iterative approach of learning by doing and adapting as you learn. While monitoring results collected from single devices may help predict the effects of larger arrays, most environmental interactions may not be properly understood until multiple devices are actually deployed and monitored in real sea conditions (Copping 2018). An AM approach is therefore likely to be needed to address the risks and uncertainties associated with larger commercial arrays and their potential incremental effects on marine ecosystems.

S12.2.1. THE USE OF ACCEPTABLE IMPACT THRESHOLDS IN ADAPTIVE MANAGEMENT

AM can incorporate decision triggers such as thresholds to help guide implementation. To date, thresholds of acceptable change/harm are more commonly used in the pre-consenting phase to define the acceptability of projected wind farm impacts on seabird populations (Green et al. 2016). Where thresholds are introduced to inform consenting processes, AM is rarely implemented post-consent to refine their accuracy and adjust mitigation actions and monitoring accordingly. In some cases, comprehensive monitoring around consented OWFs did not exceed three years following construction (Ashley et al. 2014).

Taking an AM approach based on thresholds requires definitions of acceptable and unacceptable risks. Three types of thresholds are commonly distinguished: ecological, utility and decision thresholds. Ecological thresholds are values of ecosystem state variables at which a small change will trigger a shift in the system dynamics (Nichols et al. 2015). Utility thresholds are values at which a substantial change in management objectives will occur (Copping et al. 2018; May 2019; Sinclair et al. 2018). Decision thresholds are the set of conditions that should prompt specific management actions (Copping et al. 2018; McDonald and Styles 2014; Sinclair et al. 2018). These thresholds are derived from both ecological and utility thresholds and may also be informed by regulatory conservation objectives. Linking the iterative phase of AM to decision thresholds that are tied to rigorous monitoring data may provide a relevant evidence-based management approach to operate wave and tidal energy farms in the face of remaining scientific uncertainty while protecting biodiversity. This approach, also referred to as threshold-based or trigger approach to AM, allows for iterative adjustment of project operations and mitigation practices as new empirical data collected through routine monitoring indicate that an acceptable threshold of change or impact on a particular receptor is being approached. Regulatory decision-makers can thus authorize new developments despite remaining scientific uncertainty and review consenting conditions on the basis of monitoring data with the goal of avoiding pre-identified thresholds of acceptable change/harm.

At the project level, thresholds of acceptable change or harm are the maximum degree to which a proposed development can alter the receiving ecosystem. Project-specific thresholds can determine the safe operating conditions within which MRE developments can be approved and operated, despite uncertainty, without causing unacceptable harm to valuable receptors/features. For sensitive receptors, thresholds or limits of acceptable change/harm should draw on statutory conservation objectives. Acceptable thresholds should be formulated as values to be avoided throughout the lifecycle of a consented project.

In the initial set up phase, development consent is normally contingent upon developer, regulator and an independent advisory body agreeing upon the content of an AM plan. The AM plan is designed to ensure that the potential effects on particular receptors are properly understood and do not exceed acceptable thresholds of change/impact. Developers and regulators should have a clear understanding of the mitigation/conservation objectives they intend to achieve before authorizing the implementation of a project. In this vein, AM plans should be as detailed as practical and be explicit on how uncertainty is to be responded to at all development stages. If information from routine monitoring shows that the level of an effect or change is likely to cause an unacceptable impact, corrective mitigation actions should be taken. On the other hand, if the monitoring data indicate that risks have been overestimated during the consenting phase, monitoring and mitigation requirements may then be reduced and progressively removed in subsequent management decisions.

The specifics of the framework have to be adapted to each receptor and the impact pathways of each technology. Collision risks are predominantly an issue for devices with exposed rotor blades such as tidal energy turbines. On the other hand, disturbances from acoustic noise, electro-magnetic fields and/or barrier effect of multiple turbines or devices are common issues to all types of technologies deployed in arrays. The nature of impacts, either direct/lethal (i.e. collision, entanglement, hearing damages) or indirect/non-lethal (e.g. disruption of behavior and changes in animal's physiology) determines the nature of thresholds of acceptable change/impacts as well as relevant indicators for threshold detection in monitoring programs. With respect to lethal impacts, if one considers that every collision leads to injuries and death, then a decline in population trajectory is expected to occur. Here, the threshold of acceptable impact can be formulated as a maximum level/number of mortalities from collisions that a species population can sustain without adversely impacting upon its stability.

Regarding non-lethal impact, the process is more complex. Displacement of animals may have chronic effects on health and survival (vital rates) if animals expend more energy to avoid the source of disturbance or reach alternative and potentially less profitable habitats (Nabe-Nielsen et al. 2014). Similarly, Permanent Threshold Shifts (PTS) or Temporary Threshold Shift (TSS) resulting from exposure to acoustic noise may alter animals' vital rates if it reduces an individual's capacity to detect their predators, locate their mates and capture their prey (King et al. 2015). If a sufficient number of animals are exposed, this may affect demographic rates and lead to population decline. In the context EU Natura 2000 species, if the population declines, a significant effect on Natura 2000 sites' conservation objectives and hence, on the integrity of these sites will occur. In this context, acceptable thresholds of change may be formulated as, for example, 1) a maximum level of animal displacement above which an animal's energy intake and vital rates will be adversely affected; 2) maximum thresholds of habitat loss, 3) maximum decrease in prey availability as a result of project disturbance; 4) maximum levels of underwater noise above which acoustic disturbance is projected to cause PTS or TSS.

Threshold levels for lethal and sub-lethal impacts are rarely prescribed in policy or regulations and, as such, must be determined on a case-by-case basis, for example through the examination of species conservation status (Le Lièvre et al. 2016). Both lethal and sub-lethal effects such as changes in animal behavior, density, and distribution are extremely challenging to measure because of the difficulty to confidently measure direct mortality and monitor population changes. Identifying and detecting the metrics of concern with the necessary levels of accuracy to inform management decisions is even more difficult to determine with certainty. Population models that seek to translate sub-lethal impacts to population-level consequences can be applied to MRE developments, but they may not always help identify the appropriate metrics to monitor. Uncertainty and the lack of consistent methods for detecting and estimating acceptable impacts or thresholds are significant limitations to the use of thresholds/triggers in AM (Johnson 2013).

The need to develop and adapt modeling approaches and tools that can ascertain thresholds relevant to wave and tidal energy farms has been identified as a high research priority for addressing consenting risks (ORJIP Ocean Energy 2017). Statistical and modeling approaches to assess risks at the population level exist and may well be used to identify impact thresholds in AM plans. Potential Biological Removal (PBR) was applied, as part of the AM of the DeltaStream tidal energy turbine, to determine acceptable thresholds of collision-related mortalities for marine mammal. (Sparling et al. 2017). Other methods include Limits of Acceptable Change (Stankey et al. 1985) and Population Viability Analysis modeling approaches such as Population Consequences of Disturbance (iPCoD) (King et al. 2015). As an interim approach, iPCoD is subject to significant data limitations and as such, heavily relies on expert elicitation to inform its parameters (Donovan et al. 2016). A variety of population modelling approaches are also employed to estimate impacts on seabird populations (Cook and Robinson 2017). Impact thresholds that have been derived from these modelling tools have been criticized for being inadequate, arbitrary and grounded in poor empirical basis (Green et al. 2016). Progress in scientific methods and modelling tools may progressively increase the levels of confidence necessary to authorize future arrays of wave and tidal energy devices under an AM approach. Approaches like iPCoD may be well suited to an AM scheme where expert opinions would be progressively replaced by new observational and empirical data from monitoring, thus increasing the precision and accuracy of modelling outputs (Christiansen et al. 2013; Lusseau et al. 2012). New empirical data must be used to refine acceptable thresholds and review monitoring and project operations accordingly (Cook et al. 2016).

Conservative thresholds will help reconcile AM with the precautionary principle and assure that actions are taken before an unacceptable impact occurs. However, at a larger development scale, unfavorable progress toward thresholds may not be detected in time and remedial actions may fail to effectively respond and avoid unacceptable impacts on sensitive receptors. AM-based thresholds may be more appropriate for the early (smaller) scale of the wave and tidal energy sector where project-led monitoring focuses on understanding device-specific stressor-receptor interactions such as collision risk. As the industry moves to commercial deployment, taking an AM approach would be more acceptable if it were implemented through staged consenting processes, whereby projects are deployed in stages, starting with small numbers of devices or a small spatial area, with subsequent expansion being dependent on monitoring findings. Monitoring should provide meaningful evidence showing that the effects of the larger-scale deployments are properly understood, prior to approving any subsequent phases.

S12.2.2. MITIGATION OF RISK

If an MRE development is likely to adversely affect the marine environment, the mitigation hierarchy of the precautionary principle should apply. The mitigation hierarchy is a cautious approach to decision-making that consists of taking a sequence of steps to avoid, reduce, and minimize potential negative impacts and, as a last resort, to compensate for any residual impacts (Figure S12.2) (Elliott et al. 2019).

As a learning process, the success of AM is contingent upon the capacity of medium/long-term monitoring programs to provide meaningful information to inform responsive management/mitigation actions. The temporary nature and severity of impacts associated with construction works may restrict the possible degree to which construction noise mitigation measures can be adapted on the basis of monitoring results. A key example is the underwater noise from seismic surveys and pin-piling for the installation of devices. Thomsen et al. (2015) argue that construction sound levels in array projects could be similar to wind farms if pile-driving is used. Many devices will, however, not require pile-driving, but drilling. The drilling of anchor points and armoring of cables using concrete mates and rock-dumping may also generate harmful noise levels (ICES 2019). The prescription of one-time noise mitigation measures may be preferable to maintain construction noise below allowable thresholds of impulsive noise. Several warning systems available for offshore wind farms are transferrable to wave and tidal energy farms (Lüdeke 2018), for example:

- Deterrent devices and ‘soft start’ allowing animals to leave the area before maximum noise levels are reached
- Monitoring of exclusion zones to delay piling operations
- Bubble curtains and hydro sound dampers
- Restriction of vessels operation and installation works to specific duration windows
- Spatial separation distance with sensitive areas.

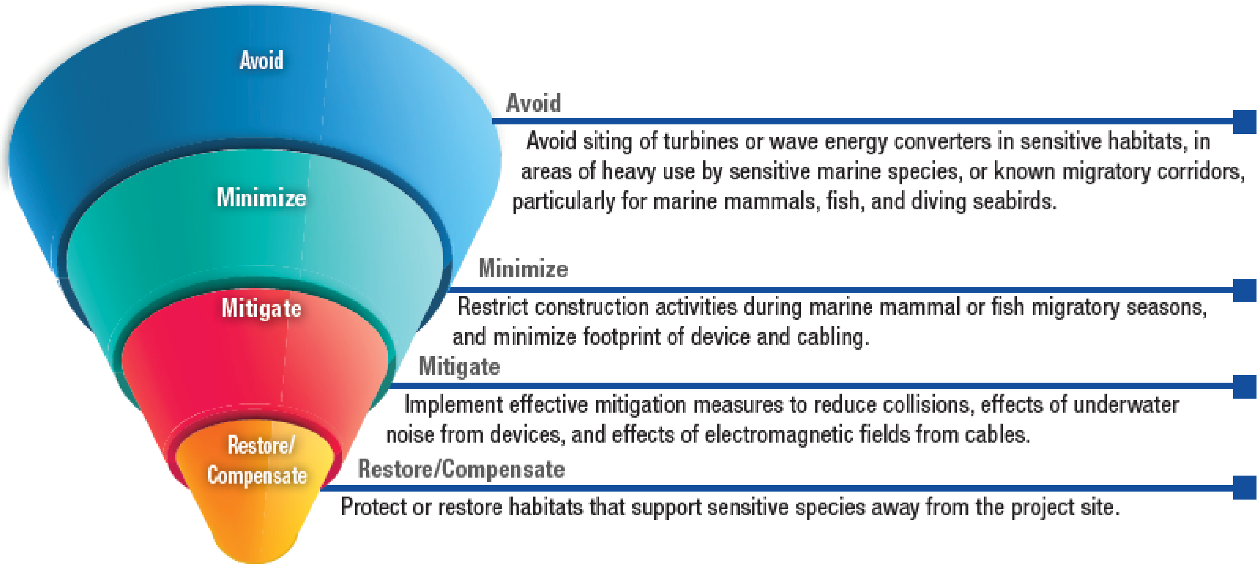

Figure S12.2. The mitigation hierarchy. The mitigation hierarchy is used to avoid impacts when possible, minimize remaining impacts, mitigate to diminish impacts, and provide compensation for unavoidable impacts. (Graphic by Robyn Ricks. Adapted from Elliott et al. 2019)

Seasonal restriction of pile-driving activities is also a reliable option in the presence of protected species. Some of these techniques may work well as part of an AM approach where construction works are temporarily paused on the basis of marine mammals sighting by marine mammal observers (MMOs) or detection through passive acoustic monitoring (PAM). On-site and off-site habitat enhancement measures, including creation of favorable conditions for artificial reefs or sand supplementation (Levrel et al. 2012; van Hees 2018), may also be envisaged as part of AM to compensate for the loss of suitable habitats or address residual impacts resulting from changes in hydrodynamics and sediment regime.

No matter what mitigation measures are taken, applying the mitigation hierarchy to AM would provide a prescribed approach for addressing unacceptable impacts that may materialize as a result of data gaps, uncertainties or imperfect monitoring design. If rigorously designed, AM offers an opportunity to correct scientific mistakes, thereby ensuring that best scientific knowledge is relied upon at each level of the mitigation hierarchy (Köppel et al. 2014). As such, AM should not be envisaged as an alternative to the mitigation hierarchy. Instead, AM supplements the mitigation hierarchy by providing an evidence-base to assess the efficacy of mitigation measures, learn from experience and inform more effective and proportionate mitigation requirements in current and future developments (Copping et al. 2019). As more data is gathered through continuous monitoring, the role of AM should focus on reducing uncertainties and progressively removing mitigation constraints where monitoring results indicates that it is appropriate to do so.

Although the mitigation hierarchy provides a prescribed approach for reducing impacts, it may not reduce uncertainty and facilitate learning as emphasized by AM principles (Hanna et al. 2016). In the face of data gaps and uncertainty, the mitigation hierarchy may instead result in the continuation or reinforcement of mitigation or compensatory measures throughout the project, thereby hampering the generation of useful science for regulatory decision-makers. Conversely, the purpose of AM is to reduce scientific uncertainty through an iterative process of environmental monitoring and adjustment of management actions. As rightly observed by Hanna et al. (2016), “striking the appropriate balance between mitigating and compensating for potential impacts versus detecting change is a dilemma with which regulators and industry must concern themselves if they are to develop AM approaches that meaningfully reduce scientific uncertainty".

AM and the mitigation hierarchy are not incompatible and can be reconciled. The mitigation hierarchy offers a prescribed approach for addressing unacceptable impacts that may materialize as a result of data gaps, uncertainties, or imperfect monitoring design in an AM process. As more data are gathered through continuous monitoring, the iterative phase of AM provides a mechanism for evaluating the effectiveness of mitigation and compensatory measures, learning from experience, and informing a more effective mitigation toolkit for future developments (Hanna et al. 2016).

Practically speaking, for single devices or small arrays, mitigation takes the form of post-deployment monitoring and feedback mechanisms as integral parts of the project design. At the large development scale, mitigation measures must be considered and, in some cases, implemented from the beginning of the project and not solely when monitoring data indicate an undesirable trend toward impact thresholds. At the top of the mitigation pyramid (Figure S12.2), impacts may be avoided through technology choice and/or by means of well-informed designated development areas for MRE projects within an overarching marine spatial plan. This technique, also known as macro-siting, may not always be feasible where sites with MRE resources correspond to biodiversity hotspots and protected sites. In these cases, the focus of mitigation in AM should be to assure that the impacts of consented MRE projects are reduced and mitigated to acceptable levels. Mitigation measures may consist of spatially arranging the MRE device layout, a mitigation measure also known as micro-siting or smart device positioning.

Curtailment and shut-down protocols have been tested in combination with AM to mitigate and reduce the uncertainty surrounding collision risks with marine mammals (Copping et al. 2016; Fortune et al. 2017). Where no collision events are allowed to occur, curtailment could limit the ability of AM to reduce uncertainty and could be poorly suited to undertaking AM. However, the approach taken by SeaGen (Section S12.4.2) shows that, despite strict protection of species for which zero tolerance of loss is acceptable, AM may still be employed to decrease uncertainty about collision risks by progressively reducing the precautionary shut-down perimeter of a tidal turbine from an excessive distance of 200 m to less than 30 m. Curtailment and temporary shutdowns of turbine operation may be overly restrictive in addition to being technically difficult to implement for certain turbine designs. Likewise, these measures are arguably insufficient to address all negative impacts, especially those resulting from displacement and disturbance-related habitat loss or changes in the physical system.

12.2.3. POST-INSTALLATION MONITORING

Creating a successful AM scheme is highly contingent upon the design of monitoring programs that are sufficiently well designed to detect changes, as well as management triggers that can meaningfully inform regulators (Le Lièvre et al. 2016; Wiesebron et al. 2016). AM also requires a consenting regime that has the flexibility to encompass such an approach if it is being used as a tool to enable deployments in areas in which the knowledge base is incomplete. Post-installation monitoring is generally required by regulators to validate model predictions in environmental assessments. In the context of AM, the primary purpose of post-installation monitoring is to provide an evidence base for reducing the scientific uncertainty associated with impact assessments and for informing decision-making related to future MRE proposals (Bennet et al. 2016). In addition, monitoring serves the purpose of 1) validating model predictions against empirical observation; 2) assessing the efficacy of mitigation in avoiding that pre-determined thresholds of change or impacts; 3) integrating new data to refine thresholds accuracy and 4) determining whether additional mitigation or modification in the project operational scheme are required to address predicted or unforeseen impacts (Hawkins et al. 2017).

Monitoring is not only necessary at the project level; it is also critical as part of a double loop learning process to support more effective licensing decision-making for future MRE developments. Monitoring activities often follow the before-after-control impact (BACI) methodology to account for changes prior to installation (baseline monitoring), during the construction and during the operational phase of a project. Indicators and early warning triggers for threshold detection in monitoring must also be rigorously defined. Careful consideration of the mechanisms by which the risks associated with MRE projects may have meaningful biological effects on animals' health, fecundity and survival (vital rates) is necessary to identify key monitoring indicators/variables (Hawkins et al. 2017). In population-impact assessments, monitoring indicators/variables should be those for which there is sufficient understanding of cause-and-effect relationships between measurable effects (e.g., collision, displacement, behavioral changes) and animals' vital rates (Hawkins et al. 2017). With respect to behavioral changes, the process is particularly complex in that it implies quantifying the magnitude of animals' dose-responses above which there will be meaningful effects on animals' vital rates.

Poor monitoring precision produces inaccurate evidence leading to inappropriate management decisions. If the statistical power of monitoring data is too low, regulators may make decisions believing that monitoring indicates no change beyond their thresholds of tolerance (Le Lièvre et al. 2016). Monitoring programs will yield more useful information if a question-directed approach is used and data collection methods are designed to answer well-defined and hypothesis-driven environmental questions (Copping et al. 2019). A question-led approach to monitoring will help design surveys that provide useful data for validating model predictions and supporting AM processes (Hanna et al. 2016). Question-directed monitoring also may help address the problem of Data-Rich Information Poor (DRIP), i.e., an undesirable situation in which, despite extensive data collection in the field, post-consent monitoring results do not provide useful information that can be used to reduce scientific uncertainty (Ward et al. 1986; Wilding et al. 2017). This is crucial because DRIP monitoring undermines the success of AM and, in turn, the confidence regulators have in the process. It is increasingly accepted that targeting project-led monitoring on site-specific stressor-receptor interactions will allow for available resources to be rationalized on those changes or impacts that can be effectively detected at the project scale with sufficient statistical power (Fox et al. 2018), thus "turning off" the problem of DRIP (Wilding et al. 2017). Population impacts in AM may be best addressed at a strategic level, through strategic environment assessments, using data from multiple projects over appropriate ecological scales.

To date, the application of AM has been primarily directed at reducing uncertainty about the near-field effects of single or limited numbers of MRE devices and their moving parts. Post-consent monitoring has mainly been implemented to determine whether collisions occur, hence monitoring is not necessarily designed to follow a BACI approach. For larger array-scale deployments, the MRE industry may benefit from applying more systematic BACI studies whereby changes in receptors of value to stakeholders are monitored prior to installation, during construction, and during operation of an MRE project (Bennet et al. 2016; Magagna et al. 2012). Embracing a BACI or similar monitoring design will be useful in framing relevant monitoring questions and evaluating changes in response to installation and operation of multiple devices.

AM includes other actions beyond monitoring. For individual projects, additional information gained through single-loop learning may not be sufficient to reduce uncertainty about population impacts and may not deliver the full benefit that AM has to offer to the MRE sector. Small-scale MRE projects sited in areas where marine animals are widely dispersed will significantly complicate the evaluation of impacts on populations at the individual project level (Fox et al. 2018). By adopting a bottom-up approach where data gained from multiple projects feed into broader marine governance processes through, for example, strategic environmental assessments and strategic research studies supported by government bodies, it may be possible for monitoring to yield additional information, thereby enabling greater regulator confidence and supporting risk retirement during future consenting processes. The MRE sector will particularly benefit from the double-loop learning cycle of AM (Jones 2005) in which lessons learned from past and current projects can inform collective AM for future planning of MRE projects and scientifically informed licensing decisions. In principle, double-loop learning in AM may fill many data gaps, allowing developers to save significant time when developing detailed environmental assessments to inform consenting. This will, however, only be possible if monitoring data and methods for data collection, analysis, and presentation are consistent and shared at the appropriate level (Copping 2018).

S12.3. ADAPTIVE MANAGEMENT AND THE PRECAUTIONARY PRINCIPLE

The precautionary principle involves several key components in environmental science: preventive action in the face of uncertainty; shifting the burden of proof to the proponents of an activity; exploring a wide range of alternatives to possibly harmful actions; and increasing public participation in decision making (Kriebel et al. 2001). In many jurisdictions, the sitting and consenting of MRE projects is regulated by the precautionary principle in an attempt to avoid and minimize potential adverse impacts on marine biodiversity (Bulling and Köppel 2016).

The universal acceptance of the precautionary principle was sealed at the 1992 UN Conference on Environment and Development (Principle 15, Rio Declaration). Since then, the precautionary principle has been incorporated in various environmental law treaties, conventions and soft law instruments. Implementing AM within the bounds of the precautionary principle demands rigorous procedural safeguards and a commitment to communicate uncertainty with transparency. AM cannot be used to offer unbounded discretion to decision-makers. Likewise, AM cannot substitute for demonstrating that substantive legal and regulatory conservation standards will be met throughout the lifespan of MRE projects.

The interplay between AM and the precautionary principle is ambiguous. AM has sometimes been described as a concept countering the "paralyzing effect" of the precautionary principle (Pembina Institute v. Canada 2008). Moyle notes that an exclusive focus on avoiding risks makes the precautionary principle extremely timid: "the fear of a loss ignores the potential conservation benefits that may be gained from different strategies" (Moyle 2005). More pragmatic views see AM and the precautionary principle as complementary approaches in biodiversity conservation (Cooney 2006; Morgera 2017; Raitanen 2018). AM has also been advanced as necessary to "correct the bias of precaution towards no action in the face of uncertainty" (Tarlock 2014). The rationale behind the principle is that scientific uncertainty about the gravity or probability of a potential environmental threat or impact shall not be used as a reason for postponing the adoption of preventive actions (May 2019). The primary way the precautionary principle has been applied to MRE, albeit with different degrees of intensity, is through the mitigation hierarchy of avoidance, reduction, minimization and compensation (Figure S12.2).

While application of the precautionary principle provides a rational approach to avoiding irreversible harm, its implementation through the mitigation hierarchy offers reduced flexibility for addressing scientific uncertainty and promoting iterative learning for future developments. Regulators are faced with an uncertainty paradox, i.e., a paradoxical situation in which regulators take a precautionary approach, requesting an extensive amount of data and information from developers to understand the risks, but the data, in turn, cannot deliver decisive evidence to meet the requested level of certainty (van Asselt and Vos 2006). While the monitoring of single devices may help understand the incremental effects of sizable arrays, the 2016 State of the Science Report stressed that it is unlikely risk will scale in a simple linear fashion as the number of devices increase (Copping et al. 2016). Relying on the precautionary principle alone could lead to situations in which developers and regulators will never understand whether the perceived negative interactions of MRE technologies really exist and, if they do, how they can be resolved and minimized efficiently for future projects (Copping 2018; Todt and Luján 2014). The purpose of the precautionary principle is the use of rigorous science to prevent unacceptable harm to marine life. Critical to the achievement of rigorous science is the flexibility to integrate scientific methods and data outputs into regulatory decision-making (Tickner and Kriebel 2008). AM may play an important role in the application of the precautionary principle, while working to reduce uncertainty and provide early warnings of adverse effects on marine receptors.

Complementing the application of the precautionary principle with AM is increasingly accepted as a best practice for delivering proportionate and risk based MRE consenting (Köppel et al. 2014; Le Lièvre 2019). In most nations, reliance on the precautionary principle is subject to the principle of proportionality, which, in simple terms, requires that measures adopted on the basis of precaution must be proportionate to the perceived level of environmental risk. As such, it is generally accepted that precautionary measures should be of a temporary nature pending the availability of additional scientific evidence (Gillespie 2013). As new data are gathered through continuous monitoring, the intensity of monitoring and mitigation requirements should be proportionally responsive to the extent and probability of the environmental threat (Trouwborst 2006).

The use of AM allows for provisional decisions to be made despite uncertainty and responds to knowledge deficits by constantly monitoring and re-evaluating the mitigation initially considered appropriate on the precautionary basis. When viewed in this context, AM has an important role to play, within the confines of precaution, for characterizing complex ecological risks and providing early warnings of adverse effects on sensitive features. Follow-up monitoring provides an opportunity to validate model predictions and correct scientific mistakes made in consenting processes, thereby ensuring that best available science is relied upon at all development stages. As such, rigorously structured AM could be implemented as a compliance mechanism whereby the effects of MRE projects are continually monitored and adjustments are made in responses to specific circumstances in order to ensure adherence to relevant environmental legislation and biodiversity protection standards (Craik 2020). The precautionary principle in turns serves as a constant reminder of the limits of science and informs interim mitigation actions until more complete scientific evidence become available from monitoring. As new data is gathered through environmental monitoring, the intensity of monitoring and mitigation activities should be proportionally responsive to the gravity and probability of the threat. As such, AM may be viewed as a good practice for applying proportionate precautions and risk management to MRE consenting.

Implementing AM while adhering to the precautionary principle demands the use of rigorous procedural safeguards and a commitment to communicating uncertainty with transparency. AM cannot be used to offer unbounded discretion to decision-makers. AM should not be proposed without any degree of certainty that mitigation measures will be effective. Likewise, AM cannot substitute for demonstrating that substantive legal and regulatory conservation standards will be met throughout the lifespan of MRE projects. The conditions under which AM is acceptable depend on the form of AM and the strength of the application of the precautionary principle in the jurisdiction in which the consenting is taking place.

AM has already achieved some success in judicial review in North America. In 2016, the Supreme Court of Nova Scotia has for example allowed the deployment of two demonstration tidal energy turbines on the grounds that, despite the existence of gaps in baseline data, the AM approach was not adopted as a 'bureaucratic convenience' but as a practical response to address these uncertainties (Bay of Fundy Inshore Fisherman's Association v. Nova Scotia (Environment) 2016). In the United States, Federal Courts have come forwards with a set of legal standards that AM must satisfy to comply with the no jeopardy clause of the Endangered Species Act and the least practical adverse impact standard of the Marine Mammals Protection Act. Federal Courts have made a strong case against a trial and error approach to AM (or AM-lite) (Fischman and Ruhl 2015). This approach is considered as a "watered down" version of AM in which "management objectives are loosely defined, monitoring protocols are vague and management actions triggered by monitoring thresholds are not clearly detailed" (Frohlich et al. 2018). AM-lite is a form of ad hoc contingency planning, which offers greater flexibility and discretion to approve developments with uncertain impacts and holds little promise to meaningfully reduce scientific uncertainty through structured AM and monitoring (Nie and Schultz 2012). Monitoring programs, mitigation measures and their associated monitoring triggers must be clear, non-discretionary and enforceable for AM to survive judicial scrutiny (Benson and Schultz 2015). All these elements must be agreed upon in the set-up phase of AM plans. If a threshold of unacceptable change or harm is threatened, competent authorities must be bound to take corrective mitigation measures. Mitigation measures must be 'reasonably specific, certain to occur and capable of implementation' (Centre for Biological Diversity v. Rumsfeld 2002; Natural Resources Council v. Kempthorne 2007; Pacific Coast Federation of Fishermen's Association 2008). Competent agencies must also demonstrate a clear commitment to act in the face of new scientific evidence (National Wildlife Federation v. National Marine Fisheries Service 2008). These judicial requirements have been repeatedly endorsed in AM litigations including in judicial reviews involving permissions for onshore wind farms (Animal Welfare Institute v. Beech Ridge Energy LLC 2009).

The Supreme Court of New Zealand has also elaborated its jurisprudence on AM in cases involving marine consents for seabed mining and aquaculture farms. The Court has developed judicial standards that broadly reflect those adopted in the American case law. Before an AM approach can be considered as part of a development consent, there must be an adequate evidential foundation providing reasonable assurance that the AM approach will achieve its goals in reducing uncertainty and mitigating any remaining risk. The extent to which AM process will be effective in reducing risks and uncertainty constitutes the vital part of the test when evaluating the consistency of AM with the precautionary principle. The ability of an AM regime to deal with risk and uncertainty is assessed in light of the following factors: 1) good baseline data on the receiving environment must be available, 2) consent conditions must provide for effective monitoring using appropriate indicators, 3) appropriate thresholds are set to trigger adaptive responses before the effects become overly damaging; and 4) the effects that might arise can be remedied before they become irreversible (Sustain our Sounds Incorporated v. The New Zealand King Salmon Company Ltd 2014).

A distinction has been made between prescriptive and flexible AM (Copping et al. 2019) as described in Table S12.1 below. Flexible AM has been predominantly used to address uncertainty about the interactions of single devices that have negligible adverse effects on marine features. At the scale of larger arrays, the value of using prescriptive AM lies in its capacity to incorporate new monitoring feedback into decision-making, while providing regulators with a degree of certainty that corrective mitigation measures will be taken before acceptable thresholds of change or disturbance are exceeded (Hanna et al. 2016). Hanna et al. (2016) also point out that this latter approach would provide developers with greater certainty about the costs of implementing AM. AM may still be used flexibly in larger developments to provide the regulator with a safeguard for prohibiting further deployment phases until specified corrective actions have been taken.

Table S12.1. Prescriptive and flexible adaptive management (AM).

	Description	Example(s)
Prescriptive	AM explicitly prescribes a range of management measures in response to specific monitoring results or trigger levels. These parameters are binding on developers and regulators and must be agreed upon prior to authorizing the deployment of devices and documented in an Adaptive Management Plan.	This approach was taken in the MeyGen tidal project (Section S12.4.1) in Scotland, which required phased development with monitoring requirements specifically designed to answer key scientific questions about biological impacts before receiving consents to proceed to the next phase. A prescriptive approach was also used in the AM framework for the PacWave project (formerly Pacific Marine Energy Center South Energy Test Site) in the United States (U.S.) where monitoring results are reviewed by designated regulatory agencies to implement predefined corrective actions, if the project effects exceed certain thresholds or mitigation criteria (Section S12.4.7).
Flexible	Flexible AM does not necessarily prescribe predetermined tiers for monitoring or mitigation actions. It may set out specific monitoring triggers but defer the determination of remedial actions to the later decision of the regulator and/or an advisory group. These types of AM plans generally defer to an advisory group or resource agency to consider outputs from monitoring and determine appropriate management measures.	A flexible approach was taken to inform the AM of Ocean Renewable Power Company's RivGen, U.S. (Section S12.4.6), SeaGen, UK (Section S12.4.2), DeltaStream, UK (Section S12.4.3), and Ocean Power Technology's Reedsport Wave Park, U.S. (Section S12.4.5), where specific monitoring results or a set of triggers could re-start consultation with the regulator and/or an advisory group, in order to adopt changes in project design, operations, and/or monitoring studies. For example, in the AM process for Reedsport, Implementation Committees had the ability to determine whether a change in the project was required as a result of meeting a screening criterion, and whether the prescribed management practices continued to be appropriate (Section S12.4.5).

At a larger deployment scale, prescriptive AM may be more easily reconciled with the precautionary principle to address uncertainties associated with multiple devices. For AM to be consistent with the precautionary principle, regulators should have sufficient certainty that AM plans will achieve their goal in reducing uncertainty while avoiding and mitigating risk of adverse impacts. The value of using prescriptive AM lies in its capacity to incorporate new monitoring feedback into decision-making while providing regulators with a degree of certainty that actions will be taken before the impacts exceed acceptable thresholds. While prescriptive AM may solve many implementation issues, it places a strong emphasis on mitigating potential impacts, which may hinder the flexibility of AM and as such, reduce its ability to address uncertainties about the mechanisms of impacts (Hanna et al. 2016). When developing such detailed AM plans, it will be important to maintain some flexibility in the process to ensure the plans can be modified over time to take into account new monitoring information. There is also a risk that the threshold is detected too late and that remedial actions fail to effectively respond and avert irreversible damage. The adoption of conservative thresholds and trigger levels in the design phase of AM plans that incorporate precautionary margins and acknowledge the extant levels of uncertainty will be a key for AM to be consistent with the precautionary principle. The size of precautionary margins may be informed by a number of factors, including the risk appetite of regulators and stakeholders, the conservation and ecosystem value of the affected receptor, and, the level of confidence in modelling outputs. The level of statistical certainty in monitoring may also serve as a reference point to set more or less precautionary margins when setting impact thresholds and associated triggers or decision points (Nie and Schultz 2012). Monitoring in the iterative process of AM should help refine impact thresholds and progressively reduce or remove constraints on project operations where monitoring indicates that risks have been overestimated in the pre-consenting phase.

Finally, it is worth noting that risk-based approaches embedding a flexible AM approach may not be compatible with conservation laws and regulations endorsing a stringent precautionary principle. At the EU level, it remains unclear how AM will be reconciled with the protection threshold taken by the EU judiciary under the Birds and Habitats Directives. Applying the precautionary principle, the European Judge has consistently held that licensing authorities can only authorize a new development if, after an appropriate assessment of its implication for a Natura 2000 site, no reasonable scientific doubt remains as to the absence of threats to the integrity of the site concerned. An appropriate assessment embedding an AM approach should provide definitive data to guarantee, beyond all reasonable scientific doubt, that the mitigation measures envisaged in an AM process will achieve their goal in preventing adverse impacts. Such a strict requirement for front-loaded certainty may represent an important impediment to the use of AM strategies. In its more recent case law, the EU judiciary may have taken a more nuanced approach whereby it is only when it is “sufficiently certain that a [mitigation] measure will make an effective contribution to avoiding harm, guaranteeing beyond all reasonable doubt that the project will not adversely affect the integrity of the area”, that such a measure may be taken into account in the appropriate assessment. While a conclusion of no reasonable scientific doubt as to the absence of adverse impacts should be the ultimate goal pursued by an AM process, sufficient certainty in the design phase that mitigation measures will make an effective contribution towards this objective, may suffice for AM to be implemented within the bounds of EU Natura Directives. This interpretation appears to be consistent with the European Commission’s guidelines on the implementation of the Birds and Habitats Directive in estuaries and coastal zones (European Commission 2011). The Guidelines recognize that a prescriptive approach to AM may be envisaged where competent authorities cannot fully ascertain the adverse effects of a plan or project because of science limits or uncertainty on the functioning of complex and dynamic ecosystems. In this case, a rigorous monitoring scheme, together with a pre-defined validated package of corrective measures must be established. Such corrective measures must guarantee that the initially unforeseen adverse effects will be neutralized. These Guidelines apply to estuaries and coastal zones where most wave and tidal energy projects located in the EU are operated. Despite this, the extent to which this document applies to the specifics of MRE projects is not clearly specified (Le Lièvre et al. 2016; O'Hagan 2016).

Overall, the question of whether AM is consistent with the precautionary principle should be informed by a case-by-case evaluation of the level of scientific uncertainty and the gravity of the anticipated threat. Grieg and Murray (2008) have described AM as a “safe-fail”, which means that AM should be applied when failure is an acceptable outcome. This suggests that AM may not be appropriate for all receptors, especially at a large deployment scale. If the overriding goal is to protect features of high conservation value, the need to protect these sensitive features may be more important than the desire to address the uncertainty associated with MRE projects. The conservation status of affected species or habitats should always inform the regulator and developers' appetite for risk (Le Lièvre et al. 2016). The adoption of conservative thresholds and trigger levels that incorporate precautionary margins and acknowledge the extant levels of uncertainty will be key for AM to work consistently with the precautionary principle. Implementing AM in this manner offers a relevant response mechanism for reducing scientific uncertainty while assuring that no unintended adverse impacts will occur as a result of insufficient or imprecise data available during the initial approval phase.

S12.4. EVALUATING THE SUCCESS OF ADAPTIVE MANAGEMENT AT SELECTED MRE DEVELOPMENT SITES

AM implementation has supported the deployment of several wave and tidal projects, thereby contributing to the testing of certain monitoring technologies, and it has answered some fundamental questions about the environmental interactions of single devices and small arrays. The case studies described in the following sections demonstrate how AM has been applied to consented projects, including the MeyGen tidal project (Scotland), the SeaGen tidal turbine (Northern Ireland), the DeltaStream tidal turbine (Wales), the Roosevelt Island Tidal Energy project (U.S.), and Ocean Power Technology's Reedsport Wave Park (U.S.), the Ocean Renewable Power Company's TidGen and RivGen turbine power systems (U.S.), and the PacWave South test site (U.S.).

S12.4.1. MEYGEN TIDAL PROJECT

The MeyGen Tidal Energy demonstration project in Pentland Firth (Scotland) is the world's largest commercial tidal development and has applied an AM approach through a staged consenting process. Development consent was granted by Marine Scotland, on behalf of the Scottish Minister, for the construction and operation of 61 fully submerged turbines with a consented capacity of 86 MW. The Scottish Minister, on the advice of nature conservation bodies, consented the whole project on the condition that the first phase of development was implemented with only six turbines and those turbines were monitored before the deployment of additional turbines (Marine Scotland 2013). The conclusions derived from the environmental assessment process, prescribed under the European Union Habitats Directive (European Commission 2011), were that significant adverse effects might occur as a result of predicted levels of collision with protected species, including seabirds, grey seals (*Halichoerus grypus*), harbor seals (*Phoca vitulina*), Atlantic salmon (*Salmo salar*) and sea lampreys (*Petromyzon marinus*).

Phase 1a was limited to six turbines and subject to a comprehensive monitoring program designed to measure the behavior of mobile species near the turbines and the findings were to be used to validate collision risk models. All subsequent project phases are subject to prior approval to assure development consents are given with full knowledge of the potential impacts on protected species. AM enabled the developer to achieve the full project consent necessary for investor confidence, while delivering a phased approach following the survey-deploy-monitor licensing policy for licensing (Marine Scotland 2016). In 2017, Marine Scotland granted development consent to install Phase 1b, which comprised four more turbines of 6 MW each. Deployment of Phase 1c is intended to take place in 2021-2022 and will be highly contingent upon monitoring outcomes from Phases 1a and 1b. If deployed, Phase 1c will consist of a further

49 turbines, bringing the total capacity of Phase 1 to 86 MW. Further information about the specifics of the AM plan and results of environmental monitoring for MeyGen is commercially sensitive and not yet publicly available.

S12.4.2. SEAGEN TIDAL TURBINE

The Northern Ireland Environment and Heritage Service and Marine Current Turbines (MCT) installation applied an AM approach to the deployment and operation of MCT's SeaGen turbine in Strangford Lough (Northern Ireland). Strangford Lough is designated as a Special Area of Conservation (SAC) and Special Protection Area under the European Union (EU) Habitats and Birds Directives (European Commission 2011). The main environmental concern was whether the turbine would have an adverse impact on the use of the Lough by harbor seals, a feature of the SAC that has an unfavorable conservation status (Keenan et al. 2011). There was also uncertainty about whether there was a risk of collision for harbor seal and harbor porpoises (*Phocoena phocoena*) with the turbine blades. Although not a protected species of the SAC, harbor porpoises are subject to a strict protection regime to keep them from harm, including death, physical injury, and disturbances, under the Habitats Directive. In this case, the key aspects of AM focused on marine mammals. A comprehensive Environmental Monitoring Plan was developed as a condition of the license and was complemented by an AM approach that required continuous review of monitoring data and management measures by an independently chaired Scientific Steering Group. Monitoring objectives for marine mammals included a zero-risk mortality tolerance for collision with the turbine blades (Savidge et al. 2014). Associated mitigation measures included a restriction to daylight operation and the use of MMOs on board the tidal platform; the MMOs had the ability to shut down the turbine whenever marine mammals were observed to cross the agreed-upon shutdown action perimeter of 200 m (Fortune et al. 2017). The effectiveness of an active experimental sonar system was also tested as a mitigation measure to assist in the detection of marine mammals (Hastie et al. 2014).

After three years of post-installation monitoring, marine mammals appeared to be unlikely to collide with the turbine within the agreed-upon shutdown action perimeters. Monitoring activities showed that seals and harbor porpoises tend to avoid the SeaGen turbine, which reduced the likelihood of marine mammal collisions (Keenan et al. 2011). Field data provided indications that SeaGen did not create a barrier effect for harbor seals transiting through the Strangford Narrows; they continued to use haul-out sites during turbine operation (Sparling et al. 2018). Monitoring data also demonstrated that active sonar was effective in mitigating collision risk in a manner comparable to MMOs (Fortune et al. 2017). Mitigation monitoring changed from daylight only with MMOs on the turbine structure to 24-hour manual observation of active sonar, which allowed the turbine to be operated on a 24-hour basis, but with the significant requirement for trained personnel to be on duty whenever the turbine was operating. As knowledge of the environmental effects of SeaGen increased, the precautionary shutdown distance was progressively reduced from 200 m to 100 m, and then to less than 30 m (Savidge et al. 2014). Final removal of the shutdown protocol, with associated fine-scale monitoring around the turbine blades using a new multibeam sonar system, albeit authorized, was not implemented before the device stopped operating in 2015, prior to eventual decommissioning in 2019. The mitigation requirements resulted in missed opportunities to gain relevant knowledge about how marine mammals interact with the operating turbine blades. Despite this, the AM process allowed MCT to install and operate the SeaGen turbine over a period of five years, thereby increasing the developer's confidence in the technology and its capacity to deliver power to the grid (Fortune et al. 2017).

S12.4.3. DELTASTREAM TIDAL TURBINE

An AM approach was used to license Tidal Energy Limited's grid-connected 400 kW DeltaStream tidal energy project in Ramsay Sound, off the Pembrokeshire coast in Wales. The license for installation and operation was granted in 2011 by Natural Resources Wales for a 12-month deployment period of a single 400 kW turbine mounted on a steel triangular gravity-based frame. DeltaStream was successfully deployed and connected to the grid in 2015. The greatest environmental concerns were for the collision of harbor porpoise and grey seal with the turbine. The DeltaStream project relied on a threshold-based approach to AM where acceptable collision thresholds were set using a PBR approach (Copping et al. 2016.). PBR is a widely used method of determining the level of additional man-made mortality a population can sustain without adversely affecting its size and stability (Wade 1998). A detailed Collision Monitoring and Adaptive Management Plan established the approach to marine mammal monitoring to determine the real level of collision risks in the face of uncertainty (Copping et al. 2016; Sparling pers. comm.). The near-field monitoring planned for this project included a passive acoustic monitoring system with several hydrophones directly mounted on the turbine sub-structure together with an active acoustic monitoring system that used a multibeam sonar to detect animals approaching the device (Malinka et al. 2018). Unlike the SeaGen turbine project, the DeltaStream project had no shutdown mitigation requirements, but it applied a flexible AM approach in which the need for mitigation could be identified and required by Environmental Management Body to reduce the risk of collision-related mortalities (Copping et al. 2016; Sparling pers. comm.). The mitigation steps outlined in the collision risk management plan included the potential for limiting turbine operation during sensitive times and the use of acoustic deterrents. By consenting the project without the need for a shutdown protocol, the deployment of the DeltaStream turbine was designed to provide information about close-range interactions between marine mammals and the operating device. In this particular case, AM was designed based on a high level of confidence in the ability to detect collisions using a strike detection system. As the project progressed, the ability of the near-field monitoring to confidently detect collisions using a strike detection system became highly uncertain. The DeltaStream project illustrates the challenges of monitoring in the presence of thresholds in AM, because these thresholds require the ability to accurately monitor and detect certain metrics of concern to confirm whether an unacceptable impact has occurred, or a threshold/trigger has been reached. Because of equipment failure and subsequent liquidation of Tidal Energy Limited, the DeltaStream turbine and monitoring system was never operated for any significant length of time.

S12.4.4. ROOSEVELT ISLAND TIDAL ENERGY PROJECT

In 2012, the U.S. Federal Energy Regulation Commission (FERC) issued a 10-year Pilot License (FERC No.12611) to Verdant Power for the installation of up to 30 hydrokinetic turbines to be deployed during three phrases in the east channel of the East River (New York, U.S.). The first phase of Verdant Power's Roosevelt Island Tidal Energy (RITE) project consisted of three turbines mounted on a tri-frame with a total capacity of 105 kW (Verdant Power 2010a). Three additional redesigned tri-frames and nine turbines (the Install B-1 phase) will be installed in 2020, with a total capacity of 420 kW. The last phase will culminate with the installation of six tri-frames supporting 18 additional turbines, with a total capacity of 1 MW. The project represents the application of AM to support the execution of a series of seven RITE Monitoring of Environmental Effects (RMEE) plans (Verdant Power 2010b). In this particular case, AM was not applied to adapt the management of the project. Instead, AM was directed at reducing scientific uncertainty within the RMEE plans to address key environmental questions related to the characterization of species and the effects of the turbine (and generated operating noise) on the presence, distribution, and abundance of aquatic species. The RMEE plans consisted of seven focal monitoring studies addressing (1) the micro-scale interaction of aquatic species with the turbine (RMEE-2), (2) the fish composition in the immediate vicinity of the project (RMEE-3), (3) the occurrence of protected fish species under the Endangered Species Act (RMEE-4), (4) the potential for turbine impacts on sea birds (RMEE-4), (5) the occurrence of underwater noise generated by the project (RMEE-6), and (7) the installation's impact on recreation (RMEE-7) (Verdant Power 2019). During the AM process, the usefulness of the data collected was reviewed to suggest adjustments of the RMEE plans and/or suspend their implementation until the data yielded sufficient information to provide complete understanding of the fundamental questions to be answered under each RMEE plan. Hydro-acoustic data enabled Verdant to suspend use of the seasonal Dual-Frequency Identification Sonar (DIDSON) observation plan based on the finding that further DIDSON data collection would not yield additional information about fish interactions (Verdant Power 2018). The DIDSON system also was found to have achieved its objective of providing real-time observation of fish behavior at the micro-scale to enable refinement of the Fish Interaction Model. With these data incorporated, the model suggested that there was a low probability that fish would collide with the turbine blades of the up to the 30 turbines planned for installation. AM allowed Verdant to discontinue surveys that do not yield meaningful information and redirect monitoring efforts toward continually enhancing monitoring plans for species of concern.

S12.4.5. REEDSPORT WAVE PARK

Ocean Power Technology (OPT)'s Reedsport Wave Park project received a full commercial-scale license in August 2012 to operate up to 10 grid-connected PowerBuoy wave energy converters (WECs), each of which has a capacity of 1.5 MW. A preliminary consent was also secured by OPT to install additional WECs during future phases, which could have brought the overall capacity to 50 MW. Reedsport Wave Park was proposed under a phased consenting approach using AM as a cornerstone. Under terms of the license, Phase 1 consisted of installing a single 150 kW unit largely intended to test the mooring system and the WEC operation, and to collect data about electromagnetic fields (EMFs) and the underwater noise of the device. An AM process was embedded in a Settlement Agreement, which included following a long-term process of engagement with stakeholders and regulatory agencies (OPT 2010). The AM process for OPT aimed at "managing the development and operation of the project in an adaptive manner to avoid and minimize adverse effects to aquatic resources, water quality, recreation, public safety, crabbing and fishing, terrestrial resources and cultural resources" (OPT 2010). Specifically, the project AM was intended to support the implementation of monitoring studies and to identify and adjust measures required to address any unanticipated effects of the project and its potential expansion (OPT 2010). The Settlement Agreement included detailed environmental studies for pinnipeds and cetaceans, EMFs, fish, and seabirds, as well as changes in waves, currents, and sediment transport. The requirements of the agreement relied on the screening criteria that could define changes in project design, monitoring, or management practices if prescribed by an advisory body (or Implementation Committee), to avoid or minimize potential adverse impacts. The screening criteria included detailed baseline characterizations of marine mammal behavior (in the absence of devices) and their response to EMFs and underwater noise. Particular attention was given to whether marine mammals were likely to collide with or become entangled in mooring systems. If the project had an adverse effect on baseline conditions, OPT was required to prepare an avoidance, minimization, and mitigation plan (Response Plan) that included alternative management measures. Alternative management measures were not determined at the start but were left to the later determination of the developer and approval by the competent Implementation Committee. At this point in time, the extent to which AM contributed to reducing uncertainty and informing the future expansion of Reedsport Wave Park cannot be evaluated, because the FERC license was surrendered two years after the project was approved. The license was surrendered mainly because of difficulties related to financing Phase 1 and technical complications resulting from installation of the floating gravity-based anchor, as well as the unfortunate sinking of the subsurface buoyancy float. The project was withdrawn before the AM process could be applied to the full project timeline (O'Neil et al. 2019).

S12.4.6. ORPC's TIDGEN AND RIVGEN POWER SYSTEMS

Ocean Renewable Power Company (ORPC) has a track record of implementing AM to reduce scientific uncertainty when modifying project operations and monitoring methodologies at the scale of single devices (e.g., TidGen and RivGen projects). Using conditional licensing, with AM as a basis, ORPC was granted a Pilot Project License (FERC No. 12711-005) by FERC in 2012 to install and operate TidGen, a single horizontal-axis tidal turbine, in Cobscook Bay, Maine (U.S.) (FERC No. 12711-005). An AM plan that served as the foundation for monitoring and science-based decision-making was required under the Pilot License. The AM plan was developed by ORPC's Adaptive Management Team (AMT) in consultation with regulatory agencies, stakeholders, and local communities. Using the AM process, ORPC, with the support of the AMT, was able to demonstrate that their single tidal unit would have minimal effects on marine wildlife; the process resulted in a number of license modifications that clarified the monitoring requirements and, in some cases, lowered the frequency of monitoring required for specific surveys (ORPC 2017). The core objective of monitoring was to collect data about fisheries and marine life interactions with the turbine and to measure the effects of underwater noise on sockeye salmon, marine mammals, and sea birds (ORPC 2013). Data were collected under six monitoring plans; AM provided a strategy for evaluating the monitoring results and making informed decisions about the modification of monitoring plans, as needed.

Initially, the Pilot License for the TidGen project imposed a seasonal restriction window on pile-driving operations because of the presence of migrating Atlantic salmon. Alleviation of seasonal restrictions under the AM plan was dependent on the results of underwater monitoring, which demonstrated that sound levels produced by pile-driving hammer techniques (outside the restriction period) did not exceed the acceptable threshold established by the National Marine Fisheries Service (NMFS 2018). Underwater noise measurements from the installation of TidGen indicated that noise levels were below the thresholds of concern for Atlantic salmon when sound absorption measures, including the placement of plywood between the impact hammer and the follower, were used during pile driving (ORPC 2013). Using these thresholds and transferring underwater noise data from a previous project allowed ORPC to request the removal of seasonal restrictions on pile-driving for Phase 1 operations, which was granted by FERC.

Monitoring for marine mammals during the installation and operational phase included incidental and dedicated observations made by trained MMOs. Incidental observations were performed over several seasons to observe marine mammal presence and behavior around the turbine prior to, during, and after key installation and maintenance activities, including pile-driving (ORPC 2013). Mitigation for the presence of marine mammals entering or approaching a 152 m marine mammal exclusion zone during pile-driving included curtailment and delay of installation activities (ORPC 2013). Cessation of pile-driving activities was required until the marine mammal had moved beyond 305 m (1000 ft) from the exclusion zone or 30 minutes had passed since the last sighting (ORPC 2013). Dedicated marine mammal observations indicated minimal changes in animal presence and behavior as a result of generated noise levels during pile-driving activities (ORPC 2013). Marine mammals were not visually observed to enter the exclusion zone; therefore, the shutdown and delay procedures were not triggered during the installation period (ORPC 2013).

Incidental marine mammal sightings did not indicate any behavioral changes or evidence of adverse encounters or collisions during the installation and operation of TidGen (ORPC 2014). These findings resulted in a FERC license order that allowed ORPC to fully transition from dedicated observations, whereby marine mammals are recorded by certified MMOs as part of a dedicated survey effort, to incidental marine mammal observations (ORPC 2014).

In a similar approach, during 2014 and 2015 AM allowed for the deployment of the RivGen demonstration project in the Kvichak River in Alaska, U.S., without requiring a FERC Pilot License. A fish monitoring plan required the use of underwater video cameras to monitor fish interactions with the device and the evaluation and mitigation of possible adverse effects on sockeye salmon (*Oncorhynchus nerka)*. The video footage revealed the absence of physical injuries and no altered behavior of the fish in the immediate vicinity of the turbine. It was determined that mitigation measures were not necessary. In this way, AM was able to contribute to the retirement of collision risk for fish around the single RivGen tidal unit (ORPC 2016). These findings were also presented by ORPC at the Cobscook Bay Tidal Energy Project Adaptive Management Team meeting in 2014 and 2015 (ORPC 2015, 2016), suggesting that transfer of data is a real possibility from the industry perspective and can definitely be used to inform future developments. The 2015 monitoring project is referenced in the FERC license for the next stage of the Iguigig Hydrokinetic Project (FERC No. 13511-003) and the methods used previously will be implemented again, more extensively (FERC 2019). The short sampling periods in 2014 and 2015 limited broader transferability of the data.

Knowledge gained at the RivGen demonstration project facilitated the issuance of a recent Pilot License authorizing the installation and operation of the current phase of the RivGen project in the Kvichak River, near the village of Iguigig. The RivGen project consists of two in-stream turbine generator units (TGUs), each of 35 kW capacity, to be deployed in two distinct phases. Installation of TGU 1 (Phase 1) was completed in 2019. Installation of TGU 2 (Phase 2) is planned for 2020 (FERC No.13711-003). The project relies heavily on AM to address environmental unknowns and take corrective actions if monitoring indicates any unanticipated adverse effects on aquatic animals (FERC No.13711-003, Article 403). The Pilot License includes requirements for real-time video monitoring and the immediate shutdown of the project within one hour if injuries or mortality of out-migrating sockeye smolts are detected as a result of turbine operation. The Emergency Shutdown Plan, which includes provisions for monitoring and reporting, will serve as a source of information for recommending corrective mitigation actions (FERC 2019). If fish monitoring data provide evidence of negative interactions (injuries or mortality) on migrating salmon, the AMT may have to consider additional monitoring efforts and implement work timing windows to reduce and/or eliminate negative impacts on fish populations (FERC No.13711, Article 403). Conversely, if no adverse effects are observed throughout the first year of operation, the AMT may submit recommendations to FERC to modify the monitoring protocol and shutdown plan.

Overall, the RivGen and TidGen projects provide examples of how AM may be used to understand environmental risks, inform best management practices, and modify license requirements based on increased data collection and understanding of environmental effects and species interactions (Johnson 2016).

S12.4.7. PACWAVE SOUTH TEST SITE

Oregon State University (OSU) developed a detailed AM framework to support a license application to install and operate a grid-connected wave energy test facility: the PacWave South Project, formerly known as Pacific Marine Energy Centre South Energy Test Site. The project consists of four grid-connected berths to support testing of up to 20 commercial-scale WECs with a maximum installed capacity of 20 MW. As part of their AM framework, OSU has committed to implementing monitoring programs for underwater noise, habitat changes, and EMFs to confirm assumptions about the levels and durations of potential effects, coupled with processes for taking corrective actions in consultation with competent regulatory agencies (OSU 2019). The AM framework for PacWave South seems to embody a prescribed approach to AM whereby monitoring results are evaluated in consultation with an Adaptive Management Committee (AMC) and agency stakeholders to review project effects, make changes to monitoring, and engage specific responsive actions where these effects exceed certain thresholds or mitigation criteria. The AM framework will also inform decisions, including those about the need to adopt additional protection, mitigation, and enhancement measures to assure that the potential effects are within the thresholds and meet the criteria prescribed for the project.

For example, with respect to benthic habitats, if monitoring results indicate that WECs and their components have a statistically significant impact beyond the range of seasonal/interannual variability on macrofaunal species composition or abundance, OSU will be obliged to submit a draft plan to implement the following mitigation actions with accompanying implementation timelines and monitoring provisions to assess the effectiveness of the measures (OSU 2019):

- Limit use of specific anchor types in future installations.
- Modify and manage the deployment frequency or location to enable recovery of macrofauna.
- Use permanent anchoring systems (e.g., for the life of the project).
- Conduct additional in situ monitoring.

Similarly, if underwater noise monitoring results show persistent exceedance of published harassment thresholds (120 dB re 1 μPa) at a distance of 100 m from the WECs or their mooring systems, OSU is obliged to instruct testing clients to diagnose and repair or modify the WECs or mooring systems within 60 days and to continue monitoring activities, and to demonstrate the effectiveness of the noise abatement measures. In addition, OSU is required to notify NMFS about whether further exceedances of harassment thresholds occur after implementation of the corrective actions. If, despite repairs and modifications, the noise level is not reduced below acceptable thresholds, further actions are prescribed, including the provision of a draft plan specifying the following, among other actions:

- Alternative or additional methods of monitoring to identify the source and cause of the noise and to inform specific actions necessary to reduce the noise below the threshold
- Modifications to the operation of the WECs (e.g., modify controls to change the motion of the WECs)
- Necessary repairs and modifications to reduce noise levels.

If after taking these steps, noise levels are not abated within 14 days, the operation of WECs will be temporarily ceased to halt noise threshold exceedances (OSU 2019).

While it goes beyond the scope of this chapter to detail the catalog of measures and the AM process applied by PacWave South, the approach is relatively similar with respect to EMFs. If post-installation field measurements and modeling results detect EMF emissions in excess of biologically relevant levels (e.g., 3 mT), OSU has the obligation to notify the AMC and instruct testing clients to adopt specific actions, including, but not limited to, installing additional shielding of subsea cables or other components such as hubs or subsea connectors. Further in situ monitoring is prescribed to verify the abatement of excess EMF levels, and if EMF levels cannot be minimized, a draft mitigation plan must be prepared to implement specified mitigation actions until the source of exceedance is reduced to below the acceptable threshold.

Further information can be found in the FERC license application (OSU 2019) and the accompanying Adaptive Management Framework (OSU 2019).

S12.5. EVALUATING THE SUCCESS OF ADAPTIVE MANAGEMENT IN RETIRING RISKS

Prior to deploying commercial arrays under an AM approach, the success of AM in retiring risks associated with the interactions of single devices should be established. Little evidence is currently accessible in the public domain to identify the attributes of successful AM. With so few operational turbines deployed to date, AM has not yet facilitated the full retirement of collision risks with marine mammals, fish and seabirds. Its implementation has nonetheless contributed to testing a number of monitoring technologies and answering fundamental questions about the interactions of fish and marine mammals with single operating turbines. Monitoring results at SeaGen have shown that seals and harbor porpoises tend to avoid the turbine hence reducing marine mammal strike risks (Keenan et al. 2011). Field data collected through telemetry provided indications that SeaGen did not result in a barrier effect as harbor seals were still detected to transit through the Narrow and used haul-out sites despite turbine operation (Sparling et al. 2018). No changes in seal abundance were observed but tagged harbor seals exhibited avoidance behavior by transiting further away from the turbine zone. A recent study found a decline of 68% of harbor seals occurrence within 200m of the turbine when SeaGen was operating suggesting a capacity of animals to detect the turbine by sound, sight or vibration (Joy et al. 2018). Because the final removal of the shut-down protocol was never implemented before decommissioning, the AM process did not provide relevant information regarding the fine-scale behavior of marine mammals around the turbine structure and its moving blades (Sparling et al. 2018). At this stage, collision risks associated with operating devices cannot be fully discounted. Passive acoustic monitoring (PAM) around the Delta Stream turbine in Ramsay Sound revealed that cetaceans, primarily harbor porpoises and dolphins, would be able to detect and avoid the turbine, albeit these findings cannot be generalized to all tidal energy sites (Gillespie et al. 2020; Malinka et al. 2018). It was also found that the PAM system could successfully and almost continuously track the movements of small cetaceans around the turbine (Gillespie et al. 2020; Malinka et al. 2018). The limited duration of operation however meant that sufficient data could not be collected to evaluate the effects of the turbine rotation on the presence and movement of marine mammals (Gillespie et al. 2020; ICES 2019; Malinka et al. 2018).

The approach developed by ORPC is perhaps the most conclusive example of the role of AM in retiring risks at the scale of single devices. A notable example of risk retirement at the TidGen tidal energy project is related to license restrictions on pile-driving activities. The Pilot License for the TidGen project imposed a seasonal restriction window on pile-driving operations due to the presence of migrating Atlantic salmon (*Salmo salar*). Alleviation of seasonal restrictions was dependent upon the results of acoustic monitoring showing that sound levels produced by pile-driving hammer techniques (outside the restriction period) did not exceed the acceptable threshold established by NMFS (NMFS 2018). Acoustic measurements in the vicinity of TidGen found that noise levels were below the thresholds of concerns for the Atlantic salmon where appropriate sound absorption devices were used (ORPC 2012). Acoustics monitoring results were used to request a license modification removing the restrictive window on pile-driving activities for Phase 1 operations. In addition, monitoring and mitigation measures for marine mammals during the installation phase of TidGen encompassed dedicated MMOs in charge of monitoring animals approaching the development site before, during and after pile-driving activities. The mitigation plan provided for the curtailment or delay of installation activities in the event that a marine mammal was observed entering or approaching the exclusion zone (ORPC 2013). Results from MMOs indicated no changes in animals' presence and behavior as a result of generated noise levels during pile-driving (ORPC 2013). Marine mammals were not observed to enter the exclusion zone and as such, the shut-down and delay procedures were not triggered (ORPC 2013). No evidence of adverse encounter interactions or strikes with the single turbine during deployment and retrieval activities were reported (ORPC 2014). These findings similarly resulted in a license modification allowing ORPC to transition from dedicated to incidental marine mammal observations. The TidGen turbine was retrieved from the water in 2013 (ORPC 2017). In a similar approach, AM has contributed to retiring collision risk with fish around the single RivGen tidal unit. The RivGen project was first deployed in Alaska in 2014 and 2015 for testing purposes. A fish monitoring plan relying on mounted underwater video cameras was in place to monitor, evaluate and mitigate possible adverse effects on the sockeye salmon. The video footage revealed the absence of physical injuries or altered behaviors by fish in the immediate vicinity of the turbine. Monitoring results were used to inform the license conditions for the Igiugig project. The RivGen and TidGen projects provide an example of how AM may be operated to reduce developer risks and modify license requirements based on increased data collection and increased understanding of environmental effects and species presence (Johnson 2016).

The extent to which AM will be successful in retiring risks is species-specific and highly dependent upon the characteristics of the development site. It also depends on the capacity of monitoring methodologies in detecting close-range animal behaviors around operating devices and their moving components. By way of an example, fish behavior such as avoidance, attraction, evasion or blade strikes vary with the species concerned and the life stage of fish present within the deployment site. Whilst monitoring results collected from single devices may help predict the effects of larger arrays, most interactions with marine animals and the physical environment may not be properly understood until multiple devices are actually deployed and monitored in real-sea conditions (Copping 2018). An adaptive approach to management is therefore likely to be needed to address environmental unknowns associated with future commercial arrays and move the industry forward through more effective consenting processes.

S12.6. CONCLUSIONS AND RECOMMENDATIONS

This chapter provides an explanation of AM and how its underlying principles may be applied to developing effective approaches for addressing uncertainty and knowledge gaps in consenting processes. To date, AM has contributed to risk retirement by allowing single devices or small arrays to be deployed under a structured incremental approach with embedded mitigation and monitoring, thereby providing useful information about device-specific stressor/receptor interactions. Despite this, AM remains the exception rather than the standard and in many jurisdictions, there is no clearly established legal basis supporting its implementation. It is now increasingly understood that unless AM is given some legal definition [and legal grounding] and is enforceable in some way, the approach can be used as a smokescreen for open-ended and discretionary decision-making that lacks accountability and fails to incorporate some of the most important aspects of the paradigm including rigorous monitoring and feedback loops that inform the AM cycle (Benson and Schultz 2015; Nie and Schultz 2012). As the industry moves to commercial deployment, implementation guidance should be issued by responsible governmental bodies to support a common understanding of AM and guide the design of AM plans at the scale of MRE arrays. The industry will particularly benefit from guidance documents that specify the circumstances under which AM is acceptable and establish clear and mandatory elements of AM plans, including the design of and conditions for post-installation monitoring, stakeholder engagement, information sharing, and thresholds for AM intervention.

As the industry moves forward, MRE developers that use AM for marine renewables could learn from their fisheries counterparts by using clearly controlled rules for monitoring and evaluating project effects relative to pre-defined thresholds, including the ability to adjust mitigation and monitoring as part of a formal structured AM process (McDonald et al. 2017; Sainsbury et al. 2000). Monitoring approaches must be question-driven and the questions must be directly connected to thresholds/triggers to avoid unacceptable impacts. In practice, designing monitoring that informs and works with thresholds may be extremely challenging; it requires the ability to confidently measure and monitor the appropriate metrics of concern with the required levels of accuracy and precision to inform management decisions.

It is important to realize that engaging in an AM approach may not result in quick wins: AM is an onerous process that requires forethought and commitment, and comes with a degree of risk for developers. Developers must accept that the operational schemes of their projects might be altered or terminated if monitoring indicates harm is being done to sensitive species or other valuable uses. Large MRE projects consented based on AM informed project phasing might never achieve full build out, and regulators might require project decommissioning if the related impacts are deemed unacceptable. Likewise, the success of AM widely depends on the regulator's risk acceptance and attitude about proportionality. Before engaging in an AM approach, regulators and developers should undertake an explicit, structured analysis of the resources they have available and consider the need and practicality of reducing uncertainties. While AM offers some flexibility to consent and deploy MRE projects despite uncertainty, AM at larger deployment scales has the potential to become a burdensome process that creates significant financial uncertainty for project developers. To date, AM is the only known method capable of dealing with the levels of existing uncertainty associated with MRE projects as well as the interaction of MRE projects with other industries and other challenges, including climate change. Advancing the use of AM for MRE will require the development of mechanisms that minimize undue financial risks for developers, while assuring adequate protection of the marine environment and consistency relative to the precautionary principle.

S12.7. REFERENCES

Animal Welfare Institute v. Beech Ridge Energy LLC, 675 F. Supp. 2d. 540 (D. Maryland 2009).

Ashley, M., Mangi, S., and Rodwell, L. 2014. The potential of offshore windfarms to act as marine protected areas – A systematic review of current evidence. *Marine Policy*, 45: 301-309. doi:10.1016/j.marpol.2013.09.002. https://tethys.pnnl.gov/publications/potential-offshore-windfarms-act-marine-protected-areas-systematic-review-current

Bay of Fundy Inshore Fisherman's Association v. Nova Scotia (Environment) 2016 NSSC 286.

Bennet, F., Culloch, R., and Tait, A. 2016. Guidance on effective adaptive management and post-consent monitoring strategies. RiCORE Project, Aberdeen, UK. https://tethys.pnnl.gov/publications/guidance-effective-adaptive-management-post-consent-monitoring-strategies

Benson, M., and Schultz, C. 2015. Adaptive Management and Law. In Allen, C.R, Garmestani, A.S. (eds.), *Adaptive Management of Socio-Ecological System.* Dordrecht: Springer.

Bulling, L., and Köppel, J. 2016. Exploring the trade-offs between wind energy and biodiversity conservation. In D. Geneletti (ed) *Handbook on Biodiversity and Ecosystem Services in Impact Assessment*. Cheltenham, UK: Edward Elgar Publishing.

Centre for Biological Diversity v. Rumsfeld 198 F. 2d. 1139 (D. Az. 2002).

Christiansen, F., Rasmussen, M., Lusseau, D. 2013. Inferring activity budgets in wild animals to estimate the consequences of disturbances. *Behavioral Ecology*, 24(6), 1415-1425. doi:10.1093/beheco/art086

Cook, C., De Bie, K., Keith, D., and Addison, P. 2016. Decision triggers are a critical part of evidence-based conservation. *Biological Conservation*, 195, 46-51. doi:10.1016/j.biocon.2015.12.04

Cook, A., and Robinson, R. 2017. Towards a framework for quantifying the population-level consequences of anthropogenic pressures on the environment: The case of seabirds and windfarms. *Journal of Environmental Management*, 190, 113-121. doi:10.1016/j.jenvman.2016.025. https://tethys.pnnl.gov/publications/towards-framework-quantifying-population-level-consequences-anthropogenic-pressures

Cooney, R., and Dickson, B. 2005. *Biodiversity and the Precautionary Principle: Risk, Uncertainty and Practice in Conservation and Sustainable Use* (1st edition). Routledge.

Cooney, R. 2006. A long and winding road? Precaution from principle to practice in biodiversity conservation. In E. Fisher, J. Jones, and R. von Schomberg (Ed.), *Implementing the Precautionary Principle; Perspectives and Prospects* (pp. 223-244). Cheltenham, UK: Edward Elgar Publishing Limited.

Copping, A. 2018. The State of Knowledge for Environmental Effects: Driving Consenting/Permitting for the Marine Renewable Energy Industry. Ocean Energy Systems. https://tethys.pnnl.gov/publications/state-knowledge-environmental-effects-driving-consentingpermitting-marine-renewable

Copping, A., Gartman, V., May, R., and Bennet, F. 2019. The Role of Adaptive Management in the Wind Energy Industry. In R. Bispo, J. Bernardino, H. Coelho, and J. L. Costa (Eds.), *Wind Energy and Wildlife Impacts* (pp. 1-25). Cham, Switzerland: Springer. https://tethys.pnnl.gov/publications/role-adaptive-management-wind-energy-industry

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchinson, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Ocean Energy Systems. https://tethys.pnnl.gov/publications/state-of-the-science-2016

Craik, N. 2020. Implementing adaptive management in deep seabed mining: legal and institutional challenges. *Marine Policy,* 114(103256). doi:10.1016/j.marpol.2018.09.001.

Elliott, K., Smith, H. C. M., Moore, F., van der Weijde, A. H., and Lazakis, I. 2019. A systematic review of transferable solution options for the environmental impacts of tidal lagoons. *Marine Policy,* 99, 190-200. doi:10.1016/j.marpol.2018.10.021 https://tethys.pnnl.gov/publications/systematic-review-transferable-solution-options-environmental-impacts-tidal-lagoons

European Commision. 2011. The implementation of the Birds and Habitats Directives in estuaries and coastal zones with patricular attention to port development and dredging. European Commision Guidance Document. https://tethys.pnnl.gov/publications/implementation-birds-habitats-directives-estuaries-coastal-zones

Federal Energy Regulatory Commission (FERC). 2019. Environmental Assessment for Hydropower License: Igiugig Hydrokinetic Project - FERC Project No. 13511-003. Office of Energy Projects, Washington, D.C. https://tethys.pnnl.gov/publications/environmental-assessment-hydropower-license

Fischman, R., and Ruhl, J. 2015. Judging adaptive management practices of US agencies. *Conservation Biology,* 30, 268. doi:10.1111/cobi.12616.

Fortune, F., Gilmore, P., and Bennet, F. 2017. Adaptive Management Systems - Don't make the same mistakes twice! Webinar conducted by European Technology and Innovation Platform for Ocean Energy (ETIP) Ocean. https://tethys.pnnl.gov/events/webinar-adaptive-management-systems-dont-make-same-mistakes-twice

Fox, C. J., Benjamins, S., Masden, E. A., and Miller, R. 2018. Challenges and opportunities in monitoring the impacts of tidal-stream energy devices on marine vertebrates. *Renewable and Sustainable Energy Reviews,* 81(2): 1926-1938. doi:10.1016/j.rser.2017.06.004 https://tethys.pnnl.gov/publications/challenges-opportunities-monitoring-impacts-tidal-stream-energy-devices-marine

Frohlich, M., Jacobson, C., Fiderman, P., and Smith, T. 2018. The relationship between adaptive management of social-ecological systems and law: a systematic review. *Ecology and Society,* 23(2), 23. doi:10.5751/ES-10060-230223

Fujitani, M., McFall, A., Randler, C., and Arlinghaus, R. 2017. Participatory adaptive management leads to environmental learning outcomes extending beyond the sphere of science. *Science Advances,* 3(6): e1602516. doi: 10.1126/sciadv.1602516

Gillespie, A. 2013. Conservation, Biodiversity and International Law. Cheltenham, UK: Edward Elgar Publishing. https://tethys.pnnl.gov/publications/conservation-biodiversity-international-law

Gillespie, D., Palmer, L., Macaulay, J., Sparling, C., and Hastie, G. 2020. Passive acoustic methods for tracking the 3D movements of small cetaceans around marine structures. *PLoS One,* 15(5): e0229058. doi: 10.1371/journal.pone.0229058. https://tethys.pnnl.gov/publications/passive-acoustic-methods-tracking-3d-movements-small-cetaceans-around-marine

Green, R., Langston, R., McCluskie, A., Sutherland, R., and Wilson, J. 2016. Lack of Sound Science in Assessing Wind Farm Impacts on Seabirds. *Journal of Applied Ecology,* 53(6), 1635-1641. doi:10.1111/1365-2664.12731. https://tethys.pnnl.gov/publications/lack-sound-science-assessing-wind-farm-impacts-seabirds

Greig, L., and Murray, C. 2008. Peer Review of Rockfort Quarry Adaptive Management Plan. Jagger Hims Ltd., Collingwood, Ontario. https://www.peelregion.ca/planning/pdf/rockfort/rockfort2.pdf

Hanna, L., Copping, A., Geerlofs, S., Feinberg, L., Brown-Saracino, J., Bennet, F., May, R., Köpel, J., Bulling, L., and Gartman, V. 2016. Adaptive Management White Paper. IEA Wind Task 34:

Assessing Environmental Effects (WREN) Technical Report. https://tethys.pnnl.gov/publications/assessing-environmental-effects-wren-adaptive-management-white-paper

Hastie, G. D., Gillespie, D. M., Gordon, J. C. D., Macaulay, J. D. J., McConnell, B. J., and Sparling, C. E. 2014. Tracking Technologies for Quantifying Marine Mammal Interactions with Tidal Turbines: Pitfalls and Possibilities. In M. A. Shields and A. I. L. Payne (Eds.), *Marine Renewable Energy Technology and Environmental Interactions* (pp. 127-139). Dordrecht: Springer Netherlands. https://tethys.pnnl.gov/publications/tracking-technologies-quantifying-marine-mammal-interactions-tidal-turbines-pitfalls

Hawkins, E., Harcourt, R., Bejder, L., Brooks, L., Grech, A., Christiansen, F., Marsh, H., and Harrison, P. 2017. Best practice framework and principles for monitoring the effect of coastal development on marine mammals. *Frontiers in Marine Science,* 4(59). doi:10.3389/fmars.2017.00059

Holling, C. 1978. Adaptive environmental assessment and management. London: John Wiley and Sons.

International Council for the Exploration of the Sea (ICES). 2019. Working Group on Marine Benthal Renewable Developments (WGMBRED). *ICES Scientific Reports,* 1(6). doi:10.17895/ices.pub.4914

Johnson, C. J. 2013. Identifying ecological thresholds for regulating human activity: Effective conservation or wishful thinking? *Biological Conservation,* 168, 57-65. doi:10.1016/j.biocon.2013.09.012 https://tethys.pnnl.gov/publications/identifying-ecological-thresholds-regulating-human-activity-effective-conservation-or

Johnson, N. 2016. Adaptive Management in the Marine Renewable Energy Industry. Webinar conducted by Ocean Energy Systems Annex IV. https://tethys.pnnl.gov/events/adaptive-management-marine-renewable-energy-industry-webinar

Jones, G. 2005. Is the management plan achieving its objectives? In G. L. Worboys, M. Lockwood, and T. De Lacy (Eds. Second ed.), *Protected Area Management: Principles and Practice* (pp. 555-557). Melbourne: Oxford University Press. https://tethys.pnnl.gov/publications/management-plan-achieving-its-objectives

Joy, R., Wood, J., Sparling, C., Tollit, D., Copping, A., and McConnel, B. 2018. Empirical measures of harbor seal behavior and avoidance of an operational tidal turbine. *Marine Pollution Bulletin,* 136, 92-106. doi:10.1016/j.marpolbul.2018.08.052 https://tethys.pnnl.gov/publications/empirical-measures-harbor-seal-behavior-avoidance-operational-tidal-turbine

Keenan, G., Sparling, C., Williams, H., and Fortune, F. 2011. SeaGen Environmental Monitoring Programme: Final Report. Royal Haskoning, Edinburgh, UK. https://tethys.pnnl.gov/publications/seagen-environmental-monitoring-programme-final-report

Keith, D., Martin, T., McDonald-Madden, E., and Walters, C. 2011. Uncertainty and adaptive management for biodiversity conservation. *Biological Conservation,* 114, 1175. doi:10.1016/j.biocon.2010.11.022

King, S., Schick, R., Donovan, C., Booth, C., Burgman, M., Thomas, L., and Harwood, J. 2015. An Interim Framework for Assessing the Population Consequencse of Disturbance. *Methods in Ecology and Evolution* 6(10, 1150-1158. doi:10.1111/2041-210X.12411 https://tethys.pnnl.gov/publications/interim-framework-assessing-population-consequences-disturbance

Köppel, J., Dahmen, M., Helfrich, J., Schuster, E., and Bulling, L. 2014. Cautious but Committed: Moving Toward Adaptive Planning and Operation Strategies for Renewable Energy's Wildlife Implications. *Environmental Management,* 54(4), 744-755. doi:10.1007/s00267-014-0333-8

https://tethys.pnnl.gov/publications/cautious-committed-moving-toward-adaptive-planning-operation-strategies-renewable
Kriebel, D., Tickner, J., Epstein, P., Lemons, J., Levins, R., Loechler, E. L., Quinn, M., Rudel, R., Schettler, T., and Stoto, M. 2001. The precautionary principle in environmental science. *Environmental Health Perspectives*, 109(9), 871-876. doi:10.1289/ehp.01109871 https://tethys.pnnl.gov/publications/precautionary-principle-environmental-science
Le Lièvre, C. 2019. Sustainably reconciling offshore renewable energy with Natura 2000 sites: An interim adaptive management framework. *Energy Policy*, 129, 491-501. doi:10.1016/j.enpol.2019.02.007 https://tethys.pnnl.gov/publications/sustainably-reconciling-offshore-renewable-energy-natura-2000-sites-interim-adaptive
Le Lièvre, C., O'Hagan, A., Culloch, R., Bennet, F., and Broadbent, I. 2016. Legal feasibility of implementing a risk-based approach to MRE consenting and compatibility with Natura 2000 network. RiCORE Project, Aberdeen, UK. https://tethys.pnnl.gov/publications/legal-feasibility-implementing-risk-based-approach-mre-consenting-compatibility-natura
Levrel, H., Pioch, S., and Spieler, R. 2012. Compensatory measures in marine ecosystems: which indicators for assessing the "no net loss" goal of ecosystem services and ecological functions. *Marine Policy*, 36(6), 1202. doi:10.1016/j.marpol.2012.03.004
Lüdeke, J. 2018. Exploitation of Offshore Wind Energy. In M. Salomon, T. Markus (eds.), *Handbook on Marine Environment Protection: Science, Impacts, and Sustainable Management* (pp. 165-188). Cham, Switzerland: Springer. https://tethys.pnnl.gov/publications/exploitation-offshore-wind-energy
Lusseau, D., Christiansen, F., Harwood, J., Mendes, S., Thompson, P., Smith, K., and Hastie, G. 2012. Assessing the risks to marine mammal populations from renewable energy devices: an interim approach. Report for Joint Nature Conservation Committee (JNCC). https://tethys.pnnl.gov/publications/assessing-risks-marine-mammal-populations-renewable-energy-devices-interim-approach
Magagna, D., Greaves, D., Conley, D., O'Hagan, A. M., Holmes, B., Witt, M., Simas, T., Olivares, C. H., Leitão, J. C., Mouslim, H., Torre-Enciso, Y., Sundberg, J., and Rousseau, N. 2012. How Experiences of the Offshore Wind Industry Can Aid Development of the Wave Energy Sector: Lessons Learnt From EIA Studies. Paper presented at the 22nd International Offshore and Polar Engineering Conference, Rhodes, Greece. https://tethys.pnnl.gov/publications/how-experiences-offshore-wind-industry-can-aid-development-wave-energy-sector-lessons
Malinka, C. E., Gillespie, D. M., Macaulay, J. D. J., Joy, R., and Sparling, C. E. 2018. First in situ passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales. *Marine Ecology Progress Series*, 590, 247-266. https://tethys.pnnl.gov/publications/first-situ-passive-acoustic-monitoring-marine-mammals-during-operation-tidal-turbine
Marine Scottland. 2012. Survey, Deploy and Monitor Licensing Policy Guidance. Scottish Government. https://tethys.pnnl.gov/publications/survey-deploy-monitor-licensing-policy-guidance
Marine Scottland. 2013. MeyGen Decision - Decision Letter Consent and Conditions. Scottish Government. https://tethys.pnnl.gov/publications/consent-granted-scottish-ministers-construct-operate-meygen-tidal-energy-project
McDonald, J., and Styles, M. 2014. Legal strategies for adaptive management under climate change. *Journal of Environmental Law*, 26(1), 25-53. doi:10.1093/jel/equ003
McDonald, G., Harford, B., Arrivillaga, A., Babcock, E. A., Carcamo, R., Foley, J., Fujita, R., Gedamke, T., Gibson, J., Karr, K., Robinson, J., and Wilson, J. 2017. An indicator-based adaptive management framework and its development for data-limited fisheries in Belize. *Marine Policy*, 76, 28-37.

doi:10.1016/j.marpol.2016.11.027. https://tethys.pnnl.gov/publications/indicator-based-adaptive-management-framework-its-development-data-limited-fisheries

May, R. 2019. The Mitigation of Impact and the Impact of Mitigation: An Ethical Perspective. *Wind Energy and Wildlife Impacts* (pp. 93-113). https://tethys.pnnl.gov/publications/mitigation-impact-impact-mitigation-ethical-perspective

Morgera, E. 2017. The ecosystem approach and the precautionary principle. In M. Faure, E. Morgera, and J. Razzaque (Eds.), *Elgar Encyclopedia of Environmental Law: Biodiversity and Nature Protection Law* (Vol. III, pp. 70-80). Cheltenham, UK: Edward Elgar Publishing. https://tethys.pnnl.gov/publications/ecosystem-approach-precautionary-principle

Moyle, B. 2005. Making the Precautionary Principle Work for Biodiversity: Avoiding Perverse Outcomes in Decision-Making Under Uncertainty. In R. Cooney, B. Dickson (eds.), *Biodiversity ad the Precautionary Principle: Risk, Uncertainty and Practice in Conservation and Sustainable Use* (1st edition,) Routledge.

Nabe-Nielsen, J., Sibly, R., Tougaard, J., Teilmann, J., and Sveegaard, S. 2014. Effects of Noise and By-Catch on a Danish Harbour Porpoise Population. *Ecological Modelling*, 272, 242-251. doi:10.1016/j.ecolmodel.2013.09.025. https://tethys.pnnl.gov/publications/effects-noise-catch-danish-harbour-porpoise-population

Natural Resources Council v. Kempthorne 506 F. 2d. 322 (E.D. Cal. 2007).

National Marine Fisheries Service (NMFS). 2018. 2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts (NMFS-OPR-59). National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD. https://tethys.pnnl.gov/publications/2018-revisions-technical-guidance-assessing-effects-anthropogenic-sound-marine-mammal

National Wildlife Federation v. National Marine Fisheries Service 524 F. 3d. 917 (9th Circ. 2008)

Nichols, J., Johnson, F., Williams B., and Boomer, G. 2015. On formally integrating science and policy: walking the walk. *Journal of Applied Ecology*, 52(3), 539. doi:10.1111/1365-2664.12406

Nie, M., and Schultz, C. 2012. Decision-making triggers in adaptive management. *Conservation Biology*, 26(6), 1137. doi:10.1111/j.1523-1739.2012.01915.x

Ocean Power Technologies (OPT). 2010. Reedsport OPT Wave Park Settlement Agreement. https://tethys.pnnl.gov/publications/reedsport-opt-wave-park-settlement-agreement

Ocean Renewable Power Company (ORPC). 2012. Order Issuing Pilot Project License (Minor Project), Docket 12711.

Ocean Renewable Power Company (ORPC). 2013. Cobscook Bay Tidal Energy Project: 2012 Environmental Monitoring Report. Portland, Maine. https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2012-environmental-monitoring-report

Ocean Renewable Power Company (ORPC). 2014. Cobscook Bay Tidal Energy Project: 2013 Environmental Monitoring Report. Portland, Maine. https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2013-environmental-monitoring-report

Ocean Renewable Power Company (ORPC). 2016. Cobscook Bay Tidal Energy Project: 2015 Environmental Monitoring Report. Portland, Maine. https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2015-environmental-monitoring-report

Ocean Renewable Power Company (ORPC). 2017. Cobscook Bay Tidal Energy Project: 2016 Environmental Monitoring Report. Portland, Maine. https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2016-environmental-monitoring-report

O'Hagan, A. 2016. Consenting Processes for Ocean Energy Updated on Barriers and Recommendations. Report for Ocean Energy Systems (OES). https://tethys.pnnl.gov/publications/consenting-processes-ocean-energy-updated-barriers-recommendations

O'Neil, R., Staines, G., and Freeman, M. 2019. Marine Hydrokinetics Regulatory Processes Literature Review. Pacific Northwest National, Richland, WA. https://tethys.pnnl.gov/publications/marine-hydrokinetics-regulatory-processes-literature-review

Oregon State University. 2019. Final License Application for the PacWave South Project (FERC Project No. 14616). Volume III. https://tethys.pnnl.gov/publications/pacwave-south-license-application

ORJIP Ocean Energy. 2017. The Forward Look: An Ocean Energy Environmental Research Strategy for the UK. Aquatera, Stromness, Orkney. https://tethys.pnnl.gov/publications/forward-look-ocean-energy-environmental-research-strategy-uk

Pacific Coast Federation of Fishermen's Association, 606 F. 2d. 1122 (E. D. Calfi. 2008).

Pahl-Wostl, C. 2007. Transitions towards adaptive management of water facing climate and global change. *Water Resources Management*, *21*(1), 49-62. doi:10.1007/s11269-006-9040-4

Pembina Institute for Appropriate Development v. Canada, 2008 FC 302, para. 32.

Raitanen, E. 2018. Legal weaknesses and windows of opportunity in transnational biodiversity protection: as seen through the lens of an ecosystem approach-based paradigm. In S. Maljean-Dubaois, *The Effectiveness of Environmental Law* (1st edition). Intersentia. doi:10.1017/9781780687384.006

Sainsbury, K. J., Punt, A. E., and Smith, A. D. M. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science*, 57(3), 731-741. doi:10.1006/jmsc.2000.0737 https://tethys.pnnl.gov/publications/design-operational-management-strategies-achieving-fishery-ecosystem-objectives

Savidge, G., Ainsworth, D., Bearhop, S., Christen, N., Elsaesser, B., Fortune, F., Inger, R., Kennedy, R., McRobert, A., Plummer, K. E., Pritchard, D. W., Sparling, C. E., and Whittaker, T. J. T. 2014. Strangford Lough and the SeaGen Tidal Turbine. In M. A. Shields and A. I. L. Payne (Eds.), *Marine Renewable Energy Technology and Environmental Interactions* (pp. 153-172). Dordrecht: Springer Netherlands. https://tethys.pnnl.gov/publications/strangford-lough-seagen-tidal-turbine

Sinclair, K., Copping, A., May, R., Bennet, F., Warnas, M., Perron, M., and Elmqvist, A. 2018. Resolving environmental effects of wind energy. *WIREs Energy and Environment* 7, e291. doi:10.1002/wene.291 https://tethys.pnnl.gov/publications/resolving-environmental-effects-wind-energy

Sparling, C., Lonergan, M., and McConnel, B. 2018. Harbour seals (*Phoca vitulina*) around an operational tidal turbine in Strangford Narrows: No barrier effect but small changes in transit behaviour. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 28(1), 194-204. doi:10.1002/acq.2790 https://tethys.pnnl.gov/publications/harbour-seals-phoca-vitulina-around-operational-tidal-turbine-strangford-narrows-no

Sparling, C., Thompson, D., and Booth, C. 2017. Guide to Population Models used in Marine Mammal Impact Assessment. JNCC Report No. 605. Joint Nature Conservation Committee (JNCC), Peterborough, UK. https://tethys.pnnl.gov/publications/guide-population-models-used-marine-mammal-impact-assessment

Stankey, G., Cole, D., Lucas, R., Petersen, M., and Frissell, S. 1985. The limits of acceptable change (LAC) system for wilderness planning. General Technical Report, Intermountain Forest and Range Experiment Station, USDA Forest Service No. INT-176. doi:10.5962/bhl.title.109310

Sustain our Sounds Incorporated v. The New Zealand King Salmon Company Ltd (2014) NZSC 40, [133].

Tarlock, D. 2014. ‘Ecosystems’ in Bodansky, D., Brunée, J., Hey, E., (eds.) *The Oxford Handbook of International Environmental Law* (Oxford University Press) 581. OCLC Number 71541584.

Thomsen, F., Gill, A., Kosecka, M., Andersson, M., André, M., Degraer, S., Folegot, T., Gabriel, J., Judd, A., Neumann, T., Norro, A., Risch, D., Sigray, P., Wood, D., and Wilson, B. 2015. MaRVEN – Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy. Report No. RTD-K3-2012-MRE. https://tethys.pnnl.gov/publications/marven-environmental-impacts-noise-vibrations-electromagnetic-emissions-marine

Tickner, J., and Kriebel, D. 2008. The role of science and precaution in environmental and public health policy. In E. Fisher, J. Jones, and R. Von Schomberg (Eds.), *Implementing the Precautionary Principle: Perspectives and Prospects* (pp. 58-78). Glos, UK: Edward Elgar Publishing. https://tethys.pnnl.gov/publications/implementing-precautionary-principle

Todt, O., and Luján, J. L. 2014. Analyzing Precautionary Regulation: Do Precaution, Science, and Innovation Go Together? *Risk Analysis,* 34(12), 2163-2173. doi:10.1111/risa.12246 https://tethys.pnnl.gov/publications/analyzing-precautionary-regulation-do-precaution-science-innovation-go-together

Trouwborst, A. 2006. Precautionary Rights and Duties of States. Leiden, Netherlands: Martinus Nijhoff Publishers. https://tethys.pnnl.gov/publications/precautionary-rights-duties-states

van Asselt, M., and Vos, E. 2006. The Precautionary Principle and the Uncertainty Paradox. *Journal of Risk Research,* 9(4), 313-336. doi:10.1080/13669870500175063 https://tethys.pnnl.gov/publications/precautionary-principle-uncertainty-paradox

van Hees, S. 2018. Large-scale Water-related Innovative Renewable Energy Projects and the Habitats and Birds Directives: Legal Issues and Solutions. *European Energy and Environmental Law Review,* 27(1), 15-36. https://tethys.pnnl.gov/publications/large-scale-water-related-innovative-renewable-energy-projects-habitats-birds

Verdant Power. 2010a. Roosevelt Island Tidal Energy Project FERC No. 12611 (Volume 1 of 4). New York, NY. https://tethys.pnnl.gov/publications/final-pilot-license-application-roosevelt-island-tidal-energy-project

Verdant Power. 2010b. Roosevelt Island Tidal Energy Project FERC No. 12611 (Volume 4 of 4). New York, NY. https://tethys.pnnl.gov/publications/roosevelt-island-tidal-energy-project-rite-proposed-monitoring-plans-rite-monitoring

Verdant Power. 2018. Appendix B: P12611- Addendum to Verdant Power RITE Draft License Application. New York, NY. https://tethys.pnnl.gov/publications/addendum-verdant-power-rite-draft-license-application

Verdant Power. 2019. Roosevelt Island Tidal Energy Project, FERC No. P-12611, Article 401 RMEE Plan Amendments. New York, NY.

Wade, P. R. 1998. Calculating Limits to the Allowable Human-Caused Mortality of Cetaceans and Pinnipeds. *Marine Mammal Science*, 14(1), 1-37. doi:10.1111/j.1748-7692.1998.tb00688.x https://tethys.pnnl.gov/publications/calculating-limits-allowable-human-caused-mortality-cetaceans-pinnipeds

Walters, C. 2007. Is Adaptive Management Helping to Solve Fisheries Problems? *AMBIO,* 36(4), 304. doi:10.1579/0044-7447

Walters, C. 1986. Adaptive Management of Renewable Resources. Basingstoke, UK: MacMillan Publishers Ltd. https://tethys.pnnl.gov/publications/adaptive-management-renewable-resources

Ward, R. C., Loftis, J. C., and McBride, G. B. 1986. The “data-rich but information-poor” syndrome in water quality monitoring. *Environmental Management,* 10(3), 291-297. doi:10.1007/BF01867251 https://tethys.pnnl.gov/publications/data-rich-information-poor-syndrome-water-quality-monitoring

Wiesebron, L., Horne, J., and Hendrix, N. 2016. Characterizing Biological Impacts of Marine Renewable Energy Sites. *International Journal of Marine Energy*, 14, 27-40. doi:10.1016/j.ijome.2016.04.002 https://tethys.pnnl.gov/publications/characterizing-biological-impacts-marine-renewable-energy-sites

Wilding, T. A., Gill, A. B., Boon, A., Sheehan, E., Dauvin, J. C., Pezy, J.-P., O’Beirn, F., Janas, U., Rostin, L., and De Mesel, I. 2017. Turning off the DRIP (‘Data-rich, information-poor’) – rationalising monitoring with a focus on marine renewable energy developments and the benthos. *Renewable and Sustainable Energy Reviews,* 74, 848-859. doi:10.1016/j.rser.2017.03.013 https://tethys.pnnl.gov/publications/turning-drip-data-rich-information-poor-rationalising-monitoring-focus-marine

Williams, B. K. 2011a. Adaptive management of natural resources—framework and issues. *Journal of Environmental Management,* 92(5), 1346-1353. doi:10.1016/j.jenvman.2010.10.041 https://tethys.pnnl.gov/publications/adaptive-management-natural-resources-framework-issues

Williams, B. K. 2011b. Passive and active adaptive management: Approaches and an example. *Journal of Environmental Management,* 92(5), 1371-1378. doi:10.1016/j.jenvman.2010.10.039 https://tethys.pnnl.gov/publications/passive-active-adaptive-management-approaches-example

Williams, B. K., and Brown, E. D. 2014. Adaptive Management: From More Talk to Real Action. *Environmental Management*, 53(2), 465-479. doi:10.1007/s00267-013-0205-7 https://tethys.pnnl.gov/publications/adaptive-management-more-talk-real-action

Williams, B. K., and Brown, E. D. 2018. Double-Loop Learning in Adaptive Management: The Need, the Challenge, and the Opportunity. Environmental Management 62, 995–1006. doi:10.1007/s00267-018-1107-5 https://tethys.pnnl.gov/publications/double-loop-learning-adaptive-management-need-challenge-opportunity

Williams, K., Szaro, R., and Shapiro, C. 2009. Adaptive management: The U.S. Department of the Interior technical guide. U.S. Department of the Interior, Washington, D.C. https://tethys.pnnl.gov/publications/adaptive-management-us-department-interior-technical-guide