Effects of small marine energy deployments on oceanographic systems

Jonathan Whiting, Lysel Garavelli, Hayley Farr, Andrea Copping

Abstract—**The placement and operation of marine energy deployments in the ocean have the potential to change flow patterns, wave climate, and/or remove energy from the oceanographic system. Changes in oceanographic systems resulting from harvesting marine energy, particularly tidal and wave energy, may be of concern. These changes include alterations in nearfield and farfield physical processes, as well as potential secondary environmental effects such as changes in sediment transport patterns, biological processes, or coastal erosion. Knowledge of changes in oceanographic systems associated with marine energy is primarily available from numerical modeling studies, informed by some laboratory tests and very few field measurements. A literature review was conducted using the Tethys knowledge base and other online sources, building on conclusions from the Ocean Energy Systems-Environmental State of the Science report. Potential changes in oceanographic systems that may be caused by marine energy differ between tidal and wave energy devices because of different extraction mechanisms and siting locations. Numerical models show that tidal extraction on the order of hundreds of megawatts or with significant channel blockage is required to create changes in oceanographic processes that exceed natural variability. Effects from wave energy extraction in arrays are localized and dependent on array spacing and proximity to the shore. Available evidence supports the conclusion that the risk of significant environmental effects from such changes could be retired (i.e., less investigation required for every project) for small deployments—those representative of the state of the industry in 2023. Determining changes in oceanographic systems to be low risk for small deployments can thereby streamline environmental consenting by reducing monitoring needs at this early stage in the industry.**

Keywords—**Environmental Effects, Marine Renewable Energy, Oceanographic Systems, Tidal, Wave**

I. INTRODUCTION

MARINE energy harvests power from the movement of water including waves, tides, and ocean currents, as well as thermal and salinity gradients in ocean water. To date, global marine energy development has primarily focused on tidal and wave energy. In the past decade alone, the cumulative energy produced by tidal stream and wave resources increased from less than 5 gigawatt-hours (GWh) in 2009 to 45 GWh in 2019 [1]. As an emerging industry, marine energy is on the cusp of moving from test, demonstration, and pilot projects toward larger arrays. However, uncertainties about environmental effects continue to slow and complicate deployments worldwide [2]. In addition to potential effects such as marine animals colliding with operating devices and underwater sound from marine energy devices impacting animal communications and navigation, there is concern about how marine energy development might affect oceanographic processes.

Since 2009, researchers at Pacific Northwest National Laboratory have worked closely with the marine energy community to identify and add documents that address the environmental effects of marine energy to the Tethys Knowledge Base (https://tethys.pnnl.gov/knowledge-base-marine-energy), a public database that organizes documents about the environmental effects of marine energy [3]. Tethys also functions as the primary platform for the Ocean Energy Systems Environmental (OES-Environmental) task, which conducts extensive literature reviews and has released comprehensive State of the Science reports about the environmental effects of marine energy in 2013, 2016, and 2020 [4][5][6]. Each of these reports has dedicated sections about changes in oceanographic systems that summarize existing

Manuscript submitted 9 December 2021; accepted revised 22 May 2023, published 14 December 2023.

This article has been subject to single-blind peer review by a minimum of two reviewers. It is part of the special issue of ICOE2021 conference.

This work was supported in part by the US Department of Energy.

J. Whiting, L. Garavelli, H. Farr and A. Copping are with Pacific Northwest National Laboratory, WA, USA (e-mail: firstname.lastname@pnnl.gov).

Digital Object Identifier: https://doi.org/10.36688/imej.6.45-54

information and highlight the need for advancing global understanding of the topic.

Changes in oceanographic processes due to energy removal may affect ocean circulation, wave climate, sediment transport, and ultimately ecosystems [7]. For example, tidal circulation and wave action influence the concentration of dissolved gases and nutrients, transport sediments, and help maintain the habitats and water quality that support healthy ecosystems. Harnessing tidal and wave energy may affect environmental processes in both the nearfield (within a few device lengths) and the farfield (farther afield, including whole tidal basins).

With so few devices in the water and the inherent challenges of conducting oceanographic research in high-energy environments over large temporal and spatial scales, virtually all of what is known about changes in oceanographic systems is derived from numerical models. Hydrodynamic models describe fluid motion with approximating equations assessed along a grid representation of the domain space, while wave models estimate wave direction, energy, and frequency and can be coupled with hydrodynamic or sediment dynamics models [8]. While most marine energy modeling efforts have focused on resource assessment, power generation, and device efficiency, some numerical models have examined the changes in oceanographic systems that may potentially impact marine animals, habitats, and ecosystem processes (e.g., [9][10][11]). Models that have been developed for both tidal and wave energy vary significantly depending on the resolution, quality of calibration data, and accuracy of energy extraction parameterizations.

Regulators often expect developers to undertake comprehensive baseline and post-installation monitoring studies to prove that the devices do not pose unacceptable risk to marine animals and habitats. Monitoring is expensive, creating a cost barrier to early technology adopters. As an International Energy Agency collaboration focusing on the environmental effects of marine energy, the OES-Environmental task has developed a process for risk retirement to facilitate the consenting of small marine energy deployments, whereby stressor-receptor interactions deemed to be of low risk need not be fully investigated for every proposed project [2]. Rather, marine energy regulators and developers should rely on what is known from consented projects, related research studies, or findings of analogous offshore industries. When larger arrays of marine energy devices are planned, or when new information comes to light, these risks can be revisited and new decisions about the level of risk down-scoping or retirement can be made. The purpose of this review is to present the evidence base for changes in oceanographic systems caused by tidal and wave energy devices, and to propose that the risk of significant environmental effects from such changes can be retired for small marine energy deployments.

Small deployments might be defined as only a few devices, less than 10 megawatts (MW), or 2% of the total theoretical undisturbed resource [12], although each of these definitions far exceed the present level of deployment of wave or tidal farms. The largest existing tidal array is the MeyGen project in the United Kingdom, with four devices and a cumulative nameplate capacity of 6 MW [13]. The largest wave array deployed was Pelamis Wave Power's Aguçadoura Wave Farm in Portugal, with three devices and a cumulative nameplate capacity of 2.25 MW during a short period in 2008 [14]. Nuances make it challenging to provide a fixed definition for small deployments, but the largest tidal and wave projects deployed as of 2023 fall short of established definitions and can be considered small deployments. It is within the context of small deployments that risk retirement is being proposed.

II. METHODS

A literature review was conducted for documents addressing changes in oceanographic systems, amounting to 178 documents about tidal energy and 120 documents about wave energy. This was a continuation and update of the literature review for the 2020 State of the Science report [4], which included content from Web of Science and Google Scholar searches, references in key seminal documents, and the Tethys knowledge base. The majority of documents were peer-reviewed journal articles, but technical reports by researchers, developers, and government agencies were also reviewed. As previously noted, most papers about the topic address resource assessment, power generation, and device efficiency; these were not considered further. A total of 59 tidal papers and 33 wave papers addressing changes in oceanographic systems as an environmental concern were reviewed in greater detail. All these documents were added to Tethys. Additionally, a subset of these documents that address small deployments has been listed on Tethys as the primary evidence base: https://tethys.pnnl.gov/oceanographic-changes-evidence-base.

This review only considers tidal and wave energy devices because they represent the majority of marine energy devices deployed to date; it excludes tidal barrages and tidal lagoons because such installations largely block the channel or waterbody in which they are installed, causing greater environmental effects than in-stream tidal devices [15][16]. Changes in oceanographic systems differ for tidal and wave devices because of different extraction mechanisms and different siting locations; tidal devices are largely deployed in channels and land constrictions, while wave devices typically collect energy in open coastal areas. Numerical models and investigations that address the potential oceanographic systems changes differ in their approaches and are addressed separately.

The evidence naturally grouped into research addressing nearfield effects, farfield physical changes, and research detailing changes in secondary environmental processes. Secondary effects are defined as impacts on organisms or ecosystems resulting from changes in oceanographic systems, including sediment transport, coastal erosion, or biological impacts. Papers that advance fundamental understanding of the changes in oceanographic systems caused by marine energy extraction were summarized to detail the current understanding of the topic. Knowledge of farfield processes is often informed by numerical models of large arrays, so understanding of the concerns that will arise in future large-scale deployments is described for context. However, conclusions of the study were made only within the context of small deployments.

A recurring conclusion for changes in oceanographic systems has been that research should compare anticipated changes with natural variability and translate the change to meaningful ecological implications. References to the environmental significance of change are referring to tangible impacts to marine animals and habitats. This paper builds upon these conclusions by applying them to the present status of the industry to support risk retirement for small tidal and wave deployments for small deployments.

III. RESULTS

The effects of tidal turbines and wave energy converters (WECs) on the marine environment differ, based on the placement of the devices, and the operating aspects needed to capture the marine energy. The potential effects of each technology are considered separately here.

The definition of environmental effects of marine energy has different meanings among the disciplines of the researchers who make up the community studying these new technologies. For example, a numerical modeler may consider a relative change in tidal height or bed shear stress as an environmental effect, while an ecologist may consider changes to the food web affecting an endangered fish species. This paper creates a distinction between physical effects (both nearfield and farfield) and secondary environmental effects where the change impacts organisms or habitats. Therefore, the nearfield physical effects inform the farfield physical effects, which inform the secondary environmental effects. Trends in the change caused by energy extraction are qualitatively described, but quantitative values are intentionally not mentioned because they are highly dependent on contextual details such as shoreline geometry, extraction amount, layout configuration, and model parameterizations.

A. Tidal Energy

Tidal energy resources are strongest in channels or around land constrictions. Tidal energy deployments as of 2023 have consisted of single devices or small arrays with no more than four individual turbines. But larger arrays have been planned for staged development, starting with a few devices and increasing in number with time and environmental observations. Some of the key physical and environmental effects of tidal energy extraction are illustrated in Fig. 1.

1) Nearfield Physical Effects

A single tidal turbine placed in the water forms a blockage that creates a turbulent wake downstream of the device and dissipates with distance. This wake field breaks down the natural flow structure and reduces mean velocity downstream from the turbine [17]. The wake field may vary in shape, length, and strength and will return to ambient conditions quicker with more turbulent inflow conditions [18]. Ramos et al. [19] and O'Donncha et al. [20] applied numerical models to show that as water seeks the path of least resistance, flow velocities increase to the sides of the turbine and over or under the turbine, depending on whether the turbine is bottom-mounted or floating . These increases in flow create more seabed stress, which may affect benthic habitats [21] and can cause the seabed to scour, particularly with smaller grain size [22].

The nearfield physical effects around single tidal devices are primarily informed by measurements from laboratory flume tests (e.g., [23][24]) and deployed prototypes (e.g., [17][25]).

Nearfield physical effects of tidal energy extraction have been observed in and around device or array footprints as described above. Nearfield effects are localized and therefore have little impact on the greater environment because of the small scale [26], but nearfield changes in flow help inform our understanding of farfield effects.

2) Farfield Physical Effects

Measurements taken around single devices and small arrays have focused on the nearfield wake and are not expected to detect any changes in the farfield after wake recovery. Because no large tidal arrays have been deployed, current knowledge is primarily derived from numerical models that lack real-world validation. Very few models use the number of devices that might be expected in early deployment scenarios, but a few that do conclude that downstream effects dissipate quickly and farfield effects will be negligible [9][11][27].

Many of the observations around single devices apply to arrays, viewing the array as a single unit with a greater magnitude of effect, causing greater cumulative blockage for a channel. The same blockage effect causes a decrease in water velocities upstream and downstream of the tidal arrays, while velocities increase to the sides and in parallel channels as flow seeks the path of least resistance, an effect that is most notable where flow is constrained by coastlines [19][28]. Changes in flow depend greatly on site-specific channel geometry and seasonality and can increase tidal asymmetry within a channel [29]. A large amount of tidal energy extraction in a channel may change the natural tidal phase or decrease tidal range on the order of centimeters [30]. Phoenix and Nash [31] demonstrated

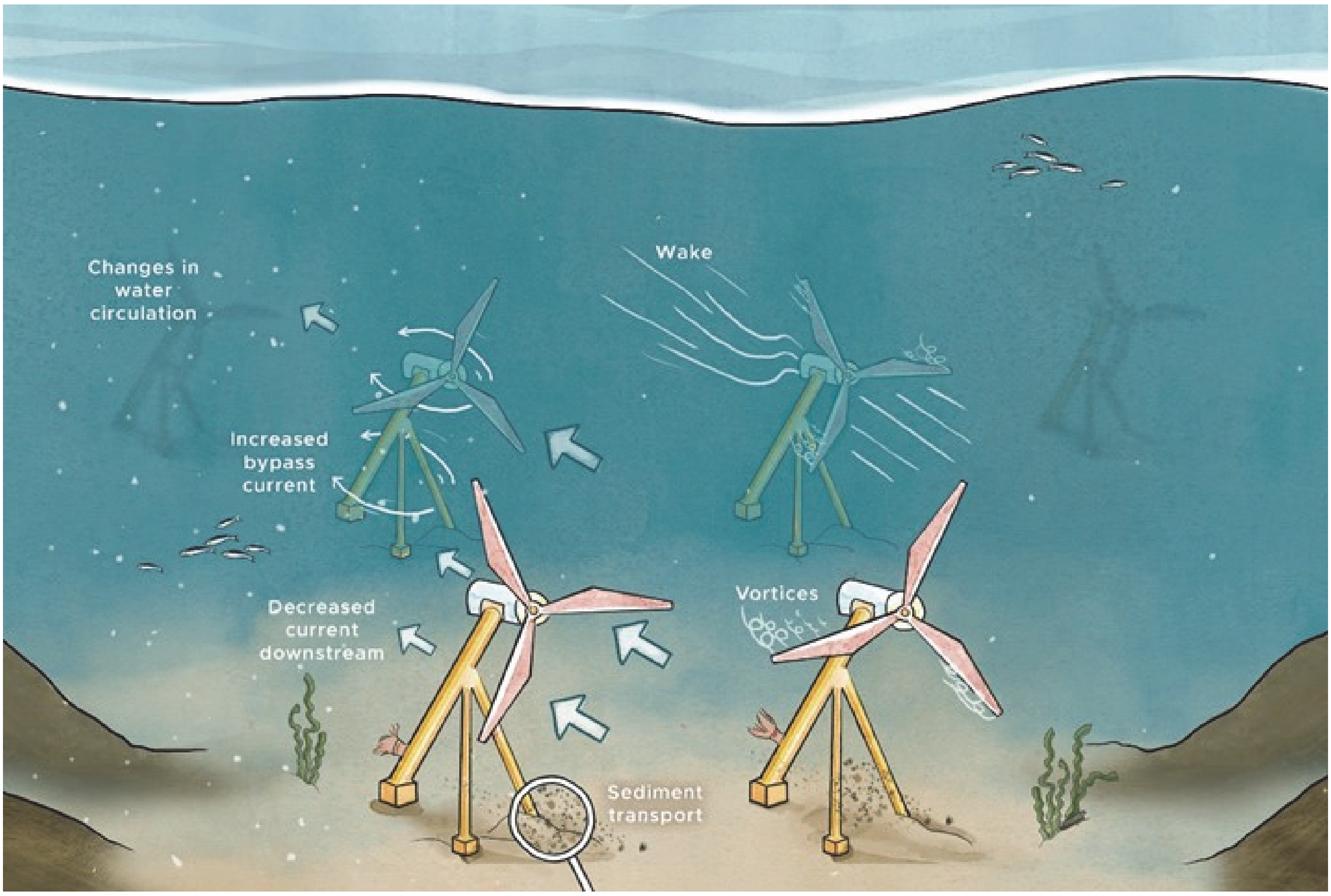

Fig. 1. Schematic of a tidal energy array and the potential effects on hydrodynamics and sediment transport. (Illustration by Stephanie King – Pacific Northwest National Laboratory)

that two arrays with the same power generation in the same location might cause very different magnitudes of physical change, depending on the inter-array device configuration and the characteristics of each device. Extracting tidal energy from one channel will cause a parallel channel to increase in current velocities [11][32][33], thereby implying that neighboring farms may interact with one another [32].

Potential Secondary Effects on Environmental Processes

Understanding the potential for tidal extraction to cause significant environmental harm requires an assessment of secondary effects resulting from physical changes. Changes caused by installing tidal turbines are often of greatest concern within estuaries, where significant blockage by a large tidal array can alter the circulation, tidal range, and timing of tides. Potential secondary effects are site-specific based on estuary geometry, tidal regime, turbine dynamics, seasonality, and the magnitude of energy extraction [34] and should be compared to the natural variability at a given location [35]. Shapiro [35] used numerical models to show that tidal extraction on an open shelf results in smaller magnitude effects but may extend over a larger distance. Secondary effects are likely to occur only in the presence of large tidal arrays, allowing insight into the effects to be drawn from simulations using numerical models. Key areas of secondary effects of large-scale extraction include biological processes, sediment transport, and water levels.

Biological Processes

Food webs in the ocean are based on unicellular organisms including phytoplankton and other microorganisms, which generally depend on dissolved nutrients and gases in seawater. Models predict that the reduction of tidal velocities caused by tidal energy extraction may increase vertical mixing and flushing times, leading to a potential increase in the concentration of dissolved nutrients and contaminants [36][37][38]. Changes in nutrients may lead to eutrophication and harmful algal blooms or alter phytoplankton species diversity, which may have cascading effects on the food web [39]. While changes in biological processes are most notably related to tidal extraction in estuaries, changes in farfield circulation have also been predicted for tidal extraction on open shelves [19][37]. Some farfield effects on the ecosystem may be considered positive depending on the setting. Van der Molen et al. [40] modeled a case where turbid waters reduced light and limited primary production, while tidal energy extraction reduced bed-shear stress and turbidity in distant shallow waters, increasing the productivity of shellfish beds.

The effects on biological processes have only been studied using numerical models that extract energy on the order of hundreds or thousands of megawatts, far greater than current deployments. Changes in biological processes are likely to scale with the level of extraction, and the absence of studies assessing small deployments suggests that changes in biological processes from small numbers of devices are likely to be less than natural variability.

Sediment Transport

Tidal channels experience a balance of sediment fluxes between flood and ebb flows carrying suspended sediment in and out of an estuary, respectively. Tidal asymmetry can influence this balance by increasing the peak velocities in one direction, while there is typically a net export of sediment as the tidal basin is replenished from rivers [41]. Fine sediment will suspend and transport more quickly, while energetic conditions at peak ebb and flood may be able to transport some coarser material. Tidal extraction can reduce the total sediment fluxes and modify the pathways of the sediment transiting through an array, depending on siting of individual devices within an array [42]. Tidal extraction can cause a decrease in suspended sediment concentrations in shallow waters within an estuary [43] and a decrease in the export capacity of tidal channels, causing a gradual infilling of tidal creeks [44]. Ramírez-Mendoza et al. [24] and Neill et al. [45] modeled modifications to tidal asymmetry caused by tidal extraction in estuaries, enhancing changes in hydrodynamics and sediment transport.

Although most tidal installations are not located on sandy-bottom habitat, the geomorphology of tidal areas can vary widely. Large-scale tidal extraction can alter the transport and distribution of sediments from their natural range of conditions [30]. Modeling by Fairley et al. [46] and Chatzirodou et al. [47] shows that the introduction of large arrays on open continental shelves may cause alterations of local sandbanks that are used as habitat and breeding grounds for numerous marine species. Sediment accumulation occurs upstream, downstream, and inside tidal arrays as velocities decrease, while scour increases along the sides of the array [48]. Local sediment accumulation can create an obstruction that further affects sediment transport, an effect that may be emphasized in areas of vorticity generation [49]. Altering regional eddies can have implications for nearby sandbanks, potentially transporting sandbanks as a sand-wave [50][51][52][53]. Models predict different magnitudes of the impact caused by large arrays on sandbanks that range from minimal effects on natural morphology (e.g., [46]) to changes that far exceed natural morphology (e.g., [47]).

The numerical models used to generate these results assume very large energy extraction scenarios, often in the gigawatt range, and tidal devices sited in relatively shallow water. This size of deployment is not likely until the industry matures. For small deployments, changes in sediment transport are likely to fall within the natural variability of the system if sited appropriately.

Water Level

When a large tidal array is located within a channel or estuary, the blockage effect may reduce the overall tidal range and delay the times of high and low water within and upstream of the array [54]. The decrease in tidal range will cause a decrease in the maximum water level, though dampened low tides also reduce the extent of intertidal habitats [55]. De Dominicis et al. [56] showed that large tidal extraction can assist with the adaptation to climate change by reducing flood risk from sea level rise but may also exacerbate climate change by increasing stratification through reduced water column mixing. However, these effects will be of much lower magnitude than the present climate change signal. In addition, there will be a slight increase (on the order of several centimeters based on Kresning et al. [57]) in tidal range just before the blockage. Nearly all models addressing change to water levels use large extraction scenarios to create changes that exceed natural variability, and these changes have not been measured with present deployments. If the deployment is not blocking a substantial portion of a channel, water level is not expected to be changed by small tidal energy deployments.

B. *Wave Energy*

Waves are comprised of surface waves and swell; surface waves are generated from wind blowing along the water surface, while swell is caused by distant storms. Wave energy resources are strongest on open continental shelves, particularly on the eastern sides of ocean basins due to the Coriolis effect. Wave energy deployments as of 2023 have been single WECs or small arrays of no more than three devices, while other WECs are sited on shore or breakwaters. Future arrays have been planned with adequate spacing or staggered rows to avoid interference between WECs for a variety of wave directions. Some of the key physical and environmental effects of wave energy extraction are illustrated in Fig. 2.

1) *Nearfield Physical Effects*

The nearfield physical effects associated with wave energy extraction have been assessed through in situ observations, laboratory experiments, and numerical models. In the proximity of a single WEC or a small array, these studies focused on the effects on the wave climate (i.e., wave height, direction, period) and the associated wake effects.

In the vicinity of a small wave array, a decrease in wave energy slightly reduces wave height, particularly immediately down wave from the array [25][58]. Aderinto and Li [59] show that this reduction scales with the efficiency of the WECs and attenuates toward the coastline. The presence of a WEC acts as a physical obstacle and can potentially affect the diffraction and reflection of waves [60]. These effects may change the direction of waves but have small effects on the overall wave climate [58].

The diffraction of waves because of the presence of a WEC can redistribute wave energy down wave from the WEC and create a wake effect. With individual WECs, the dimensions and magnitudes of the wake depend on the device type and incident wave climate and increase in the presence of long wave periods [61].

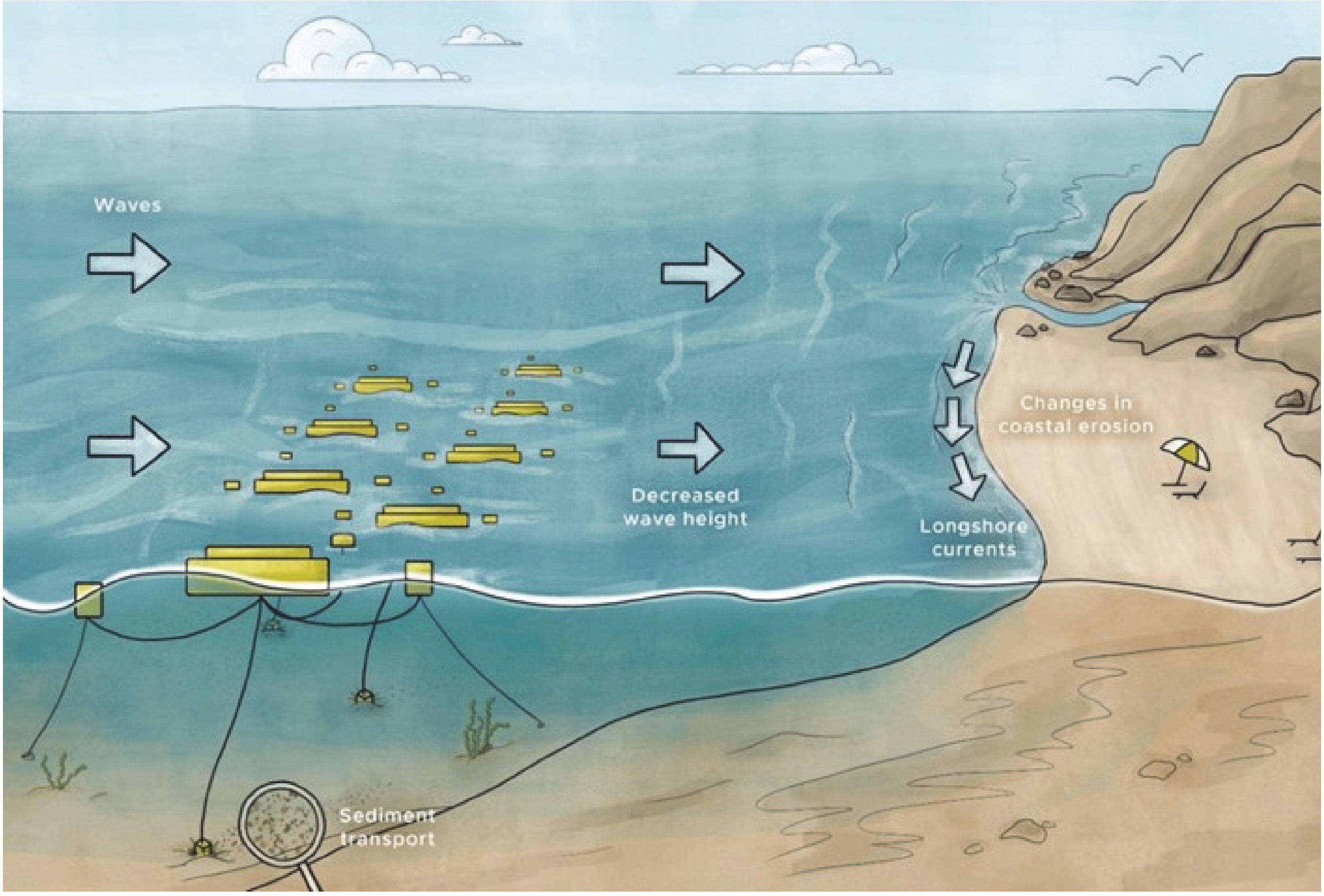

Fig. 2. Schematic of a wave energy array and the potential effects on wave height, longshore currents, sediment transport, and coastal erosion. (Illustration by Stephanie King – Pacific Northwest National Laboratory)

Nearfield physical effects of wave energy extraction have been observed around device footprints as described above. Nearfield effects are localized, quickly dissipate with distance, and should have little impact on the environment [26]. However, descriptions of nearfield effects inform understanding of farfield environmental effects.

2) *Farfield Physical Effects*

Farfield effects from wave energy extraction have been examined using numerical models applied to an array of WEC devices. Common farfield effects include changes in wave climate, longshore currents, and rip currents.

In a wave array, energy absorption increases with the number of WECs and could affect wave climate [10]. However, the effects of an array on wave height decrease with distance from the array [62] and are negligible a few kilometers away [63][64][65]. WEC type and array configuration also have limited effects on wave direction and period [10].

A WEC array located farther offshore generates a wave shadow with reduced wave heights that extends towards the coast, decreasing with distance. The reduction is more pronounced when device spacing is more compact [66]. When the array is located closer to shore, wave energy dissipation can also generate longshore currents converging in the lee of the farm and increase longshore current velocities [66][67]. O'Dea et al. [68] demonstrated that compact device spacing within arrays creates more significant wave height reduction and can induce greater longshore current changes, compared to widely spaced array.

Reductions in wave height dissipate with distance, and moderately sized arrays with tens of devices are expected to dissipate before reaching the shore [66]. WEC arrays located closer to shore will cause changes similar to marine construction like breakwaters, causing local change in the lee of the WEC array.

3) *Potential Secondary Effects on Environmental Processes*

Like tidal energy, the potential secondary effects of wave energy extraction are project- and site-specific and should always be compared to the natural variability of a given location [35]. Site-specific conditions need to be considered when describing how farfield changes affect secondary processes like sediment transport and coastal erosion.

Sediment Transport

Sediment transport is a coastal process that cyclically moves sediment toward and away from shore with tides, storms, and seasons. Littoral transport also moves sediment laterally along the coast within drift cells defined by shoreline geometry, driven by breaking waves and induced longshore currents. Sediment deposition can create new habitats and provide nutrients to vegetation, though excessive deposition can bury existing habitats. Wave action is a major driver for sediment resuspension and transport, so wave energy extraction can influence this process.

Numerical models are used to describe the effect of potential changes in the farfield wave climate and nearshore circulation caused by wave energy extraction on the nearshore transport of sediment, particularly in bays. The local accumulation and divergence of sediments around a wave array are common secondary effects [66]. Modeling by González-Santamaría et al. [69] shows that at low tide during a storm, an increase in sediment concentration associated with bottom shear stress and changes in seabed elevations may occur in the lee of a large array and adjacent bays along the coastline. The lee of a large WEC array may also accumulate fine sediments, such that a large storm event may cause more significant bed height changes [70]. These models assume very large extraction scenarios, and small arrays are not expected to significantly affect sediment transport relative to natural variability.

Coastal Erosion

Coastal erosion is largely driven by wave action that removes rock, soil, and sand along the coast, particularly in combination with storm surge and high tide. Coastal erosion is exacerbated by sea level rise and can cause the loss of coastal wetlands and damage coastal properties. Wave energy extraction located close to shore can alter natural erosion, similar to other built structures.

Local characteristics such as geomorphology, wave climate, and sediment composition play a role in the variability of erosion rates [71]. Various numerical approaches used to assess the effects of wave energy extraction on erosion suggest a reduction of coastal erosion and no negative impact on the coastline (e.g., [69][72]). Under specific wave conditions and array configurations, the presence of a wave farm could even provide coastal protection by reducing beach erosion [73][74]. In a sea level rise context, wave farms could also reduce coastal erosion and increase the accumulation of sediment, thereby contributing to coastal protection [75]. The impact on coastal erosion depends on the magnitude of energy extraction and proximity to shore, so while the effects are viewed as a positive change, they are likely to be minimal for small deployments.

IV. DISCUSSION

While there is extensive literature exploring changes in oceanographic systems, there are few opportunities to validate the numerical models that inform our understanding due to a lack of open water deployments. Although the industry has been slowed over extended permitting and licensing processes, most concerns are associated with threats to marine animals and habitats; however, there are also continuing concerns about potential changes in circulation or wave climate.

More than a decade of laboratory studies, small deployments, and numerical models provide adequate knowledge about changes in oceanographic systems. Laboratory studies and measurements around deployments inform understanding of nearfield effects, but the largest deployments as of 2023 do not cause a measurable change in the farfield. Therefore, numerical models that have been calibrated with measurements and laboratory tests provide the best quantitative understanding of farfield physical processes, but only a subset of models consider small deployments or potential secondary effects on environmental processes. Numerical modeling of marine energy often uses simple parameterizations to represent energy extraction, and the nuances of different device types and their operation are rarely represented. Model results can be used to reach consensus related to the patterns of change, but this change is driven by the location, geometry, and size of the array, and should always be compared to the natural variability of the system and the tolerance thresholds of local species [76].

For single tidal energy devices and small tidal energy arrays, the evidence shows that the environmental effects are dependent on the channel characteristics (i.e., depth, width, shape) and the degree of blockage caused by the installation. The few numerical models that simulate small deployments indicate that any changes will be immeasurable relative to the natural variability of the system [9][11][27]. The remaining models that simulate large deployments offer insight into cumulative trends, but do not provide useful quantitative information about effects of small deployments.

For wave energy, the evidence base shows that nearfield and farfield effects are typically minor, dissipate with distance, and are dependent on array spacing and proximity to shore. Single devices and small arrays are not expected to exceed natural variability or cause significant environmental harm. As the industry moves toward larger arrays, proper siting of devices farther offshore and away from sensitive habitats should reduce risk.

A common theme of this paper is assessing the magnitude of change to natural variability, which defines a threshold in which even the most sensitive habitats and organisms can survive. However, as several modeling studies directly address, it is important to remember that the environmental baseline is shifting from climate change and anthropogenic activities, which may already be stressing habitats and organisms. Marine energy can be a solution for coastal communities by aiding the transition from fossil fuels, but it is important to understand how a new influence on oceanographic systems may amplify existing stressors, as the industry moves towards commercialization.

This review indicates no evidence that changes in oceanographic systems due to small tidal and wave energy deployments will cause significant environmental effects. Assuming proper device siting, the evidence presented herein supports risk retirement for changes in oceanographic systems caused by single devices and small arrays. When large arrays are planned, or when new information comes to light, this risk should be revisited and new decisions about the level of risk down-scoping or retirement can be made. By distinguishing between perceived and actual risk to the marine environment, risk retirement can reduce environmental monitoring requirements for developers, provide a level of certainty for stakeholders, and support efficient consenting processes [2].

V. CONCLUSION

This review assesses the available evidence of changes in oceanographic systems caused by tidal and wave energy deployments, to inform our understanding of whether small deployments will cause significant environmental effects to marine animals or their habitats. Potential environmental effects caused by large arrays described by numerical models were presented for a comprehensive understanding of anticipated effects, while the few studies assessing small deployments indicate no significant environmental change. Therefore, the evidence supports risk retirement for small deployments, implying that regulators have sufficient information that this environmental stressor is unlikely to have a significant effect on the environment and need not be investigated at each new project site.

Researchers should continue to explore the complex relationship between physical and biological changes in the ocean, reviewing natural proxies like multi-year weather patterns and extreme storm events. Modelers should improve device parameterizations, including representing non-mechanical components such as foundations, moorings, anchors, power cables, and substations. Models of large extraction scenarios should not focus on unvalidated quantifications of change, but rather on trends and patterns and the implications of those changes on habitats and animals.

Developers are encouraged to site projects responsibly and sustainably, recognizing site-specific sensitivities and scaling extraction appropriately to the available resource. Partnership between developers and researchers are recommended to conduct farfield monitoring around small deployments. If this monitoring finds inconclusive results that are not detectable above natural variability, they are encouraged to publish those findings. When developers are required to conduct environmental monitoring, they should follow international collection standards and to make data publicly available for further research.

REFERENCES

[1] Ocean Energy Systems, "OES Annual Report 2019," 2020.

[2] A. Copping, M. Freeman, A. Gorton, L. Hemery, "Risk Retirement—Decreasing Uncertainty and Informing Consenting Processes for Marine Renewable Energy Development," *Journal of Marine Science and Engineering*, vol. 8, no. 3, pp. 172-194, 2020. DOI: 10.3390/jmse8030172, [Online].

[3] J. Whiting, A. Copping, M. Freeman, A. Woodbury, "Tethys knowledge management system: Working to advance the marine renewable energy industry," *International Marine Energy Journal*, vol. 2, no. 1, pp. 29-38, 2019. DOI: 10.36688/imej.2.29-38, [Online].

[4] A.E. Copping, L.G. Hemery, "OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World," Ocean Energy Systems, 2020. [Online] Available: https://tethys.pnnl.gov/publications/state-of-the-science-2020

[5] A. Copping, et al., "Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World," Ocean Energy Systems, 2016. [Online] Available: https://tethys.pnnl.gov/publications/state-of-the-science-2016

[6] A. Copping, et al., "Environmental Effects of Marine Energy Development Around the World: Annex IV Final Report," Ocean Energy Systems, 2013. [Online] Available: https://tethys.pnnl.gov/publications/environmental-effects-marine-energy-development-around-world-annex-iv-final-report

[7] J. Whiting, G. Chang, "Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices," in *OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World*, 2020, ch. 7, pp. 127-145. [Online], Available: https://tethys.pnnl.gov/publications/state-of-the-science-2020-chapter-7-oceanographic-systems

[8] K.E. Buenau, L. Garavelli, L.G. Hemery, G. García Medina, "A review of modeling approaches for understanding and monitoring the environmental effects of marine renewable energy," *Journal of Marine Science and Engineering*, In Review.

[9] P. Robins, S. Neill, M. Lewis, "Impact of Tidal-Stream Arrays in Relation to the Natural Variability of Sedimentary Processes," *Renewable Energy*, vol. 72, pp. 311-321, 2014. DOI: 10.1016/j.renene.2014.07.037, [Online].

[10] G. Chang, K. Ruehl, C. Jones, J. Roberts, C. Chartrand, "Numerical modeling of the effects of wave energy converter characteristics on nearshore wave conditions," *Renewable Energy*, vol. 89, pp. 636-648, 2016. DOI: 10.1016/j.renene.2015.12.048, [Online].

[11] T. Wang, Z. Yang, "A Modeling Study of Tidal Energy Extraction and the Associated Impact on Tidal Circulation in a Multi-Inlet Bay System of Puget Sound," *Renewable Energy*, vol. 114, part A, pp. 204-214, 2017. DOI: 10.1016/j.renene.2017.03.049, [Online].

[12] International Electrotechnical Commission, "IEC TS 62600-201:2015 - Part 201: Tidal energy resource assessment and characterization," 2015.

[13] Meygen, "Lessons Learnt from MeyGen Phase 1a: Design Phase," 2017.

[14] G. Dalton, R. Alcorn, T. Lewis, "Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America," *Renewable Energy*, vol. 35, no. 2, pp. 443-455, 2010. DOI: 10.1016/j.renene.2009.07.003, [Online].

[15] B. Polagye, B. Van Cleve, A. Copping, K. Kirkendall, "Environmental Effects of Tidal Energy Development. Proceedings of a Scientific Workshop," NOAA Technical Memorandum NMFS F/SPO–116, March 22-25, 2010

[16] C. Frid, E. Andonegi, J. Depestele, A. Judd, D. Rihan, S. Rogers, E. Kenchington, "The environmental interactions of tidal and wave energy generation devices," *Environmental Impact Assessment Review*, vol. 32, no. 1, pp. 133-139, 2012. DOI: 10.1016/j.eiar.2011.06.002, [Online].

[17] S. Fraser, V. Nikora, B. Williamson, B. Scott, B. "Hydrodynamic Impacts of a Marine Renewable Energy Installation on the Benthic Boundary Layer in a Tidal Channel," *Energy Procedia*,

vol. 125, pp. 250-259, 2017. DOI: 10.1016/j.egypro.2017.08.169, [Online].

[18] P. Mycek, B. Gaurier, G. Germain, G. Pinon, E. Rivoalen, “Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part I: One single turbine,” *Renewable Energy*, vol. 66, pp. 729-746, 2014. DOI: 10.1016/j.renene.2013.12.036, [Online].

[19] V. Ramos, R. Carballo, M. Sanchez, M. Veigas, G. Iglesias, G. “Tidal stream energy impacts on estuarine circulation,” *Energy Conversion and Management*, vol. 80, pp. 137-149, 2014. DOI: 10.1016/j.enconman.2014.01.027, [Online].

[20] F. O'Donncha, S. James, E. Ragnoli, “Modelling Study of the Effects of Suspended Aquaculture Installations on Tidal Stream Generation in Cobscook Bay,” *Renewable Energy*, vol. 102, part A, pp. 65-76, 2017. DOI: 10.1016/j.renene.2016.10.024, [Online].

[21] R. du Feu, S. Funke, S. Kramer, J. Hill, M. Piggott “The trade-off between tidal-turbine array yield and environmental impact: A habitat suitability modelling approach,” *Renewable Energy*, vol. 143, pp. 390-403, 2019. DOI: 10.1016/j.renene.2019.04.141, [Online].

[22] X. Li, M. Li, L. Amoudry, R. Ramírez-Mendoza, P. Thorne, Q. Song, P. Zheng, S. Simmons, L-B. Jordan, S. McLelland, “Three-dimensional modelling of suspended sediment transport in the far wake of tidal stream turbines,” *Renewable Energy*, vol. 151, pp. 956-965, 2020. DOI: 10.1016/j.renene.2019.11.096, [Online].

[23] P. Ouro, L. Ramírez, M. Harrold, “Analysis of array spacing on tidal stream turbine farm performance using Large-Eddy Simulation” *Journal of Fluids and Structures*, vol. 91, pp. 102732, 2019. DOI: 10.1016/j.jfluidstructs.2019.102732, [Online].

[24] R. Ramírez-Mendoza, L. Murdoch, L. Jordan, L. Amoudry, S. McLelland, R. Cooke, P. Thorne, S. Simmons, D. Parsons, M. Vezza, “Asymmetric effects of a modelled tidal turbine on the flow and seabed,” *Renewable Energy*, vol. 159, pp. 238-249, 2020. DOI: 10.1016/j.renene.2020.05.133

[25] S. Contardo, R. Hoeke, M. Hemer, G. Symonds, K. McInnes, J. O'Grady, “In situ observations and simulations of coastal wave field transformation by wave energy converters,” *Coastal Engineering*, vol. 140, pp. 175-188, 2018. DOI: 10.1016/j.coastaleng.2018.07.008, [Online].

[26] M. Elliott, A. Borja, R. Cormier, “Activity-footprints, pressures-footprints and effects-footprints-Walking the pathway to determining and managing human impacts in the sea,” *Marine Pollution Bulletin*, vol. 155, pp. 111201, 2020. DOI: 10.1016/j.marpolbul.2020.111201, [Online].

[27] Z. Yang, T. Wang, A. Copping, S. Geerlofs, “Modeling of In-Stream Tidal Energy Development and its Potential Effects in Tacoma Narrows Washington USA,” *Ocean & Coastal Management*, vol. 99, pp. 52-62, 2014. DOI: 10.1016/j.ocecoaman.2014.02.010, [Online].

[28] A. Gallego, et al., “Large Scale Three-Dimensional Modelling for Wave and Tidal Energy Resource and Environmental Impact: Methodologies for Quantifying Acceptable Thresholds for Sustainable Exploitation,” *Ocean & Coastal Management*, vol. 147, pp. 67-77, 2017. DOI: 10.1016/j.ocecoaman.2016.11.025, [Online].

[29] M. Sanchez, R. Carballo, V. Ramos, G. Iglesias, “Tidal stream energy impact on the transient and residual flow in an estuary: A 3D analysis,” *Applied Energy*, vol. 116, pp. 167-177, 2014. DOI: 10.1016/j.apenergy.2013.11.052, [Online].

[30] R. Murray, A. Gallego, “A modelling study of the tidal stream resource of the Pentland Firth, Scotland,” *Renewable Energy*, vol. 102, no. B, pp. 326-340, 2017. DOI: 10.1016/j.renene.2016.10.053, [Online].

[31] A. Phoenix, S. Nash, “Optimisation of tidal turbine array layouts whilst limiting their hydro-environmental impact, “*Journal of Ocean Engineering and Marine Energy*, vol. 5, no. 1, pp. 1-16, 2019. DOI: 10.1007/s40722-019-00145-8, [Online].

[32] S. Waldman, S. Weir, R. Murray, D. Woolf, S. Kerr, “Future policy implications of tidal energy array interactions,” *Marine Policy*, vol. 108, pp. 103611, 2019. DOI: 10.1016/j.marpol.2019.103611, [Online].

[33] G. Deng, Z. Zhang, Y. Li, H. Liu, W. Xu, Y. Pan, “Prospective of development of large-scale tidal current turbine array: An example numerical investigation of Zhejiang, China,” *Applied Energy*, vol. 264, no. 114621, 2020. DOI: 10.1016/j.apenergy.2020.114621, [Online].

[34] B. Polagye, P. Malte, M. Kawase, D. Durran, “Effect of large-scale kinetic power extraction on time-dependent estuaries. Proceedings of the Institution of Mechanical Engineers, Part A,” *Journal of Power and Energy*, vol. 222, no. 5, pp. 471-484, 2008. DOI: 10.1243/09576509JPE519, [Online].

[35] G. Shapiro, “Effect of Tidal Stream Power Generation on the Region-Wide Circulation in a Shallow Sea,” *Ocean Science Discussion*, vol. 7, no. 5, pp. 165-174, 2011. DOI: 10.5194/os-7-165-2011, [Online].

[36] T. Wang, Z. Yang, A. Copping, “A Modeling Study of the Potential Water Quality Impacts from In-Stream Tidal Energy Extraction,” *Estuaries and Coasts*, vol. 38, no. 1, pp. 173-186, 2015. DOI: 10.1007/s12237-013-9718-9, [Online].

[37] M. De Dominicis, R. Murray, J. Wolf, “Multi-Scale Ocean Response to a Large Tidal Stream Turbine Array,” *Renewable Energy*, vol. 114, part B, pp. 1160-1179, 2017. DOI: 10.1016/j.renene.2017.07.058, [Online].

[38] N. Guillou, J. Thiébot, G. Chapalain, “Turbines’ effects on water renewal within a marine tidal stream energy site,” *Energy*, vol. 189, pp. 116113, 2019. DOI: 10.1016/j.energy.2019.116113, [Online].

[39] Z. Yang, T. Wang, A. Copping, “Modeling Tidal Stream Energy Extraction and its Effects on Transport Processes in a Tidal Channel and Bay System Using a Three-Dimensional Coastal Ocean Model,” *Renewable Energy*, vol. 50, pp. 605-613, 2013. DOI: 10.1016/j.renene.2012.07.024, [Online].

[40] J. van der Molen, P. Ruardij, N. Greenwood, “Potential Environmental Impact of Tidal Energy Extraction in the Pentland Firth at Large Spatial Scales: Results of a Biogeochemical Model,” *Biogeosciences*, vol. 13, pp. 2593-2609, 2016. DOI: 10.5194/bg-13-2593-2016, [Online].

[41] V. Gatto, B. van Prooijen, Z. Wang, “Net sediment transport in tidal basins: quantifying the tidal barotropic mechanisms in a unified framework,” *Ocean Dynamics*, vol. 67, pp. 1385-1406, 2017. DOI: 10.1007/s10236-017-1099-3, [Online].

[42] J. Thiébot, P. de Bois, S. Guillou, “Numerical Modeling of the Effect of Tidal Stream Turbines on the Hydrodynamics and the Sediment Transport - Application to the Alderney Race (Raz Blanchard), France,” *Renewable Energy*, vol. 75, pp. 356-365, 2015. DOI: 10.1016/j.renene.2014.10.021, [Online].

[43] L. Ashall, R. Mulligan, B. Law, “Variability in Suspended Sediment Concentration in the Minas Basin, Bay of Fundy, and Implications for Changes due to Tidal Power Extraction,” *Coastal Engineering*, vol. 107, pp. 102-115, 2016. DOI: 10.1016/j.coastaleng.2015.10.003, [Online].

[44] C. O'Laughlin, D. van Proosdij, T. Milligan, “Flocculation and Sediment Deposition in a Hypertidal Creek,” *Continental Shelf Research*, vol. 82, pp. 72-84, 2014. DOI: 10.1016/j.csr.2014.02.012, [Online].

[45] S. Neill, E. Litt, S. Couch, A. Davies, “The Impact of Tidal Stream Turbines on Large-Scale Sediment Dynamics,” *Renewable Energy*, vol. 34, no. 12, pp. 2803-2812, 2009. DOI: 10.1016/j.renene.2009.06.015, [Online].

[46] I. Fairley, I. Masters, H. Karunarathna, “The Cumulative Impact of Tidal Stream Turbine Arrays on Sediment Transport in the Pentland Firth,” *Renewable Energy*, vol. 80, pp. 755-769, 2015. DOI: 10.1016/j.renene.2015.03.004, [Online].

[47] A. Chatzirodou, H. Karunarathna, D. Reeve, “3D modelling of the impacts of in-stream horizontal-axis Tidal Energy

Converters (TECs) on offshore sandbank dynamics," *Applied Ocean Research*, vol. 91, pp. 101882, 2019. DOI: 10.1016/j.apor.2019.101882, [Online].

[48] R. Martin-Short, J. Hill, S. Kramer, A. Avdis, P. Allison, M. Piggott, "Tidal Resource Extraction in the Pentland Firth, UK: Potential Impacts on Flow Regime and Sediment Transport in the Inner Sound of Stroma," *Renewable Energy*, vol. 76, pp. 596-607, 2015. DOI: 10.1016/j.renene.2014.11.079, [Online].

[49] D. Haverson, J. Bacon, H. Smith, V. Venugopal, Q. Xiao, "Modelling the Hydrodynamic and Morphological Impacts of a Tidal Stream Development in Ramsey Sound," *Renewable Energy*, vol. 126, pp. 876-887, 2018. DOI: 10.1016/j.renene.2018.03.084, [Online].

[50] N. Guillou, G. Chapalain, "Assessing the impact of tidal stream energy extraction on the Lagrangian circulation," *Applied Energy*, vol. 203, pp. 321-332, 2017. DOI: 10.1016/j.apenergy.2017.06.022, [Online].

[51] L. Blunden, S. Haynes, A. Bahaj, "Dynamic sandbanks in close proximity to sites of interest for tidal current power extraction," presented at *4th Asian Wave and Tidal Energy Conference*, Taipei, Taiwan, 2018.

[52] N. Guillou, G. Chapalain, "Evaluating the Effects of Tidal Turbines on Water-Mass Transport with the Lagrangian Barycentric Method," in *Estuaries and Coastal Zones in Times of Global Change*, pp. 217-233, Singapore: Springer, 2020.

[53] L. Blunden, S. Haynes, A. Bahaj, "Tidal current power effects on nearby sandbanks: a case study in the Race of Alderney," *Philosophical Transactions of the Royal Society A*, vol. 378, pp. 2178, 2020. DOI: 10.1098/rsta.2019.0503, [Online].

[54] D. Fallon, M. Hartnett, A. Olbert, S. Nash, "The effects of array configuration on the hydro-environmental impacts of tidal turbines," *Renewable Energy*, vol. 64, pp. 10-25, 2014. DOI: 10.1016/j.renene.2013.10.035, [Online].

[55] M. Garcia-Oliva, S. Djordjević, G. Tabor, "The impacts of tidal turbines on water levels in a shallow estuary," *International Journal of Marine Energy*, vol. 19, pp. 177-197, 2017. DOI: 10.1016/j.ijome.2017.07.006, [Online].

[56] M. De Dominicis, J. Wolf, R. Murray, "Comparative Effects of Climate Change and Tidal Stream Energy Extraction in a Shelf Sea," *Journal of Geophysical Research*, vol. 123, no. 7, pp. 5041-5067, 2018. DOI: 10.1029/2018JC013832, [Online].

[57] B. Kresning, M. Hashemi, S. Neill, J. Green, H. Xue, H, "The impacts of tidal energy development and sea-level rise in the Gulf of Maine," *Energy*, vol. 187, pp. 115942, 2019. DOI: 10.1016/j.energy.2019.115942, [Online].

[58] E. Rusu, C. Soares, "Coastal Impact Induced by a Pelamis Wave Farm Operating in the Portuguese Nearshore," *Renewable Energy*, vol. 58, pp. 34-49, 2013. DOI: 10.1016/j.renene.2013.03.001, [Online].

[59] T. Aderinto, H. Li, "Review on Power Performance and Efficiency of Wave Energy Converters," *Energies*, vol. 12, no. 22, pp. 4329, 2019. DOI: 10.3390/en12224329, [Online].

[60] L. O'Boyle, B. Elsäßer, T. Whittaker, "Experimental Measurement of Wave Field Variations around Wave Energy Converter Arrays," *Sustainability*, vol. 9, no. 1, pp. 70, 2017. DOI: 10.3390/su9010070, [Online].

[61] P. Troch, C. Beels, J. De Rouck, G. De Backer, "Wake effects behind a farm of wave energy converters for irregular long-crested and short-crested waves," *Coastal Engineering Proceedings*, vol. 1, no. 32, 2010. DOI: 10.9753/icce.v32.waves.53, [Online].

[62] V. Venugopal, R. Nemalidinne, A. Vögler, "Numerical modelling of wave energy resources and assessment of wave energy extraction by large scale wave farms," *Ocean & Coastal Management*, vol. 147, pp. 37-48, 2017. DOI: 10.1016/j.ocecoaman.2017.03.012, [Online].

[63] A. Bento, E. Rusu, P. Martinho, C. Soares, "Assessment of the Changes Induced by a Wave Energy Farm in the Nearshore Wave Conditions," *Computers & Geosciences*, vol. 71, pp. 50-61, 2014. DOI: 10.1016/j.cageo.2014.03.006, [Online].

[64] R. Carballo, G. Iglesias, G. "Wave farm impact based on realistic wave-WEC interaction," *Energy*, vol. 51, pp. 216-229, 2013. DOI: 10.1016/j.energy.2012.12.040, [Online].

[65] R. Atan, R, W. Finnegan, S. Nash, J. Goggins, "The effect of arrays of wave energy converters on the nearshore wave climate," *Ocean Engineering*, vol. 172, pp. 373-384, 2019. DOI: 10.1016/j.oceaneng.2018.11.043, [Online].

[66] D. Rijnsdorp, J. Hansen, R. Lowe, "Understanding coastal impacts by nearshore wave farms using a phase-resolving wave model," *Renewable Energy*, vol. 150, pp. 637-648, 2020. DOI: 10.1016/j.renene.2019.12.138, [Online].

[67] S. Diaconu, E. Rusu, "The Environmental Impact of a Wave Dragon Array Operating in the Black Sea," *The Scientific World Journal*, vol. 2013, pp. 1-20, 2013. DOI: 10.1155/2013/498013, [Online].

[68] A. O'Dea, M. Haller, H. Ozkan-Haller, "The impact of wave energy converter arrays on wave-induced forcing in the surf zone," *Ocean Engineering*, vol. 161, pp. 322-336, 2018. DOI: 10.1016/j.oceaneng.2018.03.077, [Online].

[69] R. González-Santamaría, Q. Zou, S. Pan, "Modelling of the impact of a wave farm on. Nearshore sediment transport," presented at *33rd Conference on Coastal Engineering*, Santander, Spain, 2012.

[70] C. Jones, J. Magalen, J. Roberts, "Wave Energy Converter (WEC) Array Effects on Wave, Current, and Sediment Circulation: Monterey Bay, CA," no. SAND2014-17401, 2014.

[71] C. Ozkan, K. Perez, T. Mayo, "The impacts of wave energy conversion on coastal morphodynamics," *Science of The Total Environment*, vol. 712, pp. 136424, 2020. DOI: 10.1016/j.scitotenv.2019.136424, [Online].

[72] J. Abanades, D. Greaves, G. Iglesias, "Coastal defence through wave farms," *Coastal Engineering*, vol. 91, pp. 299-307, 2014. DOI: 10.1016/j.coastaleng.2014.06.009, [Online].

[73] S. Neill, G. Iglesias, "Impact of Wave Energy Converter (WEC) Array Operation on Nearshore Processes," presented at *4th International Conference on Ocean Energy*, Dublin, Ireland, 2012.

[74] R. Bergillos, C. Rodriguez-Delgado, G. Iglesias, "Wave farm impacts on coastal flooding under sea-level rise: A case study in southern Spain," *Science of The Total Environment*, vol. 653, pp. 1522-1531, 2019. DOI: 10.1016/j.scitotenv.2018.10.422, [Online].

[75] C. Rodriguez-Delgado, R. Bergillos, M. Ortega-Sánchez, G. Iglesias, "Wave farm effects on the coast: The alongshore position," *Science of the Total Environment*, vol. 640-641, pp. 1176-1186, 2018. DOI: 10.1016/j.scitotenv.2018.05.281, [Online].

[76] M. Shields, D. Woolf, E. Grist, S. Kerr, A. Jackson, R. Harris, M. Bell, R. Beharie, A. Want, E. Osalusi, S. Gibb, J. Side, "Marine Renewable Energy: The Ecological Implications of Altering the Hydrodynamics of the Marine Environment," *Ocean & Coastal Management*, vol. 54, no. 1, pp. 2-9, 2011. DOI: 10.1016/j.ocecoaman.2010.10.036, [Online].