CHAPTER

15

Environmental Impact Assessment

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15.1 INTRODUCTION

There are many environmental concerns associated with the introduction of a large infrastructure of marine energy technology in coastal and offshore environments. The concerns relate to the interaction of the technology with the environment as well as the placement of the infrastructure in suitable areas and how this may impact both physical and ecological processes. Site licensing remains one of the key constraints for market development, primarily arising from the uncertainties of quantifying the environmental impacts of marine renewables. Without a large-scale array in operation, predicting the environmental effects is impossible using quantitative field-based studies. The most effective approach therefore is to use modelling techniques as predictive tools to ascertain the environmental effects. This chapter draws upon the information provided in the previous chapters and how this can be used to model potential environmental impacts of wave energy converters (WECs).

The use of hydrodynamic modelling is well established within the engineering community for coastal engineering applications such as the construction of harbours, maintenance dredging, coast protection, and coastal erosion projects. As software and hardware computer technology advances, the development of high-resolution models coupled with ecological models increases our ability for accurately predicting important physical and biological processes, such as marine pollution dispersal, including oil spills (Sayol et al., 2014) and wastewater plumes (Pritchard et al., 2013); sediment transport processes (Martin-Short et al., 2015); establishing how hydrodynamic flows structure population genetics of marine organisms (eg, Brennan et al., 2014) and connectivity of larval populations (eg, Elsäßer et al., 2013; Thomas et al., 2015). This coupling of hydrodynamic and ecological models provides a powerful tool for assisting in forecasting the potential environmental impacts of one or more WECs.

The potential environmental impacts that may occur during the operation of either small or large arrays of WECs are diverse. While factors such as collision, entanglement, evasion or avoidance effects of marine animals with WECs are of considerable concern, these potential issues result from the presence of the infrastructure in the environment and are not due to changes in the hydrodynamic environment and are therefore beyond the scope of this chapter. For information relating to these issues, the reader is referred to a number of reviews on the subject (Gill, 2005;

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Boehlert and Gill, 2010; Miller et al., 2013). The present chapter focuses on the physical and biological environmental processes that may be influenced as a direct result of changes to the hydrodynamic environment by the deployment of WECs, including sediment transport, organism transport, and pollution dispersal processes. However, hydrodynamic models can also be used to assist in deriving benthic community distributions, as well as noise radiation and the surfing community: examples of these will be included where appropriate.

When considering the environmental implications on marine fauna and flora resulting from the installation of any infrastructure in the marine environment, it must be recognized that the environment that is being investigated is not likely to be the typical coastline where seaside resorts are located. Areas considered for WEC array developments, especially inshore environments, are typically in very high energy areas where physical disturbance is a frequent occurrence, particularly during storm events. Areas targeted for WEC developments are ecologically classified as exposed to extremely exposed, particularly in the case of inshore coastal regions (Connor et al., 2004). The wave resource required for economically viable wave energy production will generally have large seas with significant wave height (H_{m0}) > 2 m. Such environments are located along open coastlines with no land obstructions, receiving both local and offshore wind-driven swells. In these high energy environments, orbital water velocities can reach over 5 m/s with velocities associated with waves breaking onto the shore exceeding 14 m/s (Denny, 1988). These areas are harsh, dynamic marine environments ensuring the most challenging conditions for ecologists to study, not only practically, but also for the prediction of potential anthropogenic impacts on the natural variability of biological processes occurring in the marine environment (Hewitt et al., 2001). A further complexity is that the wave climate is heterogeneous, changing both seasonally and interannually (Reguero et al., 2015). Thus, the inshore environment is a physically challenging environment for organisms to live in and have the ability to tolerate and adapt to a changing wave climate and associated physical forces (Fig. 15.1)

The present chapter is designed to provide guidance on factors that should be considered when developing a coupled hydrodynamic-ecological model for a designated WEC array in order to address questions on the environmental effects/impacts of each process, as described in the following sections. It is not

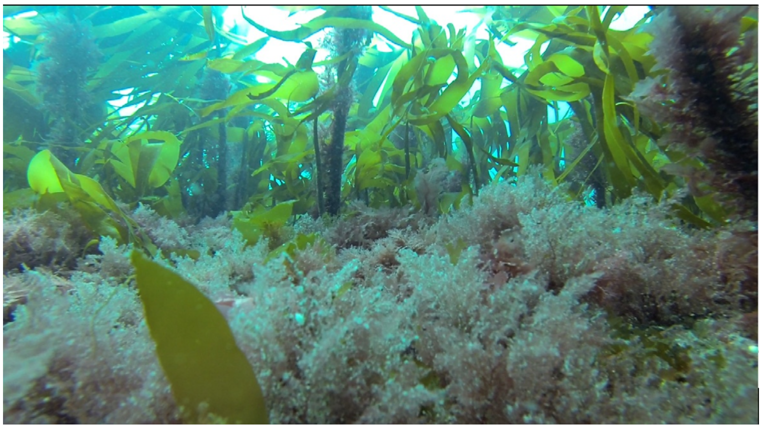

FIG. 15.1 Kelp forest of *Laminaria hyperborea* and associated flora found in high energy shallow nearshore environments in the western European seaboard between the latitudes ~40 and 60°N

intended to provide an in-depth review of each ecological process, but rather what factors should be considered when developing a model. We begin with a short overview of the ecological processes that may be influenced by the changes in hydrodynamics as a result of WEC arrays. This is followed by a description of what factors should be taken into consideration when choosing a model followed by the different modelling tools that can be used. The chapter ends with a brief description of the limitations of current coupled ecological hydrodynamic models and summary.

15.2 ECOLOGICAL PROCESSES

15.2.1 Sediment Transport

Sediment transport is the movement of different sized particles in coastal waters by the forces or shear stress associated with wave- and current-driven water movement. Particles may be transported along the surface of the seafloor, termed bed load, or in the water column as suspended sediment. The mode of particle transportation will depend primarily on magnitude of the shear stress, the particle size and the distribution of particle sizes of the sediment. For very fine sediments such as muds, the cohesiveness also becomes an important parameter. Sediment particles may be derived from either inorganic sources such as silt and clay from land runoff, sand from the weathering of rocks and minerals, or organic sources such as calcium carbonate from molluscs, bryozoans, and calcifying macroalgae (seaweeds). Regardless of the origin of the sediment particle, water motion ultimately shapes the form and nature of the seafloor and coastal regions and the distribution of benthic organisms and also controls the shore management of coastal zones.

For any large-scale infrastructure introduced into coastal regions, such as an array of WECs, the main concern is the impact on seabed stability and beach morphology. Protruding objects on the seafloor, whether they be a sunken ship, natural geological formation, or an array of WECs, will influence water motion and thus sediment transport and texture. Initial studies suggest that the presence of an array of WECs may alter the morphological response of coastline beaches (Abanades et al., 2014), although this will be dependent on the distance that an array is from the shoreline (Abanades et al., 2015). Of equal concern, however, are the effects of changes in sediment distributions on the organisms present at any given location. It is well-known that sediments influence reef-associated organisms (eg, Battershill and Bergquist, 1990; Culotta, 1994; Oliver et al., 2014; Bell et al., 2015) with an increase in sedimentation rates or suspension of sediment affecting turbidity, which in turn can affect suspension feeders and inhibit the recruitment and growth of algae and other benthic organisms (Kregting et al., 2008; Shields et al., 2011; Storlazzi et al., 2015). Therefore, changes in hydrodynamics as a result of the installation of WECs may potentially have both near- and far-field effects depending on the coastal process of interest.

It can be expected that nearshore WECs may be placed in three different environmental settings: (i) in locations with very dynamic sediment transport characteristics, or (ii) in locations with high shear stress but very little sediment availability, or (iii) in locations with very large sediment size (shingles, boulders, or rocks). For WECs placed far offshore with large water depths, the fine sediment deposited on the seabed in these regions may remain undisturbed due to the water depth. For nearshore devices, the disturbance caused by the device to the surrounding hydrodynamics can be divided into near- and far-field disturbance caused by the flows around the device or mooring. For near-field disturbances, in such cases, flow modelling presented and discussed in Chapter 6 on CFD models may be more appropriate than conventional wave models. For far-field disturbances, changes will occur to the wave climate resulting in changes in bed shear stress and wave-induced currents or wave setup. To make informed decisions about these effects, the models employed need to be suitable for long-term wave climate scenario modelling, as often a range of different events can cause sudden changes in sediment profile, mobilization patterns and transport rates.

15.2.2 Organism Transport

Numerous marine organisms spend all or part of their life history stage as plankton in the water column where ambient water flow controls or strongly regulates their transport through the fluid medium (Kinlan et al., 2005) (Fig. 15.2). Plankton communities are made up of a diverse range of groups including animals, protists, archaea, algae, and bacteria. Water motion helps transport plankton over vast oceanic distances, providing a vital food source for larger marine species such as fish, whales, and some sharks. Equally important is the transport of larvae in coastal environments in assisting dispersal processes, here defined as the spread of larvae from a spawning source to a settlement site (Pineda et al., 2007). Larval dispersal is important in influencing factors such as reef connectivity (Elsäßer et al., 2013; Thomas et al., 2015) and gene flow (Brennan et al., 2014). Changes in hydrodynamics arising from the presence of WECs may result in changes in dispersal patterns impeding species from reaching their optimal or suitable habitat and hence potentially affecting trophic relationships and ecosystem functioning (Kinlan et al., 2005). Again, changes in wave climate can result in a variation of wave-induced currents similar to those found in sediment transport.

15.2.3 Pollution

The term *pollution* in this context is used to describe those substances such as dissolving chemical antifoulants, hydraulic fluids, lubricants or other petroleum-based products originating from either the energy extracting device or associated vessels involved during the installation and operation of the device. It is conceivable that small amounts of any number of substances may be released at any stage during the life history of an operating WEC array—for

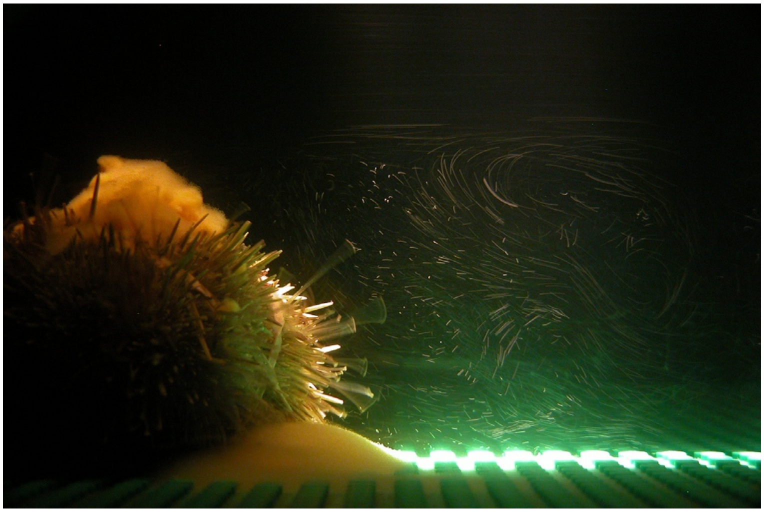

FIG. 15.2 Seawater flow around a broadcast spawning female sea urchin (*Strongylocentrotus droebachiensis*), commonly found in high energy environments.

example, diffusing chemicals from marine coatings or flaking off coatings of the structure into the environment, leakage of hydraulic fluids from the device during operation, or vessel fuel spillage or leakage during the installation/maintenance activities. Leaching of trace elements, alloys or metals from cathodic protection over the lifetime of a device can potentially be considerable and while for single devices would result in very low concentrations, for large arrays may give rise to elevated levels in the surrounding water. It should be noted that this does not necessarily mean a negative impact. There is also the possibility of large accidental spills owing to vessel or infrastructure failure. The effects of large accidental spills such as from offshore platforms or sinking vessels are more well-known compared to the potential ecological impact of small leakages into the marine environment.

The concern of these substances entering the environment, while most likely small in quantity at any one time, is the bioaccumulation of toxic substances in the food chain affecting the water and sediment quality near the devices. It is estimated that low-level routine releases from sources such as vessels throughout the world represent as much as 90% of the hydrocarbon input into the marine environment (Ivshina et al., 2015). However, identifying and quantifying slow release pollution problems from a WEC array will most likely be difficult owing to the nature of the substances. For substances such as oil, it remains in motion and is transported easily by waves, currents, and winds as it spreads to form a thin layer on the surface. However, it is usually slow moving and easy to define on the sea surface, particularly in calm conditions. But WEC arrays are not likely to be located in calm conditions and so the fate, behaviour, and environmental effects will be more difficult to observe and predict; thus modelling tools may be the only method in quantifying and predicting potential effects.

15.2.4 Biogeochemical Processes

The potential changes in water flow resulting from the deployment of one or more arrays of WECs along a coastline may not only alter the local but also the regional hydrography (van der Molen et al., 2015). A wide variety of physical effects may occur as a result of large-scale infrastructure changes, including changes in wave climate and tidal/residual currents. There is also the potential for changes in turbulence and bed shear stress. Such changes will give rise to changes in turbidity, water temperature, salinity, stratification, and nutrients. These environmental factors are essential drivers of primary productivity (phytoplankton) with the result that any change to primary productivity can have a major knock-on effect to higher trophic levels, as they form the basis of the food chain. What influences on biogeochemical changes will occur as a result of the installation of WEC arrays is unknown. However, there is potential that a reduction in wave climate may result in reduced turbidity at the device scale due to lower wave climate condition resulting in increased primary productivity owing to higher light levels in the vicinity of the devices (van der Molen et al., 2014). Therefore the changes in the biogeochemical processes may occur at both local and regional scales and spatial scale effect will need to be considered when choosing and developing a model.

15.2.5 Noise

Anthropogenic (man-made) underwater noise resulting from the installation and operation of an array of marine energy devices has the potential to affect a number of marine animals, including mammals and fish. A range of acoustic frequencies is generated throughout the various stages of the installation and operation process of WECs. During the installation phase, noise from increased vessel traffic, and also possibly pile driving, will be severe, with the latter creating high-energy impulsive sounds. However, the sound exposure will occur over a relatively short period of time as these increases are restricted to the installation phase and will be of an intermittent nature. Of greater concern is the continuous noise emission during the operation of a WEC array. Noise may be derived not only from the power take-off system or other mechanical working parts of the device but also the interaction of the device with the water, for example, slamming events in the case of flap devices. The range of frequencies generated has the potential to mask an animal's hearing, interfering with locating prey, social interaction, predator avoidance strategies, and navigating underwater hazards. Noise in an area may also lead to behavioural changes prompting avoidance of an area; however, there is also the possibility that the noise of an array of devices could attract animals.

The marine environment is naturally 'noisy'. Noise occurs from many natural sources such as turbulent water, breaking waves, sediment/boulder movement or biological organisms and is termed ambient or background noise. The ambient noise is classified as broadband, composed of a range of frequencies over the entire frequency spectrum. Of these ambient noises, spray and bubbles from breaking waves are major contributors to noise in coastal environments with a frequency range typically between 500 Hz and 100 kHz. While there are very little data on sound emission from a marine energy device, the few published studies suggest that the noise output is in the range between 100 Hz and 10 kHz (Schmitt et al., 2015; Polagye and Murphy, 2015; Tougaard, 2015), which falls within the same frequency range as breaking waves. That ambient noise frequencies overlap in the same range as marine energy devices has been identified as one of the main challenges when sampling noise measurements: determining background noise versus the device noise. A further complexity is the noise resulting from the turbulence advected over hydrophones in a high energy environment termed pseudo-noise, which must also be taken into account when making measurements. However, each device will behave differently and the characteristics of the noise radiating from a WEC array are essentially unknown.

15.2.6 Other (Benthic Communities, Surfers)

WEC implemented wave models may also be used to assist in predicting the environmental effects on (i) benthos distribution and (ii) coastal users. Benthos refers to a collection of organisms that either live attached to the seabed (epifauna), live in the sediment (infauna) or live close to the seabed, such as reef fish. The spatial pattern observed in their distribution is closely linked with substrate type as a direct result of flow speed (Coggan et al., 2012). The term *coastal users* is generally used to refer to the surfing community that may be affected by the development of WEC arrays with their primary concern that wave height and formation will be influenced (Stokes et al., 2014). An array of WECs will result in some reduction in wave height and changes in the flow field surrounding an array as the water interacts with the devices (eg, Iglesias and Carballo, 2014; Abanades et al., 2015). By developing high-resolution spatial and temporal hydrodynamic models with accurate representation of WEC arrays, predictions can potentially be made of changes in the wave field and how these two groups, benthos distribution and surfing community, may be affected by the development of WEC arrays in the marine environment.

15.3 MODELLING APPROACH

15.3.1 Considerations

Before discussing the ecological modelling tools available to simulate the transport of environmental variables such as solutes, sediment, and microscopic organisms in the marine environment, it is essential to consider what criteria should be employed when choosing an appropriate numerical wave model. This is essential in order to accurately predict the environmental effects of an array as knowledge of the hydrodynamic background is fundamental for the understanding of the underlying mechanisms driving the ecological processes described in the previous section. As discussed in the previous chapters of this book, there is a wide variety of numerical wave models with the implementation of WECs incorporated into the model in order to simulate the interaction of the WECs with each other and the physical environment. Choosing the right wave model to investigate the environmental effects of an array of WECs, however, is not straightforward because, while there is a range of different wave models to choose from, there is no universally applicable model. Which model is selected depends on the scale and process being investigated. Therefore it is necessary to take a system-view approach and consider a range of temporal and spatial scales in order to capture and predict the potential environmental effects.

For the purpose of this section we split the spatial scale into four different levels. Firstly we have the local impact or near-field effects, which are at the device scale. In the hydrodynamic context we expect to see the direct effect of different parts of the device at this scale. Next we consider the far-field effects (1–10 km), a scale at which a device may be represented as one item, rather than a series of components. Further we distinguish regional effects (>10 km) and finally global effects. A global effect could, for example, be a reduction in CO_2 emission and thus a reduction of greenhouse gas, or very large scale changes in circulation patterns as a reduction of wave energy stretching over hundreds of kilometres along a coastline. Alongside spatial scale considerations, other factors that should be considered when choosing a numerical wave model include the process to be investigated, the WEC design, location of the WECs and the physical processes of the wave climate (eg, swell wave or wind wave domination, wave current interaction, etc.). Of the models developed and described in this book, the most versatile are arguably spectral wave models (phase averaging energy propagation model) capable of representing numerous coastal processes including refraction, shoaling, diffraction, reflection, bottom friction, wind generation, wave to wave interaction, wave current interaction, wave breaking and white capping (Fig. 15.3).

The development of a wave model requires knowledge of the following parameters:

- Water level
- Bathymetry
- Wind data and boundary wave data
- Calibration and validation data
- Current speeds (if relevant)

Water level and bathymetry data can be obtained from ports and harbour authorities. Good quality wind data can be obtained from hindcast models. The general accessibility of these data sets to some extent reflects the importance of these data for regional climate models, port and harbour developments as well as chart information for the shipping community. Thus the wave field may be modelled with reasonable confidence. However, as other sections of this book have shown, modelling the direct effect of the WEC on the wave field has to be undertaken with less confidence.

The complexity of the physical and ecological environment cannot be overemphasized. While we can describe ecological processes and construct mathematical formulations to make predictions, acquiring the environmental data to calibrate and validate the model is more difficult. In contrast to a wave model where data are relatively easy to obtain, it is more difficult to obtain data on the ecological processes that are being investigated. If we take modelling sediment transport as an example, the environment

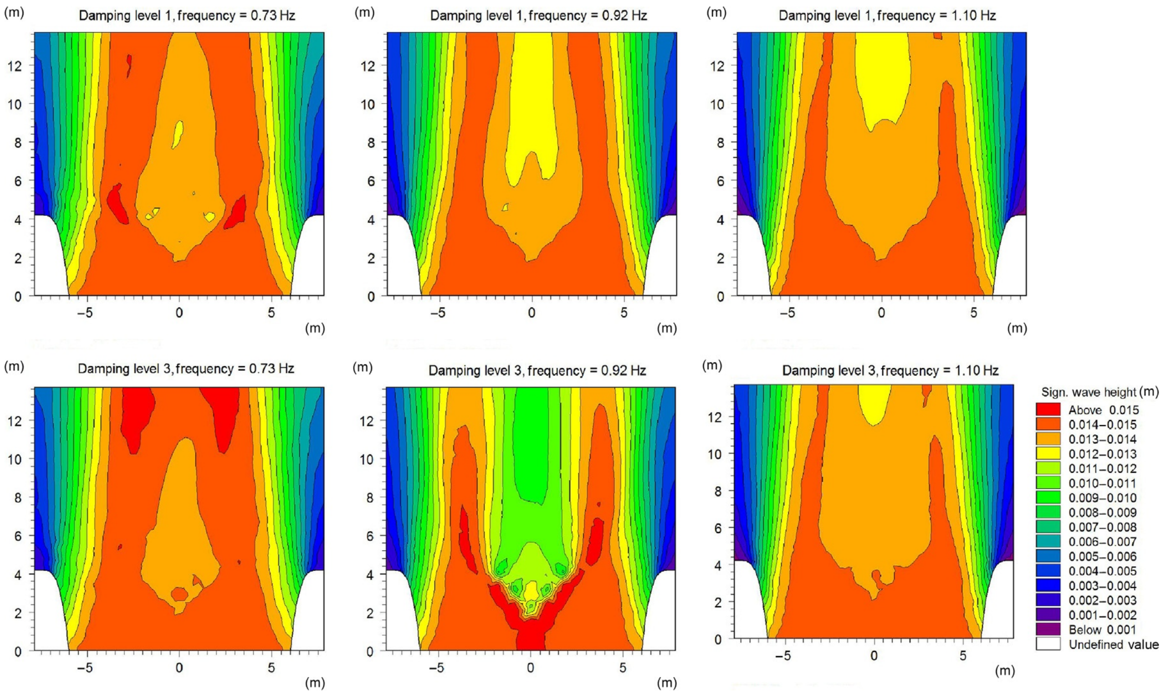

FIG. 15.3 Variation in significant wave height for array of oscillating water columns with different dampening levels based on a spectral wave model – taken from O'Boyle (2013).

suitable for WEC development is challenging and appropriate information on sediment in an area is usually largely unknown as it has not been required previously. The lack of information on sediments is further complicated by the often temporally and spatially varying nature of sediment cover (Fairley et al., 2015). Further, in the model each particle can have a defined size, density, settling velocity as well as a critical stress for erosion and erodibility. Although the critical parameters can be readily defined, the essential difficulty is obtaining the information required as input into the model.

An added complexity in modelling planktonic organisms is that they do not necessarily behave as passive particles owing to their motile ability. Many plankton species are able to 'swim' which enables vertical and horizontal migration to ensure optimal light levels for photosynthesis and avoidance of predators as well as movement towards a substrate during the settling stages. However, plankton are usually microscopic and hence unable to be observed with the naked eye. Their swimming speed is slow, typically on the order of mm/s (McDonald and Grünbaum, 2010) in a low Reynolds environment. In the types of environments that WECs will generally be located, plankton transport will experience and be affected by very turbulent and energetic conditions. Here the key processes influencing any vertical transport of these organisms are likely to be the turbulence generated by the bathymetry and the oscillatory motion associated with the waves. In addition, numerous WECs in a location will act as obstacles generating additional turbulence. While it is well established that behavioural characteristics are important, again there is a need to consider the relevant scales in the environment being investigated.

Therefore, limitation of data availability does not only apply to sediments, but also biological organisms. While the size, density and settling velocity of particles can all be parameterized in a model, availability of this information is often the limiting factor in model initiation. Thus, while we can develop high-resolution wave models, accessing the relevant ecological data to validate and calibrate the models remains a significant challenge.

15.3.2 Modelling Tools

The effects of changes in the hydrodynamic environment as a result of the introduction of infrastructure can be assessed in several ways. One simple approach is to look, for example, at residual currents and the changes therein, or at bed shear stress and the associated changes (before/after scenario). This approach can also be used to derive values to assess changes in benthos distribution. If the changes are more complex and interactive, for example, mobilization of matter or release of larvae or eggs, a transport model would be more suitable. When considering transport in the marine environment, two main mechanisms directly affect the transportation of solid matter in the marine environment: advection and dispersion. Advection describes the transport of particles from one location to another by the means of water flow ($\bar{u}$) whereas the dispersion of particles is influenced by diffusive processes such as turbulence and concentration gradients in the water flow. Both these processes as well as other aspects such as settling, buoyancy or active swimming behaviour can be simulated with particle tracking simulations.

Particle tracking models are used to simulate the fate of dissolved and suspended substances. While particle tracking models are typically not directly coupled to wave models, they can easily be coupled to hydrodynamic models that include the residual current obtained from a wave model as an input file in order to simulate coastal processes. Such models therefore can be used to determine the movement of planktonic organisms and in this application they have been successfully used to establish the influence of hydrodynamic flows on the structuring of population genetics of marine organisms (Brennan et al., 2014) and connectivity of larval populations (Elsäßer et al., 2013; Thomas et al., 2015; Smyth et al., 2016). Further, particle tracking models have also been used to describe sediment transport processes (Dimou and Adams, 1993), making the particle tracking module a versatile tool.

In order to understand the impacts of WEC arrays on complex biogeochemical fluxes, ecosystem models can be used to simulate the effects of small and large spatial and temporal scales on biogeochemical cycling. Examples of such models are European Regional Seas Ecosystem Model (ERSEM) (van der Molen et al., 2014), which is used on very large regional scales or the EcoLab templates in MikeByDHI on estuarine scale. An overview of different modelling techniques and advances in this area can be found in Park et al. (2015). In addition to hydrodynamic effects the propagation of underwater sound is also of concern. Whether or not a WEC will emit significant noise depends on its type, operation and the environmental condition it is in. However, if noise is found to be of significance, a range of underwater acoustic simulation approaches are available to assess noise propagation and effect, with the most common propagation model approaches used being the ray theory, normal mode and parabolic equations (Farcas et al., 2016).

15.4 LIMITATIONS

Intrinsically models are a limitation as they are a simplification of the complex ecological processes being investigated. While high-resolution wave models can be developed that provide results with reasonable confidence, as is crucial to many engineering applications, the results are a prediction of what may occur under different scenarios that have been applied as an input into the model.

Another further limitation is that there are no WEC arrays at present, nor even a full-scale commercially developed single operating device. This presents a series of challenges to the investigator from the beginning with no information with which to validate or calibrate the model. The output of the numerical model thus only provides a prediction of the potential changes to the wave climate and the perturbations in the area of the array. The uncertainty in the results increases when coupling hydrodynamic with ecological models, as explained in the previous sections due to the lack of input data.

We are aware that much effort is being put into such modelling both by industry and the research community to establish efficient array design. However, even provided that a suitable physical model can be developed, to attain the ecological perspective it will be necessary to integrate the physical models with a suitable ecological model. This is by no means always straightforward, as the two model types may well have been developed for different specific purposes or from contrasting perspectives.

And, finally, out of the five transport processes important for coastal processes (deep or shallow water): surface currents, density and temperature-induced currents, ocean circulation currents, tidal currents and wave-induced currents, only the wave-induced currents can be modelled using a wave model. If the ecological process investigated requires knowledge of, for example, tidal currents, then a hydrodynamic model will also be required to be coupled to a wave model in order to capture and predict the potential environmental effects.

15.5 SUMMARY

- The range of ecological processes that may be influenced by changes in hydrodynamics as a direct result of the installation of WECs includes sediment transport, organism transport, pollution, and biogeochemical
- Wave models may also be used to predict changes in flow rates at the seabed in order to assess changes in benthos distribution, used to generate sound propagation from the device and how waves may be altered for coastal users
- The effects of the presence of WECs may occur at a range of temporal scales (seasonal) and spatial scales (the device scale up to global scales)
- Arguably the most versatile model is the spectral wave model, which is capable of representing numerous coastal processes including refraction, shoaling, diffraction, reflection, bottom friction, wind generation, wave to wave interaction, wave current interaction, wave breaking, and white capping
- In order to simulate transport processes the most versatile approach is to couple a particle tracking simulation with a hydrodynamic model that includes residual currents from a wave model.

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