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The Impact of Marine Renewable Energy Extraction on Sediment Dynamics

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Abstract

The extraction of marine energy, through either tidal or wave array operation, will clearly influence the hydrodynamics of a region. Although the influence on tidal currents and wave properties is likely to be very small for most extraction scenarios, the influence on bed shear stress is likely to be greater, because bed shear stress is quadratically related to tidal currents and wave orbital velocities. Further, the transport of sediments is a function of tidal current and wave orbital velocity cubed. Therefore, even small modifications to the flow field through tidal or wave array operation could lead to significant impacts on regional sediment dynamics. In this chapter, after providing an introduction to sediment dynamics in the marine environment, we explore the impact of tidal energy devices/arrays on regional sediment dynamics, with a particular emphasis on offshore sand banks—important sedimentary systems that protect our coastlines from the full impact of storm waves. Next, we discuss how generating electricity from waves could influence nearshore sediment processes, such as beach erosion or replenishment, over a range of time scales. To assess the magnitude of impacts on sedimentary systems, it is essential to consider the scale of the impact in relation to the range of natural variability. We suggest ways in which impacts can be assessed using numerical models, tuned by in situ measurements, that quantify variability over a range of time scales from individual storm events and lunar cycles to seasonal and interannual periods. We also

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discuss the sedimentary processes associated with tidal lagoons, such as scour and sediment drift outside a lagoon, and sediment accretion inside a lagoon.

Keywords: Marine energy; Sediments; Sediment transport; Tidal energy; Wave energy; Lagoons; Tidal turbine; Morphodynamics; Bed shear stress; Sand banks; Beaches; Beach response; Monitoring

1. Introduction

Previously identified research priorities on the environmental impacts of marine renewable energy (MRE) extraction have focused on issues that do not directly affect the resource, such as the collision risk of marine mammals and the effects of underwater noise generated by turbines (e.g., Aquatera Ltd and MarineSpace, 2015). However, apart from the direct feedback of energy extraction on the resource itself (e.g., Adcock et al., 2013), it is primarily impacts on sediment dynamics and associated morphodynamics that will significantly affect the resource, and hence alter the environment in which devices operate (Neill et al., 2009). Of the potential impacts of MRE electricity generation on the marine environment, the impact on sediment transport pathways, and its effect on associated morphodynamic features such as offshore sand banks, is probably the most easily quantified (Shields et al., 2011), particularly since the transport of sediments can be described by a defined set of equations (Soulsby, 1997) that can readily be incorporated into regional hydrodynamic models (e.g., Neill et al., 2007). However, field data are important for parameterising and tuning such sediment transport models, because the models are sensitive to a range of variables, including sediment grain size distribution and the underlying hydrodynamic flow field (e.g., Camenen and Larroudé, 2003). In addition, it is essential that the natural variability of sedimentary systems (pre-construction) are fully understood, so that impacts attributed to energy extraction can be quantified (Robins et al., 2014).

Developers seek highly energetic tidal-stream and wave sites, because the theoretical resource at such sites is generally considered to lead to the highest electricity yield. It is often assumed that the seabed sediment is composed exclusively of bedrock or cobbles at such high-energy sites, but that is rarely the case. Even in extremely energetic sites such as the Pentland Firth in Scotland (Figure 1), the bedrock will be overlain with a veneer of mobile sediment (e.g., Evans, 1990), and predominant bedrock will be interspersed with regions of sand (e.g., Easton et al., 2011; Robins et al., 2014; Fairley et al., 2015). Such pockets of mobile sediment are important habitats for fisheries, and important repositories of sediment that exchange material with neighbouring beaches over a range of time scales (Neill et al., 2008). Further, although many of the high-energy wave sites are located in regions where the coastline is rocky, these regions of rocky intertidal and cliffs are punctuated by pocket beaches; for example, the Outer Hebrides of Scotland, and in particular the Isle of South Uist (Vögler et al., 2011). Many of the beaches in such regions that are adjacent to proposed wave energy arrays will be characterised by subtidal sand bars, which exhibit strong seasonal variability (Gallagher et al., 1998). In addition, such high-energy wave and tidal sites may not be representative of the global MRE resource, which is likely to be characterised by lower tidal streams, and less energetic wave conditions (Lewis et al., 2015b). Many of the high-energy sites, for example in the northwest of Scotland, are far from population centres, and so remote from regions of high electricity demand; hence, the development of less energetic sites could be advantageous from a transmission perspective. Development of lower tidal energy sites also has the added advantage of offering more phase diversity than the development of high tidal energy sites alone (Iyer et al., 2013; Neill et al., 2014, 2016). Therefore, a wide range of sedimentary regimes should be reviewed when considering the wider topic of the impacts of MRE schemes on sediment dynamics.

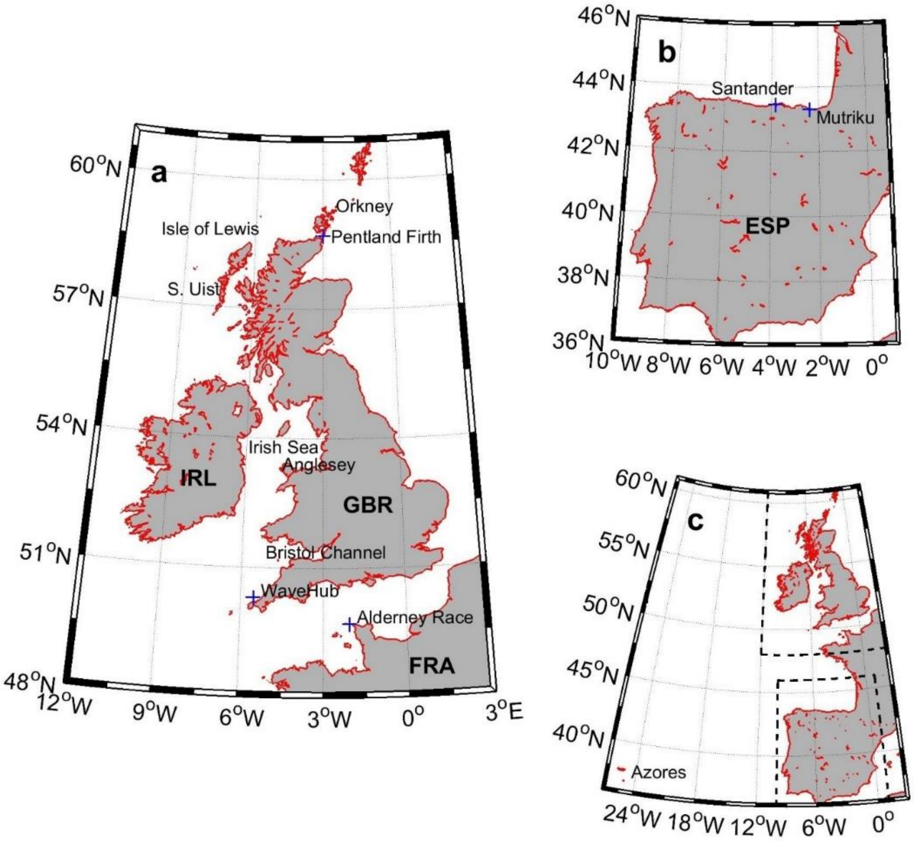

Figure 1. Key locations referred to throughout this article.

2. The Transport of Sediment in the Marine Environment

Sediment transport in the marine environment is a combination of tide- and wave-induced bedload and suspended load,[1] and it occurs over a range of time scales from a single wave orbital excursion of order seconds to semi-diurnal and storm events extending to seasonal, interannual, and decadal variability. Sediment spans a wide range

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[1] Although sediment transport can also be induced by storm surge and ocean currents, it is generally dominated by wave and tidal processes.

of sizes, from clay (grain size less than 0.002 mm) through silt (0.002–0.06 mm), sand (0.06–2 mm), and up to cobbles and boulders (Figure 2). The most commonly used measure of sediment grain size is the median grain size (d_{50})—the grain size at which 50% of particles, by mass, are smaller. Although the transport of sediments includes both fine (cohesive) and coarse (non-cohesive) material, here we consider only coarse material, i.e., sand and gravel, because such non-cohesive material will generally be representative of sediment that is available for transport at high-energy wave and tidal sites (Neill et al., 2012).

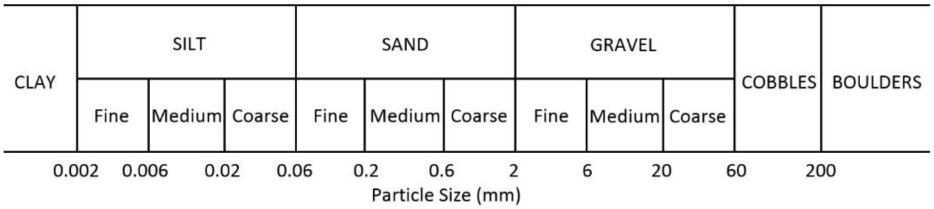

Figure 2. Particle size ranges.

2.1. Sediment Transport Due to Tides

Tidal currents are capable of stirring up sediments from the seabed and transporting them instream with the tidal flow direction—a process known as bedload transport. Hence, any net tidal transport is likely to determine the net direction of sand transport, subject to other forces such as wave stirring (see Section 2.2). In high-energy environments, coarse sands and gravel move along the seabed via bedload transport if the tidal currents are strong enough to exceed the threshold of motion, above which the friction on the seabed—the bed shear stress—is large enough to force sediment from its resting position. The rate of bedload transport can be expressed in SI units as volume (m^3) per unit time (s) per unit width of bed (m), i.e., $m^2\ s^{-1}$ (Soulsby, 1997). A number of competing formulae have been proposed to calculate the bedload transport rate. Most of them are a function of the bed shear stress (τ_0), expressed in dimensionless form as the Shields parameter, defined by (Soulsby, 1997):

$$\theta = \frac{\tau_0}{g(\rho_S - \rho)d}$$

where g is acceleration due to gravity, ρ is the density of sea water, ρ_s is the density of sediment grains, and d is the diameter of sediment grains. The bed shear stress can be expressed as $\tau_0 = \rho C_D \overline{U}^2$, where C_D is the drag coefficient and $\overline{U}$ is the depth-averaged flow speed. The threshold flow speed (U_{cr}), above which transport occurs, has been experimentally calculated for coarse sediments by Soulsby (1997):

$$\overline{U_{cr}} = 8.5 d_{50}^{0.6} \log_{10}(4h/d_{90}), \text{ for } 500 \leq d_{50} \leq 2000 \text{ mm}$$

where h is water depth, and d_{50} and d_{90} represent the median and 90% (of particles finer than) grain sizes, respectively. Where sediment has accumulated, the seabed will invariably be formed of sand ripples or dunes, conveniently represented by the total roughness length z_0, which can be used to calculate the total drag coefficient and bed shear stress (Soulsby, 1997).

Nonlinear tidal propagation in shallow shelf seas has been shown to control patterns of bedload transport over long time scales and with distinct zones of bedload divergence, transport, and convergence (e.g., Pingree and Griffiths, 1979). Additional nonlinear interactions of tidal motions and geomorphology can generate eddy systems (e.g., Neill, 2008; Neill and Scourse, 2009) and constricted currents (e.g., Brown and Davies, 2009), which can further modify bedload transport in areas where tidal energy extraction may occur, such as the Bristol Channel (Neill et al., 2009) and the Orkney archipelago (Scotland; Martin-Short et al., 2015).

Sediment transport is typically subdivided into bedload and suspended load transport. Suspended load transport consists of lighter material that is entrained in the water column once current speeds are significantly above the threshold of motion and carried over large spatial and temporal scales at the speed of the ambient currents. For material to remain in suspension, its settling speed must be less than the upward turbulent motion (Soulsby, 1997). There are numerous methods of calculating the threshold of suspension and sediment settling speed, which are determined by the sediment grain size and density, and the viscosity of the water. Most of these methods are described in detail by Soulsby (1997).

For tidal current speeds that significantly exceed the threshold of suspension, strong tidal dissipation can generate regions of turbidity maxima, which are characterised by high concentrations of suspended material such as fine (mineral) sediments and organic particulate matter such as detritus, zooplankton, and fish early-life stages (Bowers et al., 2005). Turbidity maxima are important ecologically at the shelf scale; these regions of highly concentrated suspended material enhance nutrient supply for marine species, thereby serving as critical nursery areas and increasing secondary production (Ellis et al., 2008; Robins et al., 2014). They also mediate marine population dynamics (e.g., Morgan et al., 1997) and potentially species connectivity across shelf regions. However, the associated turbid waters can have a negative ecological impact, because they reduce solar input at depth (Robins et al., 2014).

By their very nature, some regions of highly concentrated suspended material or turbidity maxima are also regions of interest for tidal-stream energy extraction. One important example is the Anglesey Turbidity Maxima in the Irish Sea (Bowers et al., 2002; Ellis et al., 2008)—a region of strong tidal currents that is also a region of interest for tidal-stream MRE developers (Lewis et al., 2015b). Hence, the impact of tidal-stream arrays on the turbidity maxima, and conversely the impact of the suspended material on the devices and the resource itself, are of obvious concern. From an initial study of the impact of energy extraction on suspended sediment concentrations, Robins et al. (2014) concluded that tidal energy converter (TEC) arrays of order <100 MW were unlikely to affect the suspended sediment concentrations beyond natural levels of variability—a criterion that could be applied to environmental impact assessments for MRE schemes elsewhere.

2.2. Sediment Transport Due to Waves

In sufficiently shallow water ($h < L/2$; where L is wavelength), wave motion extends to the seabed. This oscillatory motion leads to the generation of a wave-induced bed shear stress, which acts on seabed sediments. The threshold, or incipient, motion of seabed sediment is primarily controlled by the amplitude of the bottom orbital velocity, in conjunction with sediment grain size and (relative) sediment density. For linear, or Airy, waves (i.e., sinusoidal wave forms), the oscillatory motion over each half of a wave cycle is symmetrical, so there is no net sediment motion. However, when waves are nonlinear, for example when relatively steep waves propagate in shallow water, there is increased sediment motion beneath the wave crest compared to the sediment motion that occurs beneath the wave trough. This leads to asymmetry in sediment transport and net transport in the direction of wave propagation, in the absence of a tidal mechanism.

2.3. Sediment Transport Due to Combined Tides/Waves

Waves provide a stirring mechanism that keeps sediment grains in suspension. The tidal current adds to this stirring, but also provides a mechanism for net sediment transport (Soulsby, 1997), which is particularly important in the case of linear (Airy) waves. Although marine sediment is transported as both bedload and suspended load, it is generally the *total sediment transport rate* that is required for addressing practical applications such as the morphodynamic response of coastal regions to engineering structures (Soulsby, 1997). Although many competing formulae are used to quantify total load transport by waves plus currents, one of the most popular methods is Soulsby-Van Rijn formula, particularly because this method is very easy to embed within hydrodynamic models, or apply to the outputs of such models as an offline post-process (e.g., Neill et al., 2007; Neill et al., 2012). Neglecting bed slope, total load sediment transport rate q_t is given by

$$q_t = A_s \overline{U} \left[\left(\overline{U}^2 + \frac{0.018}{C_D} U_{rms}^2 \right)^{1/2} - \overline{U}_{cr} \right]^{2.4} \tag{1}$$

where $\overline{U}$ is the depth-averaged current speed, C_D is the drag coefficient due to the current alone, U_{rms} is the root-mean-square wave orbital velocity, $\overline{U}_{cr}$ is the threshold current speed, and

$$A_s = A_{sb} + A_{ss}$$

where

$$A_{sb} = \frac{0.005h(d_{50}/h)^{1.2}}{[(s-1)gd_{50}]^{1.2}}$$

$$A_{ss} = \frac{0.012 d_{50} D_*^{-0.6}}{[(s-1)gd_{50}]^{1.2}}$$

and s is the relative density of sediment, and D_* is the dimensionless grain size, given by

$$D_* = \left[\frac{g(s-1)}{\nu^2} \right]^{1/3} d_{50}$$

where ν is the kinematic viscosity of water.

2.4. Morphodynamics

Morphodynamics describes the study of changes in the shape of the seabed over time. When the morphodynamic change is a result of an object or structure, the process is referred to as scour. For the MRE industry, morphodynamics and scour are important for determining scales and rates of accretion and erosion as a direct result of any device, array, or tidal range scheme development. This is achieved by means of the sediment budget equation, which can be written for one-dimensional (x) applications over large distances (e.g., 100 m) and times as (Soulsby, 1997):

$$\frac{\partial \zeta}{\partial t} = -\frac{1}{1-\varepsilon}\left(\frac{\partial q_t}{\partial x}\right)$$

where ζ = bed level change, t = time, ε = porosity of the bed, q_t = volumetric total (bedload + suspended load) transport rate in the x-direction.

Using the sediment budget equation, in conjunction with sediment transport methods such as the Soulsby-Van Rijn formula (Eq. 1), coastal morphodynamic models can be used to compute the distribution of erosion and accretion over the coastal model domain (e.g., De Vriend, 1993). Presently, morphodynamic models are computationally expensive compared to hydrodynamic-only models, meaning that long-term (e.g., decadal) simulations are challenging, particularly if feedback between the evolving morphodynamics and hydrodynamics are included. One way around this problem is to use make use of a "morphological factor"; for example, where a short-term simulation of bed level change over one tidal cycle is scaled-up by a factor of *n* to represent *n* tidal cycles of morphological change (e.g., Roelvink, 2006; McCann, 2011). Care must be given to the magnitude of the factor *n*. While values of 100 or greater have been shown to produce reasonable results (e.g., Dissanayake et al., 2009), appropriate values depend upon both the situation being modelled and the properties of the model grid (Ranasinghe et al., 2011).

2.5. Natural Variability

Offshore sand banks are important natural systems that protect coastal communities from the impact of storm waves, and they can be important nursery grounds for fisheries (Neill, 2008). Sand banks can be generated and maintained by strong tidal currents and bathymetric irregularities (see Huthnance, 1982), and are generally found in or near regions that are suitable for tidal energy extraction (e.g., Neill et al., 2012). Strong tidal flow past a headland leads to the generation of large eddy systems, which feature an opposite sense of vorticity between the flood and ebb phases of the tide (Robinson, 1981). The outward-directed centrifugal force within each transient eddy system is balanced by the inward-directed pressure gradient, and, because the centrifugal force is weaker at the sea bed (as a result of bed friction), this leads to the inward movement of relatively coarse sediment at the bed (Pingree, 1978). Hence, the interaction between pressure gradient forces, centrifugal forces, and friction results in the convergence of sand and the formation and maintenance of headland sand banks (Bastos et al., 2002).

The morphology (and hence volume) of offshore sand banks is affected by a variety of processes that occur over a range of time scales, such as long-term sediment supply and sea-level rise (Lewis et al., 2015a). Shorter time-scale processes that affect sand banks include storm wave events (e.g., Fairley et al., 2016) and semi-diurnal tidal currents (Neill et al., 2007). During storms, near-bed wave orbital velocities from waves can greatly exceed the critical speed of sediment motion, even in water depths of 10s of metres (Mitchell et al., 2012). This short-term (relative to the action of tidal currents) wave-induced sediment transport can affect the evolution and maintenance of an offshore sand bank (Van de Meene and Van Rijn, 2000). Therefore, the frequency and intensity of storm wave events between each year (i.e., the interannual variability of the storm wave climate) may be an important process affecting sand bank evolution over decadal time scales. However, the role of the annual storm wave climate, within the interannual variability of offshore sand bank morphology, is unclear (Lewis et al., 2015a).

Beach profile variability is often considered on a seasonal basis and features distinct summer and winter profiles (Figure 3). Summer profiles are accretive profiles with steeper gradients and the presence of a high tide berm; such profiles are formed under low-energy conditions. Winter profiles typically have shallower gradients, and one or more offshore bars may be present caused by accumulation of sediment under the breakpoint of storm waves. Such breakpoint bars are beneficial, because they dissipate some of the wave energy prior to its reaching the shoreline. The transition from summer and winter conditions can occur rapidly over the course of one storm event, but the transition between winter and summer is a more gradual process. On coastlines in areas that experience little seasonality, similar profiles may be termed pre- and post-storm profiles. While storm-induced intertidal change is relatively well understood, the processes and time scales involved with storm recovery is still an ongoing research area.

Interannual variability can be related to larger scale atmospheric processes such as the North Atlantic Oscillation (Masselink et al., 2014; Vespremeanu-Stroe et al., 2007) or El Nino/La Nina (Ruggiero et al., 2005; Barnard et al., 2015). The frequency of occurrence of storm events has been linked to these cycles.

The rate of profile variability can also be linked to the region of the beach profile. Intertidal areas vary on daily time scales or less. Time scales of variability increase further offshore in deeper water depths (Ruggerio et al., 2005).

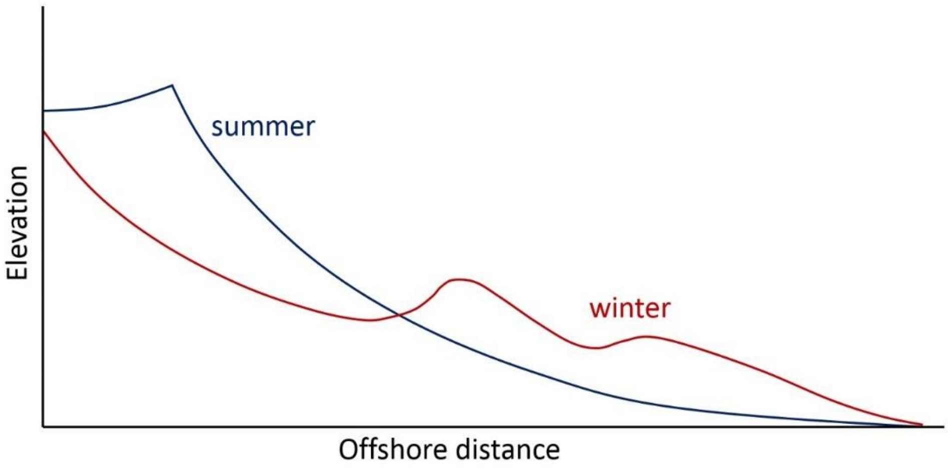

Figure 3. Illustrative beach profiles for a sandy beach. A schematic example summer profile is shown in blue, and a winter profile in red.

3. Impact of Marine Energy Devices on Sediment Dynamics

Extracting energy from the marine environment will clearly alter local, and possibly regional, hydrodynamics. Although, for most extraction scenarios, the influence on tidal currents and wave properties is likely to be very small; the influence on bed shear stress will be greater, because bed shear stress is quadratically related to tidal currents and wave orbital velocities. Further, the transport of sediments is a function of tidal current and wave orbital velocity cubed. Therefore, even small changes in the flow field caused by tidal or wave array operation could lead to significant impacts on regional sediment dynamics.

3.1. Individual Tidal-Stream Devices

Turbulence produces a net upward flux of sediment that is balanced by the tendency of the sediment to settle back toward the bed. The vertical distribution of sediment in the water column can be described using a Rouse profile (e.g., Neill, 2009):

$$\frac{C}{C_a} = \left[\frac{h-z}{h-a}\frac{a}{z}\right]^{w_s/\kappa u_*}$$

where C is the concentration of sediment, C_a is the reference concentration at level $z = a$, h is water depth, and $w_s/\kappa u_*$ is the Rouse Parameter, where w_s is the settling velocity, κ is Von Karman's constant (=0.41), and u_* is the frictional velocity. Taking a range of settling velocities and corresponding sediment grain sizes, we can calculate theoretical sediment concentration profiles at a typical tidal energy site with an assumed peak depth-averaged current speed of 2.5 m/s^{-1} (Figure 4).

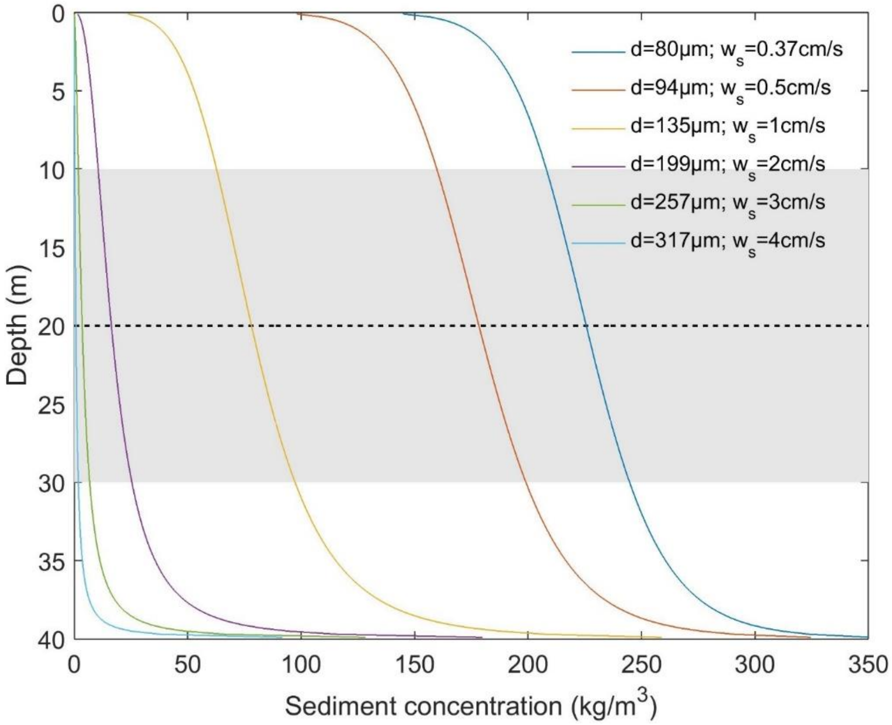

Figure 4. Calculated sediment concentration profiles for a range of sediment grain sizes (d) (with corresponding settling velocities w_s) and depth-averaged current speed of 2.5 m/s in 40 m water depth. The horizontal dashed line is (mid-depth) hub height, and the gray shaded area is the swept area for a turbine diameter of 20 m.

The Rouse profiles in Figure 4 demonstrate two important features of sediment concentrations in relation to tidal-stream turbines. First, the finer sediments have a higher concentration in the water column. Second, because of the higher Rouse Parameter associated with higher settling velocities, the coarser sediments are confined to the lower part of the water column, whereas it is only the finer sediments that have a substantial concentration higher in the water column, particularly with respect to device hub height and the turbine-swept area. In the example shown in Figure 4, sediment grain sizes of <135 µm (fine sand; see Figure 2) have an appreciable concentration at hub height, whereas medium sands (257 µm and 317 µm) have minimal concentrations either at hub height or over the swept area of the turbine. Because the seabed at the majority of tidal energy sites will be characterised by medium/coarse sands and gravels, sediment concentrations are not likely to impose significant loadings on turbine blades; however, in some regions where there is a localised source of finer sediment, or energy extraction leads to a change in the sediment regime in favour of finer sediments, consideration should be given to the possible impact of finer sediments on the wear of hub bearings and turbine blades.

A single TEC, for example of the horizontal axis configuration, is composed of a support structure and a rotor. The support structure alone will generate a wake, possibly characterised by eddy shedding, analogous to the flow past a bridge pier or a small island (e.g., Neill and Elliott, 2004a; Neill and Elliott, 2004b). Flow past the support structure will influence sediment dynamics in two ways. First, localised scouring will occur in regions of strong tidal flow (Den Boon et al., 2004), and for this reason, when installing turbines in regions that have a sufficient local source of mobile sediment, developers will need to consider providing scour protection, e.g., rock armour, to prevent undermining of foundations. Second, wakes lead to a winnowing of sediments (Wolanski et al., 1984), where the fine component of an initially poorly sorted (well-graded) sediment is removed and the coarser fraction remains. This could result in the wake zone being characterised by well-sorted (poorly graded) sediment, leading to further erosion problems associated with a less stable sedimentary structure. Further, and in contrast to obstacles placed in a riverine environment, such processes will be bi-directional in the case of tidal turbines, so scouring and winnowing will occur alternately on opposite sides of the support structure during either the flood or ebb phases of the tidal cycle. However, of even more interest, and a topic that is considerably under-researched, is the influence of the turbine rotor on sediment dynamics, particularly because the rotor is a dynamical component of the turbine, in contrast to the static nature of the support structure.

Figure 5 shows the main influence of tidal turbine rotors on the velocity profile. Because the depth of energy extraction spans only a portion of the water column, energy extraction over the depth of the rotor will be accompanied by an increase in flow speed (a bypass) both above and below the rotor, in addition to a velocity deficit over the height of the rotor (e.g., Yang et al., 2014). Of greatest significance to sediment dynamics, the near-bed bypass will lead to increased bed shear stress, so it will enhance the transport of sediments, particularly bedload and the near-bed component of the suspended load. Therefore, studies that have used depth-averaged terms to account for energy extraction (e.g., Neill et al., 2012; Robins et al., 2014) are likely to underestimate the impacts of arrays on sediment dynamics.

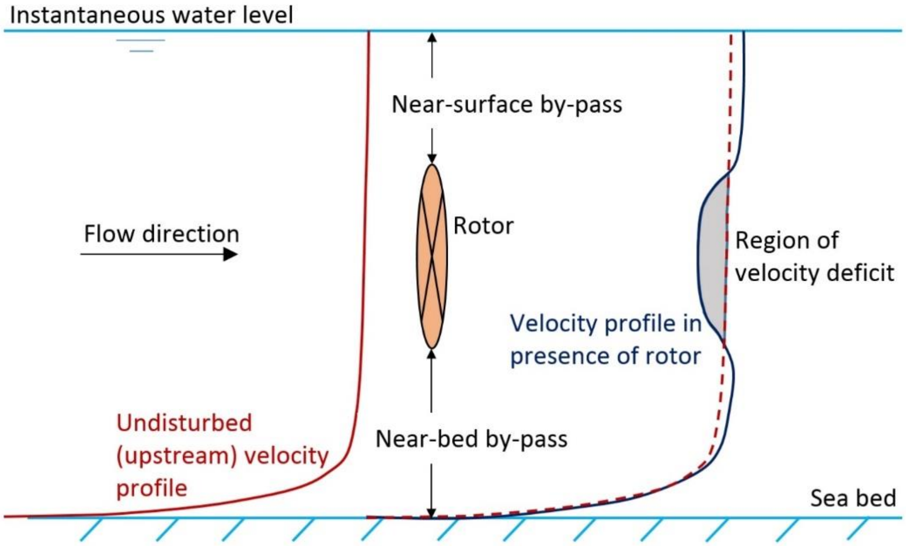

Figure 5. Influence of tidal turbine rotor on velocity profile.

3.2. Arrays of Tidal-Stream Devices

Although the impact of single turbines will be localised (<1 km), it is when devices are arranged in arrays, providing the potential for significant scales of electricity generation, that the impacts on regional (1–10 km) and far-field (>10 km) sediment dynamics could become important (e.g., Neill et al., 2009, 2012; Ahmadian et al., 2012). Tidal-stream energy extraction tends to reduce the bedload transport rate and deflect the sediment fluxes (e.g., Figure 6). One obvious concern about TEC array development is the arrays' potential near-field and far-field influence on the natural range of seasonal and interannual variability of sand features such as offshore sand banks (Neill et al., 2012). Therefore, when developers are planning the micro-siting of an array within an area, the device layout within the array, and the design of the devices. they should give careful consideration not only to the potential economic yield, but also to minimising the impact on the sedimentary environment. This is a crucial step in any site-specific micro-siting of TEC arrays. For example, energy extraction from regions that exhibit significant tidal asymmetry, such as in tidal channels or near headlands or islands, is likely to have a far greater impact on sedimentary systems than energy extraction in regions of tidal symmetry (Neill et al., 2009). Even regions of minimal sediment accumulation, such as bed parting (divergence) zones, could in theory accumulate sediment over long time scales because the influence of a TEC array on the hydrodynamic flow field (Neill et al., 2009).

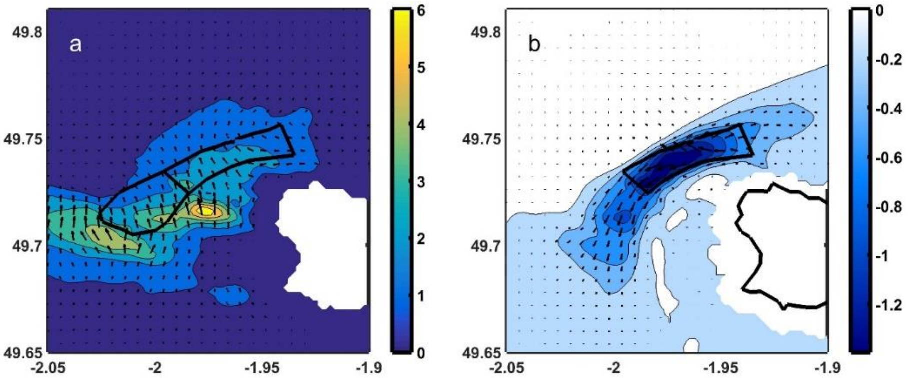

Figure 6. Changes in bed shear stress (in pascals) as a result of a 290 MW tidal energy array in the Alderney Race. (a) Mean stress exceedance magnitude and mean direction of the exceedance for the baseline case; and (b) mean changes induced by a tidal array sited within the enclosed region offshore. The arrows represent the direction of the perturbation. Results correspond to a sediment grain size of 3.8 mm. Results are averaged over 1 month. (Thiébot et al., 2015, reproduced with kind permission of Elsevier).

Morphodynamic model simulations provide the only realistic means for achieving economic-environmental optimisation of TEC arrays prior to their deployment and to aid in the assessment of environmental impacts. But there are several shortcomings of state-of-the-art morphodynamic applications relevant to such studies. At the regional scale, TEC array energy extraction is commonly represented in models as a momentum sink term distributed across the block array area (e.g., Neill et al., 2012; Robins et al., 2014; Thiébot et al., 2015). Such a methodology does not account for detailed internal array configuration or design, which can have important implications for the resulting hydrodynamic flow field (e.g., Ahmadian and Falconer, 2012). Another limiting issue at present appears to be a general lack of knowledge of the sedimentary environment (and hence, spatial variability in sediment sources and bed roughness) at high-flow speed sites such as the Alderney Race (Thiébot et al., 2015) and the Pentland Firth (Fairley et al., 2015; Martin-Short et al., 2015). This means that it is both difficult to parameterise and validate models of sediment transport. At a more fundamental level, there is presently a lack of universal formulation within models of several processes, such as sediment transport rates, sediment trapping, and sediment sorting mechanisms.

Furthermore, it remains a considerable computational task to simulate morphological change over the decadal time scales that are necessary to capture interannual variability, without approximating such time scales using a morphological factor. Orthogonal model mesh configurations cannot scale up from array to regional scales without resort to nesting, which potentially introduces errors propagating from nesting boundaries and may not account for feedback between the inner and outer nest. Rather, unstructured grids are preferred for array- to regional-scale morphodynamic modelling.

Nevertheless, apparent development of scientific consensus seems to suggest that siting TEC arrays farther offshore has several resource and environmental advantages. For example, farther offshore, the tidal-stream resource capacity and its temporal variability are likely reduced, and the currents are often more rectilinear and symmetrical (Robins et al., 2015; Lewis et al., 2015b), potentially leading to reduced sedimentary impacts (Neill et al., 2009, 2012; Robins et al., 2014). On the other hand, wave heights (and hence, wave-induced bed shear stress) farther offshore are typically greater (Lewis et al., 2015b). An important consideration for sedimentary environmental impact assessments is that the potential impact of energy extraction at a TEC site should fall within the natural levels of seasonal and interannual variability in bed shear stress—a proxy for sediment transport that can easily be quantified by numerical simulations (Robins et al., 2014). Under such a condition, it is theoretically possible to calculate the threshold TEC array size for any region, using tide-wave coupled model simulations. In such simulations, it will be vital to capture the natural variability of extremes in surge and wave-tide interactions. A positive result for the MRE industry, from some initial case studies of sedimentary impacts, suggests that small- to medium-sized TEC arrays (on the order of 10–100 MW) will not significantly affect the surrounding morphology in relation to natural variability (e.g., Robins et al., 2014; Fairley et al., 2015).

3.3. Wave Energy Arrays

Wave energy converters (WECs) extract energy from a wave field, thereby leading to a reduction in wave height in their lee. Depending on the device type, there is the potential for wave reflection and local wave focusing. WECs can be grouped based on deployment area: shore-attached, nearshore, and offshore.

Shore-attached WECs are predominantly built into breakwaters, hard-rock cliffs, or other such structures where the quantity of mobile sediment is limited. Mobile sediment coastlines typically have shallower seabed gradients, where greater wave energy dissipation would occur prior to reaching the WEC, and the abundance of mobile sediment would accelerate wear on devices via abrasion. Examples of early shore-attached WECs include the Pico Oscillating Water Column in the Azores and the Mutriku wave energy plant in the Basque Country. While there may be some scouring of the seabed seaward of such structures, the impact on wider field sediment transport and morphology will likely be minimal. If shore-attached devices were deployed in series on mobile sediment coasts, they might act to alter longshore sediment transport, similar to a groyne field (e.g,. Schoonees et al., 2006), with accretion on the updrift side and erosion on the downdrift side.

Most prevalent of the specifically nearshore designs is the oscillating surge converter. These devices are typically deployed in 15–30 m water depths. The motion of a surface-piercing flap around a bottom-mounted hinge can be used to pump water ashore and then through generator turbines or to directly generate energy. The impact of such devices is discussed in Section 3.3.1.

Offshore devices are deployed in deeper water, and the range of technology types is diverse. Offshore wave energy devices have been the most intensively studied from a morphodynamic perspective by the academic community. Impacts can be categorised as either near-field or far-field, both of which are considered in Section 3.3.2.

3.3.1. Nearshore Devices

Nearshore oscillating surge converter devices such as the Aquamarine Oyster or the Resolute Marine Energy SurgeWEC, being situated close to the shoreline, have the potential to have greater impact on shoreline dynamics than devices located farther offshore. However, as far as the authors are aware, little academic research has considered the impact of these devices on nearshore morphodynamics. A report about coastal processes for the proposed Outshore Point wave farm in Orkney (Xodus Group Ltd., 2012) likens the probable impact of nearshore devices such as the Oyster to the impact of detached breakwaters. Detached breakwaters typically cause accumulation of sediment at the shoreline in the lee of the structure (Figure 7). The type of accumulation depends on the abundance of sediment, the distance of the structure from the shore, the length of the structure, the transmission coefficient of the structure, the gap distance, and the incident wave climate. Shoreline responses typically vary from no response, via the formation of a salient, to the extreme case of a tombola, where sediment accumulation reaches the breakwater because of combined refraction and diffraction processes. Similar impacts might be expected for nearshore WECs, but one aspect is different: the active back and forth movement of the paddle may lead to a different dynamical response near the device, in contrast to a passive breakwater.

Figure 7. Beach response to detached breakwaters at Sea Palling, UK. Accretion of the shoreline toward the structure can be observed.

3.3.2. Offshore Devices

Near-field effects of offshore devices can be split between localised scour effects and the impact of reduced wave climate on regional sediment dynamics. Harris et al. (2011) considered the scour associated with offshore wind installations and raised the importance of scour to wave energy developments. As far as the authors are aware, no work has been conducted on scour attributed to WECs explicitly, although there is a significant body of work on marine scour (e.g., Whitehouse, 1998). Scour must be considered both from the perspective of an environmental impact assessment and to ensure the integrity of the installation, which may require scour protection measures.

A regional-scale study by Gonzalez-Santamaria et al. (2011) showed that impacts on sediment dynamics are larger in the far-field than in the near-field vicinity of the WEC arrays. Early work that considered the far-field impact of WEC arrays on sediment dynamics assessed the suitability of WECs as a form of coastal defence—both for a hypothetical scenario (Zanuttigh et al., 2010) and the case study of Milano Marittima, Italy (Ruol et al., 2011). The presence of WECs was also shown to reduce the net volume of longshore sediment transport, and it is postulated that intelligent control of WECs could be used to mitigate coastal erosion. Similarly, Mendoza et al. (2014) considered different types of WECs at two locations: Santander (Spain) and Las Glorias (Mexico). A wave model was used to transform waves inshore in the absence and presence of WECs. Device specifics and array layouts both affected morphological change. For the case study at Santander, farm implementation led to shoreline accretion in all cases, while at Las Glorias, erosion was predicted for some locations. Due to lack of calibration, only the ratio of protected to unprotected cross-shore change was of relevance (Figure 8). The region $-1 < X_p/X_u < 1$ on the vertical axis of the figure indicates levels at which change caused by WECs are less than the baseline change. At the extremities of the beach, the impact is similar for both types of devices and is less than the baseline case. In the centre, behind the farm, device type has a large impact on morphological response.

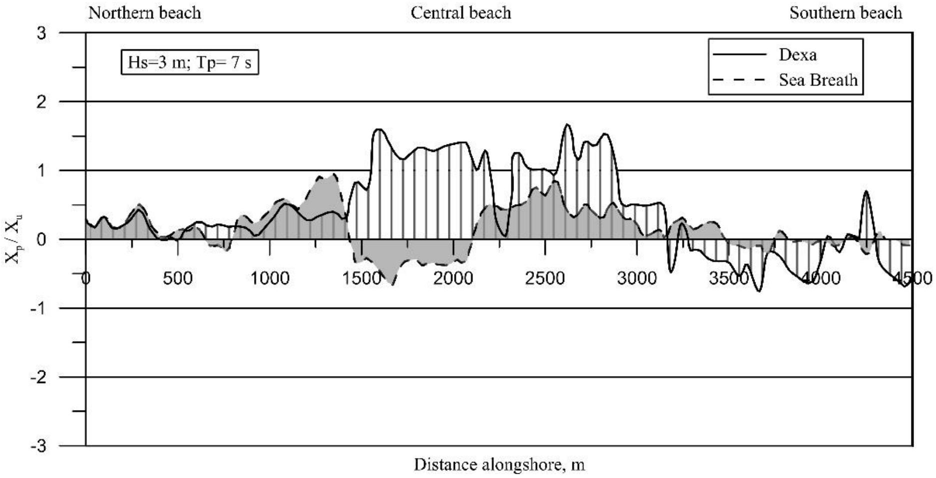

Figure 8. Predicted shoreline response at Las Glorias, Mexico, for two different types of wave energy converter. (Reproduced from Mendoza et al. [2014] with permission from Elsevier.)

A large amount of work has focused on the WaveHub site in the United Kingdom (UK). The WaveHub is a facility for the demonstration of full-scale wave energy devices; it is fully consented, its sub-sea cables are already installed, and it has a capacity of 30 MW. Gonzalez-Santamaria et al. (2011, 2015) considered regional-scale impact, while Abanades et al. (2014a, 2014b, 2015a, 2015b) focused on the nearshore and intertidal regions for hypothetical deployments close to the WaveHub site. Gonzalez-Santamaria et al. (2011) used a two-way coupled ROMS-SWAN (Regional Ocean Modeling System-Simulating Waves Nearshore) modelling system to investigate the impact of energy extraction at the WaveHub site. Wave-current interaction, sediment transport, and morphological change in the region were all considered. Importantly, inclusion of currents altered wave direction, which magnified the impact of the wave farm in this case; this suggests that fully coupled numerical models including waves, hydrodynamics, and sediment transport may be required to accurately simulate morphological change.

Abanades et al. (2014a) considered the impact that deployment of an 11-device farm might have on the two-dimensional cross-shore profile evolution at a beach adjacent to the WaveHub. Storm conditions were tested and wave height reductions of up to 3.3% were observed due to WEC array operation. Farm implementation led to reduction in erosion over the tested profiles, in particular at the beach face and over the subtidal bar. However, the scale of these impacts may be overstated, because WEC devices would not generally be expected to generate electricity during storm events when they would enter “survival mode” and become passive. The case study was extended to three dimensions and similar results were found (Abanades et al., 2014b). The greatest reduction in erosion was predicted at the dune toe, and significant modification of sediment transport pathways was observed. Abanades et al. (2015a) assessed the role of coast-to-farm distance; unsurprisingly they found that farms deployed farther offshore had less impact on shoreline morphodynamics. Consideration has also been given to the modal beach state at Perranporth (Abanades et al., 2015b). The conceptual beach model of Masselink and Short (1993) was used, and the study concluded that changes in wave height led to a shift in beach state from reflective toward dissipative. Consideration of changes in the modal beach state is likely to prove fruitful from a management perspective, because it provides a simplistic descriptor of change.

The work described thus far in this section has considered the impact of WECs on largely sandy coastlines. In the UK, the west coast of Orkney (Scotland) could be one of the early areas to be affected by large-scale wave energy conversion; similarly, interest is focused on the west coast of the Isle of Lewis (Scotland). Neither location conforms to the previously examined sandy environments. Instead the coastlines consist of hard-rock cliffs, boulder and cobble foreshore, and embayed sandy beaches. These more complex environments, which are both geologically controlled and have limited sediment supply, are more challenging to model. Fairley et al. (2014) used the commercially available MIKE 3 software to set up a fully coupled coastal area model (spectral waves, hydrodynamics, and morphological change) to investigate morphological impacts at the Bay of Skaill (west coast of Orkney). The Bay of Skaill is important because of the presence of Skara Brae, a Neolithic village and United Nations Educational, Scientific and Cultural Organisation World Heritage Site. It consists of an embayed beach, constrained by rocky headlands to the north and south, a cobble back beach, and a bedrock subtidal region (Figure 9). Only in the intertidal region of the embayment is mobile sediment present, although farther offshore sand dominates. Model results were compared to measured cross-shore profiles with limited success. It was postulated that the sparsity of sediment and the dominance of swash zone transport were the main reasons for poor model performance. Although this represents an isolated case, such atypical environments are likely to be common in regions of wave energy development, so it is important to have confidence in the assessment of potential impacts. Where impacts on complex environments are critical, a combination of measurement campaigns and expert opinion may be more fruitful than numerical modelling.

Figure 9. Survey work at the Bay of Skaill, Orkney. The cobble back beach and hard-rock headland can both be seen. The hard-rock lower intertidal region can be observed behind the surveyor as it is exposed by the receding tide.

3.4. Long-Term Variability

To better understand the potential long-term (decadal and climatic) impact of tidal-stream and wave energy extraction on regional-scale morphology, we need to first understand natural levels of morphodynamic variability, at a site-specific level and without MRE development; i.e, the variabilities and recent trends (last 50 years) in bed load transport rates (Van Landeghem et al., 2012), offshore sand bank formation and maintenance (e.g., Neill, 2008; Neill and Scourse, 2009), and beach profiles (e.g., Neill et al., 2008; Ruggiero et al., 2009). This requires long-term monitoring strategies (see Section 3.5), as well as validated morphodynamic model simulations. Then, morphodynamic models can be applied to simulate projected variability over longer time scales—either the expected life span of an MRE device or array (e.g., 25 years) or over time scales of relevance to climate change (50–100 years). Next, long-term energy extraction scenarios can be performed to determine rates of change, relative to the baseline (environment unmodified by MRE development) and to quantify their impacts. However, large model uncertainties currently exist, both in simulating transport and morphology accurately, and in representation of energy extraction (e.g., see Section 3.2).

For different potential MRE regions, the relative controls on sediment transport and morphology need to be quantified. For example, the influence of wave-induced bed shear stress is larger in shallow waters than in deeper waters, and, of course, in more exposed regions where wave heights are typically greater. Likewise, in high-flow speed regions, strong tidal currents likely control transport magnitude/direction and morphology, rather than waves. In addition, local sediment types and geophysics will influence the patterns of transport and morphology. The relative influences on bedload transport of tidal variability (e.g., transport during spring tides in comparison to neap tides) and of storm surges and storm waves are also poorly understood. It is therefore important to assess the role effect extreme (e.g., storm) events have on net sediment dynamics.

4. Monitoring

Monitoring of the impact of the first arrays on mobile sediment regions will be vital to better understand the likely impacts of future arrays. Because of the interannual and intra-annual variability of morphodynamic behaviour (Section 2.5), baseline studies of sufficient duration should be performed prior to device deployment. Monitoring of intertidal regions is relatively inexpensive (compared to offshore bathymetry surveys), and hence it is viable to expect surveys to be conducted with some regularity. Traditionally, monitoring of intertidal change has relied on repeated measurement of defined cross-shore profiles, often based on data collected by local authorities for coastal management purposes. In some areas, profile records are available for many decades, although repeatability varies due to changing measurement technology (Harley et al., 2011). Initially, profiles were measured using the emery board technique (Emery, 1961); more recently theodolites and Real Time Kinematic-Global Positioning System (RTK-GPS) surveys have been used. A key issue with profiles collected by local authorities is the temporal frequency of collection, which is often conducted on an annual or 6 monthly summer-winter basis. This is not only insufficient temporal resolution to define intra-annual changes, but the timing of surveys relative to storm events (and associated coastal recession) can obscure actual trends in the morphological evolution of beaches. Ideally, higher temporal resolution, e.g., monthly, is recommended, to ensure seasonal changes are captured. Additional surveys may be collected before and after storms to capture changes under high-energy conditions.

As technology progresses, intertidal surveys have gone beyond two-dimensional profiles to the creation of full three-dimensional digital terrain maps of intertidal regions. These are typically created from RTK-GPS surveys, which for efficiency may be conducted on a quad bike or similar device.

Novel monitoring techniques have also been applied, for example Argus video systems. Such video systems have been deployed at beaches in the lee of the WaveHub site in the UK for many years, which ensures that when devices are deployed, any impacts on morphodynamics can be compared to a long-term morphological record (Poate et al., 2012, 2014). This type of monitoring is advantageous because the video data are collected every day and analysis frequency is user-dependent. Similarly, X-Band radar can be used to remotely monitor shorelines (Bell et al., 2016).

Multibeam echosounder (MBES) systems have revolutionized offshore bathymetric surveys. Although MBES surveys are relatively expensive, they represent an accurate technique that can be used to rapidly survey large areas of seabed to investigate local and regional seabed features (e.g., Robins et al., 2014). However, MBES surveys should be supplemented by seabed grab samples and subsequent particle size analysis to provide validation of seabed type and to fully characterise seabed sediments. Although MBES surveys provide a snapshot of the seabed, it is important for monitoring purposes to repeat such surveys over appropriate and regular time intervals if possible; for example, to determine the influence of storm events on morphodynamics, and to monitor the natural variability of systems such as offshore sand banks (e.g., Schmitt and Mitchell, 2014).

5. Tidal Lagoons/Barrages

Where tidal ranges are large enough, there is potential for tidal barrages[2] and tidal lagoons[3] to contribute to substantial renewable energy generation. For example, tidal barrages and/or lagoons could contribute at least 10% to the UK's electricity demand, 5% of which could come from the Severn Estuary alone (Burrows et al., 2009). However, several barrage proposals have failed to gain governmental support to date, in part because of opposition due to significant environmental implications and high capital cost (e.g., Kirby and Shaw, 2005). Lagoons are coastal or enclosed walled embayments typically several kilometres in circumference, that create an artificial tidal phase difference and head difference between the body of water within and outside the lagoon. The water-level difference between the ocean and the lagoon (called the head of water), drives flow through turbines using various strategies such as ebb tide-only generation, or two-way (flood and ebb tide) generation, amongst more complex designs (Prandle, 1984; Ahmadian et al., 2010; Kadiri et al., 2012; Cornett et al., 2013). Two-way generation turbines have been shown to generate power for a greater proportion of the tidal cycle (e.g., Zhou et al., 2014), thereby reducing intermittency in electricity supply.

An obvious impact of lagoon structures will be a markedly reduced energetic environment within the lagoon walls, especially during the water-holding periods (Cornett et al., 2013; Angeloudis et al., 2015). Weaker tidal currents and vertical mixing will reduce suspended sediment concentrations (Wolf et al., 2009; Ahmadian et al., 2012). By concentrating turbines and sluices in one section of the lagoon wall

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[2] A tidal range power plant that spans the entire width of a channel with turbines embedded in the retaining wall.

[3] In contrast to a tidal barrage, this is a tidal range power plant that is enclosed.

(sometimes called the power house), counter-rotating eddies may form in the turbine wake (Falconer et al., 2009; Wolf et al., 2009; Cornett et al., 2013; Angeloudis et al., 2016), resulting in localised sediment resuspension and scour. Evenly spacing turbines throughout the lagoon structure would reduce this impact (Falconer et al., 2009). In practice, this may be difficult to achieve because of bathymetric or other practical constraints, in addition to increased cost.

Outside the lagoon, the alteration of the natural physical environment will depend on the regional hydrodynamics and atmospheric conditions, local topography and bathymetry, the design of the lagoon, and the operational specifications of the lagoon (Angeloudis et al., 2015). Processes that are particularly vulnerable are scour near the lagoon walls, sediment supply to neighbouring beaches and sand banks, and wave reflection/diffraction processes. Reduced or altered sediment supply to sand banks and to neighbouring beaches may affect the ability of these features to absorb wave energy from winter storms, hence making the coast more vulnerable to erosion (Neill et al., 2012; Robins et al., 2014). Considering a two-way (flood and ebb) generation regime, Angeloudis et al. (2016) suggest that the loss of intertidal regions can be minimised, which is a major source of concern with regard to ebb generation operation.

In light of these potential impacts, lagoon optimisation will be an important task; e.g., the lagoon shape and the number and position of turbines and sluices can be optimised to maximise energy yield and minimise environmental impacts. Numerical models that include a variety of lagoon designs and turbine parameterisation options are being developed (e.g., Cornett et al., 2013). The tidal and wave resource near potential lagoon sites needs to be better characterised, including the interactions of the resource with proposed lagoons and their surrounding environment; e.g., wave and storm climates and natural variability, sediment transport pathways, and turbulent mixing rates (inside lagoons), with particular attention paid to extreme events and climate change.

6. Summary and Conclusions

There is a growing body of research into the impact of wave and tidal-stream devices on sediment dynamics. The research generally reports that it is only at large scales of electricity generation (e.g., >100 MW) that the impacts could exceed natural variability, but this “rule-of-thumb” will vary depending on site conditions and the sensitivity of a region. However, consistent monitoring pre- and post-construction is necessary to ascertain the range of natural variability, so that any post-construction impacts can be quantified. Further, before arrays are installed in the marine environment, much reliance is place on numerical modelling, yet few of these sediment transport and morphodynamic models have been validated.[4] An important step toward reducing model

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[4] In contrast, the underlying hydrodynamic flow fields tend to be well validated.

uncertainty is to calibrate and validate the regional sediment transport models. This again comes back to the collection and integration of models with field data collected over appropriate time scales. In addition, it is important to ensure that arrays are correctly and consistently represented in two- and three-dimensional regional hydrodynamic models. Finally, many uncertainties about the implications of tidal lagoons relative to sedimentary processes remain. Consensus is needed how we represent lagoons in hydrodynamic models before the impacts of tidal lagoons on sediment dynamics and morphodynamics can be estimated with any certainty.

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