Impact of tidal stream turbines on sand bank dynamics

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Abstract: Previous results from one-dimensional model studies have demonstrated that large-scale exploitation of the tidal stream resource could have a significant impact on large-scale sediment dynamics. In this research, we model the impact which such exploitation would have on the dynamics of offshore sand banks. Such banks have an important role in natural coastal protection, since they cause waves to refract and induce wave breaking. As a case study, we examine the Alderney Race, a strait of water between the island of Alderney (Channel Islands) and Cap de la Hague (France). A morphological model is developed, incorporating tidal energy converter (TEC) device operation as a momentum sink in the three-dimensional hydrodynamic module. Through a series of model experiments, we demonstrate the impact which a full-scale (300 MW) TEC array would have on sediment dynamics when sited in the vicinity of headlands and islands. It is important to understand this aspect of the environmental impact of full-scale TEC operation, since headland and island sand banks comprise of readily mobile sediment grain sizes. Therefore, small changes to the tidal regime can have a large effect on the residual sediment transport pathways, and hence sand bank evolution, over the life cycle of a TEC device.

Keywords: *Tidal stream turbines, Tidal energy converter devices, Sediment dynamics, Sand banks, Alderney Race*

1. Introduction

Tidal energy converter (TEC) devices operate by intercepting the kinetic energy in strong tidal currents (typically through a turbine unit). This intercepted energy is then converted to electrical energy through a power take-off system (e.g. an induction generator) and conditioned for dispatch to the electricity network. Theoretically, this is similar to the operation of a typical wind energy device. However, what is significantly different from the wind energy analogy is the environment that TEC devices operate in [1], and the potential for TEC devices to interact with their environment [2]. Given the proliferation of at-sea demonstration devices, the environmental impacts of TEC device operation is a timely issue to consider. The major research questions in the tidal energy context have already been identified [3]. However, progress to-date has been limited in addressing these research issues. The impact of TEC operation on sediment dynamics has yet to be explored in the scientific literature beyond an idealised one-dimensional (1D) model pilot study [4], stimulating the present study.

Extracting energy from a tidal system will lead to an overall reduction in current speed over the larger area domain [2]. This reduction in current speed, even for relatively large TEC array extraction scenarios, is generally quite small. For example, in a tidal channel the impact of energy extraction on current speed U becomes noticeable only when the energy extracted reaches around 10% of the available kinetic energy flux [5], a considerably large amount of energy to extract from a channel. More realistic extraction scenarios (typically 1% of the available kinetic energy) could therefore be perceived to have very little environmental impact. However, bed shear stress is a function of U^2. Therefore, small changes in the tidal currents could potentially lead to large changes in the resulting bed shear stress. Further, the transport of sediments is proportional to an even higher power of velocity than bed shear stress, e.g. total load transport by currents (bedload and suspended load) is a function of $U^{2.4}$

[6]. Therefore, relatively small changes to the residual flow field due to exploitation of the tidal stream resource could have a significant effect on the transport of sediments. This has been reported in a 1D idealised study of the Bristol Channel (UK), where the morphodynamics were significantly impacted 50 km from the site of energy extraction [4]. In the case of a simple tidal channel or an estuary, much insight can be gained from such 1D model studies, since much of the flow is similarly 1D. However, for more complex situations such as flow past islands and headlands, two- or three-dimensional (2D or 3D) models are required to predict and understand the complexity of the flow field and estimate the impacts of energy extraction.

Strong tidal flow past headlands and islands leads to the generation of large eddy systems, with an opposite sense of vorticity between the flood and ebb phases of the tide [7]. Sand banks form either side of such headlands due to a balance between the outward-directed centrifugal force and the inward-directed pressure gradient within the eddies [8], leading to a convergence of relatively coarse sand as a function of the instantaneous tidal currents (Fig. 1). The sand banks which form as a result of this convergence can be up to 10 km in length, and have an important role in coastal defence (since offshore banks affect both wave refraction and breaking), and can be a strategic source of marine aggregates. Regions of strong tidal flow past headlands and islands have been listed as potential sites for the exploitation of the tidal stream resource, such as Portland Bill in the English Channel [9], and flow past the island of Alderney in the Channel Islands [10]. The aim of this study is to determine how such exploitation in the vicinity of headlands and islands would affect the maintenance of the associated sand banks. This is addressed through the investigation of a modelling case study: the Alderney Race.

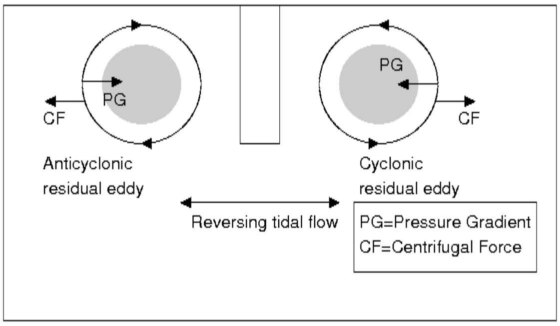

Fig. 1. Headland or island sand bank formation. Reversing tidal flow past the headland or island leads to the generation of eddy systems with an opposite sense of vorticity between the flood and ebb phases of the tide. The outward-directed centrifugal force within each eddy is balanced by an inward-directed pressure gradient. This leads to the inward movement of relatively coarse sediment near the bed (where the centrifugal force is weaker due to bed friction), and the formation of headland or island sand banks. Grey shading indicates the location of sand banks.

2. The Alderney Race

The Alderney Race is a 15 km strait of water separating the island of Alderney (Channel Islands) and Cap de la Hague in France (Fig. 2). With a mean spring tidal range of around 6 m and mean spring tidal currents exceeding 2.5 m/s [11], the Alderney Race presents one of the most hostile environments within the northwest European shelf seas. However, over 20 km^2 of the Race has a water depth in the range of 25-45 m, the typical depth range suitable for practical TEC device operation [1] which, in conjunction with consistently high current speeds, represents one of the best opportunities in the world for large-scale exploitation of the tidal stream resource. This opportunity has been recognized by the formation of the Alderney

Commission for Renewable Energy (ACRE), with powers to regulate the operation of marine energy in the territorial waters of Alderney (www.acre.gov.gg). Using current technology, the practical exploitable annual energy output for the Alderney Race has been estimated as 1340 GW h at a rated turbine array capacity of 1.5 GW [10], and a large portion of this energy is contained within the three nautical mile territorial limit of Alderney.

To the south of Alderney there are a series of sand banks known as the South Banks (Fig. 2). The scale of these banks is substantial, 4 km in length and covering an area of seabed around 3 km^2. Hence, the sand banks are important to the economy of Alderney in terms of offering natural coastal protection, as a potential strategic source of marine aggregates, and as a hazard to navigation. The South Banks are maintained by recirculating tidal flows in the lee of Alderney during the ebb phase of the tide (as described in Section 1) and, despite some degree of interannual variability (primarily due to the stochastic nature of waves and wind-driven currents), have persisted in more-or-less their current configuration for several thousand years.

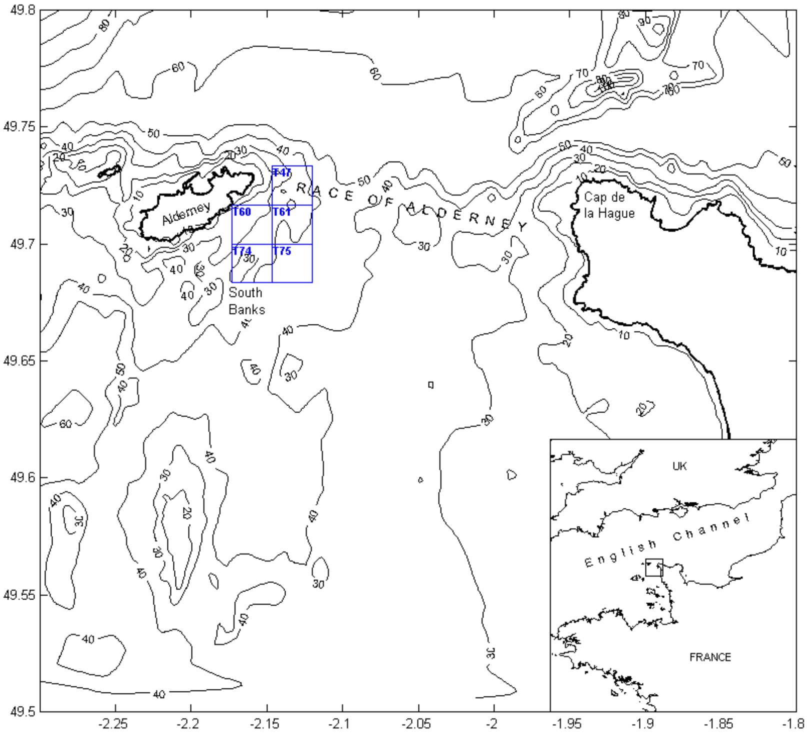

Fig. 2. Bathymetry of the Alderney Race and surrounding waters. Contours are water depths (in metres) relative to mean sea level and squares (labeled T47, T60, T61, T74 and T75) are regions (or blocks) identified by the Alderney Commission for Renewable Energy for exploitation of the tidal stream resource. For scale, the side length of each block is 1 nautical mile (1.85 km). The inset shows the location of the Alderney Race relative to the UK and France.

The ACRE has sub-divided the territorial waters of Alderney into 96 regions, or blocks. Detailed hydrographic and geophysical surveys have been carried out for blocks T60, T61, T74 and T75 (Fig. 2), and it is therefore assumed that these blocks would be developed first if the proposed tidal energy project were to proceed. However, block T47 is of particular interest to the present study since (a) it contains the highest velocities in the western part of the Alderney Race (Section 3), and (b) this location is close to the point of maximum vorticity due to tidal flow past the island. Hence, tidal currents in block T47 have a major controlling influence on the maintenance of the South Banks.

3. The Numerical Model and Baseline Results

Bathymetry for the study region was digitised from Admiralty Charts and interpolated onto a model grid with a horizontal resolution of approximately 150 m, and with 6 terrain-following (sigma) layers in the vertical. The boundary conditions were extracted from a larger area model of the northwest European shelf seas which had a resolution of 1/6° longitude × 1/9° latitude. The 3D POLCOMS model [12] was applied to the Alderney model configuration over a spring-neap cycle, using the dominant semi-diurnal tidal constituents, M_2 and S_2, as boundary conditions. The model of the Alderney region was successfully validated in terms of the magnitude and phase of the M_2 (lunar) and S_2 (solar) elevations at three stations taken from the Admiralty tide tables, and for the magnitude and phase of tidal currents at the location of four tidal diamonds taken from the Admiralty Chart of the region.

3.1. Baseline Results

The model was applied initially to a natural baseline case, in order to understand the residual currents and sediment transport pathways in the absence of artificial energy extraction. The residual currents for a spring-neap cycle are plotted in Fig. 3. Clearly, there are two large residual eddies in the vicinity of Alderney: one due to the ebb currents and one due to the flood currents. The former eddy (to the south of Alderney) is approximately centered over the South Banks, confirming the convergent process which maintains this sand bank (Section 1). Taking a median sediment grain size of 300 μm (medium sand) as representative of the region, the residual sediment transport over a spring-neap cycle is shown in Fig. 4, based on calculations of the total load transport [6]. Although the residual sediment transport vectors are similar to the residual flow field (Fig. 3), there are distinct differences. In particular, the residual sediment transport to the east of Alderney is predominantly directed southwards, partially explaining why the dominant sand bank of the region forms to the south of Alderney, with no corresponding sand bank associated with the residual eddy to the north[1].

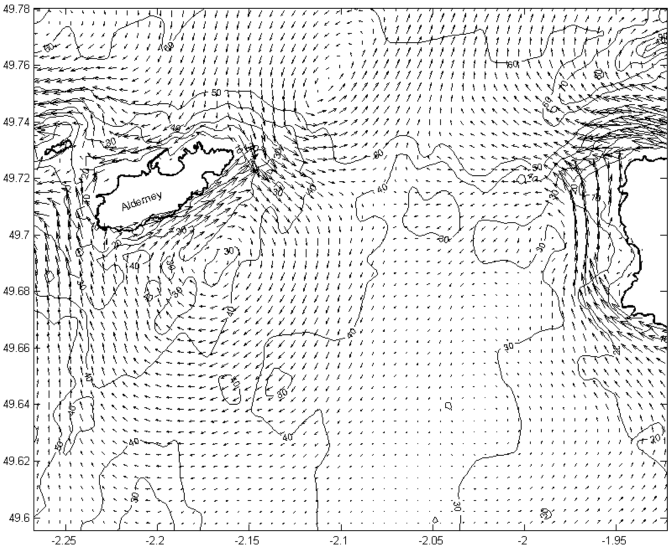

Fig. 3. Modelled residual tidal currents in the Alderney Race for baseline case (no artificial energy extraction). Contours are water depths (in metres) relative to mean sea level. For clarity, every third modelled vector has been plotted in both the x- and y-directions.

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[1] In addition, there is a distinct asymmetry in the ambient water depths to the north and south of Alderney.

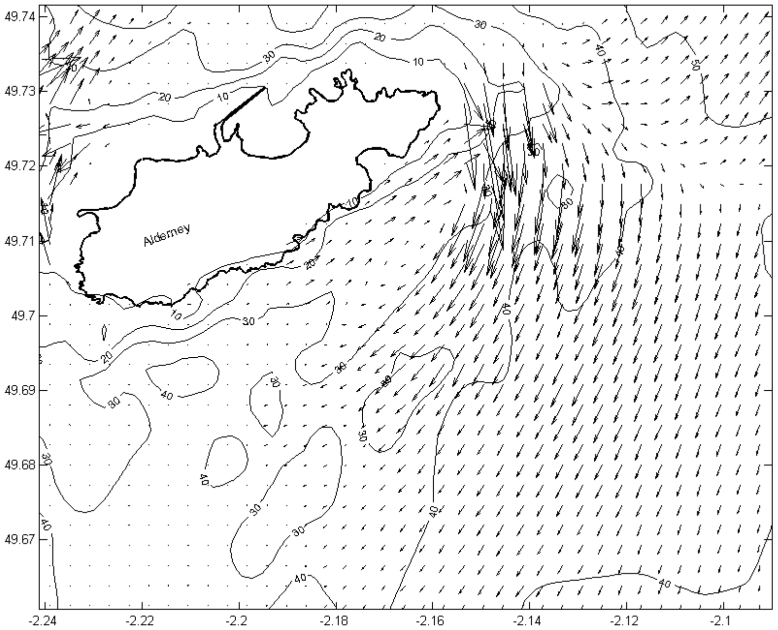

Fig. 4. Residual sediment transport around Alderney for baseline case (no artificial energy extraction). Contours are water depths (in metres) relative to mean sea level. For clarity, every second modelled vector has been plotted in both the x- and y-directions.

4. Energy Extraction

A momentum sink was incorporated in the 3D POLCOMS model code, with turbine characteristics parameterised from an OpenHydro turbine (with a 15 m diameter), the preferred technology supplier for Alderney Renewable Energy (ARE) (http://www.are.gb.com/technology-developers.php). Details of the OpenHydro power curve were taken from Bedard et al. [13], with a cut-in speed of 0.7 m/s, a rated power of 1.5 MW (at 2.57 m/s), and an assumed efficiency (at the point of extraction) of a constant 35%. Applying a minimum lateral spacing of 3 turbine widths and a minimum downstream spacing of 15 turbine widths to eliminate lateral and wake effects, respectively (e.g. [10]), a simple rectangular array of 200 OpenHydro devices (i.e. a 300 MW array) can easily be accommodated by each of the 1.85 × 1.85 km development blocks marked in Fig. 2. In this study, simulations were performed only for blocks T47 and T60.

4.1. Energy Extraction Results

The results are presented in this section as difference plots, i.e. the difference between each of the artificial energy extraction simulations *minus* the baseline simulation. In the region of energy extraction, the magnitude of mean velocity was reduced by around 0.05 m/s for each of the energy extraction scenarios (T47 and T60) (Fig. 5). The reduction in velocity was not localised to the turbine array, but extended a distance of up to 10 km from the array. Despite local reductions in the magnitude of velocity, the far-field velocity was increased by a similar magnitude (0.05 m/s), particularly to the northwest of Alderney. Changes to the sediment transport followed a similar pattern to velocity (Fig. 6). The instantaneous predictions of sediment transport were applied to a 2D continuity equation to predict the change in bed level over the 30 year life-cycle of a TEC device (Fig. 7). Again, the morphodynamic impact was non-localised, with bed level changes of about a metre occurring over a 30 year period. However, the most important result in terms of the main aim of this study is that a 300 MW TEC array would have a negligible impact on the morphodynamics of the South Banks, maintained by recirculating tidal flows in the lee of the island. However, the morphodynamics of the region will be significantly altered by such large-scale exploitation of the tidal stream resource, and this effect will be evident up to 10 km from the point of extraction.

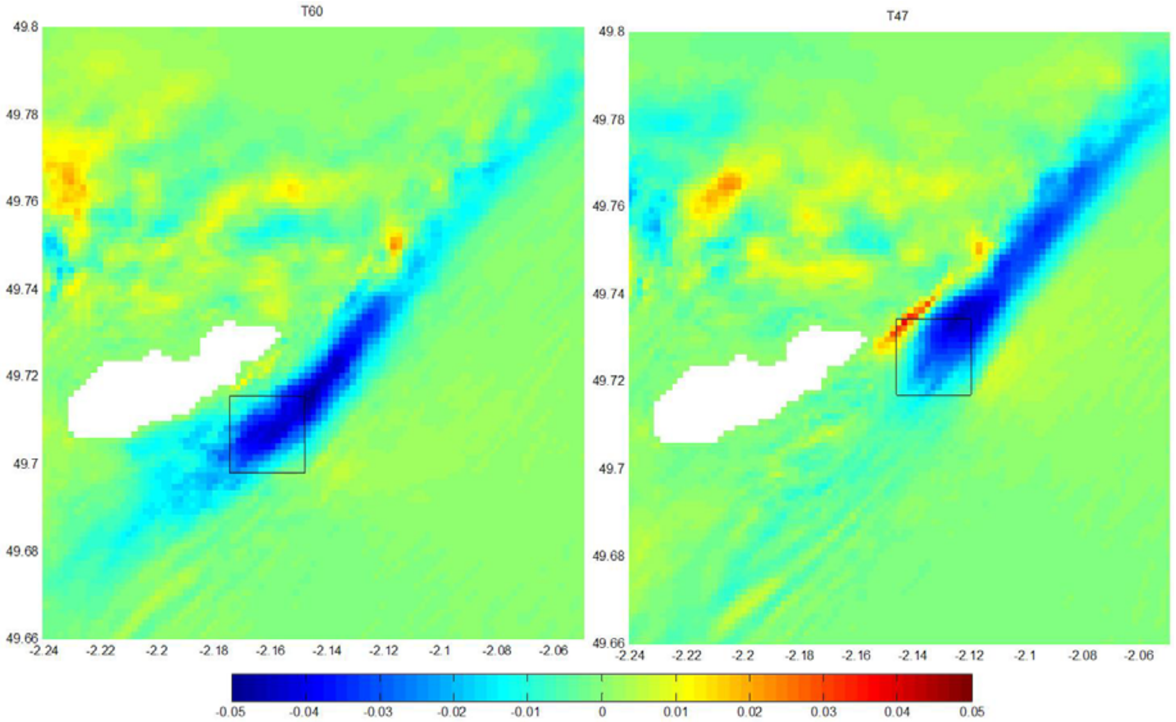

Fig. 5. Change in the magnitude of velocity (in m/s) due to energy extraction, averaged over a spring-neap cycle. Boxes show the limits of the TEC array for each case (T60 and T47).

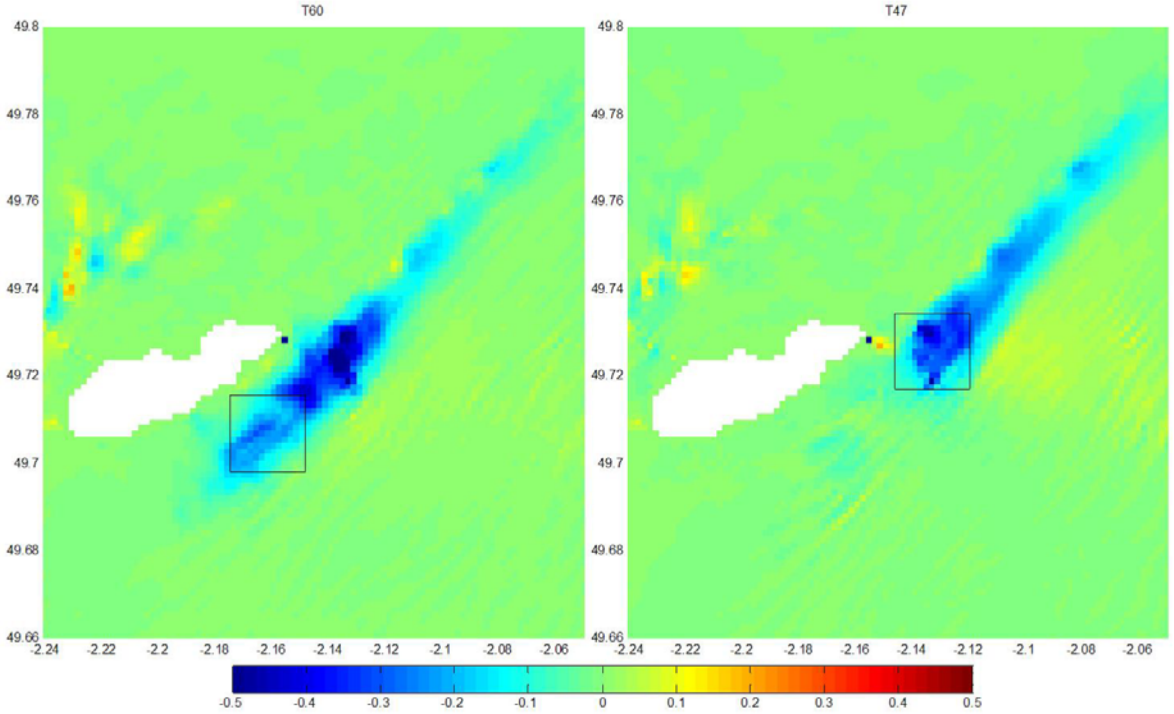

Fig. 6. Change in the magnitude of sediment transport for medium sand due to energy extraction, averaged over a spring-neap cycle. Boxes show the limits of the TEC array for each case (T60 and T47).

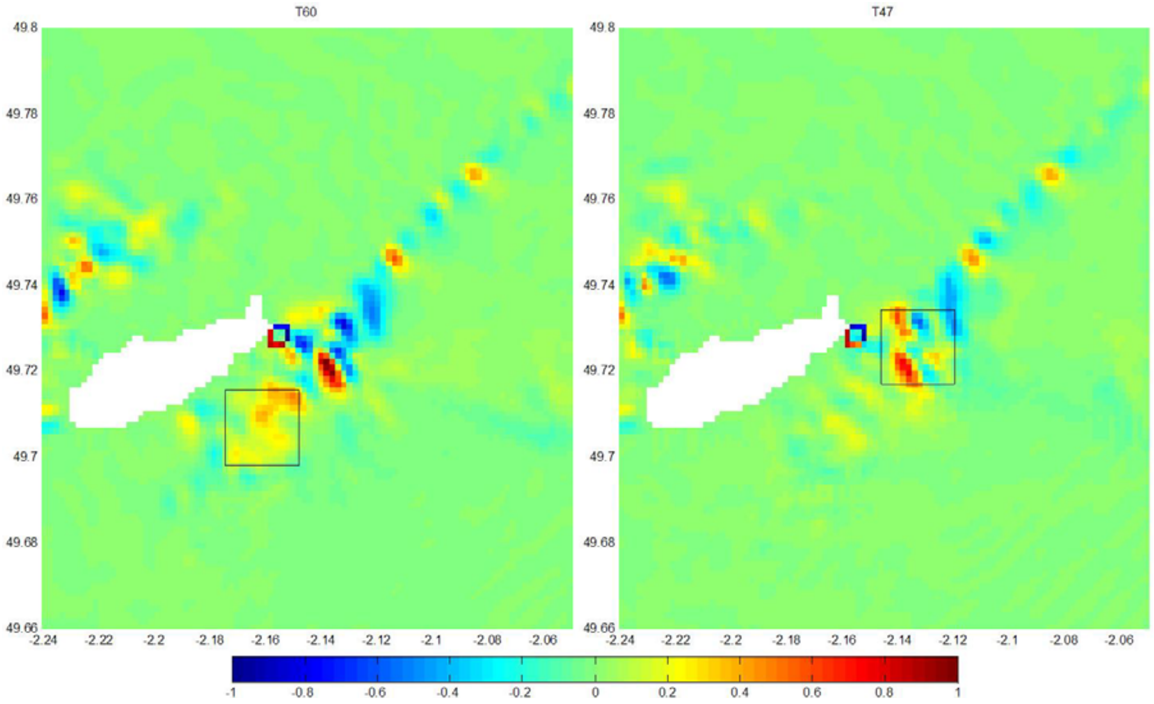

Fig. 7. Change in bed level (in metres) due to energy extraction, extrapolated to the 30-year life-cycle of a TEC device. Boxes show the limits of the TEC array for each case (T60 and T47).

5. Discussion and Conclusions

Strong tidal flow past islands and headlands leads to the generation of island wakes and headland eddies, and the formation of associated sand banks. Such strong tidal flows past islands and headlands are attractive regions in which to exploit the tidal stream resource. This study has demonstrated that despite extracting a relatively large amount of energy from the tidal streams in the vicinity of an island (a rated 300 MW TEC array), little change to the morphodynamics of the sand bank (formed by recirculating tidal currents in the lee of the island) occurs. This result is insensitive to the location of the TEC array in relation to the island. However, over the 30 year life-cycle of a TEC device, the morphodynamics of the surrounding region will change by up to a metre with such large-scale exploitation of the tidal stream resource.

References

[1] S.J. Couch and I.G. Bryden, Tidal current energy extraction: hydrodynamic resource characteristics, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 220, 2006, pp. 185-194.

[2] S.J. Couch and I.G. Bryden, Large-scale physical response of the tidal system to energy extraction and its significance for informing environmental and ecological impact assessment, In: Proceedings Oceans 2007-Europe International Conference; 2007. pp. 912–916.

[3] The Robert Gordon University, A scoping study for an environmental impact field programme in tidal current energy, DTI Publication URN 02/882, 2002.

[4] S.P. Neill, E.J. Litt, S.J. Couch and A.G. Davies, The impact of tidal stream turbines on large-scale sediment dynamics, Renewable Energy 34, 2009, pp. 2803-2812.

[5] S.J. Couch and I.G. Bryden, ME1 - marine energy extraction: tidal resource analysis, Renewable Energy 31, 2006, pp. 133-139.

[6] R. Soulsby, Dynamics of marine sands, Thomas Telford, 1997, pp. 176.

[7] I.S. Robinson, Tidal vorticity and residual circulation, Deep-Sea Research 28, 1981, pp. 195-212.

[8] R.D. Pingree, The formation of the Shambles and other banks by tidal stirring of the seas, Journal of the Marine Biological Association of the United Kingdom 58, 1978, pp. 211-226.

[9] W.M.J. Batten, A.S. Bahaj, A.F. Molland, J.R. Chaplin and Sustainable Energy Research Group, Experimentally validated numerical method for the hydrodynamic design of horizontal axis tidal turbines, Ocean Engineering 34, 2007, pp. 1013-1020.

[10] L. Myers and A.S. Bahaj, Simulated electrical power potential harnessed by marine current turbine arrays in the Alderney Race, Renewable Energy 30, 2005, pp. 1713-1731.

[11] H.M. Pantin, The sea-bed sediments around the United Kingdom: their bathymetric and physical environment, grain size, mineral composition and associated bedforms, British Geological Survey Report SB/90/1, 1991, 47 pp.

[12] J.T. Holt and I.D. James, An s coordinate density evolving model of the northwest European continental shelf: 1 model description and density structure, Journal of Geophysical Research 106, 2001, pp. 14,015-14,034.

[13] R. Bedard, M. Previsic, O. Siddiqui, G. Hagerman and M. Robinson, Survey and Characterization of TISEC Devices, report number TP-004-NA, EPRI, pp. 56-64.