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The Effects of Array Configuration on the Hydro-environmental Impacts of Tidal Turbines

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Abstract

The economic viability of tidal turbines will require the deployment of multiple devices in array formations in a manner analogous to wind farms. This research investigates the effects of the configuration of a tidal turbine array, specifically the turbine spacing and capacity, on the hydro-environmental impacts of the array. The hydrodynamic regime of the Shannon Estuary, a highly energetic estuary on the west coast of Ireland, was simulated using a depth integrated 2D hydro-environmental model. The numerical model was modified to incorporate the mechanics of energy extraction using linear momentum actuator disc theory and the impacts of a multiple device array were simulated. Three different array configurations were examined with turbine spacings of 0.5, 2 and 5 rotor diameters. The model results demonstrate that flows are attenuated inside the array and accelerated around the array. Water levels are also affected with a reduction in tidal range within, and upstream of, the array and a delay in high and low tides upstream of the array. The magnitude and extent of the observed impacts are found to reduce as the density and capacity are increased and that the impacts of large-scale arrays can be acceptable if deployed using a low density spacing of 5 rotor diameters.

Keywords

Tidal turbines; array configuration; hydro-environmental impacts; turbine spacing; actuator disc; momentum sink; Shannon Estuary

1. Introduction

While the only commercial-scale deployments of tidal stream turbines to date have been single devices, the next stage of progression will involve installation of multiple-device arrays (farms). Array configurations will be site specific and many factors will determine the array geometry and spacing. One such factor is the hydro-environmental impact of the array; for example, it is recognised that tidal turbines will alter ambient flow patterns due to extraction of kinetic energy. Studies based on open channel flow theory have shown that energy extraction in a simple channel driven by differences in static head can have a substantial effect upstream and downstream of the extraction site. This implies that the hydro-environmental impacts of energy extraction extend beyond the vicinity of the extraction location [1]. The one-dimensional theories presented by Garrett and Cummins [2, 3] and Blanchfield et al. [4] assume that the entire flow is intercepted by the tidal stream energy converters. Garrett and Cummins [5] further developed their one-dimensional theory to incorporate energy converters occupying only a fraction of the channel cross-section, as will more likely be necessary to satisfy navigational and ecological constraints. The theoretical limit on extractable power in open flow, known as the Lanchester-Betz limit, is 16/27 (0.59) of the upstream kinetic energy flux [5], although it has been shown that this limit may be exceeded if the blockage ratio, i.e. the fraction of the channel cross-section occupied by

turbines, is high. Typically, the flow speed decreases to two-thirds the upstream flow speed through the turbine and reduces further to one-third the upstream flow speed as the flow expands in the turbine wake. Garrett and Cummins [5] showed that power is lost as the slow moving water in the turbine wake merges with the fast flowing free stream downstream of a turbine in a channel. Drag on turbine support structures is also unproductive, further slowing the flow and diminishing the power potential without being associated with power generation.

There have been relatively few studies conducted on the impacts of tidal turbine arrays. Ahmadian et al. [6] modelled the energy extraction effects of a 2000 device turbine array in the Severn estuary; recorded impacts included reductions in current velocities inside the array, accelerated flows outside the array as well as consequential impacts on sediment and faecal bacteria levels. In a follow-on study which also used the Severn estuary model, Ahmadian and Falconer [7] showed that the power output and hydro-environmental impacts of a turbine array are sensitive to the shape of the array. Myers and Bahaj [8] carried out experimental work which quantified the flow field around a two-row tidal array and ascertained an optimal lateral turbine spacing where, under certain conditions flow can be increased between a pair of actuator disks. The optimal spacing for energy harvesting was shown to be an inner disk separation of 1.5 rotor diameters in a water depth of 3 rotor diameters. For this spacing, the accelerated flow contained 22% more kinetic energy than the flow upstream of the energy converters without having a negative effect on the two rotor disks. Model studies investigating the impacts of tidal energy convertor arrays on sediment dynamics have shown that arrays sited near headland sand banks could result in significant changes to their morphology [9] and arrays sited in regions of strong tidal asymmetry can have a much more pronounced effect on sediment dynamics than energy extracted from regions of tidal symmetry [10]. Finally, in a one-dimensional modelling study, Polagye and Malte [11] quantified changes to tides, transport, frictional power dissipation, and kinetic power density as a result of tidal energy extraction in four prototypical channel networks.

The objective of the present research was to investigate the effect of configuration on the hydro-environmental impacts of tidal turbine arrays. The tidal regime of the Shannon Estuary, a highly energetic estuary on the west coast of Ireland with significant potential for tidal current energy extraction, was simulated using a depth-integrated, 2D, hydro-environmental model. The numerical model was modified to simulate the mechanics of energy extraction and its effects on the tidal regime. A multiple device array was simulated and three different array configurations were examined using turbine spacings of 0.5, 2 and 5 times the rotor diameter. The numerical model details are discussed in Section 2 which explains the governing equations and the turbine representation within the model. Section 3 outlines the model application to the Shannon Estuary, including a description of the model details and a brief explanation of the model scenarios. The results are presented in Section 4 and comprise three sections describing: 1) tidal flows, 2) tidal elevations and 3) energy fluxes. Finally, discussion and conclusions are presented in Sections 5 and 6 which highlight the hydro-environmental impacts associated with tidal turbines and their sensitivity to array configuration.

2. Model Details
The numerical model used for this research was an amended version of DIVAST (Depth Integrated Velocities and Solute Transport), a two-dimensional, depth integrated, finite difference

model. The model is capable of simulating hydrodynamics, solute transport and water quality in reasonably shallow estuarine and coastal water bodies [12, 13, 14].

2.1 Governing Equations

The hydrodynamic module is based on the solution of the Navier-Stokes equations and takes account of the effects of local and advective accelerations, earth's rotation, barotropic pressure gradients, wind action, bed resistance and turbulence. The depth integrated continuity and x-direction momentum equations (similarly for y-direction) can be expressed in the following form:

Continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \tag{1}$$

x-direction momentum equation:

$$\frac{\partial q_x}{\partial t} + \beta \left[\frac{\partial U q_x}{\partial x} + \frac{\partial U q_y}{\partial y} \right] = f q_y - gH \frac{\partial \zeta}{\partial x} + \frac{\tau_{xw}}{\rho} - \frac{\tau_{xb}}{\rho}$$

$$+ 2\frac{\partial}{\partial x}\left[\varepsilon H \frac{\partial U}{\partial x} \right] + \frac{\partial}{\partial y}\left[\varepsilon H \left[\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right] \right] \tag{2}$$

where t = time; ζ = water surface elevation above mean water; q_x, q_y = depth averaged volumetric flux components in the x,y directions; U,V = depth averaged velocity components in the x,y directions; β = momentum correction factor; f = Coriolis parameter; g = gravitational acceleration; ρ = fluid density; τ_{xw}, τ_{yw} = surface wind shear stress components in the x,y directions; τ_{xb}, τ_{yb} = bed shear stress components in the x,y directions and ε = depth averaged eddy viscosity. Falconer [15] describes in detail the momentum correction factor, the wind and bed shear stress components and the depth averaged eddy viscosity.

The model employs an implicit finite difference scheme based upon the Alternating Direction Implicit technique to solve the governing differential equations. This technique divides each time step into two half-time steps, enabling a two-dimensional implicit scheme to be applied; however, only one dimension is considered implicitly for each half-time step. The major advantage with this approach is that it eradicates the requirement for solving a complete two-dimensional matrix and reduces the computational cost. The model carries out computations on a uniform rectilinear grid with equivalent grid spacings in the x- and y- planes.

2.2 Turbine Representation

Representation of horizontal-axis tidal turbines in the numerical model was based on linear momentum actuator disc theory (LMADT) [16] which considers a stream tube enclosing a turbine rotor in an open channel. The rotor is modelled as an actuator disk which takes momentum from the flow. Figure 1 illustrates five stations: (1) far upstream of the turbine, (2) immediately upstream of the turbine, (3) immediately downstream of the turbine, (4) the region where the slower moving flow from the turbine's wake merges with the free stream fluid from the by-pass flow and (5) adequately far enough downstream from the turbine that the pressure

regains uniformity. The section of flow passing through the turbine is denoted by subscript t and the bypass flow is denoted by subscript b.

The flow passing through the turbine will experience a reduction in velocity across the rotor plane (1 to 3). Immediately downstream of the turbine (3 to 4), the turbine flow is moving at a slower velocity than the bypass flow diverted around the rotor and must expand to satisfy conservation of momentum. This action generates the turbine's wake (cone-shaped region downstream of the rotor) which also contains turbulent mixing. At a sufficient distance far downstream (5) the wake will have almost entirely dissipated and the flow will revert to its undisturbed state experienced far upstream (1). In addition to retardation of flows downstream of the turbine, energy extraction is also seen to impact water depth with a drop in water depth, Δh, occurring between stations 1 and 5.

The undisturbed flow at (1) moves through the stream tube shown until it passes through the turbine (2-3) exerting a force on the turbine rotor (i.e. the actuator disc). In compliance with Newton's third law, the turbine exerts an equal and opposite force, the thrust (T), on the flow. The turbine thrust may be expressed as [16]:

$$T = \frac{1}{2}\rho u^2 A C_T \tag{3}$$

$$C_T = (\beta_4^2 - \alpha_4^2) \tag{4}$$

where ρ = fluid density, u = velocity, A = swept area of turbine defined as an actuator disc, C_T = dimensionless thrust coefficient, normalised by upstream kinetic pressure; β_4 = bypass flow velocity coefficient (usually >1) and α_4 = turbine wake flow velocity coefficient (usually <1).

The model was modified to simulate the mechanics of flow through turbines by incorporating the turbine thrust as an external force in the shallow water momentum equations (Eqn. 2). Subsequently, the x-direction momentum equation (and similarly for the y-direction) was amended as follows:

$$\frac{\partial q_x}{\partial t} + \beta \left[\frac{\partial U q_x}{\partial x} + \frac{\partial U q_y}{\partial y} \right] = fq_y - gH \frac{\partial \zeta}{\partial x} + \frac{\tau_{xw}}{\rho} - \frac{\tau_{xb}}{\rho}$$
$$+ 2 \frac{\partial}{\partial x}\left[\varepsilon H \frac{\partial U}{\partial x} \right] + \frac{\partial}{\partial y}\left[\varepsilon H \left[\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right] \right] - \frac{F_{Tx}}{\rho} \tag{5}$$

where F_{Tx} is the x-component reaction of the axial thrust induced by the turbines on the flow. Bryden and Couch [1] and Ahmadian and Falconer [7] employed variations of this momentum sink approach when modelling the effects of energy extraction by tidal turbines in an idealised rectangular channel and the Severn estuary, respectively. The total magnitude of the axial thrust induced by the turbines on the flow, F_T, is calculated per unit area of a grid cell as follows:

$$F_T = \frac{T}{\Delta x \times \Delta y} = \frac{1}{2} \times \frac{1}{\Delta x \times \Delta y} C_T \rho A_T U_{tot}^2 \tag{6}$$

4

where U_{tot}, the total flow velocity, is the magnitude of the current velocity perpendicular to the swept area of the turbine and A_T is the total swept area of all turbines within a grid cell. Assuming that the angle which the turbine axis makes with the positive y-axis is θ (Figure 2), then the x- and y- vector components of the reaction force of the axial thrust induced by the turbines on the tidal flow, F_{Tx} and F_{Ty}, can be calculated as:

$$F_{Tx} = F_T \times |sin(\theta)| \times sign(U) \tag{7}$$

$$F_{Ty} = -F_T \times |cos(\theta)| \times sign(V) \tag{8}$$

where $sign(U)$ and $sign(V)$ are a sign convention that accounts for flooding and ebbing tides.

In far-field models, the grid spacing will typically be much larger than the diameter of the turbines and multiple turbines may be located in a single grid cell. It is therefore common to distribute the combined turbine thrust across the area of the grid cell [6, 7, 9, 17]. The present model allows deployment of multiple turbines within a single grid cell and distributes the thrust across the grid cell. The model assumes that turbines are free to rotate such that the plane of their swept area is always aligned perpendicular to the direction of flow for maximum power extraction. Some turbines are unable to rotate in-stream and instead change the pitch of their blades to facilitate energy extraction on both flooding and ebbing tides. Such fixed-orientation turbines could be modelled in a similar manner to the present approach by calculating the retarding force, F_T, using only the current velocity component perpendicular to the predefined plane of the turbine's swept area and computing the x- and y-components of this force.

The thrust coefficient, C_T, in equation (6) is a function of the turbine design and depends on factors such as the number of blades and their geometry. Rearrangement of equation (3) shows that C_T also varies in relation to the flow speed. For reasons of simplicity, other far-field modelling studies have assumed constant values of C_T; for example, Bahaj et al. [18] use $C_T = 0.8$ while Ahmadian and Falconer [7] use $C_T = 1$. Given that the turbine simulated in this research was a hypothetical design for which test data was not available a constant C_T value of 0.9 was used. Tidal (and wind) turbines typically have a cut-in flow speed, U_C, below which they do not generate any power. The model therefore assumes that $C_T = 0$ for flow speeds below $U_C = 0.05$ m/s. Turbines also have a rated flow speed, above which the power output is limited to the rated power output. Again, due to the hypothetical nature of the turbine used for this study and the consequent absence of any performance data, the model does not apply any such limit on energy extraction. The assumption of a constant C_T and the absence of a rated power limitation on energy extraction mean that the present model represents a worse-case type scenario with regards hydro-environmental impacts.

Two additional impacts of turbines, namely, the drag force induced by the support structure and turbulent wake effects, were not included in the model. The former was omitted on the basis that the cross-sectional area the support structure would be very much smaller than the swept area of the turbine and thus the support structure drag force would be negligible compared to the turbine thrust. The latter was omitted because the model uses only a simple zero-dimensional turbulence

model (based on the Prandtl mixing length approach) which was unsuitable for modelling turbulent wake flows.

3. Model Application – Shannon Estuary

The Shannon Estuary is a long, narrow estuary on the west coast of Ireland where the River Shannon flows into the Atlantic Ocean; it is approximately 87km in length from head to mouth and has a surface area in excess of 500 km^2. A technical report by Sustainable Energy Ireland [19] identified the Shannon Estuary as one of eleven Irish sites suitable for harnessing tidal energy.

3.1 Model Details

Bathymetry data was obtained from a digitised Admiralty Charts of the Shannon Estuary and interpolated onto a finite difference grid at a spatial resolution of 189m x 189m resulting in a computational domain of 507 x 217 grid cells. The grid resolution was chosen so as to provide relatively high spatial resolution in the upper portions of the estuary at a relatively low computational cost. Flow boundaries were specified at the north-eastern river boundaries for the Shannon (east) and the Fergus (north), and at the northern and southern open sea boundaries; tidal elevations were specified along the western open sea boundary (Figure 3). The spring and neap tidal ranges for the study area, obtained from Admiralty Charts for the outer estuary, were 2.33m and 1.13m, respectively. An average flow of 172.78 m^3 s^{-1} was specified for the River Shannon [20] and 35 m^3 s^{-1} for the River Fergus [21]. Further details of the principal model parameters are presented in Table 1.

3.2 Model Validation

For this research, the hydrodynamic model was validated against measured values of tidal elevations at 6 locations (T1 – T6, shown in Figure 3). Contiguous tidal data were available at stations T2 and T5, while intermittent data were available at the other sites. Figure 4a compares measured and modelled water surface elevations at location T5 for the four week period from May 2nd to May 31st, 2013. A high degree of correlation was achieved; the mean error of the data shown was 0.05m with standard deviation 0.039m. Similar levels of accuracy were recorded at the other tidal monitoring stations. Tidal harmonic analysis of measured and modelled data at stations T2 and T5 was also conducted for the period May 2nd to May 31st, 2013. Table 2 compares the amplitudes and phases computed for the five major tidal constituents - M2, S2, N2, K1 and O1. The constituent values computed for the model output showed very good agreement with those computed for the measured tide gauge data.

Due to its long, narrow shape, significant natural distortion of the tidal wave occurs in the Shannon Estuary. This is demonstrated in Figure 4b which compares measured and modelled water surface elevations for a spring tide on May 27th, 2013, at T2 and T5. High tide at T5 occurs approximately 1 hour (0.04 days) after high tide at T2 and the model faithfully reproduces this time lag. Tidal wave distortion is discussed in more detail in Section 4.2.

Current velocities were validated at location C1 of Figure 3. The ambient spring and neap tidal ranges recorded at T1 during the time of velocity measurements, 1.89m and 0.8m, respectively, were specified to the model for the validation runs. Figure 5 compares measured values of spring

and neap tidal currents against model predictions. Modelled and measured data are again in close agreement.

3.3 Model Scenarios

The numerical model was used to simulate the hydrodynamic regime of the Shannon Estuary with, and without, array deployments. The location of the array was based on a resource assessment which computed the maximum available power (Figure 6a). A horizontal axis turbine with a single 16m rotor diameter was employed (this was based on the 16m rotor diameter of twin-rotored SeaGen device, the first commercial-scale deployment of a horizontal-axis tidal turbine [22]). The rated power of a turbine may be calculated as:

$$P = \tfrac{1}{2}\rho A u_r^3 C_P \tag{9}$$

where A is the turbine swept area, u_r is the rated current speed and C_p is the turbine power coefficient (or efficiency). Assuming a rated speed of 2m/s and $C_P = 0.35$ (SeaGen has reached peak efficiencies of 0.48 [23]), our hypothetical turbine has a rated power of approximately 0.3MW. The 16m rotor diameter enforced a 20m water depth restriction (measured below low spring tide) on turbine deployment. Figure 6b shows the area where deployments were permitted; location S1 is therefore sited inside the array while S2 is outside. The average water depth in the deployment area was approximately 30m.

Three turbine array configurations were simulated, each using different turbine spacings (measured tip-to-tip) and numbers of devices. The same turbine spacing was used in the lateral and longitudinal directions (Figure 7). Previous physical modelling studies [24], conducted under the supervision of the authors, indicated an optimal spacing between turbines of 5 rotor diameters for minimal hydrodynamic impacts. The first turbine configuration, therefore, used a 5 rotor diameter spacing, giving approximately 600 turbines in the deployment area with an array capacity of approximately 180 MW. This array is of a similar scale to the Meygen project which proposes to deploy 386 1MW turbines in the Pentland Firth, off the north-eastern tip of mainland Scotland [25]. As will be shown in Section 4, the model results for this array showed that the hydrodynamic impacts were minimal. In order to determine the array scale at which impacts became significant, two further arrays were simulated using higher densities of devices deployed at 2 and 0.5 rotor diameter spacings, yielding arrays of 720 MW and 2.88 GW capacity, respectively. The details of the three simulated arrays are summarised in Table 3. The authors are aware that the scale of the higher density arrays are somewhat unrealistic; they are used here to demonstrate the capacity of array one would have to deploy in order to induce significant hydrodynamic impacts.

4. Results

Model results were analysed to determine the effects of different array configurations on the hydro-environmental impacts of energy extraction. Time series (see Figure 8 for locations) of current velocities and water surface elevations were examined to determine the impacts of energy extraction on tidal flows and tidal heights, respectively. Fluxes of kinetic energy through channel cross-sections were also analysed to further quantify the effects of the turbine array. All model simulations were run for three successive spring tidal cycles (37.5 hours). Cold-start effects were

observed to have dissipated after the first tidal cycle and the results of the final tidal cycle were used for analyses.

4.1 Tidal Flows

Figure 9 compares current velocities inside (S1) and outside (S2) the turbine farm. The presence of the turbine array has an attenuation effect on the currents within the array (Figure 9a) while flow is accelerated around the array (Figure 9b); this agrees with the findings of Ahmadian et al. [6] and Myers and Bahaj [8]. The velocity changes are most significant for the highest density array and the magnitudes of the changes decrease as the turbine density is reduced. The attenuation of currents within the array is directly attributable to energy extraction by the turbines. The increase in velocities around the array is caused by 'blockage' effects which occur when the upper and lower extremities of a turbine are in close proximity to the water surface and the seabed [26]. Changes in the phase of the tidal flows can be observed inside and outside of the turbine farm, with times of both high and low slack water occurring later than normal when the arrays are included. The phase changes are more significant outside the farm than inside and the magnitude of the phase shift appears to be directly related to the turbine spacing; the longest shift occurs for the highest turbine density and the period of the shift decreases as turbine density is reduced.

Table 4 tabulates the percentage changes in peak ebb and flood tide velocities recorded at S1 and S2 for the array scenarios relative to the existing scenario. As evidenced by Figure 9, the peak velocity changes are greatest for the highest density array (0.5RD); 62% and 32% reductions in peak ebb and flood velocities, respectively, were recorded inside the farm while 39% (ebb) and 33% (flood) increases were recorded outside the farm. The changes were significantly lower for the lowest density array (5RD) with 14% (ebb) and 5% (flood) reductions inside the array and 8% (ebb) and 4% (flood) increases outside. The table also indicates that the effects of energy extraction are more pronounced on the ebb tide than the flood tide. At S1, the percentage changes in peak ebb velocities are approximately 2-3 times the corresponding changes in peak flood velocities; this is due to higher ebb tide velocities and the squared relationship between turbine thrust and current velocity (Eqn. 6).

Figure 10 compares current velocities at the locations downstream (D1) and upstream (U1) of the farm with the percentage changes in peak ebb and flood velocities shown in Table 5. Inclusion of the array results in reductions in current velocities both upstream and downstream of the array. As for S1 and S2, the changes are greatest for the highest density array and decrease in magnitude as the turbine density is reduced. Upstream of the farm, the changes in peak velocity are quite similar; for example, the 0.5RD scenario computed reductions of 36% and 32% in peak ebb and flood velocities, respectively. In contrast, the reductions in peak ebb velocities downstream of the array were between 2 and 4 times those in peak flood velocities. This difference is explained by the much larger difference in ebb and flood velocities at D1 compared to U1, and the squared relationship between thrust and current velocity. The results show that the effects of energy extraction are not limited to the extents of the array but can extend upstream and downstream from the array. This spatial aspect of the impacts is clearly demonstrated in Figure 11 which compares current vectors at mid-flood and mid-ebb, in and around the turbine array, for the NT and 0.5RD scenarios. The contoured difference plots clearly show the deceleration of

currents (up to 80%) within the array and acceleration (up to 60%) around the array, as well as the propagation of these effects upstream and downstream of the array.

The changes in phase observed at S1 and S2 are also evident at D1 and U1. Inclusion of the turbines results in slack water occurring later than is normal. As with the changes in velocity magnitude, the changes in velocity phase are most extreme for the highest density array and become less so as the turbine density is reduced.

4.2 Tidal Heights
Water Surface Elevations:
Figure 12 compares water surface elevations (output relative to mean water level) inside and outside of the farm for the array scenarios with those for the existing scenario. Table 6 tabulates the percentage change in high and low water levels, and tidal range. At both locations, the effects of energy extraction are manifest as a lowering of the high water level and a heightening of the low water level, the net result of which is a smaller tidal range. The nature of the impacts on tidal heights are the same inside and outside of the array; this is in contrast to the impacts on velocities where flows were retarded inside the array and accelerated outside. The changes in tide levels were most severe for the highest density array (0.5RD); high tide was lowered by 23% and low tide was heightened by 30% giving a net reduction in tidal range of 27%, or 1.527m. Tidal height effects became less severe as the turbine density was reduced, with changes in water levels and tidal range almost insignificant for the 5RD scenario.

The cause of the change in the times of occurrence of slack water noted for current velocities is partly explained by Figure 12. For the highest density turbine array, a distinct change in the phase of the tide can be observed; this is most noticeable at low tide where a time lag of approximately 1 hour is evident. As for the water level effects, the phase effects were most significant for the highest density turbines and became less so as the turbine density was reduced. Phase effects are explored in more detail in the next section.

Figure 13 compares water surface elevations between scenarios downstream (D1) and upstream (U1) of the array. The associated percentage changes in water levels and tidal range are presented in Table 7. The first point of note is that extraction effects at D1 were not nearly as significant as those at U1. The nature of the effects at U1 were very similar to those at S1 and S2, i.e. lower high water levels, higher low water levels, smaller tidal ranges, and changes in phase, with the changes being greatest for the highest density turbine array and decreasing as the turbine density is reduced. For each array configuration the changes at U1 were similar in magnitude to the corresponding changes inside the farm. This suggests that the changes in tidal regime that occur inside a tidal turbine farm will also be manifest upstream of the farm.

At D1, the same types of changes in water level were recorded as at the other locations but the magnitudes of the changes were much smaller. For example, the changes in high and low water at D1 for the highest density array were -2.5% and +10%, respectively, compared to -26.8% and +33.7%, respectively, at U1. The phase changes experienced at D1 were also notable; rather than high and low water occurring later than normal, as was the case at the other locations, they occurred earlier than normal.

Distortion of the Tidal Wave:
In order to better understand the distortion of the tidal wave observed in Figures 12 and 13, it was important to first understand the level of natural tidal wave distortion in the Shannon estuary. The tidal wave is a shallow-water wave, thus, its speed varies with the square-root of the average water depth. The morphology of an estuary can therefore heavily influence the speed of the crest or trough of the tidal wave. In estuaries with wide rectangular cross sections the crest of the flood tide will move faster than the trough of the ebb tide resulting in a flood tide of shorter duration than the ebb tide. Flood tide velocities will consequently be larger than ebb tide velocities and the estuary is said to be flood-dominated. Conversely, in estuaries with narrow, rectangular cross-sections the trough of the ebb tide will move faster than the crest of the flood tide resulting in an ebb tide of shorter duration than the flood tide. Ebb tide velocities will therefore be larger than flood tide velocities and the estuary is said to be ebb-dominated. In addition to the creation of asymmetries, the funnelling effect of estuaries generally results in an increase in tidal range.

The level of natural tidal wave distortion was determined by analysing variations in water surface levels at a number of locations (see Figure 14) along the axis of the estuary. Figure 15(a) compares water surface elevations at three of these locations: E1 near the mouth, E6 in the middle and E8 near the head. The figure provides clear evidence of natural tidal wave distortion. Funnelling effects are evident in the progressive increase in high wter level from E1 to E8; the tidal amplitude at E8 is approximately 0.8m larger than at E1. Asymmetries in the tidal wave are seen to develop as the wave propagates upstream from E1 to E9. At both E6 and E9 the ebb limb of the ebb limb of the wave is clearly shorter in duration than the flood limb. At E6 (Figure 15b), the duration of the ebb tide is approximately 0.7 hours (or 42 mins) shorter than the flood tide. The estuary is therefore ebb-domainated. This is confirmed by the NT velocity curves of Figures 9 and 10 which clearly show that ebb velocities are larger than flood velocities. It is also confirmed by Figure 16 which plots the ratio of maximum ebb velocities to maximum flood velocities recorded during the course of a tidal cycle for each grid cell of the model domain. A velocity ratio greater than one indicates ebb dominace and thisis the case throughout most of the estuary.

Investigation into turbine-induced tidal wave distortion involved the comparison of high and low water levels (Figure 17a), and corresponding tidal ranges (Figure 17b), at points E1 to E9 for the different scenarios. Looking, firstly, at the water levels for the existing regime (NT), it can be seen that the tidal amplitude begins increasing as soon as the tidal wave enters the mouth of the estuary at E1. From E1 to E5, the rate of change in amplitude (and water levels) is gradual and almost linear. At E5, a sudden narrowing of the channel width causes additional funnelling which results in an accelerated, but still approximately linear, rate of increase in high water levels upstream of this point. The rate of decrease in low water levels is not affected by this change in channel width and continues at the same rate to E8. Beyond this point, low water levels begin to increase, most likely due to a combination of friction losses and freshwater inflows. The net effect of this natural tidal distortion an increase of 1.5m in tidal range between E1 and E9.

Looking, next, at the water levels for the different array configurations, a number of observations can be made. First, the changes in high and low water levels due to inclusion of the array are significant. The array causes a lowering of high water levels and a heightening of low water levels, the net effect of which was a marked reduction in tidal range. For the 0.5RD scenario, the

maximum reduction recorded (at points E7 and E8) was in the region of 2.5m, equating to a 40% reduction in range. Second, there is clearly a direct relationship between the severity of the water level changes and the turbine spacing. The magnitude changes in water levels and the corresponding reduction in tidal range decreased as the turbine spacing was increased. For the largest turbine spacing (5RD) the maximum reduction in tidal range recorded at any station was 0.35m (at E7); a reduction of just 5%. Third, the changes in water level are not limited to the extents of the turbine array (located between E4 and E7) but propagate much further afield. Changes in high and low water levels were recorded as far upstream as E9, more than 20km from the upstream extents of the array. Changes in high water level only extended a few kilometres downstream of the farm, returning to normal levels at E4; however, changes in low water levels extended more than 10km downstream of the farm only returning to normal levels at E2. Given that tidal current speeds are directly proportionate to tidal range, it is plausible to infer that changes in current speeds would extend similar distances upstream and downstream of the farm.

The times of occurrence of low and high tide along the length of the estuary were also output from the model and are shown in Figure 18. The most notable feature of these plots is the significant delay in the times of low and high tides upstream of the turbine array. These time lags agree with the phase changes observed in the water elevation timeseries at U1 (Figure 13b) and are attributed to impedance, and thus slowing, of the tidal wave as it propagates through the array. The delays become progressively longer at each station upstream of the farm; the exception being a shortening of the low water delay between E8 and E9 which is attributed to the effects of freshwater discharges near E9. The longest delays were recorded for the 0.5RD scenario, with shorter delays recorded as the turbine spacing was increased. For 0.5RD, the longest delay in low tide was approximately 1.5 hrs (at E8) and the longest delay in high tide was approximately 1 hr (at E9). In comparison, the 5RD array only resulted in delays of the order of 10 minutes. Downstream of the farm there is minimal impact on the times of low tide; however, high tide occurs earlier than normal - this contrasts with the later occurrences recorded upstream. The most likely explanation is a backing-up of water downstream of the farm on the flooding tide due to the slower passage of water through the turbine farm; this slower passage is of course a result of the reduced current speeds induced by energy extraction. The magnitude of the time changes downstream of the farm were of the order of 10-25 minutes.

4.3 Kinetic Energy Fluxes

The final stage of impact analysis involved the comparison of kinetic energy fluxes between the different scenarios. The flux of kinetic energy is important as it represents the power available for extraction by tidal turbines. The model was used to calculate kinetic energy fluxes for channel cross-sections upstream, downstream and within the specified array (Figure 19) at various stages of the tide. Although fluxes were examined at thirteen different transects, for reasons of brevity only three are presented here: TFC located at the centre of the tidal array, and TD3 and TU3 located 2km downstream and 2km upstream of the array, respectively. The kinetic energy flux, E_{kf}, was calculated for each wet grid cell of a transect according to:

$$E_{kf} = \tfrac{1}{2}\dot{m}U^2 \tag{10}$$

where $\dot{m}$ is the mass flow rate through a grid cell is calculated as ($\rho A U$) and A, the cross-sectional area of the grid cell, is computed as ($H.\varDelta x$). Figure 20 shows E_{kf} calculated at mid-ebb and mid-

flood of the final tidal cycle; these are the times of maximum velocity, and thus maximum kinetic energy (or available power). Table 8 shows the total power available at each transect at the times of mid-ebb and mid-flood based on the flux data of Figure 20. The total available power is the summation of the flux through every wet grid cell of a transect. Ratios of available power when an array is included to the available power for no array are also presented in Table 8.

The flux graphs clearly demonstrate the effects of energy extraction on the available kinetic energy. Comparing the fluxes for the existing scenario (NT) with those when turbines are included, one can see significant reductions in the available energy. The lowest levels of available energy were recorded for the 0.5RD array; this array has the highest levels of energy extraction due to its greater number of devices. From Table 8 the maximum power remaining in the water for the 0.5RD scenario at any of the three transects, at either stage of the tide, is just 32% of the energy available without the array present. By contrast the 5RD array has the highest levels of available energy of the array scenarios and therefore has the least impact on the hydrodynamic regime. Table 8 shows for TD3, in all cases except mid-ebb, the power remaining in the water for the 5RD array is more than 80% of the power available with no array present. The reason for the exception at mid-ebb is that the ebbing waters from the embayment upstream and to the northeast of TD3, which have been unaffected by energy extraction, contribute a substantial proportion of the mid-ebb flux. A final point to note from the flux graphs is that the impacts of the array on kinetic energy, and therefore on current velocities, clearly propagate a considerable distance upstream and downstream of the array, as was noted for the changes in water level.

5. Discussion

A two-dimensional depth-averaged tidal flow model was successfully modified to simulate the mechanics of energy extraction by tidal turbines. Using the widely-accepted linear momentum actuator disc approach [16] a turbine thrust is computed and included in the momentum equation as a sink term. The energy extraction model was applied to the Shannon Estuary to investigate the hydro-environmental impacts of tidal turbine arrays and to determine the effects of array configuration on these impacts. Three array configurations were examined with turbine spacings of 0.5, 2 and 5 times the rotor diameter. Single rotor turbines of diameter 16m were simulated.

The model results show that energy extraction, as would be expected, has an attenuation effect on the tidal currents within the turbine array due to extraction of kinetic energy by the turbines. Current attenuation was also recorded upstream and downstream of the turbine array. In addition, currents were found to be accelerated around the array due to blockage effects. Since estuaries are commonly characterised by significant levels of suspended sediments, attenuation of tidal currents will most likely result in change to sediment dynamics in and around the turbine array [10]. An acceleration of currents in the waters between the array and the shoreline could lead to increased erosion of the shoreline and bed; consequently this would increase the suspended sediment within the water, exacerbating the potential for sedimentation within the array. Both of these processes could impact on the bed morphology and benthic ecosystems. Sediments depositing on the seabed in sufficient quantities could lead to the destruction of some floral species which, in turn, could have implications for dependent faunal communities. Increased tidal currents and bed erosion could result in extreme distress and discomfort for various species of

marine mammals and fish. Species migration to slower moving waters is a likely possibility in this situation.

The presence of the turbine array was also found to impact on the tidal regime (water surface elevations). Reductions in tidal range, due to lowering of high water levels and heightening of low water levels, were recorded within and upstream of the array while the downstream water levels were relatively unaffected. Lower high water levels could be perceived as a positive impact in light of reduced flood risk; however, higher low water levels would result in the permanent submergence of a portion of the inter-tidal zone. This would lead to destruction of the submerged ecosystems and reduction of inter-tidal zones which are typically areas of environmental significance. A further negative impact concerns the possible limitation of upstream navigation that might result from reduction of the upstream high tide level. The time delays in high and low tides were observed upstream of the array due to impedance of the tidal wave could also impact negatively on navigation.

Regarding the effect of the array configuration on the scale and extent of the hydrodynamic impacts, the impacts were most severe for the smallest turbine spacing and largest capacity array - the 0.5 rotor diameter array. The severity of the impacts, on both current speeds and tidal regime, reduced significantly when the turbine spacing was increased, due to both the increase in spacing and the subsequent increase in array capacity. The 2005 UK tidal stream resource assessment [27] was the first published work to introduce the concept of the significant impact factor, defined as the percentage of the available power that can be extracted without significant environmental impact. The SIF is site dependent and should, ideally, be ascertained for sites individually; however, due to a lack of site-specific information a SIF of 20% [27] was adopted for the 2005 UK assessment. This implies that if the power remaining in the water after a tidal array has been deployed is more than 80% of the power available prior to array deployment, then the impacts of the array will not be significant. At locations downstream, within and upstream of the array it was found that the power remaining in the water after array deployments only exceeded 80% for the 5RD array and fell well below this for the other arrays. Adopting the 20% SIF, the impacts of the 5RD array would thus not be considered significant while those of the 2RD and 0.5RD array would. Although this is a rather crude means of determining the significance of hydro-environmental impacts, in the absence of any real data it does at least provide some means of impact analysis. Analysis of the changes in the extents of inter-tidal zones agrees with this conclusion. Figure 21 compares the prevailing extents of the inter-tidal zone in the Fergus estuary, located upstream of the tidal array, with the extents when the 0.5RD array was simulated. Significant changes in extents occurred. However, for the 5RD array, the extents were virtually unchanged.

The authors recognise that the use of two-dimensional depth-averaged models have their limitations for assessing far-field impacts of tidal turbines. They most likely over-predict the impacts due to, for example, their inability to correctly model bypass flows between adjacent turbines as well as below and above individual turbines. To this end, we are currently developing a nested, three-dimensional turbine extraction model which will allow far-field modelling, but at the scale of the individual turbines. By setting the grid resolution in the nested domain equal to the turbine diameter, by-pass flows and turbine interactions can be better modelled. The inclusion of the vertical dimension also allows simulation of the changes in vertical velocity profiles due to

energy extraction which is important for modelling impacts on sediment dynamics, and the model will also employ a k-ε turbulence closure model to better incorporate both structural drag and wake effects.

6. Conclusions

Based on the research, the following conclusions are drawn:

- the research shows that although tidal turbines deployed in large multiple-device arrays will cause changes in the hydrodynamic regime, those changes will only be significant if overly large capacity array configurations using a high turbine density are deployed. For example, the research showed that the impacts of a relatively large 180 MW array containing 600 turbine but using a relatively low density of devices (a 5 rotor diameter spacing) were not significant.

- in addition to the well-recognised impacts on tidal currents, it has been shown that the tidal regime can also be affected with a reduction in tidal range, and a delay in the times of high and low water within and upstream of the array. Changes to currents and water levels are not only limited to the extents of the array but can propagate considerable distances upstream and downstream of the array. The spatial coverage of any impact analysis programme should therefore extend well beyond the extents of the array.

- the model results indicate that the severity of any hydro-environmental impacts induced by a tidal turbine array is highly sensitive to the spacing between adjacent turbines and the capacity of the array. The magnitudes of the changes in both current speeds and water levels were found to decrease significantly as the turbine density, and consequently the array capacity, was increased. Turbine density and array capacity should be treated as a critical factors in the design of array configurations.

- based on the model results, a spacing of five rotor diameters resulted in acceptable hydrodynamic impacts, even for a large capacity array. It is important to note, however, that an optimum spacing will depend on a number of site-dependent factors such as the topography, the number of turbines deployed and the spatial extents of the array. It should also be noted that the optimum spacing with respect to minimising hydro-environmental impacts will differ from the optimum spacing with respect to maximising energy yield and a balance must be sought between the two.

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Tables:

Parameters	Value	Parameters	Value
No cells {x-direction}	507	Half-timestep	10 s
No cells {y-direction}	217	Bed roughness	50 mm
Boundaries {x-direction}	2	Eddy viscosity coeff.	1
Boundaries {y-direction}	3	Momentum correction coeff.	1.016
Grid spacing	189 m	Angle of latitude	52.25 degrees

Table 1. Principal model parameters.

Station	Constituent	Amplitude [m]		Relative Phase [° GMT]	
		Measured	Modelled	Measured	Modelled
T2	M2	1.50	1.48	170.0	170.8
	S2	0.45	0.44	197.4	199.6
	N2	0.34	0.34	158.6	160.3
	K1	0.11	0.11	67.3	67.6
	O1	0.06	0.06	335.7	335.0
T5	M2	1.83	1.80	190.9	190.8
	S2	0.51	0.50	226.5	226.2
	N2	0.41	0.40	183.6	182.9
	K1	0.13	0.11	72.1	77.8
	O1	0.07	0.06	346.0	345.4

Table 2 Harmonic analysis of measured and modelled tidal elevations at T2 and T5.

Model	Turbines Included	Turbine Spacing	Approximate No. of Devices	Approximate Array Capacity
NT	No	---	0	0
0.5 RD	Yes	8 m	9,600	2.88 GW
2RD	Yes	32 m	2,400	0.72 GW
5 RD	Yes	80 m	600	0.18 GW

Table 3. Details of modelled scenarios.

Scenario	Inside Array (S1)					Outside Array (S2)			
	Mid-Ebb	% Change	Mid-Flood	% Change		Mid-Ebb	% Change	Mid-Flood	% Change
NT	1.253	-	0.945	-		0.683	-	0.637	-
0.5RD	0.478	-61.9	0.640	-32.3		0.952	+39.4	0.845	+32.7
2RD	0.815	-35.0	0.817	-13.5		0.907	+32.8	0.724	+13.7
5RD	1.075	-14.2	0.902	-4.6		0.737	+7.9	0.663	+4.1

Table 4: Percentage changes in peak ebb and flood velocities inside and outside of array.

Scenario	Downstream of Array (D1)					Upstream of Array (U1)			
	Mid-Ebb	% Change	Mid-Flood	% Change		Mid-Ebb	% Change	Mid-Flood	% Change
NT	2.575	-	1.249			1.560	-	1.275	-
0.5RD	1.012	- 60.7	0.919	- 26.46		1.004	-35.6	0.867	-32.0
2RD	1.628	- 36.8	1.130	- 9.6		1.312	-15.9	1.120	-12.2
5RD	2.261	- 12.2	1.215	- 2.8		1.484	-4.9	1.225	-3.9

Table 5: Percentage changes in peak ebb and flood velocities, downstream and upstream of array.

Scenario	Inside Array (S1)						Outside Array (S2)				
	HW	% Change	LW	% Change	% Change in Range		HW	% Change	LW	% Change	% Change in Range
NT	2.705	-	-2.953	-	-		2.699	-	-2.955	-	-
0.5RD	2.081	-23.1	-2.050	+30.6	-27.0		2.081	-22.9	-2.050	+30.6	-26.9
2RD	2.443	-9.7	-2.638	+10.7	-10.2		2.437	-9.7	-2.634	+10.9	-10.3
5RD	2.698	-0.3	-2.866	+3.0	-1.7		2.619	-3.0	-2.857	+3.3	-3.1

Table 6: Percentage changes in tide levels inside and outside of the array.

Scenario	Downstream of Array (D1)						Upstream of Array (U1)				
	HW	% Change	LW	% Change	% Change in Range		HW	% Change	LW	% Change	% Change in Range
NT	2.532	-	-2.755	-	-		2.919	-	-3.101	-	-
0.5RD	2.470	-2.5	-2.481	+10.0	-6.4		2.138	-26.8	-2.056	+33.7	-30.3
2RD	2.507	-1.0	-2.613	+5.2	-3.1		2.600	-10.9	-2.735	+11.8	-11.4
5RD	2.523	-0.4	-2.710	+1.6	-1.0		2.831	-3.0	-3.030	+2.3	-2.6

Table 7: Percentage changes in tide levels downstream and upstream of the array.

Transect	Scenario	Mid-Ebb		Mid-Flood	
		Total Power[MW]	% of NT	Total Power [MW]	% of NT
TD3	NT	102.872		20.382	
	0.5RD	8.209	8.0	6.186	30.4
	2RD	23.481	22.8	12.824	62.9
	5RD	58.953	57.3	17.772	87.2
TFC	NT	20.036		13.379	
	0.5RD	4.657	23.2	4.334	32.4
	2RD	10.619	53.0	7.682	57.4
	5RD	16.860	84.1	10.928	81.7
TU3	NT	25.139		16.054	
	0.5RD	3.052	12.1	4.719	29.4
	2RD	10.339	41.1	10.233	63.7
	5RD	20.514	81.6	13.845	86.2

Table 8: Maximum available power at transects TD3, TFC and TU3 for the different scenarios.

Figure Captions:

Figure 1: Linear momentum actuator disc theory in open channel flow [13].

Figure 2: Schematic of turbine axial thrust and velocity components.

Figure 3: Extents of model domain and turbine array (map courtesy of Geolives).

Figure 4: (a) Measured and modelled water surface elevations at T5 for May 2nd - 31st, 2013 and (b) comparison of water surface elevations at T2 and T5 on May 27th, 2013.

Figure 5: Comparison of measured and modelled current velocities at C1.

Figure 6: (a) Maximum available power (MW) for Shannon Estuary and (b) bathymetric plot of turbine array extents (darker colour = depths > 20m; lighter colour = depths < 20m).

Figure 7: Schematic of a model grid cell for 5RD array.

Figure 8: Map of time-trace locations: D1, S1, S2 and U1 (map courtesy of Geolives).

Figure 9: Comparison of current velocities at (a) S1 inside array, and at (b) S2 outside array.

Figure 10: Comparison of current velocities at (a) D1 downstream of array and at (b) U1 upstream of array.

Figure 11: (a) NT current vectors, (b) 0.5RD current vectors, (c) absolute differences (m s^{-1}) in 0.5RD current speeds relative to NT and (d) absolute differences as percentages of NT speeds at the times of (i) mid-ebb and (ii) mid-flood.

Figure 12: Comparison of water surface elevations (relative to mean water) at (a) S1 inside array, and at (b) S2 outside array.

Figure 13: Comparison of water surface elevations (relative to mean water) at (a) D1 downstream of array, and at (b) U1, upstream of array.

Figure 14: Stations where water level data was analysed (map courtesy of Geolives).

Figure 15: (a) Variation in water surface elevations over two tidal cycles at E1, E6 and E8, and (b) evidence of tidal wave distortion over a single tidal cycle at E6.

Figure 16: Ratios of maximum ebb velocities to maximum flood velocities.

Figure 17: Comparison of (a) high water levels (solid lines) and low water levels (dashed lines), and (b) tidal ranges, at locations E1 to E9 along the estuary.

Figure 18: Comparison of the times of occurrence of (a) high water and (b) low water, at locations E1 to E9 along the estuary.

Figure 19: Kinetic energy flux transect locations (*Courtesy of Geolives*).

Figure 20: Kinetic energy fluxes through (a) TD3, (b) TFC and (c) TU3 at times of (i) mid-ebb and (b) mid-flood.

Figure 21: (a) Study area highlighting the Fergus estuary and (b) comparison of prevailing extents of inter-tidal zone (light grey) with extents for 0.5RD turbine array (dark grey).