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Modelling tidal stream power potential

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ABSTRACT

In recent years, there has been an increase in interest in renewable energy sources for a number of reasons. A particular interest in tidal energy has developed within the UK due to its numerous sites of high current velocity. In this article a development, based upon previous work, of an existing hydrodynamic computational model is shown which is used to study the potential generation and the physical impacts of tidal stream farms. An idealised geometry is used to study the impacts of installed capacity and general layout of tidal stream farms and a realistic UK west coast model is used to examine the potential of presently proposed in-stream farms.

1. Introduction

As interest in renewable energy sources has increased over recent years, in response to the growing concern to the impacts of climate change, the reduction in worldwide fossil fuel availability and a desire for energy independence due to political instability, a number of potential opportunities within the United Kingdom have been suggested. Due to the geographical restraints of the UK the renewable options tend to be limited to wind, wave and tidal power, with natural hydro-power plant locations and sunny hours being at a premium.

At present, the most well developed of these newer renewable electricity generation technologies is wind power which is currently providing about 1.3% of the annual UK demand [1], with projections of a much greater percentage as the UK tries to meet its CO_2 reduction targets. The major drawbacks associated with wind power are the inherently unpredictable intermittency and the requirement to use the available generation resource immediately or lose it. The second drawback is a difficulty common to a number of renewable energy technologies and is in no way limited to wind power. As the relative importance of wind power increases in the UK energy mix the unpredictable intermittency becomes more of a problem. Large spikes of power must be accommodated by the electricity grid when strong winds blow but when they stop the power must be produced from elsewhere and at short notice.

Wave power generation is still in its infancy with the first commercial wavefarm opening in Portugal in 2008 with an installed capacity of 2.25 MW. As might be expected from such leading technologies, there are problems still to be overcome and at present the cost of power is relatively high although this is expected to fall as development continues.

Extracting energy from the tides is the subject of much discussion at the present time with a number of tidal range schemes being considered for the Severn estuary [2] and a wide range of potential schemes, both tidal range and tidal stream, being reviewed for the Mersey estuary [3], together with a number of other non-estuarine or smaller scale schemes throughout the country. Tidal range technology is well established with the tidal power plant at La Rance having been operational for over 40 years [4]. A perceived problem with tidal barrages is the potential impact that they may have on the local environment. This is partly due to the uplifted water levels within the enclosed basin and the resultant loss of habitat, partly due to the change in hydrodynamics and the impact on sediment transport regimes and also partly through consideration of the obstruction of passage upstream of fish or shipping. The impacts of each of these perceived problems may be reduced through careful choice of operational mode and engineering works, although at an economic cost [5,6].

Tidal stream devices are, like wave power, still in their relative infancy, with the first UK grid connected device being installed in Strangford Lough in 2008 [7]. The devices are located in regions of high current speed, typically off headlands or within constricted channels, which are predictable, to leading order, far into the future. The associated environmental impacts tend to be less than for tidal range schemes, but this is in general due to the much smaller magnitude of local energy extraction. Due to the predictable power

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generation and the relatively small environmental impact, tidal stream devices are a highly attractive renewable energy source. In a recent report, the total economically recoverable electrical energy available from the UK tidal stream resource was estimated to be 22 TWhy^{-1}, which represents over 5% of the current UK electricity demand [2].

There have been a number of articles investigating the power production potential and impacts of tidal stream devices through both analytical and computational models [8–13]. This article extends some of this work to examine the general power potential of tidal stream farms and their impacts on the hydrodynamics within idealised and realistic simulations.

This article is organised such that the next section describes the mathematical background to the simulation of tidal stream devices. In the following two sections, an idealised model and realistic model are used to examine the power production and hydrodynamic changes from various tidal stream farms. Finally, conclusions are drawn and possible future work is suggested.

2. Model

To model the impact upon the hydrodynamic circulation by the presence of a tidal stream farm, and the potential power output, the method of Sutherland et al. [8] has been implemented in the 2-D depth integrated shallow water coastal circulation model ADCIRC (see [14,15]). This is similar to the work done in Karsten et al. [11] within the FVCOM model. ADCIRC uses the continuous galerkin approach on an unstructured grid which is particularly useful when multiple scales are required in a modelling context. The approach adopted within this article is to model the energy extracted by a tidal stream farm as an increased bottom drag within the model. The increased drag co-efficient is based upon the rated speed and power of the tidal stream farm and its overall area. Thus, the total power from the tidal stream farm is given by

$$P_t = \iint_A \rho k_t |\overline{\mathbf{u}}|^3 \mathrm{d}A, \tag{1}$$

where ρ is the water density, k_t is the drag co-efficient associated with the tidal stream farm, $\mathbf{u}$ is the water velocity and A is the area of the tidal stream farm. Neglecting the drag effect of the support structures and any downstream wake losses, the total energy extracted from the water over the tidal stream farm can be approximated as a sum of the background bottom friction energy dissipation and the energy extracted by the tidal stream farm

$$P = \iint_A \rho(k_0 + k_t)|\overline{\mathbf{u}}|^3 \mathrm{d}A, \tag{2}$$

where k_0 is the drag co-efficient of the bottom stress.

Further research may enable the subsumation of the omitted aspects into an enhanced local bottom stress coefficient. The discrete approximation of (1) used within the model is given by

$$P_t = \sum_{m=1}^{M}\sum_{n=1}^{N_m} \frac{1}{3}\rho k_{tm}|\overline{\mathbf{u}}_m|^3 A_{mn}, \tag{3}$$

where $m = 1..M$ is the number of nodes across which the tidal stream farm is distributed, $n = 1..N_m$ is the number of elements which are attached to the node m, k_{tm} and $\mathbf{u_m}$ are the drag co-efficient and the velocity at the node m and A_{mn} is the area of the nth element attached to the node m. In practice, it is unlikely that the required drag co-efficient will be known for any given tidal stream farm and, therefore, this must be determined. However, the rated power, P_r, of the tidal stream farm for the rated speed, $|\mathbf{u}_r|$ will be known and these can be used to determine the drag co-efficient at each node m in the farm by the equation

$$k_{tm} = \frac{P_r}{\sum_{n=1}^{N_m} \frac{1}{3}\rho|\overline{\mathbf{u}}_r|^3 A_{nm}}. \tag{4}$$

This provides a way to model the energy extraction in the 2-D model and thus examine the impact of this on the hydrodynamics.

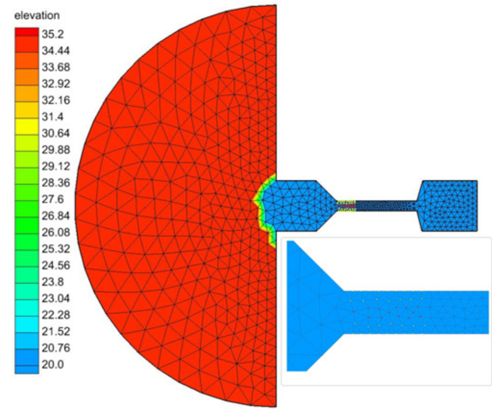

Fig. 1. Grid used in the idealised problem. Red dots show location of partial tidal stream farm and yellow dots show the extra location of the complete tidal stream farm.

3. Idealised problem

3.1. Model setup

To examine the impacts of tidal stream farms within a general setting, a simple idealised model of an estuary was constructed with a narrows region, to increase the water speed, as shown in Fig. 1. The depth in the open ocean is 35 m decreasing to 20 m in the estuary. The constricted section has a width of 1 km and a length of 8 km and the basin upstream of the narrows has an area of 29 km^2 and has a maximum width of 5 km. The model was forced at the semi-circular open ocean boundary by a single M_2 tidal component with a 3 m amplitude and a constant phase along the boundary. A background bottom friction of 2.5×10^{-3} was used throughout the model.

Within this model, four tidal stream farms were simulated. The first partially covers the width of the river narrows and is shown by the red dots in Fig. 1. The second farm completely straddles the river width and is shown by the yellow and red dots together. The third and fourth farms are the same widths but using only the first row. These final farms are a more realistic simulation of present suggestions for the placing of tidal stream devices where a single row is envisaged rather than a large matrix, although this will probably change in the future. The four farms will provide some insight into their role as a constriction to the flow and the resultant change in hydrodynamics and thus power production.

Fig. 2(a) shows the undisturbed tidal amplitude throughout the domain. The tidal amplitude increases monotonically from the ocean boundary through to the wider river portion and increases in magnitude by about 16 cm. The average peak velocity is shown in Fig. 2(b). A region of high velocity can be seen at the mouth of the estuary and especially in the narrows area associated with the tidal stream farm. The residual currents, shown in Fig. 2(c), provide insight into the transport of sediments, as it may be considered that over a long time period the suspended sediments would generally follow this flow. Of course, there are other effects on the transport of sediments which would need to be considered in the real world which are not modelled here. It is of interest to consider how a tidal stream farm may impact upon sediment transport, especially when there is a large blockage potential. In the undisturbed case, the flow in the wide river portion has two counter-rotating gyres and within the narrows the residual currents are much smaller but are all flowing seaward. In the mouth of the estuary there is a more complex set of gyre features but again the general flow direction is seaward.

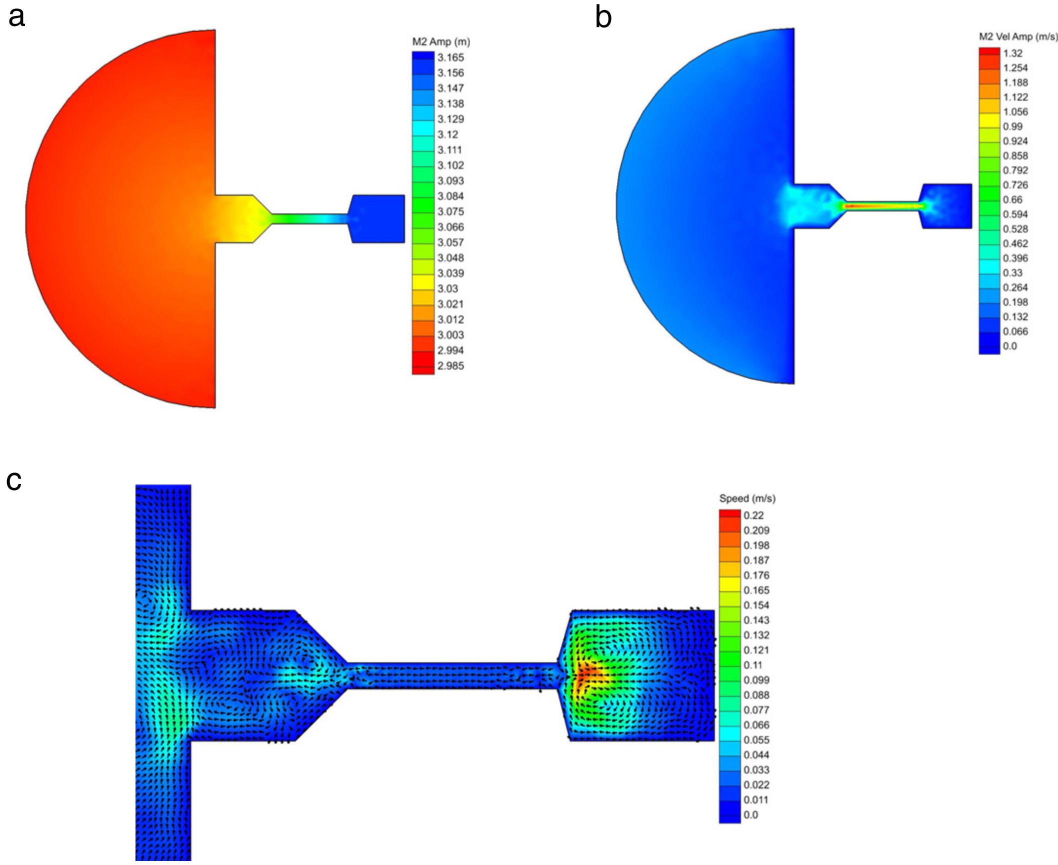

Fig. 2. Plot of undisturbed (a) tidal amplitude; (b) average peak velocity and (c) residual currents.

3.2. Results

A series of simulations for all the tidal stream farms were run which varied the rated power of each farm from 5 MW up to, an unrealistic, 4 GW. The speed at which these rated powers were derived was 2.4 ms^{-1} which is consistent with the Marine Current Turbine, SeaGen, now under trial in Strangford Lough, which is the only commercial scale tidal stream device currently operating [7].

The annual power production for all the farms is shown in Fig. 3(a) and a magnified view showing realistic installed capacities in Fig. 3(b). The power production from the farms that span the width of the river is considerably greater than for the equivalent farm that only spans a portion of the river for most installed capacities. However, for much lower, and more realistic, installed capacities this may change and the partial span farms can generate greater amounts of power, as seen in the multiple row farms for installed capacities less than 20 MW, as plotted in Fig. 3(b). This is primarily due to the greatest amount of power being present in the central stream which at low installed capacity continues relatively unaffected and thus if the capacity is concentrated in this area the power production will be larger. As the flow pattern is changed due to greater installed capacity, the energy is moved from the centre toward the walls and thus the partial farm loses this energy, whereas the full width farm can capture it.

To examine the impact on the hydrodynamics due to the tidal stream farms, a realistic installed capacity is considered. For the single row farms, the installed capacity is chosen to be 10 MW and for the multiple row farms the installed capacity is set at 30 MW. The change in peak flow velocities near the tidal stream farms are shown in Fig. 4. All the farms generate a redistribution of flow from the central fast current toward the walls, which may increase the erosion rate along the banks. Within the partial farms, shown in Fig. 4(a) and (c), the redistribution is clearly evident along the length of the farm and has little effect upriver. This is not the case though for the whole width farms, where the impact of the multiple row farm is seen throughout the river. Interestingly, the impact of the single row farm is more reminiscent of the partial width farms. This may be due to the fact that the energy extracted from this farm is very similar in size to that extracted from the partial width single row farm, as seen in Fig. 3(b), whereas the power extracted from the multiple row full width farm is greater than that obtained from the equivalent partial width farm.

The change to tidal amplitude is at its greatest within the river beyond the narrows, but even here there is only a change of the order of less than 2 cm. For the partial width farms and the single row full width farm, the tidal amplitude decreases within the upper river, whereas the opposite is true for the multiple row full width farm where the tidal amplitude increases by up to 2 cm.

The change in residual currents is similar for both single row tidal stream farms at this installed capacity, and so only the residual currents for the partial farm are shown in Fig. 5. The major change is the reduction in speed within the inner estuary, which drops from 22 cms^{-1} to 17 cms^{-1}. There are only minor changes to the direction of the currents due to these farms. However, the multiple row partial width farm has similar changes to those exhibited by the single row farms, with the major change being a reduction in flow speed in the inner estuary. The multiple row full width farm, however, shows markedly different behaviour. As seen in Fig. 6, the flow speeds in the inner estuary actually increase in size. There is also an increase in flow speed within the estuary mouth and importantly there is a reversal in residual current direction within the tidal stream farm. This leads to areas of relative convergence within the farm area, which could have major impacts on sedimentation within the farm region.

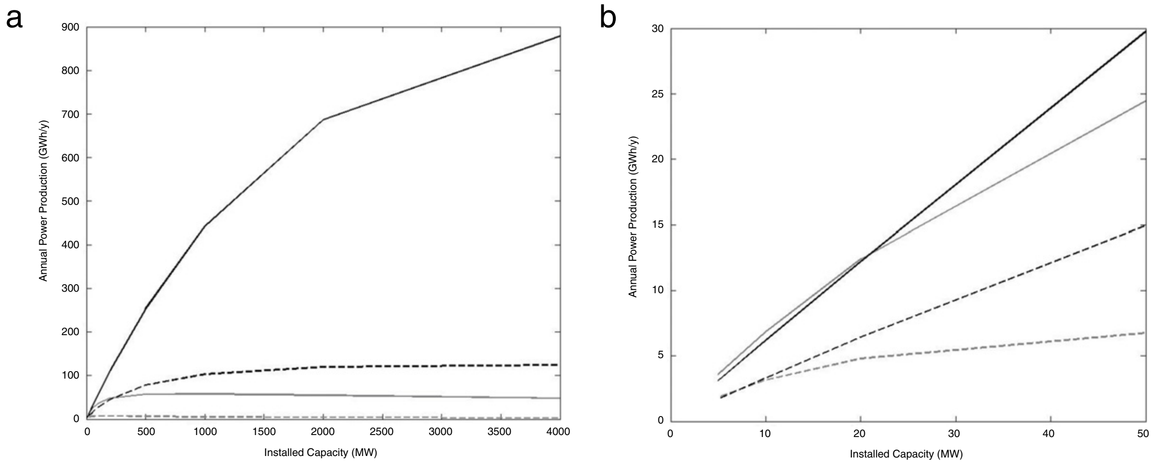

Fig. 3. Plot of annual power production for (a) all installed capacities simulated and (b) realistic installed capacities. Solid lines show full length farms and broken lines show only first row farms. Black lines are complete width farms and grey lines are partial width farms.

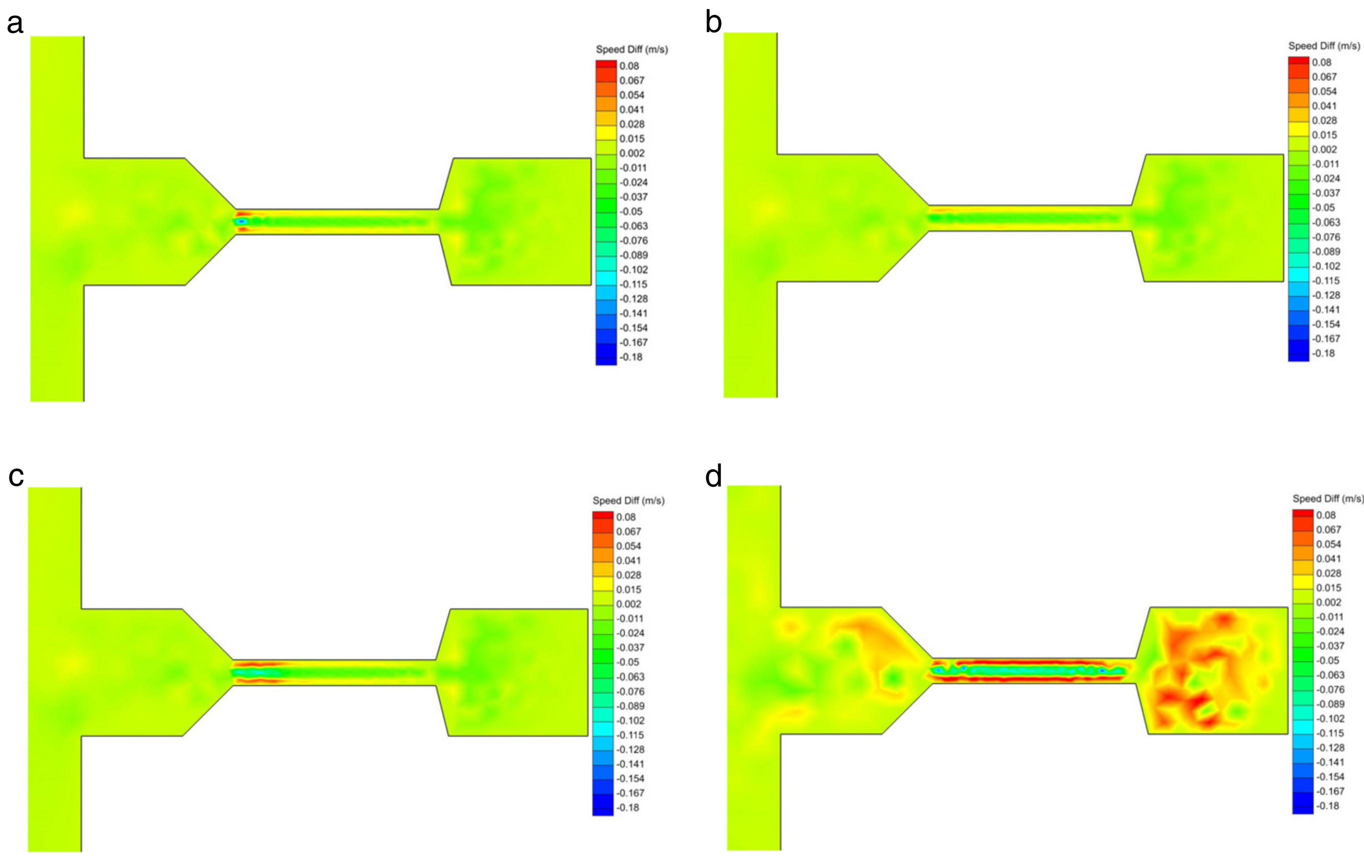

Fig. 4. Plot of change in peak velocity for the single row tidal farms (a) partial width and (b) complete width and the multiple row farms (c) partial width and (d) complete width.

4. West coast of UK model

4.1. Model setup

To examine the potential impacts and power output of tidal stream devices in a more realistic context, a model of the west coast of the UK has been developed using ADCIRC, as shown in Fig. 7. This model has the open boundaries in the deep ocean, to minimise boundary condition problems, and includes a number of major estuaries in the Northwest of England and the Severn estuary in fine resolution. This is the same model as that developed for tidal range studies [5] and full validation is available at www.liv.ac.uk/engdept/tidalpower. The model has been validated against tide gauge data for a number of ports throughout the Celtic Seas for both the M_2 and S_2 tidal constituents. The errors shown in Table 1 are for 59 ports, but a greater number are used within the full model validation. As can be clearly seen in Table 1, the ADCIRC model performs as well as the established POLCOMS model for predicting the tidal amplitude and phase for both the M_2 and S_2 tidal constituents. POLCOMS has been used extensively in tidal modelling in this area and thus provides a good comparison for the reliability of this model [16]. ADCIRC has been used in preference to a system like POLCOMS due to the flexibility of resolution throughout the model domain which an unstructured grid model provides.

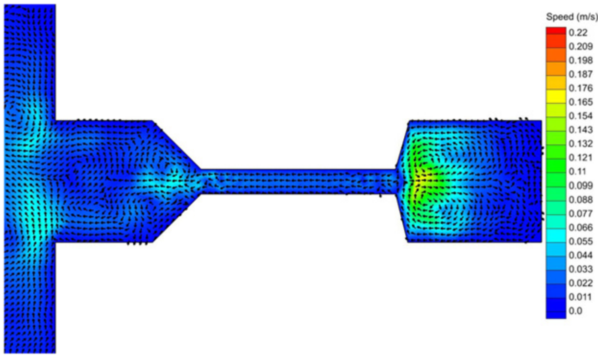

Fig. 5. Residual currents for single row partial width tidal stream farm.

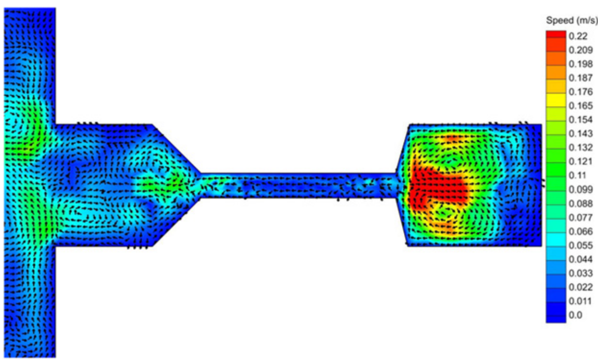

Fig. 6. Residual currents for multiple row full width tidal stream farm.

Table 1
Errors associated with the ADCIRC west coast model and the POLCOMS model for comparison.

	M_2		S_2	
	ADCIRC	POLCOMS	ADCIRC	POLCOMS
Amp mean (cm)	1.04	−4.99	−1.31	−3.83
Amp RMS (cm)	9.89	14.90	3.66	7.64
Phase mean	0.30	−1.00	−1.03	5.31
Phase RMS	9.59	14.76	11.06	22.55
H_s (cm)	11.09	21.61	4.45	12.04

The model is run for 31 days which includes a 16 day spin up and then a 15 day run from which the results are extracted. The model resolution varies from O (10 km), near the ocean boundary, down to O (10 m) within some of the estuaries and contains over 750 k elements.

Four tidal stream farms are simulated within the model and their locations are shown in Fig. 7. The installed rated capacity and speeds for each farm are shown in Table 2. The location and installed capacity for each tidal stream farm have been taken from a few of the published details available. The Mersey estuary location is suggested within the Mersey Tidal Power Study and the Lynmouth location was examined within the SDC report [2]. These are taken to be representative of unconstrained estuary locations. The Skerries and West Wales sites are both open ocean areas and are, at present, under active consideration by N-power and Eon, respectively. The rated power for each farm is a 'best guess' and is representative only of possible values, although the 2.4 ms^{-1} rated velocity is that stated for the MCT SeaGen device [7].

4.2. Results

The cumulative power production of all the farms over the final 10 days of the 30 day simulation period is shown in Fig. 8. The phase shift due to the farms locations is implicitly calculated by the model and, therefore, taken into account throughout. During the high spring tides, there is a period of 2 days when a continual power production of over 10 MW is maintained and for 1 day this is increased to 15 MW. The tidal phase differences over the domain of the model give rise to potential for more extensive 24 h electricity grid inputs from more ambitious schemes than the pilot scale project case studies considered here, especially so in conjunction with tidal range potential from the major estuaries [5]. The two ocean farms, located at the Skerries and off the West Wales coast, regularly achieve their rated power output, whereas this is not the case for either of the estuarial locations.

The total annual production for each farm is shown in Table 3 together with the utilisation rate. The two ocean farms perform well achieving high utilisation rates, and this is probably indicative of a conservative approach in device sizing performed at these sites. The estuarial sites do not perform well and reflect the need for detailed technical evaluation.

As in the idealised case, the water currents are altered by the presence of the tidal stream farms. The same tendency for the

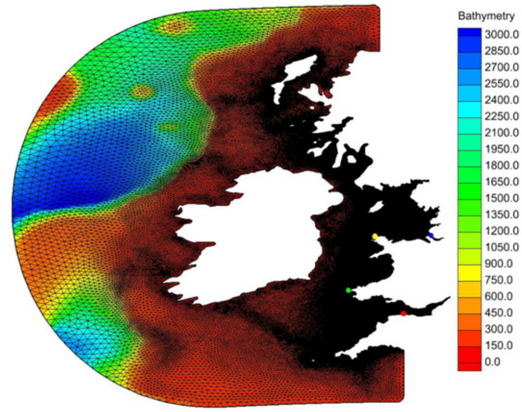

Fig. 7. Grid of the west coast model showing the locations of the four simulated tidal stream farms: Mersey (blue); Skerries (yellow); West Wales (green); Lynmouth (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Installed rated capacity and speed for each tidal stream farm.

Tidal farm	Rated capacity (MW)	Rated speed (m/s)
Mersey	20	2.4
Lynmouth	30	2.0
Skerries	10.5	2.4
West Wales	8	2.0

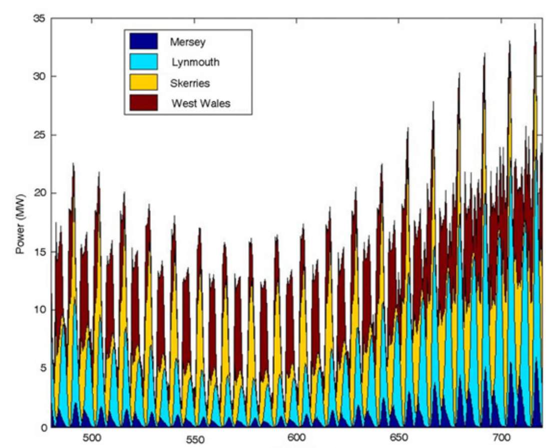

Fig. 8. Power output from the modelled tidal stream farms.

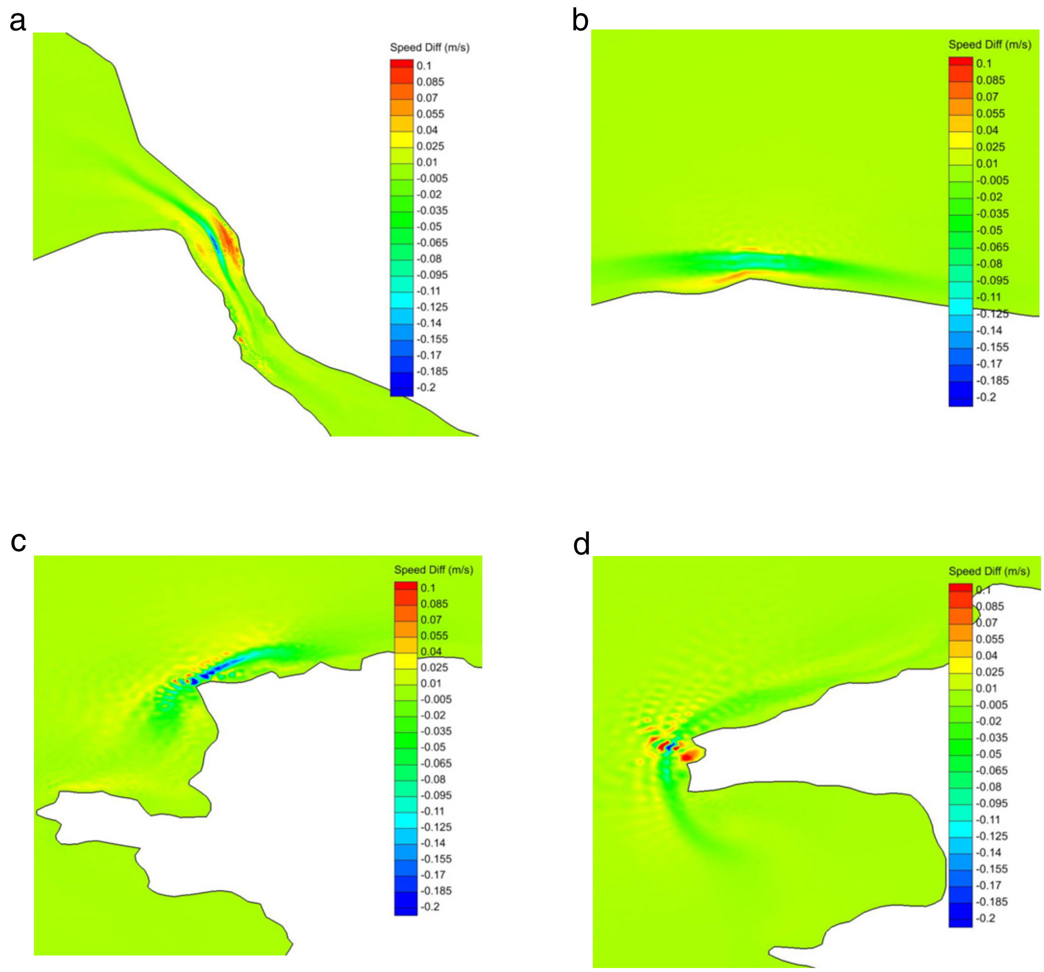

Fig. 9. Change in current speed at the tidal stream farm located at: (a) Mersey; (b) Lynmouth; (c) Skerries; (d) West Wales.

Table 3
Annual power output and utilisation rate for each tidal stream farm.

	Annual power output (GWh/y)	Utilisation (%)
Mersey	7.78	5
Lynmouth	40.92	16
Skerries	39.96	44
West Wales	37.90	55

water to flow around the farm is noted throughout all the farms simulated as shown in Fig. 9. The flow adjustment can be clearly seen in all the farms and it is especially noticeable in the Mersey, where the tidal stream farm is located in a region most similar to the idealised model. The impact on the larger scale is negligible for all cases, although there is a very small phase shift in the M_2 tidal component that impacts the entire Mersey river. This may not be the case, however, if the resources at these sites and elsewhere within the modelling domain are exploited to the full.

5. Conclusions

Due to the interest in renewable energy sources over recent years, a new model to study the potential generation capacity and physical impacts of tidal stream farms has been developed.

Within an idealised geometry significant differences in generation potential have been seen dependent upon the spatial layout of the farm. The physical impacts were generally small but could potentially have significant effects on erosion rates and sediment transport. These could in turn have an impact on the power output.

The model provided insight into the potential power output from four pilot scale farms presently under consideration, through a large scale realistic model of the Celtic Seas. Similar flow reorganisation was seen in this realistic model to that noted in the idealised case.

In future, the model resolution could be increased in the region of the tidal stream farms so that each device can be modelled individually. This would allow for an examination of the layout of tidal stream farms and the impacts this has on their performance. At present, the drag coefficient applied is constant and so when the speed is greater than the rated speed the energy extracted is greater than the rated power. In reality, the device would be modified to reduce the drag felt by the flow so that the rated power was maintained at these higher flow rates. This could be modelled through a variable drag coefficient, which is fixed until the rated speed is achieved and then modified so that only the rated power is extracted. The final modification would be to use an anisotropic drag, which provided a different drag on the flow dependent upon the flow direction.

Acknowledgements

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