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ON THE TIDAL STREAM RESOURCE OF TWO HEADLAND SITES IN THE ENGLISH CHANNEL: PORTLAND BILL AND ISLE OF WIGHT

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ABSTRACT

There are various candidate sites for tidal stream energy extraction in the English Channel. In this paper we examine the tidal stream resource at Portland Bill and the south coast of the Isle of Wight. A depth-averaged numerical model is developed and compared to field measurements. The presence of rows of tidal turbines is simulated using a line-discontinuity to represent the head loss across the turbines. The head loss is given by linear momentum actuator disc theory. At each site the length of the turbine rows, the local blockage ratio, and the location of the turbines are varied. For Portland Bill the presence of an array with multiple rows of turbines is also considered. We find that it is likely that (based purely on the hydrodynamics) power could viably be extracted at each site, with the mean power produced by each site being in the order of 10s MW.

1 INTRODUCTION

Tidal stream power generation uses the energy from fast flowing tidal currents to drive turbines which can generate power. The tidal current is only strong enough to make this technology feasible at a limited number of sites where the flow is constrained in some way. One geometry which leads to fast tidal currents is where a tidal wave propagates around a headland [1]. In this paper, we analyse the available power from two headland sites in the English Channel using a numerical model of the tidal dynamics and using linear momentum actuator disc theory to simulate the presence of rows of tidal turbines in the flow. Our study particularly focuses on the Portland Bill site with some results being shown for the Isle of Wight area for comparison.

Resource assessment of tidal stream sites can be made using various methodologies. Some studies have used the naturally occurring kinetic energy flux at a site to determine the resource. This fails to account for the change in the flow when turbines are installed, or for the fact that rows of closely packed turbines can, in theory, extract more power than just the naturally occurring kinetic energy. An alternative method, introduced by Garrett & Cummins [2], is to place a varying resistance in the flow to determine the point at which maximum energy can be extracted. In practice this over estimates the resource as it would be unlikely to be feasible to install numbers of turbines with sufficient thrust to reach this limit. A lower upper bound on the power may be obtained by placing an actuator disc type model of a tidal turbine into a numerical simulation and using this to determine the upper limit to the power before the power per swept area of the turbine falls below some set threshold [3].

Only one published study has been made of either of the sites considered in this paper, which is that carried out by Blunden & Bahaj [4]. Studies of an idealised headland site have been undertaken numerically by [5, 6] and experimentally by [7]. A study of a real headland site was made by [8].

2 NUMERICAL MODEL

The numerical model used in this investigation is only briefly described here as it is similar to that used by Adcock *et al.* [3]. The tidal hydrodynamics are modelled using the shallow water equations which are solved using a discontinuous Galerkin method [9]. Tidal turbines are included in the model using a line discontinuity to simulate the head loss across the turbines (following [10]). The head-loss is calculated using the linear momentum actuator disc theory of [11] and thus takes account of the energy lost in vertical mixing in the immediate wake of the turbines (but not the mixing between the array and the flow bypassing the array which is modelled in the depth-averaged code). Thus the turbines are idealised and no account is made for the drag from the support structure or from a real turbine power curve. In this paper we consider only the 'available' power – i.e. the power which is extracted from the flow minus the energy lost in the inevitable mixing behind the turbines.

The model is forced on the open boundaries with tidal constituents taken from the le Provost database. In this paper we just consider the model when forced with M_2 and S_2 tides and analyse half a spring/neap tidal cycle, except in the validation section where seven additional constituents are used. In this region the M_2 and S_2 constituents dominate the tidal hydrodynamics.

The bathymetry used is interpolated from a variety of sources: in the areas around the sites of interest high quality data 'TruDepth' from Seazone was used but in some areas far from the turbines data was taken from the GEBCO database. The Seazone data set is likely to be the best publicly available bathymetry data, however we note that the bathymetry did appear to be somewhat inconsistent in details with Admiralty Charts for these areas.

The boundaries of the mesh were placed in the Celtic Sea and in the North Sea, well away from any disturbance to the tidal dynamics caused by the tidal turbines. The computational elements varied in size from less than 100 m in the areas around the headland which are of interest, to over 10 km at the edge of the modelled domain. The whole mesh is shown in Figure 1 with a close up of the two sites in Figure 2.

The model used here does, of course, have numerous limitations. Many of these are discussed at length in [3] and so are not repeated here. However, a key limitations for this study is the uncertainty of depth-averaged models to correctly simulate the tidal flow around the headlands. Flow around headlands is complex and often has a structure which is strongly three dimensional and which cannot be fully modelled by a depth-integrated code [12, 13]. Further, the bathymetry shows a 'hole' to the west of the Portland Bill site (see Figure 4) which again is likely to produce flow features which are not modelled accurately by the depth-integrated shallow water equations. Nevertheless, we believe the analysis presented here captures the tidal dynamics of these sites sufficiently well to give some insight into the tidal stream resource of these two areas.

3 VALIDATION OF HYDRODYNAMIC MODEL OF ENGLISH CHANNEL

It is vital to compare the performance of the numerical model with the naturally occurring tidal dynamics before examining how these will change due to the presence of tidal turbines.

At this stage it is also possible to tune the parameters in the model. In depth-intergrated tidal modelling the key parameter is the bed friction coefficient. Numerous runs of the model were made and it was found that the nature of the amphimodromic system of the M2 tide in the English Channel was sensitive to this parameter. This was somewhat surprising since existing depth-averaged models of the English Channel do not report this sensitivity and imply a lack of sensitivity (by either getting satisfactory results with the first value tried or discussing the value of this coefficient but not noting this impact) [14–16]. One reason why the sensitivity to bed friction was so noticeable in this study was that the tidal range in the Portland Bill/Isle of Wight area is relatively small (Figure 1). Thus any discrepancy between model and observation is noticeable particularly in percentage rather than absolute terms. After analysis of the different runs a bed friction coefficient of 0.0035 was selected.

Water levels

The amplitude of the M_2 tidal constituent is shown across the modelled domain in Figure 1. It is in good general agreement with other models of the region. Harmonic analysis of the water levels in the model were compared with those given in the Admiralty tide tables. Table 1 presents these for the M_2 tidal constituent and table 2 presents the comparison for the S_2 constituent. As noted above, agreement is satisfactory but not as good as would normally be expected from this sort of modelling. In part this may be due to local factors (such as imperfect modelling of the breakwaters at Weymouth harbour), however we are clearly not capturing perfectly the dynamic balance of the tidal wave as it travels along the English Channel.

Tidal currents

Due to the high spatial variability, rapid temporal changes, and high cost of field measurements, both the quantity and quality of field measurements available to this study were severely limited. The only data available to us for the sites of interest was from the Admiralty's TotalTide software. The quality of this data is unknown and it is not known what depth the currents are for. There are however, numerous data points in the the Portland Bill tidal race and several points at the Isle of Wight. A comparison has been made between these currents and the numerically predicted depth-averaged velocities at all these locations. Agreement is generally satisfactory. As an example, Figure 3 presents a comparison of the current predicted by TotalTide and our model for a location in the tidal stream at Portland Bill $50^\circ 27.18'$N, $2^\circ 27.18'$W. It can be seen that the basic variation

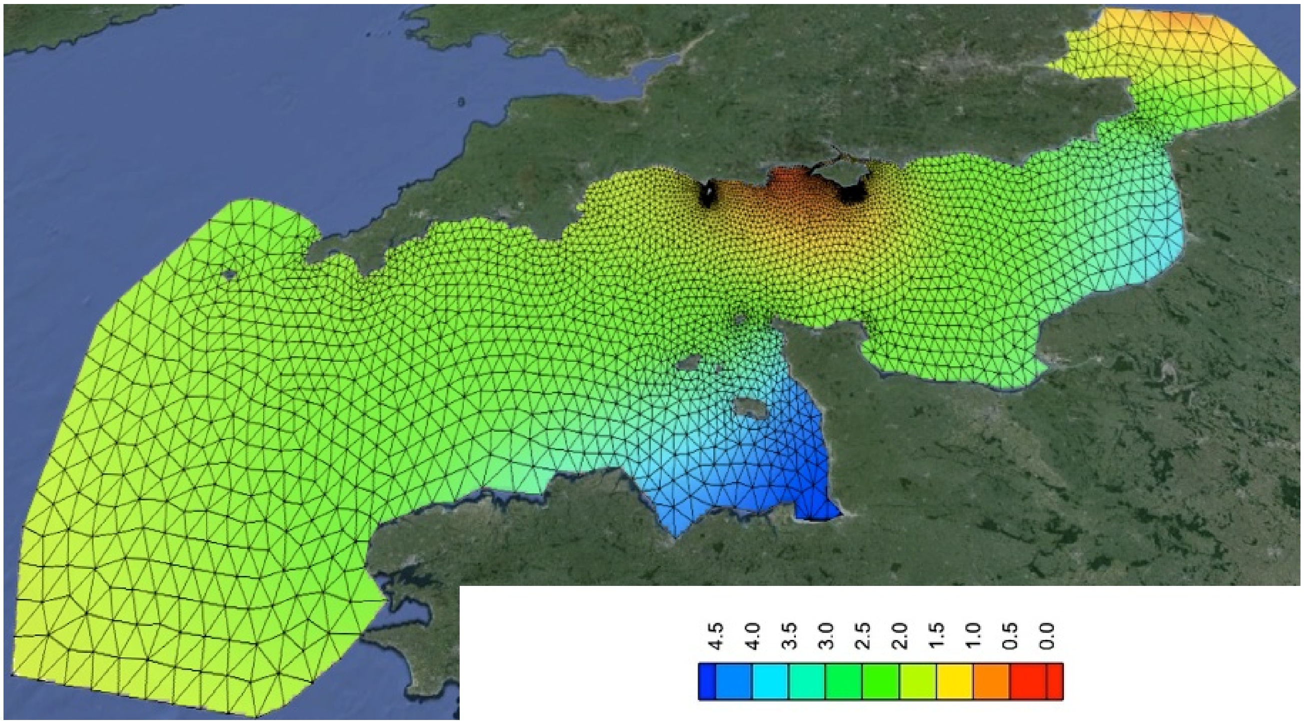

FIGURE 1. Numerical mesh used in study shown in Google Earth. Colours indicate the modelled M_2 water level amplitude in m.

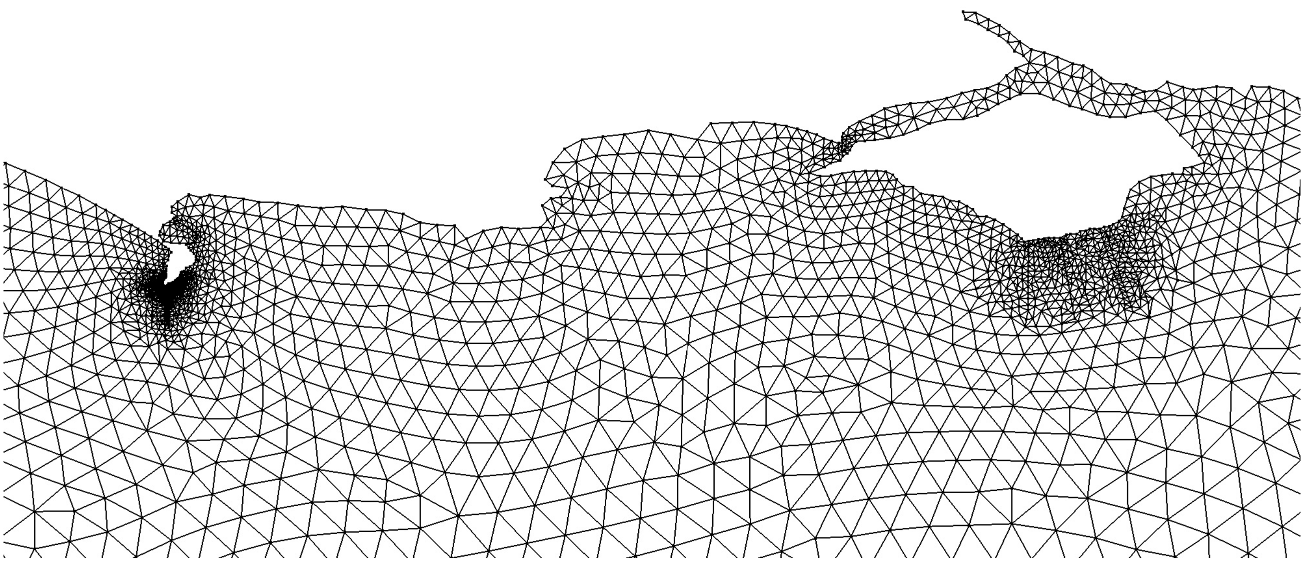

FIGURE 2. Close up of numerical mesh used showing the sites studied.

over the spring/neap cycle has been captured. The phase of the current is also in good agreement. There is a small discrepancy in the magnitude of the current. It would obviously be desirable to have better field data than these to compare our model to, and without such measurements, there can only be weak confidence in models such as this. However, we believe that our comparisons with TotalTide indicate that our model is capturing the dominant tidal hydrodynamics of these sites.

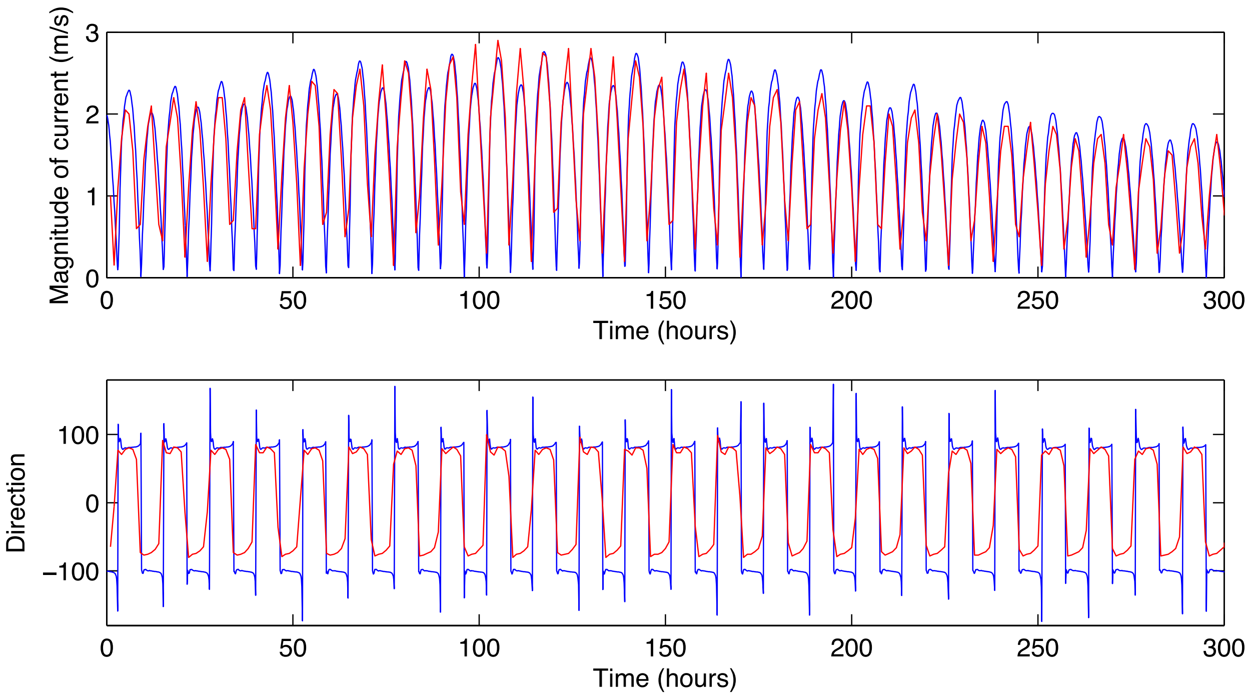

FIGURE 3. Comparison between data from TotalTide and numerical model. Blue line shows model; red line shows TotalTide. Top magnitude of current; bottom direction of current. Zero time is 8 July 1983.

Location	Amplitude (m)		Phase (deg)	
	Observation	Model	Observation	Model
Lyme Regis	1.16	1.35	175	174
Cesil cove	1.14	1.21	183	180
Weymouth	0.59	0.78	190	201
Mupe Bay	0.59	0.73	201	192
Freshwater Bay	0.58	0.43	288	277
Ventor	0.97	0.90	311	315
Sandown	1.19	1.12	318	326
Cherbourg	1.86	2.02	257	229

TABLE 1. OBSERVED AND MODELLED WATER LEVEL FOR M_2 TIDAL CONSTITUENT.

Location	Amplitude (m)		Phase (deg)	
	Observation	Model	Observation	Model
Lyme Regis	0.51	0.49	232	245
Cesil cove	0.41	0.46	228	248
Weymouth	0.31	0.39	242	256
Mupe Bay	0.31	0.37	243	258
Freshwater Bay	0.21	0.24	313	289
Ventor	0.22	0.21	0	331
Sandown	0.38	0.25	1	351
Cherbourg	0.7	0.69	301	276

TABLE 2. OBSERVED AND MODELLED WATER LEVEL FOR S_2 TIDAL CONSTITUENT

UNDISTURBED HYDRODYNAMICS AND LOCATIONS OF TURBINES IN THIS STUDY

In this study we define the ‘undisturbed’ case to be the flows predicted by the model without any tidal turbines being present. The peak flow rates at both sites are similar, with peak velocities between 3 and 4 m/s at selected points and times. The strongest velocity at Portland Bill is concentrated just offshore of the headland. At the Isle of Wight, strong velocities are observed at various locations along the south-east coast, with the strongest velocities generally correlating with bathymetry (currents being fastest in locally shallower regions).

Although not perfect, the locations of a strong current in the undisturbed case are generally a good indicator of the optimum position for tidal turbines [6]. In this study we have chosen the location for rows of turbines based on this. Figure 4 shows the locations of the turbine rows used in this study along with the magnitude of the bathymetry and the M_2 tidal current. The nomenclature used to describe each row of turbines has 1 as the most westerly and 10 as the most easterly with rows 1 to 5 being off Portland Bill and 6 to 10 being off the Isle of Wight.

ANALYSIS METHODOLOGY

In this study we analyse cases which have a given layout of turbines, defined by the row or rows numbers of the turbines, and the distance turbines extend away from the coast. We also examine different local blockages where local blockage is defined as the average proportion of the water column taken up with turbines. In all cases runs were made with a low blockage, 0.1, an intermediate blockage, 0.25, and a high blockage, 0.4. It should be noted that the blockage ratio is constant along the row for each simulation. This implies that the diameter of the turbines changed with variations in the water depth.

In this paper we focus on maximising the time-averaged available power. To do this, it is necessary to find optimum turbine thrust [17]. It is convenient to parameterise the thrust of the turbine using the wake velocity coefficient, (α_4 in terminology of [11]). The optimal thrust will vary slightly over the spring/neap cycle, but this is expected to yield negligible additional power [18]. The turbine properties can also be varied over the daily cycle [19] but this is not considered further here. To find the maximum available power we run each case four times with wake velocity coefficient varying between 0.33 and 0.8 and determine the maximum available power by interpolating between these points.

Except where we present a time series, 'available power' can be understood as the mean available power over a spring/neap tidal cycle.

AVAILABLE POWER AT PORTLAND BILL

Single row of turbines

Firstly we consider a single row of turbines extending out from Portland Bill. We vary three parameters: the length of the turbine row; the position of the single row of turbines; and the blockage, B, of the turbines (i.e. the average proportion of the water column which the turbine takes up). Figure 5 presents these results with each row of subfigures representing a different blockage and different lines representing turbines in different locations. The 'length of turbine' is always taken as the distance the row extends from the land boundary.

A very similar pattern is observed for each row of turbines. The available power from case 1 is slightly lower as the water depth there is marginally deeper reducing the velocity slightly. Unsurprisingly, the further the row of turbines extends from the coastline the greater the power. However, the power per swept area starts to fall for lengths of turbines greater than around 2 km. When assessing the feasibility of a turbine layout it should be noted that the concept of incremental power is very important [3]. To demonstrate this through an example consider a single row of turbines at location 1 with a blockage of 0.25. A single row of turbines extending 2.8 km from shore yields a power of 21.9 MW with a power per swept area of of 1800 W/m^2. Extending this fence to 4 km yields a power of 36.6 MW with a mean power per swept area of 1529 W/m^2. However, the additional power has required an additional 1.17×10^4m^2 of swept area of turbine, giving an incremental power per incremental swept area of only 1251 W/m^2 which is obviously a significantly less attractive figure.

There is also an increase in the amount of power available when higher blockages are utilised. This increase is over-and-above the increase that would be expected simply from the greater undisturbed kinetic flux passing through the swept area of the turbine, as turbines with higher blockages will have improved performance characteristics [11]. This can be seen clearly in the graphs showing power per swept area. However, it is of note that in this case the power per swept area values are only slightly better for the $B = 0.4$ case compared with the $B = 0.25$ case. This was not the case for the Pentland Firth where there was a significant improvement in this metric between these blockage ratios [3]. The difference is presumably due to Portland Bill being a headland site where flow can bypass around the end of the turbines rather than a channel site where this is impossible. For practical reasons it is unlikely that turbines will be deployed with a local blockage greater than 0.4 which is likely to be less than the optimum hydrodynamic blockage for any real site. There are significant hydrodynamic benefits to having turbines with substantial blockage as well as the obvious point that having one row of larger turbines, rather than two rows of smaller turbines, prevents the second row having to be located at a site where the resource is not quite as good since it will not be able to be share the same location as the first row. Hence the general advice to developers to aim to make turbines with high blockage remains.

Multiple rows of turbines

The study is now extended to multiple rows of turbines. In this section a single row of turbines corresponds to turbines at location 1, two rows at locations 1 and 2, three rows at 1, 2 and 3, *etc*. We investigate arrays where each row extends to a notional line normal to the end of the row of turbines in row 1 (in this case this line is due west-east). Each row in the array will therefore have a different length. For convenience, we use the length to

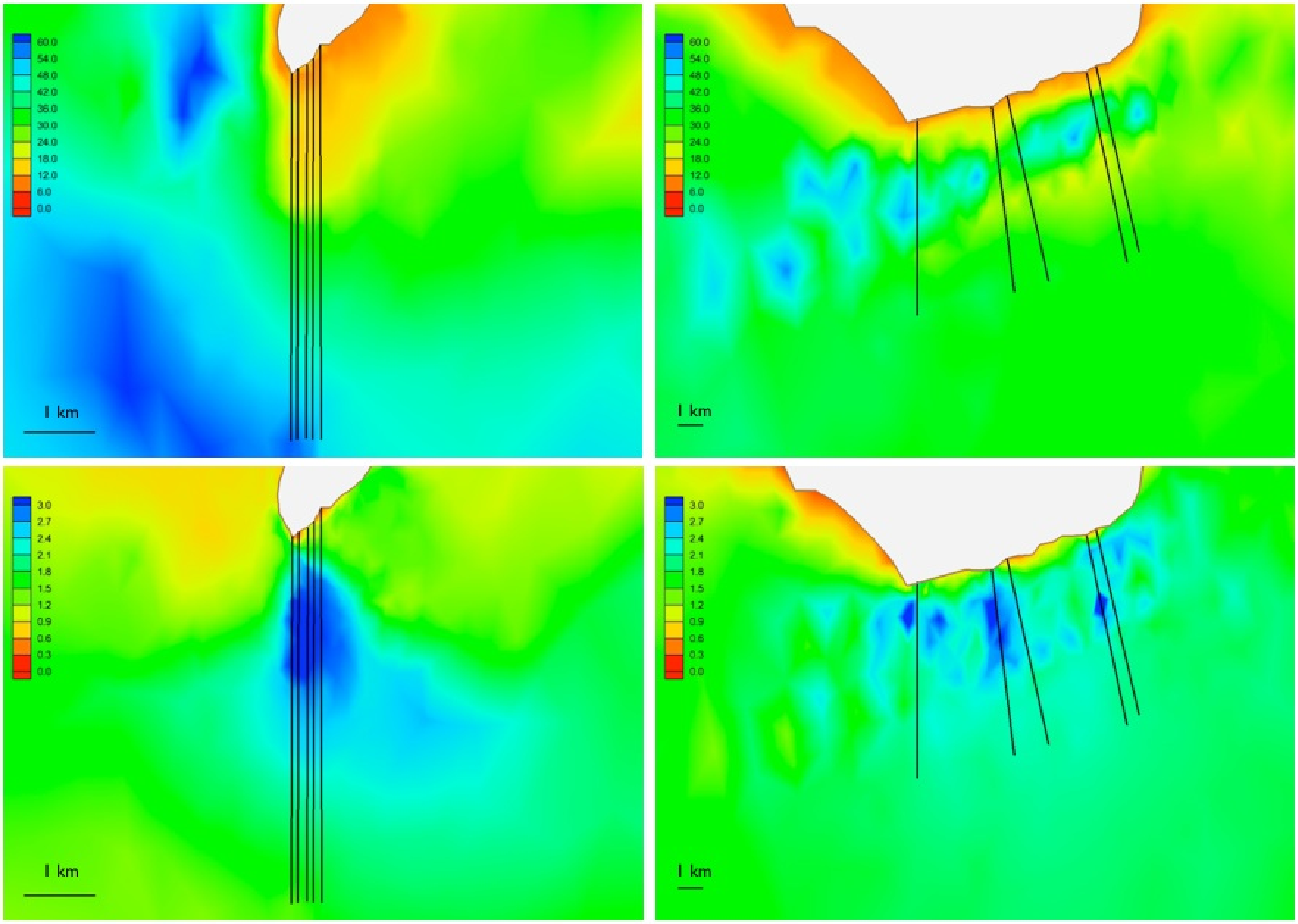

FIGURE 4. Locations of turbines at Portland Bill (left) and Isle of Wight (right). Top row: interpolated bathymetry (m). Bottom row: magnitude of M_2 tidal current m/s. Location of turbines in this study shown with black lines. These are location 1 to 5 from left to right on Portland Bill and 6 to 10 from left to right on Isle of Wight.

which turbines extend along row 1 to describe the length of the array.

The overall trends for all number of rows are similar. Each additional row increases the maximum available power. There is, however, a diminishing return as additional rows are added, a result noted in [3, 20]. This can be seen particularly clearly in the plots of power per swept area. As above, when assessing the viability of whether an additional row of turbines is worthwhile it is the incremental power which is the important metric. This suggests that even for moderate blockages only a few rows are likely to be viable at this sites.

AVAILABLE POWER AT ISLE OF WIGHT

For the Isle of Wight location we limit our investigation to single rows of turbines. As with Portland Bill, the length, blockage and position of the turbines are all varied. Figure 7 summaries the results.

For the Isle of Wight case there is a greater variation between the available power for different rows. This is due to the available power being highly dependent on the local flow velocity, which by continuity is very dependent on local bathymetric features. As can be seen from Figure 4 there is a significant variation in the bathymetry between the different locations off the Isle of Wight. The difference between the different row positions highlights the importance of understanding local bathymetry and flow details when choosing where to site tidal turbines.

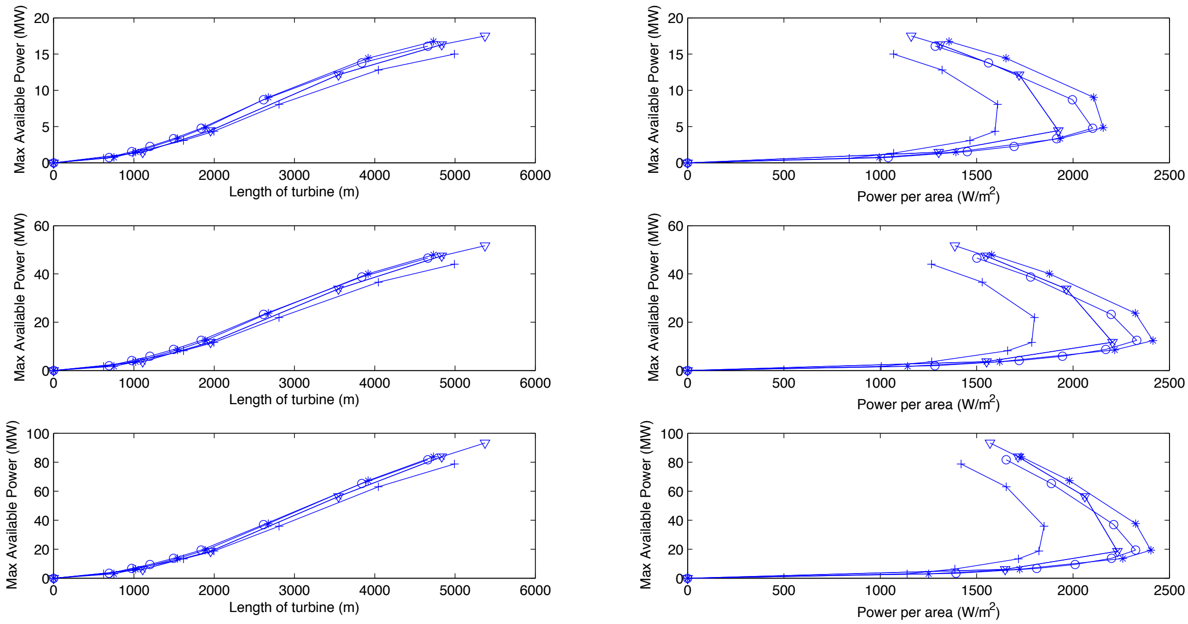

FIGURE 5. Results for single row of turbines at Portland Bill. Top $B = 0.1$; middle $B = 0.25$; bottom $B = 0.4$. Left: length of turbine array against maximum available power; right: power per swept area vs available power. Symbols indicate position of turbines: '+' – location 1; 'o' – location 2; $*$ – location 3; $\times$ – location 4; ∇ – location 5.

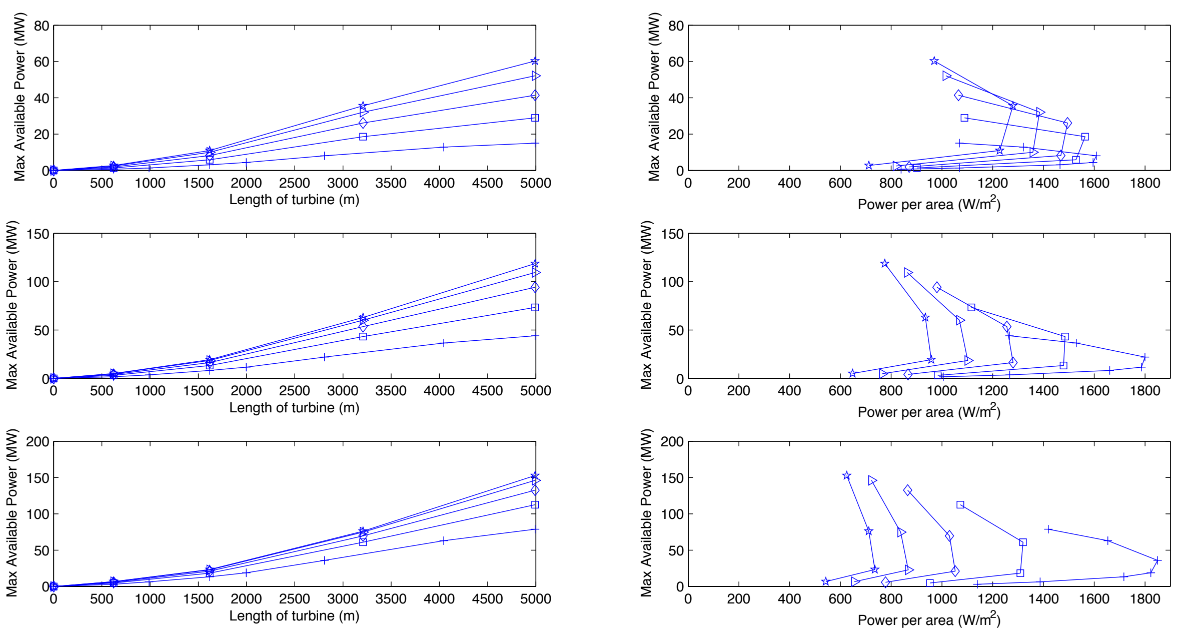

FIGURE 6. Results for multiple rows of turbines at Portland Bill. Top $B = 0.1$; middle $B = 0.25$; bottom $B = 0.4$. Left: length of turbine array against maximum available power; right: power per swept area vs available power. Symbols indicate number of turbine rows: + – one row; square – two rows; $\diamond$ – three rows; $\triangle$ – four rows; $\star$ – five rows.

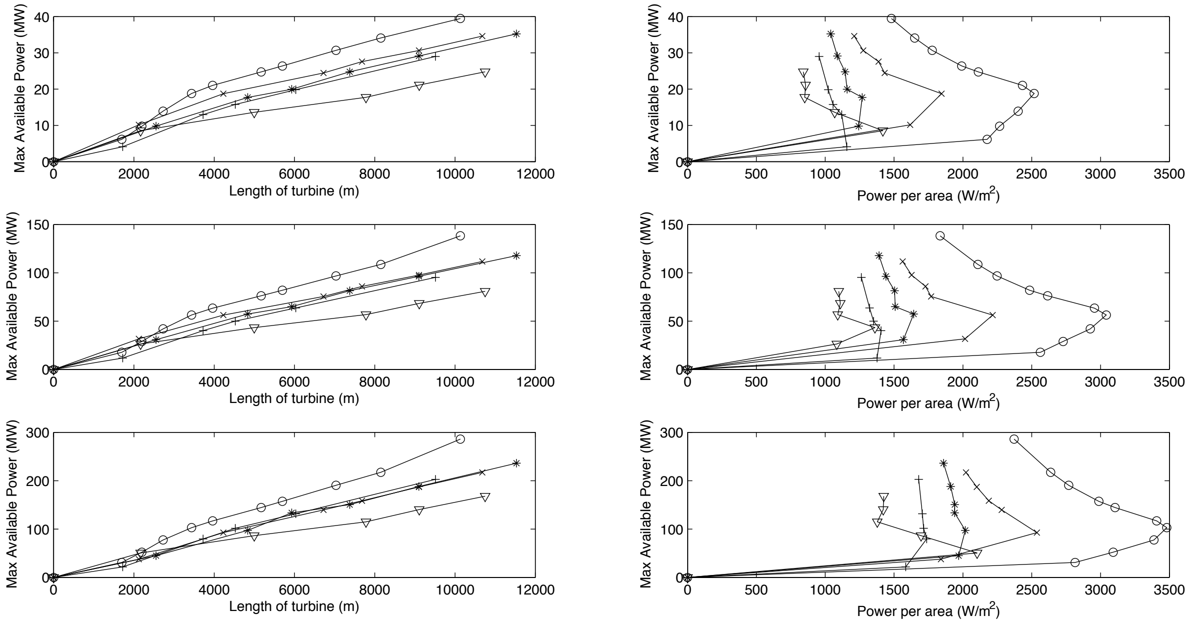

FIGURE 7. Results for single row of turbines at Isle of Wight. Top $B = 0.1$; middle $B = 0.25$; bottom $B = 0.4$. Left: length of turbine array against maximum available power; right: power per swept area vs available power. Symbols indicated location of turbines: '+' – location 6; 'o' – location 7; '$*$' – location 8; '$\times$' – location 9; '∇' – location 10.

Although there are differences between the individual rows, the general relationship between maximum available power, length of turbines, blockage, and power per swept area is similar between both sites. Based only on the hydrodynamics, the Isle of Wight appears to be a marginally more promising site for tidal stream turbines than Portland Bill, despite the peak undisturbed currents at each site being similar. The reason is due to the bathymetry of the Isle of Wight site which does not get deep as quickly as that at Portland Bill as one moves away from the shore.

CHANGES TO THE NATURALLY OCCURRING TIDAL CURRENTS

The object of this paper is to investigate the maximum available power, rather than finding a balance between power extraction and environmental change. However, to aid understanding of the problem it is useful to examine the change to the naturally occurring flow conditions. Figure 8 shows the different in the M_2 tidal current when a row of turbines extending 2.7km offshore, with $B = 0.4$, operating at the point which gives maximum available energy are deployed.

Figure 8 shows that there is a significant drop in the magnitude of the tidal current where the flow is naturally strongest ($\sim$ 3 m/s being reduced to $\sim$ 2.1 m/s). Interestingly there is a small increase in flow adjacent to the headland despite tidal turbines being deployed here. This rather shallow area usually has a rather small flow and so there the thrust applied to the flow by the turbines is much smaller than further offshore where the flow is stronger. Hence when tidal turbines are deployed some of the flow by-passes the area of highest thrust where the flow is strongest and passes through this region. There is also a small increase in the flow immediately to the south of the array of turbines. These results are consistent with the findings of Serhadlıoğlu *et al.* [8].

INTERACTION BETWEEN SITES

The question arises as to whether placing tidal turbines at Portland Bill modifies the flow and the resource at the Isle of Wight (and *vice versa*). A detailed investigation of this is made in Raperport [21]. Even for a deployment of tidal turbines on a scale much greater than that considered in this paper there is no significant interaction between the sites.

INTERMITTENCE OF POWER

Tidal stream energy, whilst predictable, is intermittent. This intermittence will be important to any practical deployment of tidal turbines. For both sites in this study have similar character-

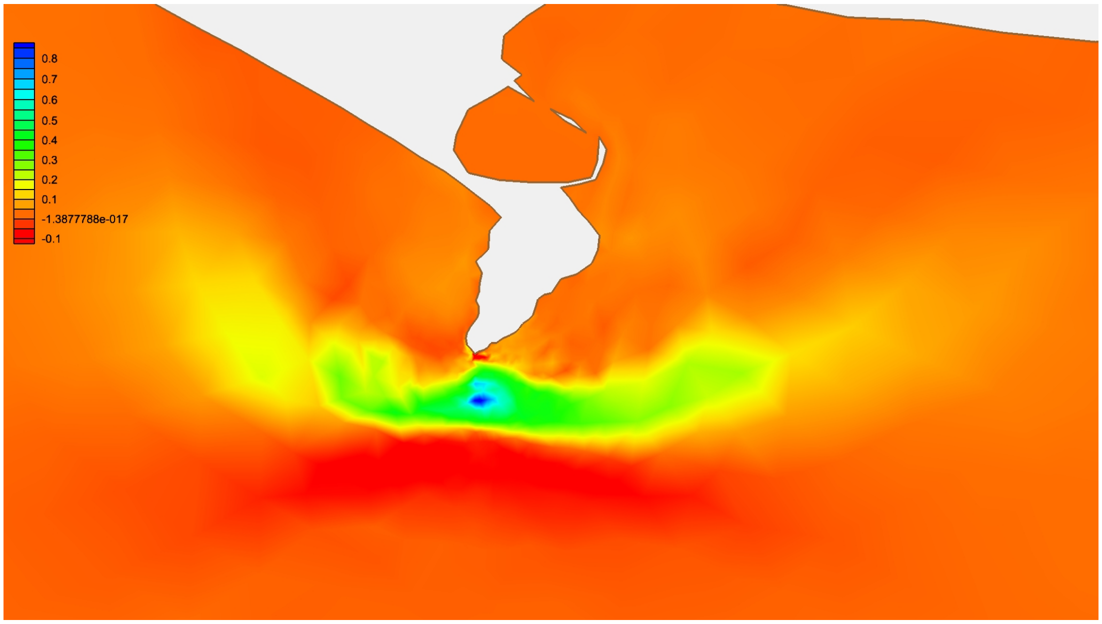

FIGURE 8. Magnitude of the change in the M_2 tidal current around Portland Bill between undisturbed flow and an array of turbines extending 2.7km offshore with $B = 0.4$ operating at the point which gives maximum available energy.

istics. At both sites almost equal power is generated on the flood tide as on the ebb tide. The tidal dynamics of the English channel take the form of a progressive wave traveling from west to east, meaning high tide is slightly later at the Isle of Wight than at Portland Bill. There is a similar time shift in the peak current, the timing of which changes only slightly when turbines are deployed. However, the sites are close together and if the power from both is added together then there is still a highly intermittent power output with periods where very little power is being produced by either site. As an example of this, Figure 9 shows the time series of available power for two examples from each site (for an arbitrary section of the tidal cycle) as well as the sum of the powers from each site.

There can be a substantial variation in the power output of tidal stream devices over the fortnightly spring/neap tidal cycle [18]. Adcock *et al.* [3] found for the Pentland Firth that the mean daily power at spring tide was typically around eight times that at neap tide. For the sites in this study the variation is rather smaller: the ratio of mean daily power at spring tide to neap tide is approximately 2.5 for Portland Bill and 3.7 for Isle of Wight with some small variations depending on the configuration of the turbines. As predicted by [18], the magnitude of spring/neap power ratio is slightly smaller when larger numbers of turbines are deployed.

CONCLUSIONS

In this paper we have constructed a numerical model of the English Channel and used this to analyse the tidal stream resource of two candidate sites for tidal energy extraction. In this paper we aim to maximise the mean available energy although we acknowledge that other factors would be important in a real development. Both sites show similar trends with respect to the location of turbines, length of turbines, and local blockage ratio. Additional power can be obtained by using additional rows of turbines, but the extra power from each additional row shows a diminishing return.

This study suffers from many limitations, and whilst we believe we have captured the key physics at each site, there is scope for much more refined modelling supported by a campaign of field measurements. It is, however, possible to try and make some assessment of the viability of the sites for tidal stream energy extraction and for the magnitude of the resource – although we reiterate that this should be treated with caution. The figures showing available power per swept area are promising, with the threshold of 1000 W/m^2, tentatively put forward by [3], being exceeded for most configurations of turbines. This suggests that it will be viable to extract some power from these sites. However, the diminishing return as more turbines are added will limit the magnitude of the resource. The figures presented in this paper give an inviscid upper bound to the power and do not account for turbine support structures or other losses – the amount of actual power that could be generated will probably be of an order of magnitude of half of the figures presented in this paper. We can

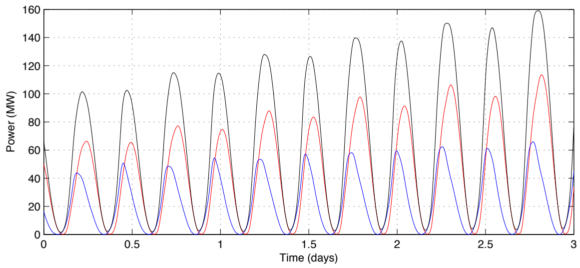

FIGURE 9. Example time series of available power. Blue: Portland Bill. Red: Isle of Wight. Black: sum of Portland Bill and Isle of Wight.

therefore conclude that it would be viable to generate something of the order of 10s of MW (averaged over time) from each site.

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