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Citation for published version:
Bryden, I, Couch, S, Owen, A & Melville, GT 2007, 'Tidal Current Resource Assessment' Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 221, no. 2, pp. 125-135. DOI: 10.1243/09576509JPE238

Digital Object Identifier (DOI):
10.1243/09576509JPE238

Published In:
Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy

Tidal current resource assessment

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The manuscript was received on 12 October 2005 and was accepted after revision for publication on 7 April 2006.

DOI: 10.1243/09576509JPE238

Abstract: This paper outlines present thinking on the determination of accessible tidal current resources within channels and other potentially exploitable locations. The fundamental principles behind tides and tidal currents are briefly discussed and the implications of temporal and spatial variations on the evaluation of the resources considered in the context of artificial energy exploitation. The thinking behind the flux approach to resource estimation is presented and an example based on the Pentland Firth is considered. The impact of energy extraction on the flow patterns is considered in both one and two dimensions and the principles required for three-dimensional analyses are presented in a generic form.

Keywords: tidal current, resource assessment, energy extraction, energy flux, modelling

1 INTRODUCTION

Anyone who has watched the sea is aware of the cyclic nature of the tides. In most coastal areas, the sea level rises and falls with a period of $\sim$12.4 h. Longer observation will reveal other cycles. The forces driving these motions are astronomic in nature and governed by the relative positions of the Earth, Sun, and Moon. Explaining the principles behind the tides was one of the first triumphs of Newtonian mechanics. Indeed, the 'equilibrium theory of tides' [**1**], which uses mechanical principles to explain the periodic nature of tides on a hypothetical water covered planet, is frequently referred to as the Newtonian theory of tides. The equilibrium theory, in effect, enables determination of the tidally generating forces on the ocean waters.

Although the Newtonian theory is capable of explaining the existence of tides, including the harmonic periods governing the temporal variations in tidal behaviour, it cannot directly explain the local variations in amplitude caused by geographic effects. The presence of coastlines, continents, islands, and depth variation all modify the response of the oceanic waters to the astronomic 'tide generating forces'. In many parts of the world, coastal and seabed conditions result in extreme acceleration in the currents associated with the tides. In many locations, the flows are sufficiently fast to suggest the possibility of using them to generate energy. Figure 1 shows the kinetic energy flux density as a function of flow speed if the water density is 1023 kg/m^3.

This graph is generated by application of equation (1), which allows determination of the kinetic energy flowing through a channel cross section in 1 s

$$P_{\mathrm{ch}} = \frac{1}{2}\rho \int_{A_{\mathrm{Chan}}} U_x^3 \, \mathrm{d}A \tag{1}$$

In any real tidal environment, the flow speed will vary in both space and time. This means that the application of equation (1), and Fig. 1, might produce misleading results if these variations are not taken properly into account.

A further issue which must be fully understood is how much energy can be theoretically and practically harvested. In wind power, the Betz limit [**2**] is frequently quoted as representing the theoretical upper limit to extraction potential for a wind energy converter. It is important to realize that the Betz model deals with a hypothetical energy extraction device removing energy from an unconstrained, incompressible flow, in which the boundaries are

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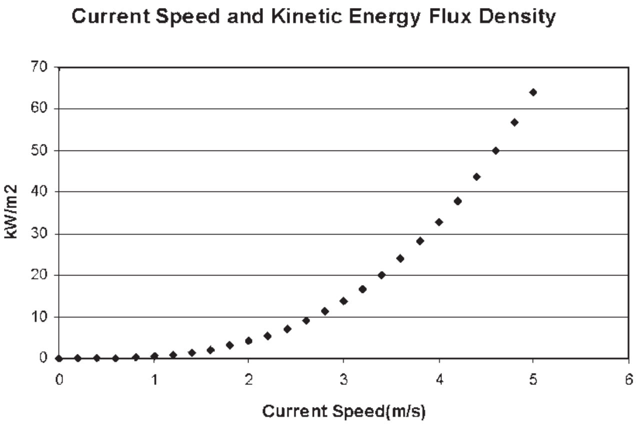

Fig. 1 Influence of current speed on energy flux density

infinitely distant from the site of the extraction. Critically, in the tidal case, the flow is constrained by the seabed and the free surface. Additionally, the constantly evolving free surface is also a key component of the tidal environment, allowing the driving tidal wave to propagate through the system. The Betz limit should not therefore be applied to determine the limits of extraction of energy from a tidal flow environment, as the assumptions made by Betz are unrealistic for the tidal case [**3**]. Nevertheless, it is still of value for resource assessment purposes to ascertain practical limits to extraction, and the results of preliminary investigations into quantifying the theoretical upper limit to extraction potential for tidal energy converters [**3**, **4**] are now becoming available and progress is, consequentially, being made towards defining an analogous representation of the Betz limit for tidal application. Such analysis does not yet take account of the feedback between the device and the fluid environment, which has been identified as having a significant impact on the localized flow development [**5**]. Further work is therefore required before the theoretical and practical limits on tidal current energy extraction can be fully defined.

2 INFLUENCE OF SPATIAL AND TEMPORAL FLOW SPEED VARIATIONS

2.1 Temporal variations

The tidal elevations in any part of the world can be described in terms of harmonic components [**6**], the periods of which are a consequence of the astronomic driving processes described in section 1. The amplitudes and phases are heavily influenced by the local geography. In general, the tidal amplitudes can be expressed as the sum of all the harmonic components as

$$\eta(t) = \sum_{\mathrm{n}} A_{\mathrm{n}} \cos\left(\frac{2\pi}{T_{\mathrm{n}}} t + \Phi_{\mathrm{n}}\right) \qquad (2)$$

Almost 400 harmonic components have been identified.

Harmonic descriptions of current velocity are more complex than for elevations. Directionality is obviously an issue and increases the complexity of the description. Obviously, the amplitudes of the harmonic components describing the currents are spatially dependent and would need to be described everywhere that energy assessments are required. Even horizontal separations of a few tens of metres will have impacts upon the flow speed amplitudes, as will be seen in section 2.3, while amplitudes governing the tidal elevations are generally applicable over separations of many kilometres.

Generally, further analysis of the size of the tidal current resource will require a mapping of the tidal current vectors, $\underline{\boldsymbol{u}}(x, y, z)$, expressed in time and space over the domain of interest, where x and y represent the horizontal coordinates and z represents the distance from the seabed.

2.2 Variations in flow speed within the water column

Equation (1) was presented as describing the energy flux passing through a section. This could equally well apply to the swept area of a device as to the cross-sectional area of a tidal flow environment. It is in this mode of use that the Betz limit might have some limited applicability as mentioned in section 1. As, however, it is known that flow speeds can vary considerably through the water column, it is vital that the nature of this variation is understood if the energy fluxes are to be effectively quantified.

The horizontal speed of water in a tidal flow varies with height above the seabed. This variation may be complex in form. It has, however, become common to represent the variation as a power law shown in equation (3)

$$U_x = \mathrm{Const}\left(\frac{\xi}{h}\right)^{(1/\mathrm{w})} \qquad (3)$$

Figure 2 represents a standard 1/7th power law speed variation over a turbine with a vertical extent of 20 m in a depth of 40 m. It is reasonable to assume that the current speed should be averaged in some manner over the swept area of the turbine, if the energy flux is to be determined.

If the current profile can be specified in terms of a power law, then the value of the power factor, 1/7 in

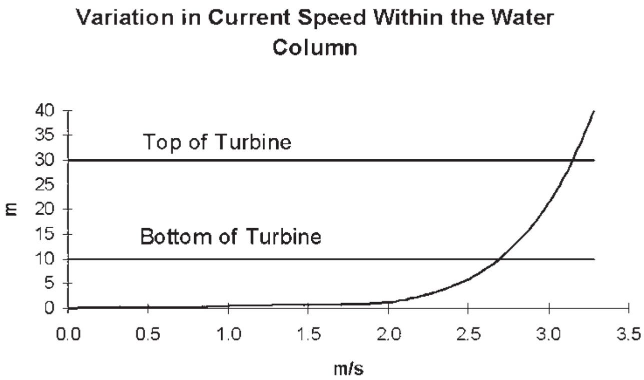

Fig. 2 Possible variation in current speed with depth of submergence

the case shown, becomes another parameter required to describe the flow conditions. Indeed, it is conceivable that the value of the power factor might change through the tidal cycle. As a first approximation, however, a single power law coefficient might suffice.

For a horizontal axis system, if the hub of the turbine is at a height Z_0, the average current speed over the swept area is given by

$$\bar{u} = \frac{4}{\pi D^2} \int_{-(D/2)}^{+(D/2)} \cos\left[\sin^{-1}\left(\frac{2y}{D}\right)\right] u(y + z_0)\mathrm{d}y \tag{4}$$

This is better than simply using the speed at the hub depth but does not take into account the cube law dependence between the speed of flow and the kinetic energy flux. Nor does it take into account the complex relationships between ambient flow and the lifting surfaces, which are likely to form components of any practical conversion system. It is more helpful to use, instead, the cube root of the mean, over the swept area, of the speed cubed. This is given by

$$\left[\overline{(u^3)}\right]^{(1/3)} = \frac{4}{\pi D^2} \int_{-(D/2)}^{+(D/2)} \cos\left[\sin^{-1}\left(\frac{2y}{D}\right)\right] u^3 \times (y + z_0)\mathrm{d}y \tag{5}$$

Figure 3, which is based upon a 1/7th power law, demonstrates the importance of using an appropriate value of the current speed in determining the energy flux. The data points show that the use of surface current values in the kinetic energy flux estimation through a swept area will result in a substantial over estimate of the energy flux through the intercepted area of the device. Use of the depth mean current speed would be more satisfactory but will still result in deviation and could even result in underestimation of the swept energy flux.

2.3 Flow speed variations in the horizontal domain

Local horizontal variations in flow speed can be driven by depth changes and coastal shape. Figure 4 shows an instantaneous map of flow speeds in the Pentland Firth, which lies between the North of the Scottish mainland and the island group of Orkney. The data shown in Figs 4 to 6 were generated using graphical interpretation of Admiralty Charts [**7**] and a Tidal Stream Atlas [**8**]. Figure 4 represents the flow distribution during a spring tide, close to the peak flood. As can be seen there are considerable horizontal variations in the flow speed.

The evolution of the flow patterns during the tide can be viewed in Figs 5 and 6, which show the speed distributions in 3 h steps. While Fig. 4 shows the flow distribution close to the peak flood tide, Fig. 5 shows the distribution close to slack water, and Fig. 6 shows the flow close to the peak ebb tide.

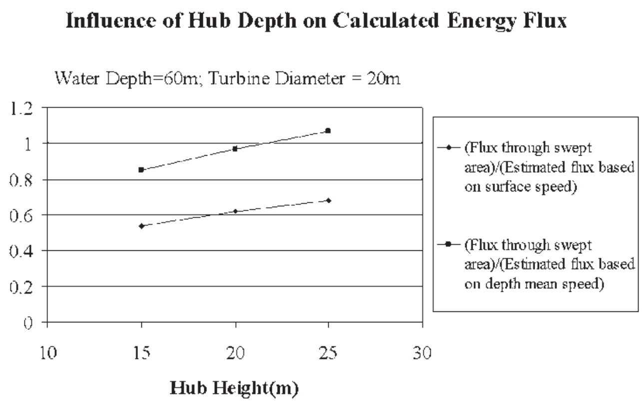

Fig. 3 Influence of hub position on energy flux estimates

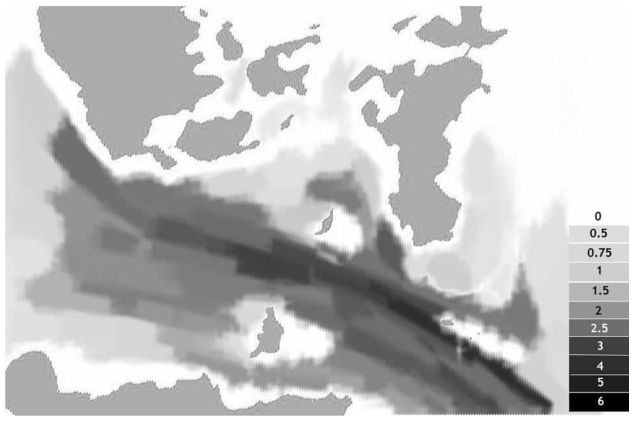

Fig. 4 Instantaneous spring tide flow speed in the Pentland Firth (nominal time: 0 h)

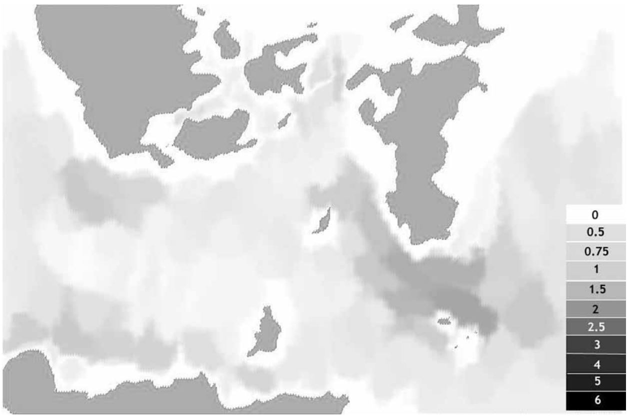

Fig. 5 Instantaneous spring tide flow speed in the Pentland Firth (nominal time: 3 h)

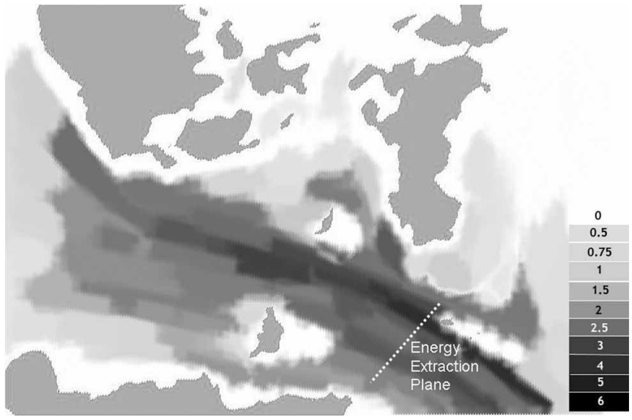

Fig. 7 Location of energy flux plane

The flow speed can be clearly seen to vary spatially as well as with time. Indeed, although it cannot be clearly discerned in the figures, the most energetic areas in the flood are not necessarily the most energetic in the ebb and vice versa.

3 GENERATING DATA SUITABLE FOR RESOURCE ASSESSMENT

The tidal energy flux has now been mapped for the entire UK continental shelf and is available for view [**9**], although it should be realized that, in most areas, the spatial resolution of available data is not sufficient to allow detailed resource assessment. The data presented in Figs 4 to 6, however, although historical, are sufficient to enable a preliminary assessment of the kinetic energy flux. Figure 7 shows the location of a flux assessment plane in the vicinity of the Pentland Skerries, through which the energy flux was assessed as part of a highly significant study into the UK tidal current resource [**10**]. The annual kinetic energy flux through this 3.2 km long plane was determined and subsequently reported as exceeding 22.6 TWh. The authors suggested that 20 per cent of this energy, 4.5 TWh, might be extractable.

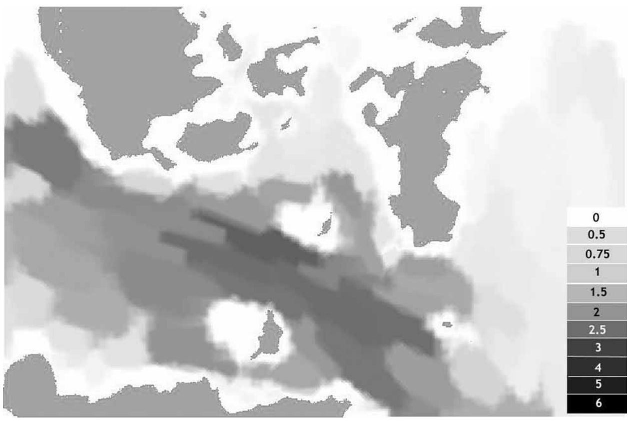

Fig. 6 Instantaneous spring tide flow speed in the Pentland Firth (nominal time: 6 h)

The first stage of a resource assessment should consist of determining the mean flux of kinetic energy, in an undisturbed tide, flowing through an extraction plane. In many situations, there will be insufficient data available directly to allow this calculation. In these cases, it will be necessary to construct a numerical model of the flow domain. Figure 8 shows, as an example, an instantaneous model output during a simulated spring tide in Yell Sound Shetland. This model was originally created using bathymetric data for the sound and with elevation boundaries at the extremities. It was subsequently calibrated with point measurements taken using acoustic doppler current profilers located within the flow domain.

It is important to adopt this 'flux' based approach. Early estimates of tidal current resource potentials

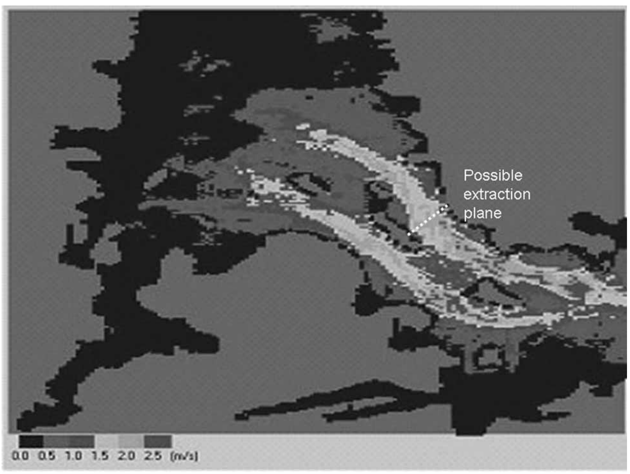

Fig. 8 Instantaneous numerical model output showing hypothetical extraction plain

based upon predictions of power per unit sea of sea surface [**11**] are now known to be in error.

4 INFLUENCE OF ENERGY EXTRACTION ON THE FLOW

4.1 Simple channel model

In the determination of wind power estimates, the influence of kinetic energy removal on the flow is generally handled by taking account of the wake generated behind the turbines and by establishing a maximum reasonable turbine separation and, therefore, energy extraction density in terms of MW/km^2. This implies that the kinetic flux recovers behind a turbine or wind farm. Wind energy systems, in effect, skim kinetic energy from the lowest layers of the atmosphere and it is not unreasonable to conclude that the energy flux recovers, although not necessarily within the dimensions of a wind farm. An array of tidal turbines across, for example, a channel as shown in Fig. 9, should be expected to produce changes in the tidal flow characteristics. These changes must be taken into account in determining the potential of a site to deliver useful energy. Indeed, it will become increasingly obvious during these analyses that undisturbed current speed alone is insufficient to make assessments of the potential for energy extraction.

In the case of a well defined channel, an early assessment of the flow impact resulting from energy extraction can be gained from a simple channel model based upon open channel flow theory [**12–14**], in which energy extraction is modelled by a flow retarding force acting on water passing through a cross-sectional plane in a constant width, finite length channel. The model is based upon a version of the traditional open channel flow equations shown by

$$\left(1 - \frac{U^2}{hg}\right)\frac{\partial h}{\partial x} = -\frac{1}{\rho g A_{\text{chan}}} P_{\text{er}} \tau_{\text{eff}} \tag{6}$$

The effective shear stress term, τ_{eff}, is the sum of the actual shear stress [**15**], given by equation (7) in terms of the Chezy friction coefficient [**16**] and an artificial stress term, which is defined in equation (8) and

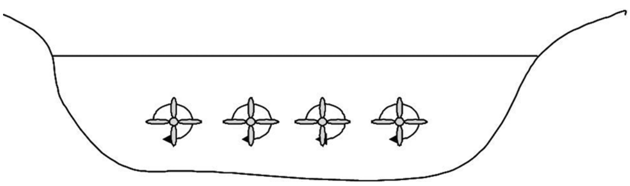

Fig. 9 Linear tidal array across a channel

mimics the effect of artificial energy extraction

$$\tau_0 = \rho g \frac{U^2}{C^2} \tag{7}$$

$$\tau_{\text{ex}} = \frac{1}{2}\rho f U^2 \frac{R}{\Delta x} \tag{8}$$

The Chezy coefficient itself can be conveniently calculated in terms of the Manning coefficient [**17**]

$$C = \frac{R^{(1/6)}}{n} \tag{9}$$

Upstream from the inlet to the channel, designated as $x = 0$, the flow is assumed to be stationary. Immediately downstream from the inlet, the flow speed is assumed to have a non-zero value. Application of the energy equation [**18**] suggests that this acceleration should be accompanied by a head drop given by equation (10) in terms of the flow speed immediately downstream from the inlet

$$\Delta h_{\text{inlet}} = \frac{U_0^2}{2g} \tag{10}$$

At the channel outlet, the assumption of a simple amplitude continuity boundary allows the implementation of a simple iterative model of the channel flow behaviour defined by equation 11.

$$h_{\text{inlet}} - h_{\text{outlet}} = \frac{U_0^2}{2g} + \int_0^{\text{L}} \frac{\partial h}{\partial x}\,\text{d}x \tag{11}$$

where $(\partial h/\partial x)$ is defined by equation (5).

Equation (11) can be 'solved' iteratively to determine the speed and depth at all points along the channel, for any distribution of artificial energy extraction. Figure 10 shows a sample model output for a channel of length 1000 m, width 500 m, inlet depth 40 m, and outlet depth 39.2 m. The manning coefficient was set to 0.035(m$^{-1/3}$ s) and an artificial energy extraction of 25 per cent was introduced over a length of 100 m in the middle of the channel length. The influence of energy extraction on the local flow speed and depth is clearly seen. Interestingly, and somewhat counter intuitively, the speed downstream of the extraction is higher than the upstream. This is an inevitable consequence of the head drop, which can also be seen and can be explained by the same theory as used to describe the commonly observed fluid flow phenomenon of friction slope, which is discussed in most texts covering open channel flow [**19**]. Although the simple channel model makes no attempt to correctly model the shallow water wave nature of tidal dynamics, a similar physical response of the system

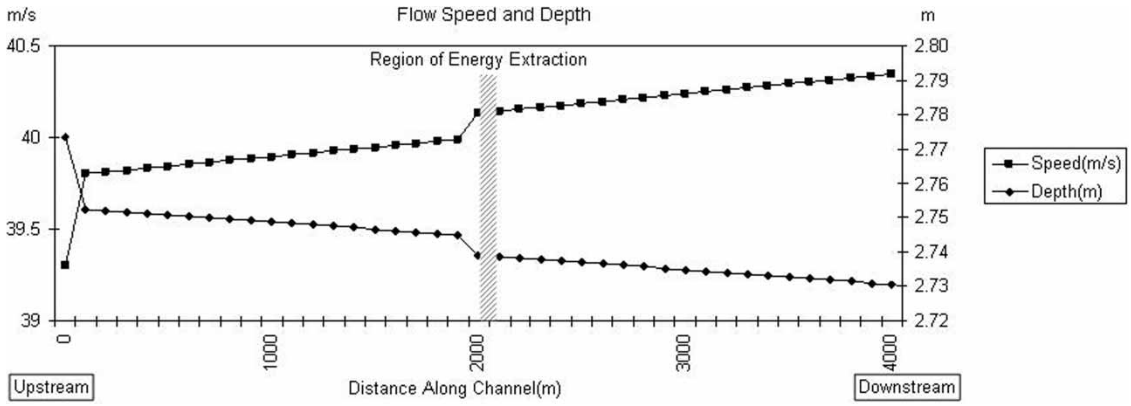

Fig. 10 Simulated changes in flow speed and depth along a simple channel

to energy extraction is also observed in cases investigated using the shallow water equations (SWE), as discussed in section 4.3, both in steady state and tidally varying analysis.

Figure 11 shows that the overall speed has been reduced appreciably as a result of the energy extraction. The overall slowing of the flow speed, both upstream and downstream, can be clearly seen. The one-dimensional iterative model can, of course, be run for a channel of any width, depth, roughness, and energy extraction proportion. It is interesting to investigate if there is any generic description of the sensitivity of a channel to exploitation. In particular, it would be useful if a non-dimensional parameter governing sensitivity could be identified. Of particular interest would be a parametric description which allows an estimation of the proportional reduction in flow speed.

4.2 Identification of a non-dimensional channel description

If the Froude number is much less than unity and the channel has a constant width, then equation (6)

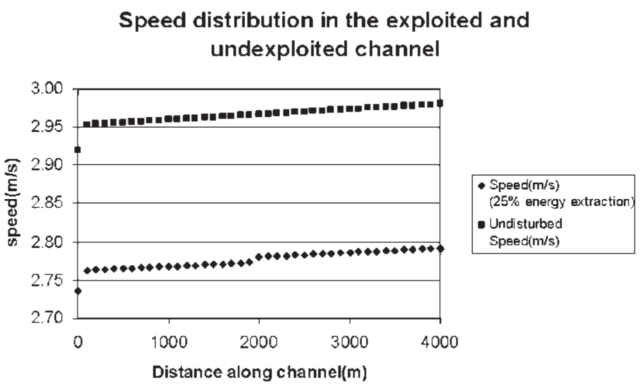

Fig. 11 Comparison between speed distributions in the exploited and unexploited channels

may be more simply written as

$$\frac{\partial h}{\partial x} = -\frac{P_{\mathrm{er}}\tau_{\mathrm{eff}}}{\rho g b h} \tag{12}$$

If the energy extraction process is assumed to be constant along the channel and, crucially, changes in depth, flow speed and wetted perimeter are small, then the equation could be further simplified as

$$\Delta h_{\mathrm{channel}} = -\frac{L P_{\mathrm{er}}\tau_{\mathrm{eff}}}{\rho g b h} \tag{13}$$

The total head difference between the inlet and outlet can, therefore, be written as

$$\Delta_{\mathrm{total}} = \frac{L U^2 n^2}{R^{(4/3)}} + \frac{1}{2} f \frac{U^2}{g} + \frac{U^2}{2g} \tag{14}$$

Crucially, the ratio, B, between the head drop resulting from energy extraction and that from the inlet condition and frictional effects can be expressed as

$$B = \frac{f}{1 + 2gLn^2/R^{(4/3)}} \tag{15}$$

Obviously, this relationship depends on rather restrictive assumptions made with respect to constancy of depth and flow speed. It would, however, be informative to plot predicted proportional flow speed reductions derived from the iterative one-dimensional model against the value of B for a wide range of values of f, L, n, and R. Table 1 shows a list of parameters with which the one-dimensional iterative model was executed. In each case, the model was executed with energy extraction proportions of 5, 10, 15, 20, and 25 per cent, expressed as a proportion of the kinetic flux in the raw undisturbed channel, rather than the flux in the exploited channel. This energy

Table 1 Channel configurations simulated with the one-dimensional iterative model

Length (m)	Width (m)	n ($m^{-1/3}$ s)	h_{inlet} (m)	h_{outlet} (m)
4000	200	0.02	40	39.6
4000	200	0.025	40	39.6
4000	200	0.03	40	39.6
4000	200	0.03	40	39.6
4000	200	0.035	40	39.6
4000	200	0.04	40	39.6
4000	200	0.045	40	39.6
4000	200	0.05	40	39.6
4000	200	0.055	40	39.6
4000	1000	0.02	40	39.6
4000	1000	0.025	40	39.6
4000	1000	0.03	40	39.6
4000	1000	0.03	40	39.6
4000	1000	0.035	40	39.6
4000	1000	0.04	40	39.6
4000	1000	0.045	40	39.6
4000	1000	0.05	40	39.6
4000	1000	0.055	40	39.6
1000	500	0.035	40	39.6
2000	500	0.035	40	39.6
3000	500	0.035	40	39.6
4000	500	0.035	40	39.6
5000	500	0.035	40	39.6
2000	500	0.035	19.6	20
2000	500	0.035	21.6	22
2000	500	0.035	23.6	24
2000	500	0.035	25.6	26
2000	500	0.035	27.6	28
2000	500	0.035	29.6	30
2000	500	0.035	31.6	32
2000	500	0.035	33.6	34
2000	500	0.035	35.6	36
2000	500	0.035	37.6	38
2000	500	0.035	39.6	40
2000	500	0.035	41.6	42
2000	500	0.035	43.6	44
4000	500	0.035	19.6	20
4000	500	0.035	21.6	22
4000	500	0.035	23.6	24
4000	500	0.035	25.6	26
4000	500	0.035	27.6	28
4000	500	0.035	29.6	30
4000	500	0.035	31.6	32
4000	500	0.035	33.6	34
4000	500	0.035	35.6	36
4000	500	0.035	37.6	38
4000	500	0.035	39.6	40
4000	500	0.035	41.6	42
4000	500	0.035	43.6	44

fraction was chosen as being of more interest to a site developer than the proportion of energy available from a subsequently modified flow.

Figure 12 shows the proportional flow speed reduction, in the vicinity of the energy extraction site, with respect to the undisturbed flow, expressed as a function of the parameter B.

Despite the assumptions used in establishing the nature of the ratio B, there does appear to be a relatively simple relationship between it and the iterative solutions. The parameter does suggest that sensitivity of a simple channel to energy

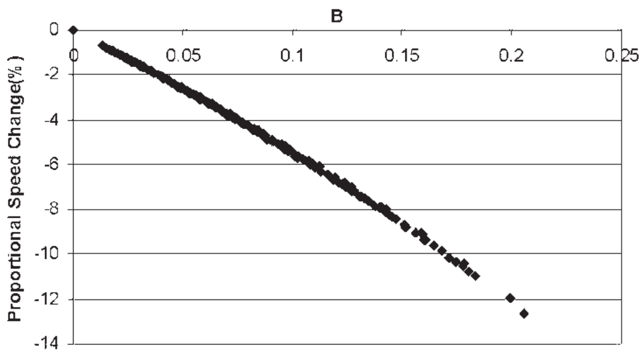

Fig. 12 Influence of B on speed reduction

extraction is related to water depth, length, width, and the nature of the boundary roughness. If this is subsequently proved experimentally, it could form the basis of a rapid analysis of the sensitivity of a channel of simple geometrical form.

4.3 Influence of energy extraction in a complex flow domain

Obviously, most tidal regimes, such as those shown in Figs 4 to 6 are more complex than a simple one-dimensional channel. The influence of energy extraction in a three-dimensional domain, can be simulated by application of an extraction related retarding force on the flow, as shown in Fig. 13.

In the case shown, the retarding force, $F_x(N)$, on the fluid as it passes through the disc will be given by

$$F_x = -\frac{P_{ex}}{U} \tag{16}$$

This equation does not include the influence of fluid blockage which the technology may also apply to the fluid. This should be included when assessing a technology concept but is ignored here in the consideration of the energy extraction itself.

Numerical models for the simulation of geographic flows are generally based upon solution of equations describing the momentum and continuity of the tidal waters, subject to seabed, coastal and open water boundaries. These equations are frequently expressed in a depth-averaged form [**20**], although appreciation of the flow through the water column requires solution of the equations in three dimensions. The large horizontal domain, with respect to the water depth, in most simulated environments, means that the vertical behaviour can generally be simulated using a variable thickness layered approach [**21**], which is more convenient than a full three-dimensional analysis with a variable surface boundary would have been.

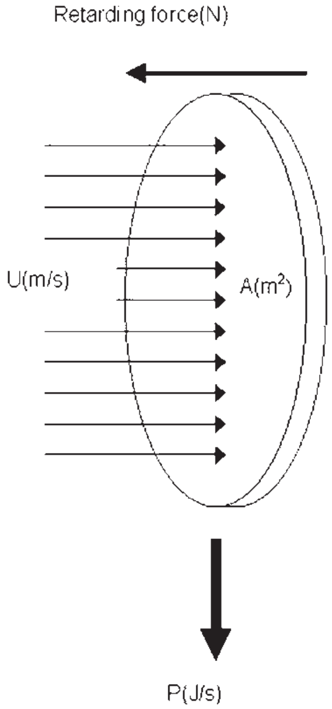

Fig. 13 Flow through an energy extraction plane

In any depth integrated analytic approach, the plane of energy extraction would extend from the surface to the seabed and, as such, could not simulate the effects of flow above and below the plane of extraction. Figures 14 and 15 show how such cells could be incorporated into a rectangular grid.

If a layered model is used, then for every cell defined in the horizontal grid, extraction could be applied on a layer-by-layer basis, as indicated by Fig. 16.

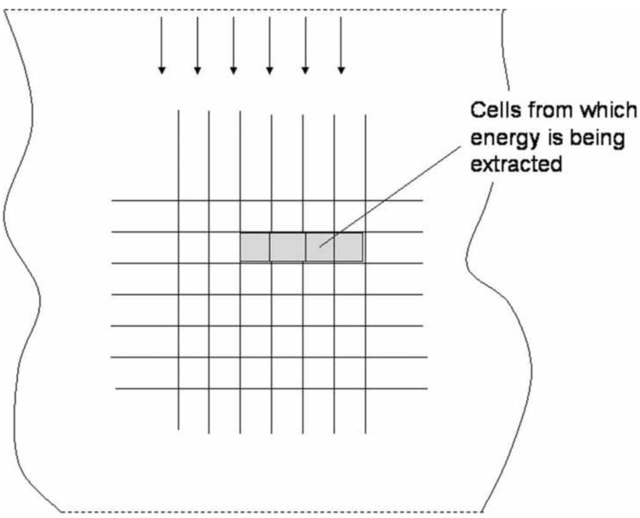

Fig. 14 Rectangular grid containing energy extraction cells

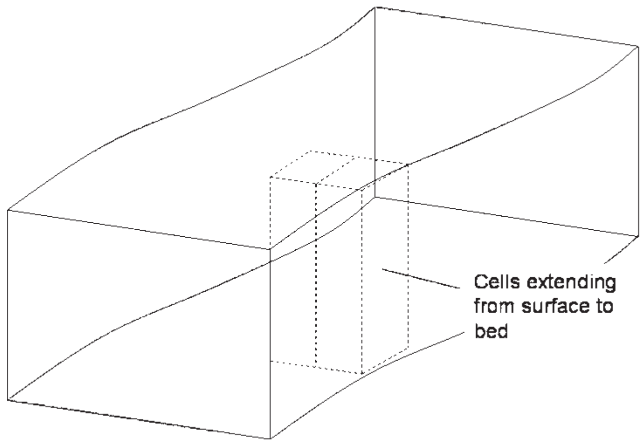

Fig. 15 Extraction cells extending from surface to bed

In principle, the incorporation of energy extraction cells into a two- or three-dimensional coastal flow model will enable assessment of the implications of energy extraction. True resource assessment should always be based upon such energy extraction modelling and only preliminary assessments can be based upon the energy flux in undisturbed flow.

Figure 17 shows the domain of a simplified two-dimensional model, which consists of a channel of length 9.6 km and width 4.8 km. The grid size was 80 m by 80 m. The domain features an island, which creates a two-channel system in its central region and is symmetrical around the centre-line. Free-slip lateral boundary conditions were applied at the closed boundaries and continuity boundaries applied at the inlet and outlet to the channel. In all of the simulations, the flow was assumed to be driven by a 3.5 m M_2 tidal wave progressing along the channel, which was run from a cold start up to one fourth of the tidal period, at which time the inlet and outlet boundary conditions were maintained.

The numerical model used here is based on an explicit, depth integrated finite difference SWE solver [**22**], to which has been added a flow

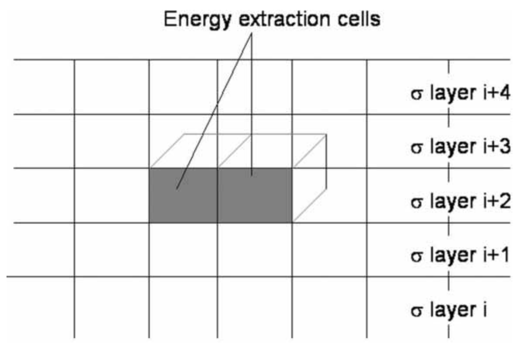

Fig. 16 Three-dimensional energy extraction cells in a σ layer model

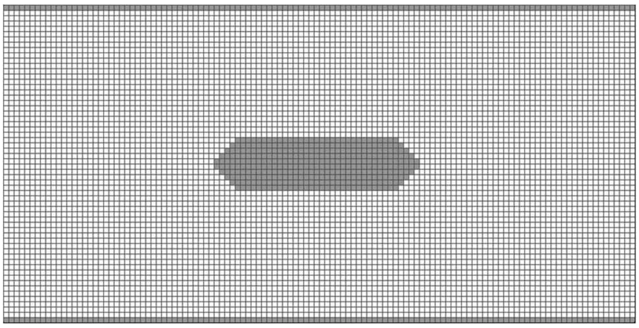

Fig. 17 Two-dimensional flow domain grid

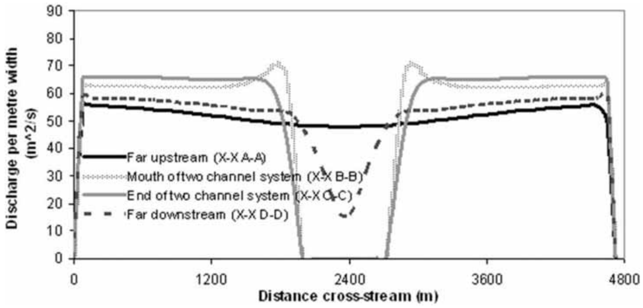

Fig. 19 Discharge across cross sections A–A, B–B, C–C, and D–D: both channels exploited

retardation algorithm based upon equation (14). Figure 18 shows the domain with two energy extraction planes to the 'North' and 'South' of the island.

The influence of the energy extraction and the island can be seen in Fig. 19. The extraction planes are set at one cell width and with an extraction figure of 6 MW per cell. This represents an extreme level of flow exploitation, which has been selected to demonstrate the nature of distortion caused by high levels of energy extraction.

Not unexpectedly, the discharge pattern is symmetric about the longitudinal axis and the most dominant observation is a wake behind the island. As the system showed eddy effects from the island, the discharge figures represent time averages, with averaging periods sufficiently greater than the shedding frequencies to allow confidence in the averaging process.

It is more interesting to consider the asymmetric case in which only one of the channels is exploited, as suggested in Fig. 20. The sectional discharges for this simulation are shown in Fig. 21. In this case, the asymmetric flow downstream of the island can be clearly seen, as can the preference of the flow to pass through the unexploited channel. The discharge, per unit width, in the northern channel has been reduced from approximately 67 m^2/s (1.75 m/s at a water depth of 38.3 m)) to approximately 50 m^2/s (1.31 m/s at a water depth of 38/2 m).

This level of exploitation in a multiply connected flow regime would result in substantial modifications to the flow pattern and the reduction in flow speed would cause problems to the system developer, who would have to design for flow speeds ~25 per cent reduced from the undistorted flow.

5 ENVIRONMENTAL ISSUES AFFECTING RESOURCE POTENTIALS

All energy extraction technologies will have environmental impact; the challenge is to ensure that these impacts do not outweigh the benefits from the energy generated. In the case of renewable technology, the benefit assessment should include the positive effects of displacing fossil fuel generation and the subsequent release of greenhouse gasses as well as the reduced reliance upon imported fuels. Scottish natural heritage (SNH) have considered the potential of most forms of renewable energy to change the environment and have recently published an in depth review [**23**] of the likely impact from marine renewable development.

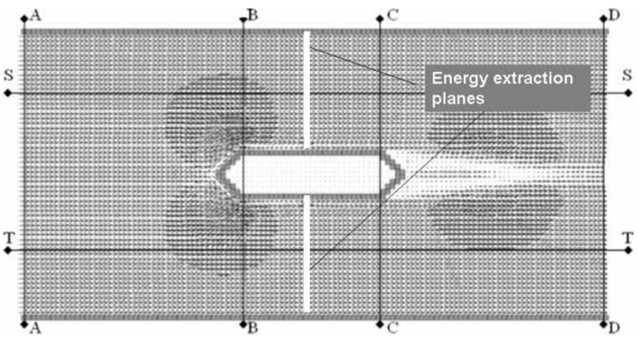

Fig. 18 Flow domain with symmetric energy extraction

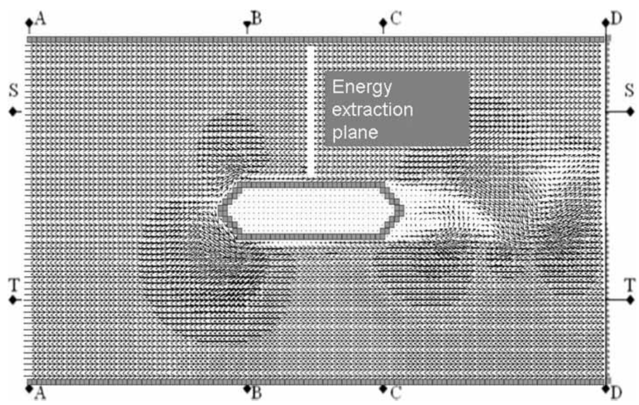

Fig. 20 Domain with 'northern' channel exploited

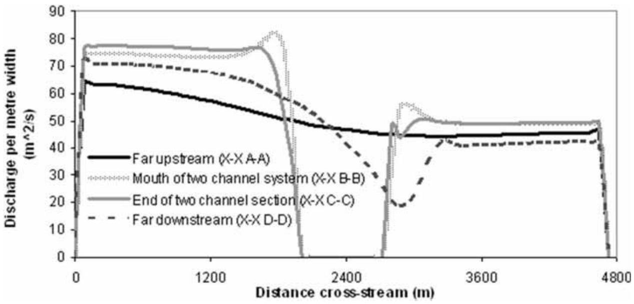

Fig. 21 Discharge across cross sections A–A, B–B, C–C, and D–D: northern channel exploited

There are four principal environmental issues that must be taken into account when identifying the potential of a tidal site to deliver useful energy.

1. Will the reduction to the energy flux cause unacceptable modifications to the natural environment?
2. Will the tidal technology pose an impact hazard to marine life?
3. Will there be local flow effects detrimental to life on the seabed?
4. Will the installation process cause unacceptable disturbance?

None of these issues is clearly defined or easily quantifiable. Use of the one-dimensional flow model in section 4.1 suggested that, in the channel illustrated, 25 per cent of the kinetic flux could be extracted with less than 7 per cent reduction in the flow speed. This is close to the limits of effective measurement in the marine environment. Would such a reduction in flow speed cause unsuspected and detrimental changes? If the tidal currents were constant, this might be rationally argued. As discussed in section 2.1, however, the tides are themselves highly variable in time and the 7 per cent variation caused by exploitation would be totally dwarfed by speed variations on an hourly, diurnal, and monthly time scale, so sensible levels of energy extraction are unlikely to cause any environmentally threatening channel scale effects resulting from large scale flow modification.

No serious research has yet been performed into the likelihood of direct interactions between wildlife and tidal current technology. Open turbines are likely to present the least threatening challenge to marine mammals and fish, but this is an issue which needs further research and *in situ* monitoring before definitive answers become available.

Extraction of energy from the mid water layers in a channel does produce modifications to the nature of flow above, around and, most significantly, below, the extraction plain. Although most tidal channels have a highly scoured bed, the location of devices will need to take this effect into account.

The installation of most systems will likely involve preparation of the seabed. Some systems such as the sea flow system [**24**] require the installation of a pillar into the seabed, which will require brief but noisy marine activity. If the site is known to be important for breeding mammals or birds, it would be wise to choose the installation time to minimize disturbance.

As well as the natural environment, it is important to consider that there may be constraints on development set by analysis of the economic and social environment. Resource development must work in full cognisance of the wide range of stakeholders in the marine environment. The fishing industry, leisure industry, and the petroleum industry are all important dependents upon UK waters and the seabed.

Resource assessment must take full consideration of constraints resulting from avoidance of unacceptable impacts on the natural and human environment. This may result in some, otherwise excellent, sites being deemed fully or partially out of bounds, or having severe restrictions placed upon the locations of devices. These restrictions must be considered within the frameworks set in sections 2 to 4.

6 CONCLUSIONS

Through the use of published tidal data and the application of modern measurement techniques and computational analysis, it is now possible to make robust estimates of the ultimate potential of a tidal site to deliver energy. These estimates must, however, be modified to take account of limitations set by concern for the natural and social/economic environment. In particular, it must be recognized that knowledge of the kinetic energy flux in the undisturbed site is not sufficient to assess the available energy and that the sensitivity of a site to exploitation is dependent upon a range of other factors relating to the geography of the chosen location.

ACKNOWLEDGEMENTS

The authors wish to thank the Engineering and Physical Science Research Council for their funding of the Supergen (marine) programme, the European Marine Energy Centre for their support of measurements of tidal flows in Orkney and beyond, The Carbon Trust for their support of the development of preliminary resource assessment methods and Black and Veitch Ltd for permission to use material and data from their documentation and the Engineering Business for permission to use an image from the numerical model of Yell Sound.

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APPENDIX

Notation

A_{n}	amplitude of a harmonic component (m)
A_{chan}	channel cross-sectional area (m^2)
b	channel width (m)
C	Chezy friction coefficient
D	turbine diameter (m)
f	fraction of the kinetic flux being extracted
g	acceleration due to gravity (m/s^2)
h	water depth (m)
L	channel length (m)
n	Manning friction coefficient (m$^{-1/3}$ s)
P_{er}	wetted perimeter of a channel (m)
P_{ex}	power being extracted (Watts)
P_{ch}	kinetic energy passing through a channel cross section in 1 s (Watts)
R	hydraulic radius (m)
T_{n}	period of a harmonic component (s)
$\bar{\boldsymbol{u}}$	flow speed averaged over the swept area of a horizontal axis turbine (m/s)
U_{d}	longitudinal component of the fluid velocity passing through a disc (m/s)
U_0	flow speed immediately downstream from a channel inlet (m/s)
U_x	longitudinal component of flow velocity (m/s)
w	power law coefficient
z_0	height of the turbine hub above the seabed (m)
Δ_x	length over which the energy is being extracted (m)
$\eta(t)$	vertical displacement of the sea surface as a function of time (m)
ξ	vertical distance above the seabed (m)
ρ	density of water (kg/m^3)
Φ_{n}	phase of harmonic component