The impact of energy extraction on tidal flow development

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Synopsis

Application of 2-d and 3-d numerical tidal models in the marine renewable energy field has typically been to identify appropriate sites for marine energy extraction and quantify the potential energy available for extraction. Implicit in such an analysis is the assumption that local flow conditions will not be significantly altered by the energy extraction process. Considering the complex hydrodynamic conditions associated with the majority of sites identified as suitable for economic extraction of tidal energy, the general validity of this assumption is questionable. It is therefore necessary to develop modelling techniques which take account of the dynamic 'feedback' of extracting energy from the system. This will enable a more rigorous assessment of suitable sites for development and aid in determining the localised environmental impact of exploitation.

Results from a simplified one-dimensional analysis of the governing equations will be summarised. This analysis demonstrates the significant upstream and downstream effect of energy extraction on velocity and elevation in a simple channel set-up. The energy extraction theory has been extended to a sigma-layer model of the hydrostatic primitive equations. Simulations using idealised domains demonstrate the limits within which the 'blocking' effect of a tidal turbine 'farm' are of significance. This will address concerns that have been raised within the research community regarding the change to the hydrodynamic regime brought about by extensive energy extraction, and potential redistribution of tidal currents away from the installed location.

INTRODUCTION

Tidal currents represent a largely ignored renewable energy resource. Most early attention to harnessing the energy of the tides concentrated on tidal barrage systems, which aim to extract the energy available from the rise and fall of the water level in locations with a high tidal range. The La Rance tidal power station developed in the 1960's in France and continued proposals for a barrage on the Severn Estuary in the UK are examples of this method of extracting energy from tides. Most recent attempts to develop the tidal energy resource have, however, been directed towards harnessing the rapid currents encountered in many coastal regions of the world. In the UK the inter island channels of Orkney and Shetland which frequently experience spring tidal currents in excess of 3 m/s appear to offer some intriguing opportunities for development[1]. The energy flux in a 3 m/s tidal current is considerable at 14 kW/m^2.

The harnessing of energy in a tidal flow requires the conversion of kinetic energy in a moving fluid, in this case sea-water, into the motion of a mechanical system, which can then drive a generator. It is not too surprising therefore, that many developers propose using technology that mirrors that which has been successfully utilised to harness the wind, which is also a moving fluid. Of course, there are obvious differences between the environment the extraction devices are exposed to and the details of the technology, but the majority of existing proposals follow the format of 'windmills in the sea'.

Tidal Energy

An initial analysis of the tidal current resource can be based upon that used for energy extraction from wind. The kinetic energy flux, expressed in Watts, in a water channel is proportional to the cube of the velocity of the water passing through the cross section of that channel:

$$E_k = \frac{1}{2}\rho \int_A \left(U^3 dA \right) \tag{1}$$

where ρ is the density of sea-water (kg/m^3), A is the cross sectional area of the channel (m^2), and U is the flow velocity perpendicular to the cross section of the channel (m/s). Equation 1 can be simplified by expressing the mean velocity across the cross section of the channel, such that $A\overline{U_A}^3 = \int_A \left(U^3 dA \right)$. Figure 1 shows the expected
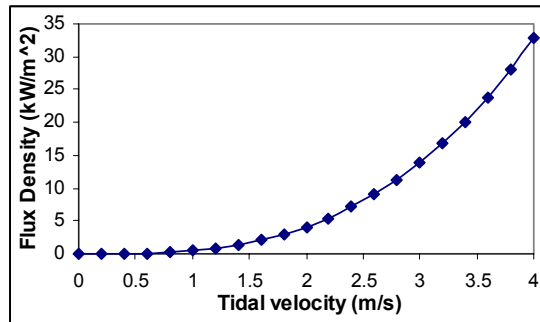

Figure 1: Flux density as a function of tidal velocity.

flux density variation with $\overline{U_A}$. As can be seen, the flux density at 3 m/s is close to 14 kW/m^2. This would equate to a total kinetic energy flux of approximately 530 MW in a channel of width 100m and depth of 40 m.

As the density of sea-water is typically 800 times more dense than air, the energy available across a representative cross-section is also 800 times more in sea water than in air. This is advantageous in that the swept area necessary to generate a given wattage from a tidal turbine is substantially less than from a wind turbine (this must be balanced against the potential for the local wind velocity to at times be significantly higher than typical tidal velocities). Figure 2 presents a schematic size comparison for two typical developments. A further desirable feature of tidal power is that tidal velocities and consequently energy harvested is both regular and predictable – this is one of the basic advantages of this renewable energy source, and is additionally advantageous when considering grid integration from a management point of view.

Figure2: Size comparison of a 1MW wind and tidal turbine ((c) Marine Current Turbines Ltd.)

ENERGY EXTRACTION

It can be tempting to overstate the similarities between wind energy extraction and tidal current energy extraction. Nonetheless, the nature of the underlying flow is quite different. Wind energy systems extract energy from the bottom layers of the atmosphere and the kinetic energy flux can be expected to recover, within these bottom layers, a relatively short distance behind the extraction device. The study of wake development behind wind turbines is well advanced and can, with some modification be extended to the behaviour of current flows in the vicinity of a tidal turbine[2]. Such models can be used to determine optimal placement of turbines within a channel to minimise interference and subsequent performance degradation. They cannot however be used to directly assess the influence of energy extraction on the underlying flow. Unlike atmospheric flows, tidal currents are constrained between the seabed and surface and may be further constrained in a channel – the consequent upstream and downstream effect of installing a 'farm' of tidal turbines is therefore potentially much more significant than for a wind farm.

One-Dimensional Channel Analysis

Not all tidal regions are suitable for energy extraction. Only areas where the tidal current reaches a large spring tidal velocity and which have consistently higher than average velocities throughout the daily and lunar cycle will prove economically attractive for development as energy extraction sites. There are three typical regions where the necessary tidal conditions are consistently encountered, (i) in areas with an unusually large tidal range, (ii) in enclosed bays and estuaries which are subject to resonance effects (e.g. the Minas Basin in the Bay of Fundy – Gulf of Maine system, the Bristol Channel/Severn Estuary, etc.), and (iii) in channels where the bodies of water at each end of the channel are out of phase with each other, and exhibit at least moderate tidal amplitudes, thereby creating a strong pressure gradient across the channel (e.g. the Pentland Firth, Straits of Messina, Naruto Strait and at smaller scales inter-island channels in Orkney and Shetland). For the analysis presented here, idealised domains of the 1st and 3rd type will be considered – the analysis will be extended in future work.
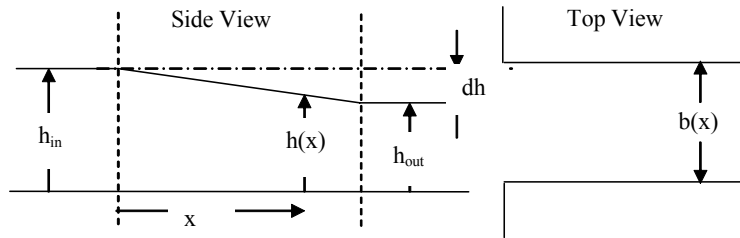

Figure 3: Schematic diagram of a hypothetical channel linking two oceans.

The case to be considered is a one-dimensional channel of uniform depth and width as in figure 3 linking two infinite oceans. If dynamic effects resulting from the time variation of the water elevation are neglected, a simple static open water flow model can be used to investigate the effects of energy extraction. The open channel flow equations familiar from standard hydraulics textbooks were therefore employed. Energy extraction from the system can be numerically modelled in one of two ways, either (i) by considering the act of extraction as an additional retarding force, or (ii) more simply by relating the power extraction to an additional shear stress applied at the perimeter. Both approaches have been successfully applied, however, only the first will be presented here as, as well as being more scientifically rigorous, it also lends itself more logically to extension to 2-d and 3-d. If energy is extracted at a rate of P_x Watts per cubic metre, the retarding force on a slug of water, assuming that the power dissipated (extracted) is equal to the product of the speed of the slug and the retarding force, will be given by:

$$F_x = \frac{P_x A U \Delta t}{U} = P_x A \Delta t \tag{2}$$

After manipulation into the correct form for application as part of the open channel flow equations, the new extraction term becomes:

$$\frac{P_x A}{\rho g Q} \tag{3}$$

where g is the gravitational acceleration (m/s^2) and Q is the volume flux (m^3/s).

The procedure established to model energy extraction will now be tested. A uniform bed channel, constant channel width of 1000 m, length 4000 m, upstream input water depth 40 m, and downstream water depth of 39.6 m will be considered. The modelled results without energy extraction are presented in figure 4. As can be seen the imposed head difference at the channel boundaries generates significant flow velocities. The elevation

decreases steadily along the channel, and there is the expected corresponding increase in flow velocities in the stream-wise direction. The equivalent model output with 10% of the cross channel kinetic energy flux calculated from the previous case removed at the centre of the domain is presented in figure 5. A substantial head drop (of the order 6 cm) can be seen across the energy extraction zone. This is associated with a local increase in velocity. However, in comparison with the no extraction case, the overall flow velocity in the channel has been reduced appreciably ($\approx$ 6%), and by 5.8% in the immediate vicinity of extraction for the same input and output elevation boundary conditions. Further analysis considering different rates of energy extraction (not shown) suggests that there is a non-linear relationship between the amount of energy extracted and velocity deficit.
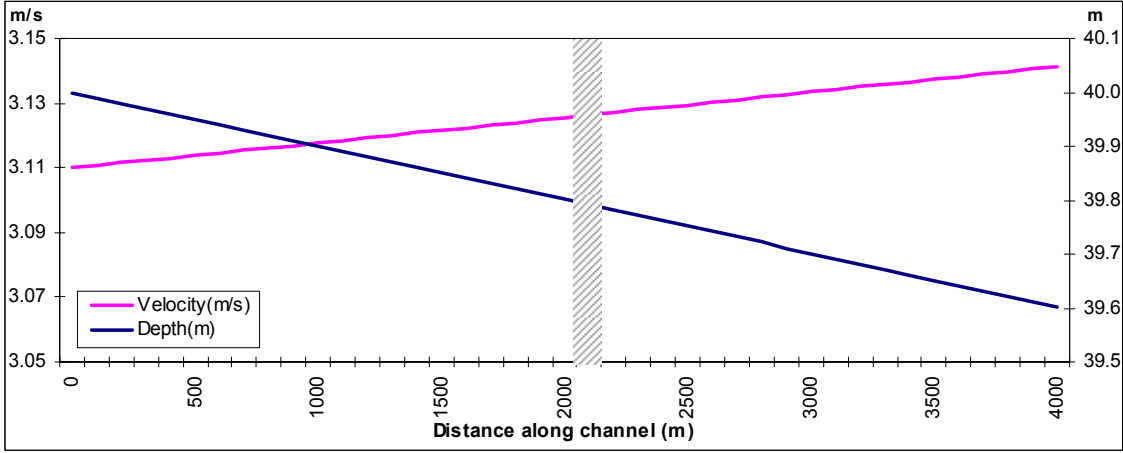

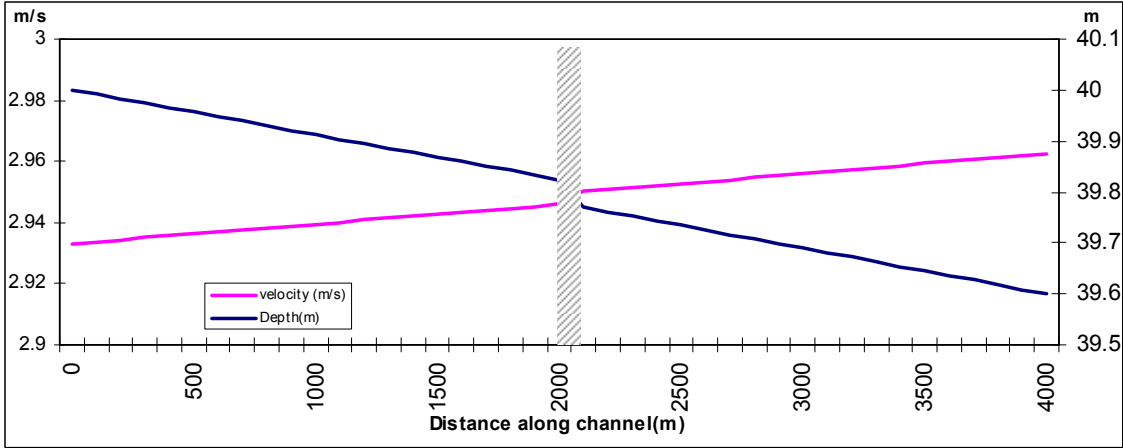**Figure 4:** Channel flow properties with no energy extraction.

Figure 5: Channel flow properties with 10% equivalent energy extraction.

Two- and Three-dimensional analysis

For 2-d and 3-d analysis the 'Tidal Flow Development' (TFD) numerical model will be applied. The TFD-2d code originally developed at the University of Strathclyde[3] implements a finite-difference representation of the conservative form of the Shallow Water Equations (equations 4, 5, and 6). The variables are arranged on an Arakawa C-grid in space and time, and the solution is determined using leapfrog time differencing with centred space differencing throughout, apart from the convective momentum terms where a fully third-order representation is applied. The model has been extended to 3-d at RGU by implementing the σ-coordinate

$$\frac{\partial \eta}{\partial t} + \frac{\partial (Uh)}{\partial x} + \frac{\partial (Vh)}{\partial y} = 0 \tag{4}$$

$$\frac{\partial (Uh)}{\partial t} + \frac{\partial (UUh)}{\partial x} + \frac{\partial (UVh)}{\partial y} = fVh - gh\frac{\partial \eta}{\partial x} - gn^2\frac{U\sqrt{U^2+V^2}}{h^{\frac{1}{3}}} + \left(\frac{\kappa\sqrt{g}n\sqrt{U^2+V^2}h^{\frac{5}{6}}}{6}\right)\left[2\frac{\partial^2 Uh}{\partial x^2} + \frac{\partial^2 Uh}{\partial y^2} + \frac{\partial^2 Vh}{\partial x\partial y}\right] \tag{5}$$

$$\frac{\partial (Vh)}{\partial t} + \frac{\partial (UVh)}{\partial x} + \frac{\partial (VVh)}{\partial y} = -fUh - gh\frac{\partial \eta}{\partial y} - gn^2\frac{V\sqrt{U^2+V^2}}{h^{\frac{1}{3}}} + \left(\frac{\kappa\sqrt{g}n\sqrt{U^2+V^2}h^{\frac{5}{6}}}{6}\right)\left[2\frac{\partial^2 Vh}{\partial y^2} + \frac{\partial^2 Vh}{\partial y^2} + \frac{\partial^2 Uh}{\partial x\partial y}\right] \tag{6}$$

$$\sigma = \frac{z - \eta}{d + \eta} \qquad (7)$$

transformation in the vertical. In a sigma-coordinate system, the number of vertical levels in the water column is the same everywhere in the domain irrespective of the depth of the water column. This is achieved by transformation of the governing equations from z-coordinate to sigma-coordinate in the vertical (see equation 7). Unlike the typical 3-dimensional z-coordinate representation where the layer thicknesses are uniform in the horizontal, it is the normalized thicknesses that are uniform in the sigma-coordinate system. The layer thicknesses therefore vary from grid cell to grid cell. The extension of the governing equations (4, 5, and 6) to σ-coordinates is well documented[3,4] and will therefore not be repeated here. Energy extraction will be implemented in a similar form to equations 2 and 3. However, the individual terms in the x- and y- momentum equations have units of L^2T^{-2} – therefore the additional term must also conform to these units:

$$\frac{hu^2}{2\Delta x} \qquad (8)$$

The domain to be considered is a simple channel of uniform depth similar to the 1-d analysis case. However, the depth of the channel is now 30 m, and the domain is described using 70x32 200 m square cells. The simulation is forced from the 'west' of the domain with the tidal elevation ramped up to a peak amplitude of 4 m over an equivalent ¼ tidal period, and then maintained at this level to generate a steady state solution. The downstream boundary is prescribed using a radiation boundary condition based on the wave equation in a similar manner to the Sommerfeld radiation condition. The same test case is considered both in 2-d and 3-d (10 σ-layers). The 2-d model output with 10%, 20% and 50% energy extraction in the centre of the domain is compared with the no extraction case in figure 6. This is a very similar case to the 1-d analysis, as is reflected in the many similarities
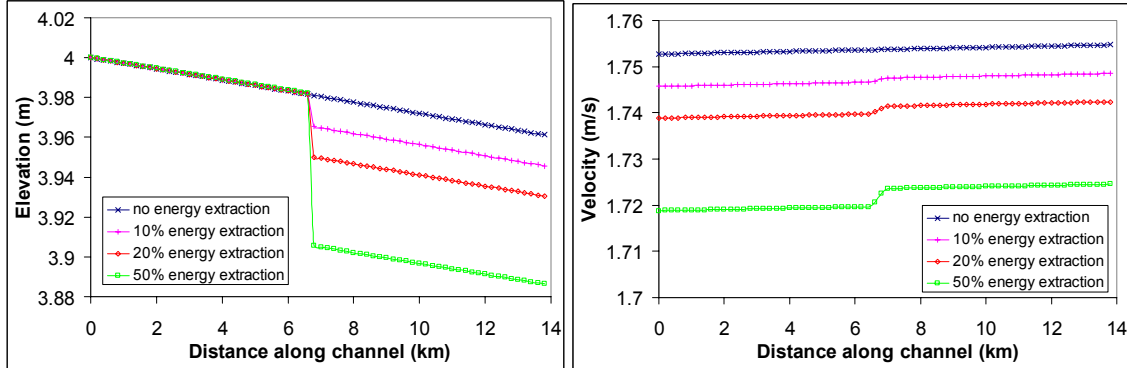

Figure 6: Comparison of 2-d stream-wise flow development with varying levels of energy extraction (a) elevation profiles, (b) depth-averaged velocity profiles.

in the results. In the no extraction case, the elevation profile demonstrates the familiar 'friction-slope' which is balanced through the continuity equation by the steadily increasing depth-averaged velocity as you move downstream. When energy is extracted from the momentum equations, the elevation is reduced in the vicinity of the extraction site, and the local depth-averaged velocity increases. However, the overall velocity in the system is reduced by energy extraction, both upstream and downstream of the extraction site. What is significant is that even when 50% of the potential energy passing through a cross-section is removed, the downstream head loss is only of the order of 2%, with the velocity reduced by a similar amount throughout the domain. It is also interesting to note that the effect of increasing the percentage of energy extracted (i.e. the percentage of equation 8 applied) is linear both in elevation and velocity once steady state has become fully established (3 to 4 hours of simulated time after initiating constant input boundary conditions). This is in contrast with the 1-d analysis.

The same experiment was conducted using the 3-d σ-coordinate version of TFD. 10 σ-layer were employed, only this time, energy was extracted from layers 3,4,5,6 and 7. This is in keeping with a turbine blade diameter of order 15 metres, giving 6 metres clearance at the sea-bed to prevent fouling and avoid boundary layer flows, and 9 metres clearance at the surface to allow for low tidal amplitudes, storm surge, wave action, etc.[5]. The results produced (figures 7 and 8) are similar to those produced in the 2-d case, as can be seen by comparing the elevation profiles (figures 6a and 7a). This is not surprising. However the 3-d results do provide some interesting results in the vertical profile. Examining the variation of velocity in the stream-wise direction, it is immediately clear that there are significant differences between the layers where energy is extracted (as in figure 7b) and those where energy is not extracted (figures 8a and 8b). Figure 7b indicates the expected reduction in velocity in the mid-layer region both upstream and downstream of the energy extraction site. The largest velocity deficit in comparison with the unexploited site occurs in the immediate vicinity and downstream wake
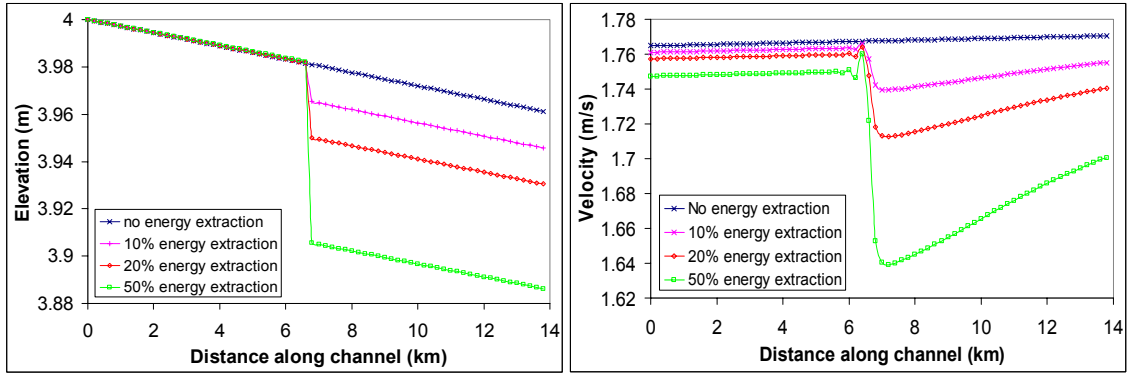
Figure 7: Comparison of 3-d stream-wise flow development with varying levels of energy extraction (a) elevation profiles, (b) layer integrated velocity for σ-layer 5 (of 10).
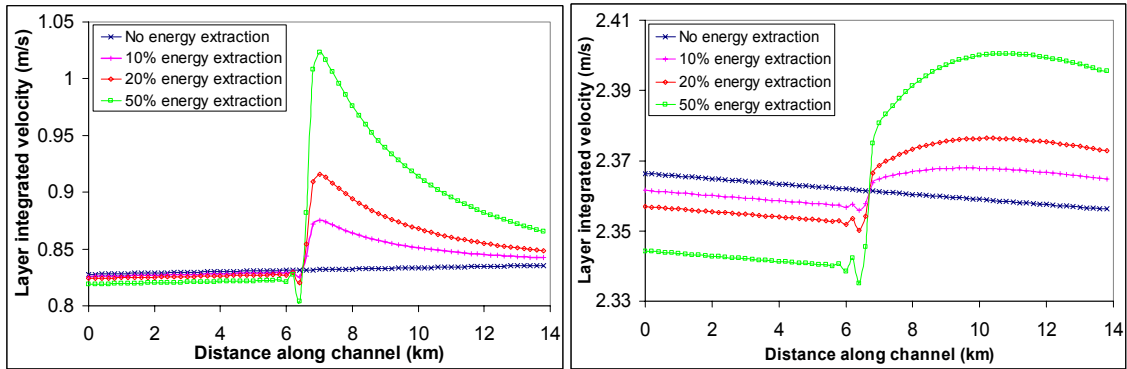

Figure 8: Layer integrated velocity profiles through the water column, (a) σ-layer 1 (bottom), and (b) σ-layer 10 (top)

of the extraction site (7.5% of the undisturbed flow velocity). In the surface and bottom layers where no extraction is taking place, the development is markedly different. In the upstream region the velocity is reduced as in the extracted layers, however downstream of the extraction site, the velocity is *increased* (20% at σ = 0.05 (bottom), and 1.5% at σ = 0.95 (top)), even although energy has been extracted from the system. It also appears that in the surface layers at least, the increased downstream flow velocity is maintained at elevated levels in contrast with the other layers where the flow variation appears to be returning to pre-extraction levels within the domain length. This is confirmed by the vertical velocity profiles presented in figure 9. The profiles were obtained from the 50% extraction simulation (at 10% and 20% extraction levels, there was little differentiation
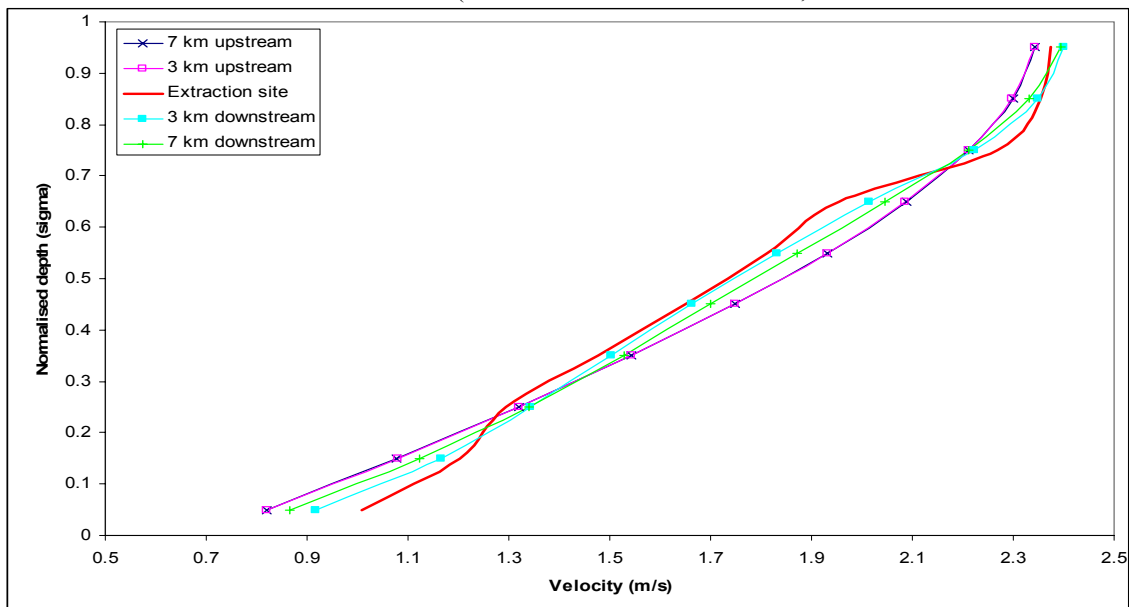

Figure 9: Representative vertical velocity profiles across the domain length indicating influence of energy extraction (set at 50%)

between the profiles). The limited effect of energy extraction upstream is indicated by the overlapping of the 2 upstream profiles which display the expected characteristic vertical profile shape. At the extraction site (thick line with no markings) a number of interesting features can be observed: (i) increased flow velocity near the sea-bed which could have important implications for scouring of bed material, (ii) the decrease in flow velocity through the layers where energy is extracted alters the traditional shape of the vertical profile, and (iii) increased flow velocity at the surface, which coupled with the decreased flow velocity in the interior creates a region of particularly high shear in the horizontal flow between $\sigma = 0.65$ and $\sigma = 0.75$ which could be of significance when considering dispersion and distribution of biological species or waste material. In the downstream region, the profiles exhibit some of the properties of both the upstream and extraction site regimes. It is apparent that the vertical structure of the stream-wise flow is slowly returning to the upstream condition with distance from the extraction site. However, even at 7 kilometres downstream (the extent of the idealised domain), the influence of energy extraction can still be observed (although the relative variation in velocity far upstream compared with far downstream is small - of the order of a couple of percent).

CONCLUSION

In the opinion of the authors the numerical modelling presented suggests that the potential for energy extraction from rapid tidal currents is significant. The analysis indicates that the potential energy extraction from the system is almost unlimited, as the feedback on the currents when considering feasible extraction limits from an engineering perspective are negligible. Continued development of this analysis and the numerical modelling tools involved will provide a powerful means of addressing potential environmental concerns that are raised from the installation and operation of tidal 'farm' sites as well as enhancing our understanding of the underlying physics. However, it must be recalled that the results presented relate to steady state flow conditions and the situation may not be as 'simple' and clear-cut when the research is extended to temporally varying tidal flows. Furthermore, the simplified approach presented assumed that energy was being extracted across the entire 2-d or 3-d cell face presented to the flow, whereas in reality the swept area of a tidal turbine would be a small fraction of this area, particularly when considering limitations on turbine spacing both laterally and horizontally to minimise wake interaction. These and other related issues (e.g. laboratory testing and comparison with numerical simulations) will be addressed as the research and model development progress.

ACKNOWLEDGEMENTS

REFERENCES

1. Bryden, I.G.; Bullen, C.; Baine, M. & Paish, O. 1995. 'Generating Electricity from Tidal Currents in Orkney and Shetland', *Underwater Technology*, Vol. 21 No. 2.
2. MacLeod, A.; Barnes, S.; Rados, K.G. & Bryden, I.G. 2002. 'Wake Effects in Tidal Current Turbine Farms', *Proceedings of Marec 2002*, Newcastle.
3. Blumberg, A.F. & Mellor, G.L. 1987. 'A Description of a Three-Dimensional Coastal Ocean Circulation Model', *In N.S. Heaps (Ed.), Three-Dimensional Coastal Ocean Models*. pp. 1-16. The American Geophysical Union, ISBN: 0-87590-253-7.
4. Drago, M. & Iovenitti, L. 2000. 'σ-Coordinates hydrodynamic numerical model for coastal and ocean three-dimensional circulation', *Ocean Engineering*, Vol. 27, pp. 1065-1085.
5. Melville, G.T., Rados, K., Bryden, I .G., Model to Optimise the Electrical and Economic Performance of Tidal Current Energy Conversion Systems published in the proceedings of *Marine Renewable Energy Conference (MAREC)* 2001, University of Newcastle. (2001)