

Hydro-environmental Impact Assessment of the Significance of the Shape of Arrays of Tidal Stream Turbines

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Abstract: This study focuses on far-field hydro-environmental impacts of turbine arrays, with different shapes located in the Severn Estuary and Bristol Channel, UK, using a dynamically linked 1-D/2-D hydro-environmental model. The estuary, including the Bristol Channel, is approximately 200 km long and has the third highest rise and fall of tide in the world, with typical spring tidal range of over 14 m, whilst the spring tidal currents in the estuary are well in excess of 2 m/s. There are a number of tidal renewable energy options being considered around the Severn Estuary, including but not limited to: tidal stream turbines, offshore tidal impoundments and a barrage - at various locations. The model was used to predict the hydrodynamic, sediment transport and water quality processes as well as power output predictions. In order to simulate the impact of the tidal stream turbines, the model was refined and the turbines were included as momentum sinks in the momentum equation.

This study shows that the impact of the arrays on the water levels was negligible. However, the impact on velocities was more significant and the flow was retarded both upstream and downstream of the arrays, whilst it was faster on the side of the arrays. It was found that changes in the suspended sediment concentrations did not follow a simple pattern and that more detailed model studies are required to achieve a better understanding of this process. Finally, it was found that the power generated was dependent on the array layouts with the power output of different arrays used in this study varied by up to 20%.

Keywords: Marine renewable energy, Hydro-environmental modelling, Tidal stream turbines, Severn Estuary and Bristol Channel.

1. Introduction

The European Union have introduced targets among member states to increase the share of renewable energy in the overall energy consumption to 20% of total energy budget by 2020, this is almost three times the levels of 2008. Amongst the different types of renewable energy, marine renewable energy is an emerging energy sector with a bright future. Tidal devices and, in particular, tidal stream turbines have attracted considerable interest in recent years, due to the vast resources available in parts of the EU, modularity, minimal visual impact and their predictable energy generation.

As for many other emerging renewable schemes, the environmental impacts of tidal stream turbines are not clear and therefore need to be investigated before considering any site for deployment of such turbines. Although every single tidal stream device has a small footprint, the overall impact of an array of turbines can only be investigated by considering the scale of the array.

This study focuses on hydro-environmental modelling of different arrays of turbines and investigating the impact of the shape and density of the arrays on the flow, water levels, sediment transport and faecal bacteria concentrations as well as the energy output. The site selected for this study is the Severn Estuary and Bristol Channel, UK (shown in Fig. 1), which has the third largest tidal range in the world with typical spring and neap tidal ranges peaking at over 14 m and 7 m respectively, and the spring tidal currents are well in the excess of 2m/s. The site is one of the most attractive sites for marine renewable energy schemes and a number

of schemes, including several barrages sites, lagoons and stream turbines have been proposed for the area.

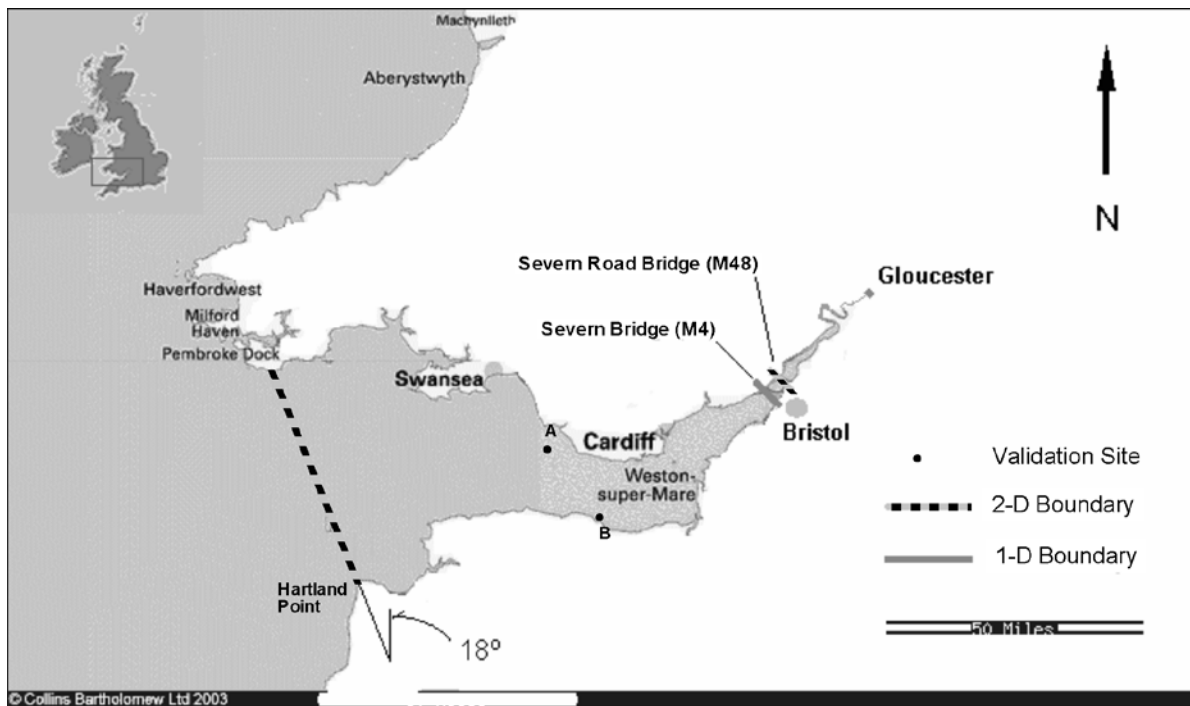


Fig 1. The model domain extent and validation sites. Site A: Southerndown Site, B: Minehead Site (Source: Yang et al. ¹)

2. Hydro-Environmental Modelling Methodology

The dynamically linked DIVAST (Depth Integrated Velocities And Solute Transport) and FASTER (Flow And Solute Transport in Estuaries and Rivers) models were implemented to model the hydro-environmental impacts of the stream turbines. The modelling domain was extended from the outer Bristol Channel, close to Lundy Island (where an imaginary line between Milford Haven and Hartland Head can be drawn) at the western end of the domain to Gloucester at the eastern extremity (Fig. 1). Both, DIVAST and FASTER models are based on a finite difference alternating direction implicit solution of the Reynolds Averaged Navier-Stokes equations and the solute transport equation in 2D and 1D, for the hydrodynamic, sediment transport and water quality process predictions respectively². The solute/sediment concentrations were calculated considering the effects of dispersion, diffusion, decay, adsorption and desorption as well as deposition and erosion.

The 2D downstream boundary was a water level boundary and the water level values for the simulation period at this location were obtained from the Proudman Oceanographic Laboratory (POL) Irish Sea model. Since this boundary was so far seawards of the region of interest, the concentrations of faecal indicator organisms were set to zero along the downstream boundary. The 2D upstream boundary was a flow boundary, flow and all the water quality indicators were dynamically transferred through the 1D-2D link. A flow rate varying between 60m³/s and 106 m³/s was used as a 1-D upstream model boundary condition, at Gloucester. The downstream boundary of the 1D model, located close to the Severn Bridge, was specified as a water level boundary and the values of the water levels were acquired from the 2D model. A structured 200×200 m² grid was used for the 2D model while the 1D model

was consisted of four reaches and two junctions with an average distance between the two consecutive cross-sections being approximately 240 m.

2.1. Governing Equation

Only the 2D model governing equations are briefly explained in this section, for more information on the 2D and 1D models refer to: Falconer³ and Kashfipour⁴. The 2D hydrodynamic equations used in this model are based on the depth-integrated three-dimensional Reynolds equations for incompressible and unsteady turbulent flows. Also, the effects of the bottom friction, wind shear and the earth's rotation are included to give for the x-direction⁵:

$$\frac{\partial \xi}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (1)$$

$$\frac{\partial q_x}{\partial t} + \beta \left[\frac{\partial u q_x}{\partial x} + \frac{\partial v q_x}{\partial y} \right] = f q_y - g H \frac{\partial \xi}{\partial x} + \frac{\tau_{xw}}{\rho} - \frac{\tau_{xb}}{\rho} + \varepsilon \left[2 \frac{\partial^2 q_x}{\partial x^2} + \frac{\partial^2 q_x}{\partial y^2} + \frac{\partial^2 q_y}{\partial x \partial y} \right] \quad (2)$$

where q_x, q_y = discharges per unit width in the x, y directions ($\text{m}^2 \text{s}^{-1}$), ξ = water surface elevation above datum (m), H = total water depth (m), β = momentum correction factor for non-uniform vertical velocity profile, f = Coriolis parameter (rad s^{-1}), g = gravitational acceleration (ms^{-2}), τ_{xw}, τ_{xb} = surface and bed shear stress components respectively in the x -direction (N m^{-2}), and ε = depth averaged eddy viscosity. The equation for the y -direction can be written similarly to that given for the x -direction (i.e. equation (2)).

The 2D advective-diffusion equation for predicting solute transport is acquired by integrating the 3D solute mass balance equation over the depth, giving:

$$\frac{\partial \phi H}{\partial t} + \frac{\partial \phi q_x}{\partial x} + \frac{\partial \phi q_y}{\partial y} - \frac{\partial}{\partial x} \left[HD_{xx} \frac{\partial \phi}{\partial x} + HD_{xy} \frac{\partial \phi}{\partial y} \right] - \frac{\partial}{\partial y} \left[HD_{yx} \frac{\partial \phi}{\partial x} + HD_{yy} \frac{\partial \phi}{\partial y} \right] = H \Sigma \Phi \quad (3)$$

where ϕ = depth averaged concentration (unit/volume) or temperature ($^{\circ}\text{C}$), H = total water depth (m) and $\Sigma \Phi$ = total depth average concentration of the source or sink solute. The bacteria decay can be modelled using a first order decay formulation according to Chick's Law⁶ and given as:

$$\frac{dC}{dt} = -KC \quad (4)$$

where K = decay coefficient, generally expressed in units of day^{-1} ; t = time (s^{-1}) and C = bacterial concentration, expressed herein as Colony-Forming Units (CFU) per 100ml.

Some researches have shown that the concentration of Faecal Indicator Bacteria (FIB) on bed sediments can be 100-2000 times higher than the concentrations within the water column^{7, 8, 9}. This suggests that the sediment re-suspension or deposition can increase or decrease the

bacteria levels, respectively. This emphasises the importance of including the interaction of sediment and bacteria while predicting the bacteria concentration. Hence, to model the bacteria processes more realistically, the interaction of the sediment and bacteria has been included in the model as outlined in: Stapleton et al.^{10,11}, Yang et al.¹ and Ahmadian et al.¹².

2.2. Model Calibration and Validation

The model predictions were initially calibrated using Admiralty Chart data and finally the field data collected by Stapleton et al.^{10,11} at two locations at two sites (shown in Fig. 1) were used to validate the model predictions. The model predictions showed good agreement with the validation data, more information regarding the model validation can be found in Ahmadian et al.¹². Typical comparisons between the measured and predicted water elevations, current speeds, sediment fluxes and faecal bacteria concentrations are shown in Fig. 2 and Fig. 3 respectively.

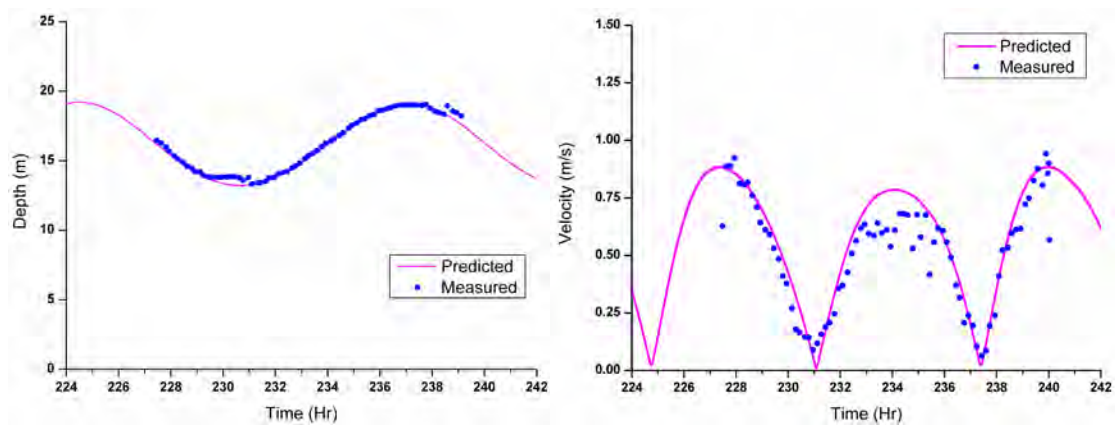


Fig 2. Comparison of predicted and measured water elevations (left) and current speeds (right) at Minehead (site B)

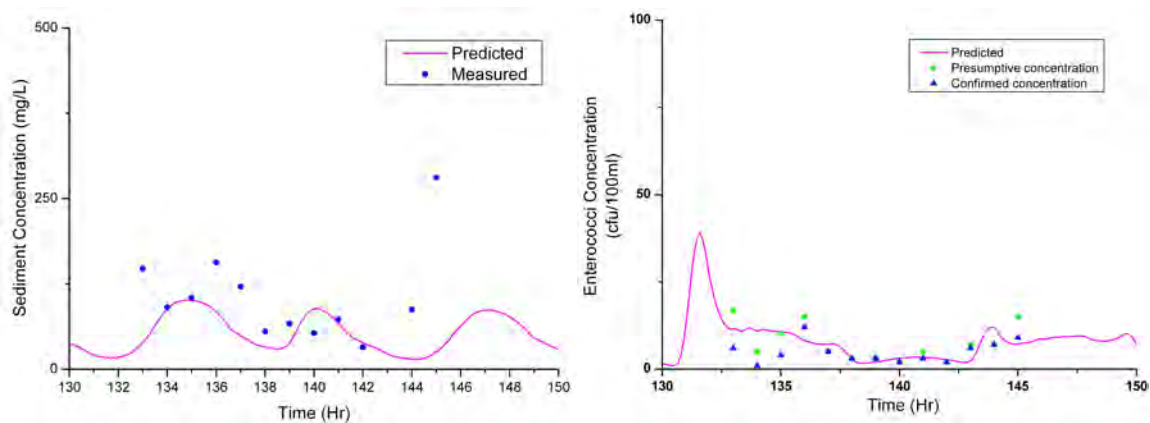


Fig 3. Comparison of predicted and measured suspended sediment concentrations (left) and enterococci concentrations (right) at Southerndown (Site A)

2.3. Turbines Modelling

Using the same analogy as used for wind turbines, the energy flux available for a turbine is ¹³:

$$P = \frac{1}{2} C_p \rho A U^3 \quad (5)$$

where P = energy flux (W m^{-2}), ρ = water density (kg m^{-3}), A = area of the control volume (m^2), U = component of the water flow velocity perpendicular to the cross-section of the channel (ms^{-1}) and C_p = power coefficient. Energy extraction by turbines, consequently, causes a thrust force (T) induced on the turbine in the direction of flow and can be calculated as¹³:

$$T = \frac{1}{2} C_T \rho A U^2 \quad (6)$$

where C_T = thrust coefficient. It is shown that both the power and thrust coefficients are related to the hub pitch and varies with the Tip Speed Ratio (TSR)¹³. In this study, the momentum equation (Eq. 2) was modified to include the impact of the turbines.

3. Modelling Results

The model was then applied to three imaginary arrays of turbines in the Severn Estuary and Bristol Channel (illustrated in Fig. 4), and the impacts of the arrays on water levels, current speed, sediment transport and faecal bacteria levels were investigated. These arrays are arbitrary and were chosen purely for the model demonstration purposes and none of the protocols required for a site selected for deployment of turbines¹⁴ have been taken into account in selecting these sites. It was assumed that the same number of turbines were deployed in each formation. Formations a and b occupied the same area and consequently, have the same number of turbines per unit area, which will be referred to as the array density in this paper, while the density of the formation c is more than 10 times less than the formations a and b.

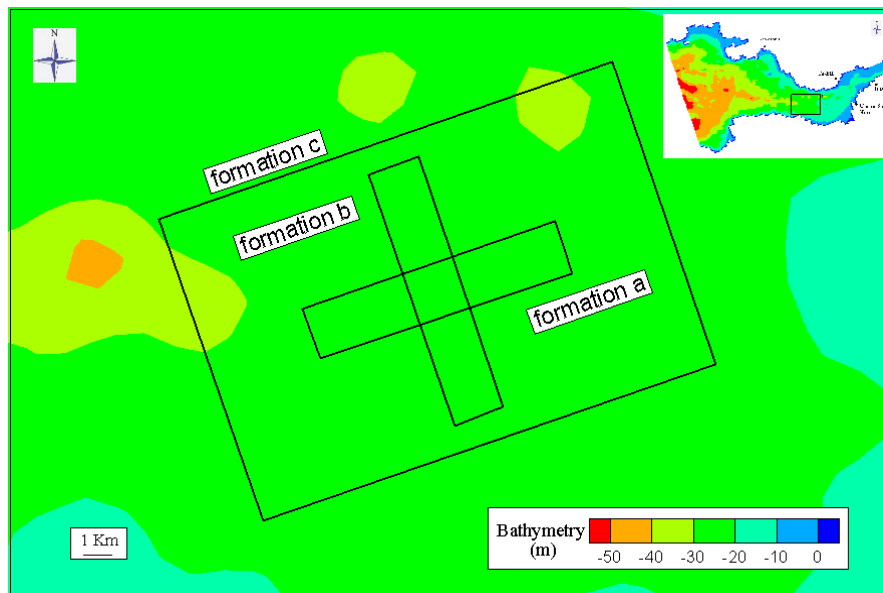


Figure 4: Array Formations

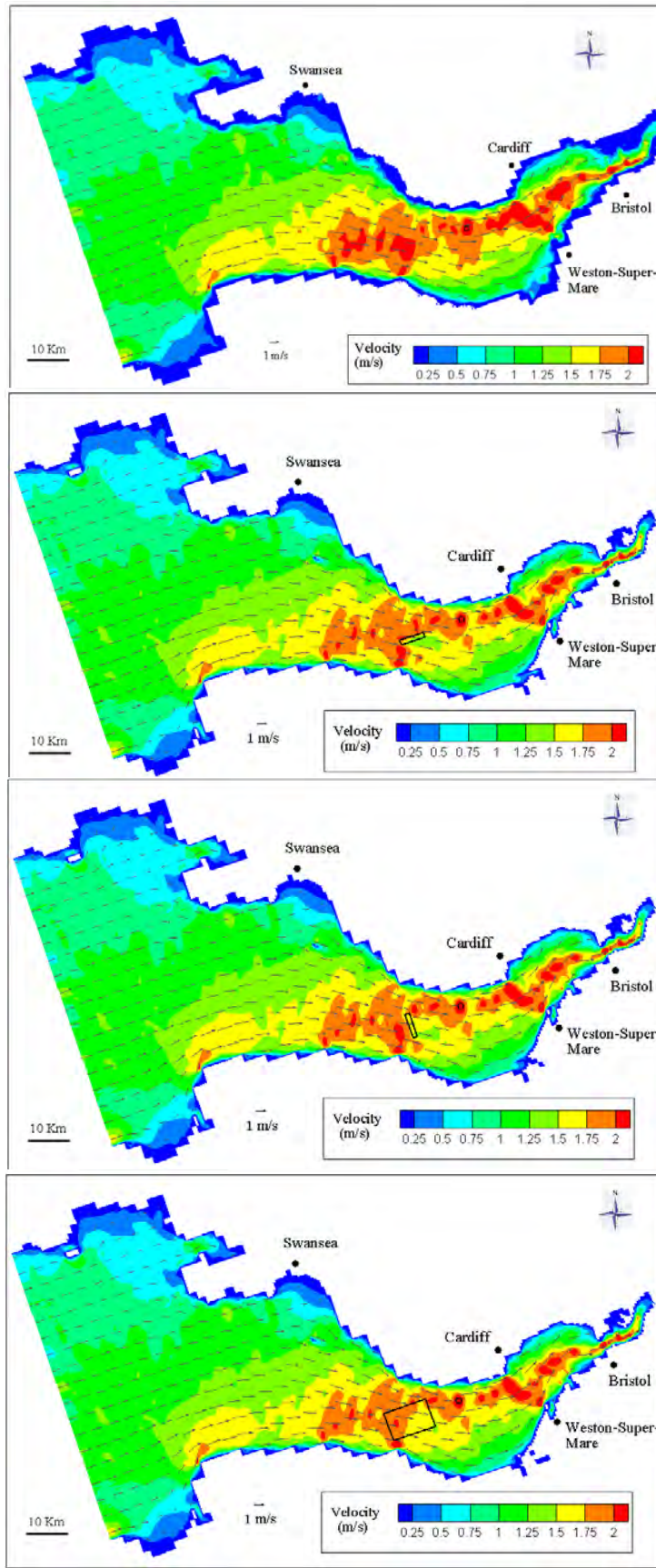


Figure5: Comparison of the velocities across the estuary without (i) and with different array formations; “formation a”(ii), “formation b”(iii) and “formation c”(iv) at mean flood at Barry (red dot)

The current speeds in the estuary at mean flood at Barry (red dot) before including the arrays and with the different arrays are shown in Fig. 5. Although, in this study it was assumed that the turbines can rotate to face the flow and subsequently the flow speed is equal to the effective velocity on the turbine, it can be seen that arrays with the same density but different orientations can impact the flow differently. It can also be seen that the arrays with a smaller density would change the currents to a much lesser extent while the average electricity generated by each turbine in this array can be up to 50% more than the average electricity generated by the turbines in the denser arrays. It was also found that the arrays would not change the water levels noticeably, however, as a result of changes in the currents sediment transport the faecal bacteria levels would be altered. These results are not shown here in the interest of space, however, publication of results will follow.

4. Conclusions

The dynamically linked 1-D/2-D hydro-environmental model of the Severn Estuary and Bristol Channel has been refined to assess the hydro-environmental impacts of an arbitrary array of tidal stream turbines by including the turbines as momentum sinks in the momentum equation. The model without the turbines was first calibrated and then was validated against field data.

The model was used to study the hydro-environmental far-field impacts of different shapes of an array of tidal turbines and the electricity generated. It was found that the impact of any formation of the arrays on the water levels were negligible. However, the impacts on velocities were more significant and the flow was retarded both upstream and downstream of the arrays, while it was faster on the side of the arrays. Although, this pattern was consistent for all the arrays, the extent of changes in the velocity was different regarding to the array formation. These changes were less significant for a less dense array (formation c), however, the average electricity generated by each turbine in this array was up to 50% more than the average electricity generated by the turbines in the denser arrays. Finally it was also found that the changes in the sediment and faecal bacteria levels were higher in the denser arrays.

5. Acknowledgements

The study is carried out as a part of MAREN project which is part funded by the European Regional Development Fund (ERDF) through the Atlantic Area Transnational Programme (INTERREG IV).

References

- [1] Yang, L., Lin, B. and Falconer, R. A., 2008. Modelling enteric bacteria levels in coastal and estuarine waters. *Proceedings of Institution of Civil Engineers, Engineering and Computational Mechanics*, 161(4), 179-186.
- [2] Kashefipour, S. M., Lin, B., Harris, E. L. and Falconer, R. A., 2002. Hydro-environmental modelling for bathing water compliance of an estuarine basin. *Water Research*, 36(7), 1854-1868.
- [3] Falconer, R. A., (1992). Flow and water quality modelling in coastal and inland waters. *Journal of Hydraulic Research, IAHR*, 30(4), 437-452.
- [4] Kashefipour, S.M., Falconer, R.A., Lin, B., Harris, E.L. (2000). *FASTER Model Reference Manual*. Hydro-environmental Research Centre Report, Cardiff University.

- [5] Falconer, R.A. (1993). An introduction to nearly horizontal flows. In: Abbott, M.B. and Price, W.A., Coastal, Estuarial and Harbour Engineers' Reference Book. London: E & FN Spon Ltd., pp. 27-36.
- [6] Chick, H. (1910). The Process Of Disinfection By Chemical Agencies And Hot Water. *Journal of Hygiene*. 10 (2), pp. 237-286.
- [7] Marshall, K.C. (1978). The effects of surfaces on microbial activity. *Water Pollution Microbiology*. vol. 2, pp. 51–70.
- [8] Burton, G.A., Gunnison, D. and Lanza, G.R. (1987). Survival of Pathogenic Bacteria in Various Freshwater Sediments. *Applied and Environmental Microbiology*, 53(4), pp. 633-638.
- [9] Obiri-Danso, K. and Johns, K. (2000). Intertidal sediments as reservoirs for hippurate negative campylobacters, salmonellae and faecal indicators in three EU recognised bathing waters in North West England. *Water Research*. 34(2), pp. 519-527.
- [10] Stapleton, C.M., Wyer, M.D., Kay, D., Bradford, M., Humphrey, N., Wilkinson, J., Lin, B., Yang, Y., Falconer, R.A., Watkins, J., Francis, C.A., Crowther, J., Paul, N.D., Jones, K. and McDonald, A.T., 2007a. Fate and Transport of Particles in Estuaries, Volume II: Estimation of Enterococci Inputs to the Severn Estuary from Point and Diffuse Sources. Environment Agency Science Report SC000002/SR2, Bristol: Environment Agency.
- [11] Stapleton, C.M., Wyer, M.D., Kay, D., Bradford, M., Humphrey, N., Wilkinson, J., Lin, B., Yang, Y., Falconer, R.A., Watkins, J., Francis, C.A., Crowther, J., Paul, N.D., Jones, K. and McDonald, A.T., 2007b. Fate and Transport of Particles in Estuaries, Volume IV: Numerical Modelling for Bathing Water Enterococci Estimation in the Severn Estuary. Environment Agency Science Report SC000002/SR4, Bristol: Environment Agency.
- [12] Ahmadian, R., Falconer, R.A. and Lin, B.L. (2010). Hydro-environmental modelling of proposed Severn barrage, UK. *Proceedings of the Institution of Civil Engineers, Energy*, 163(EN3), pp 107–117.
- [13] Bahaja, A.S., Mollandb, A.F., Chaplina, J.R. and Batten, W.M.J., 2007. Power and thrust coefficients of marine current turbines operating under various hydrodynamic conditions of flow in cavitation tunnels and towing tanks. *Renewable Energy*, 32, pp. 407–426.
- [14] Willis, M., Masters, I., Thomas, S., Gallie, R., Loman, J., Cook, A., Ahmadian, A., Falconer, R., Lin, D., Gao, G., Cross, M., Croft, N., Williams, A., Muhasilovic, M., Horsfall, I., Fidler, R., Wooldridge, C., Fryett, I., Evans, P., O'Doherty, T., O'Doherty, D., and Mason-Jones, A., 2010. Tidal Turbine Deployment in the Bristol Channel – A Case Study, *Proceeding of Institution of Civil Engineers- Journal of Energy*, 163(3), pp. 107–117.