WATER QUALITY IMPACTS OF A TIDAL BARRAGE IN THE SEVERN ESTUARY, UK

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The Severn Estuary has the third highest tidal range in the world with its spring tidal range reaching 14 m. The estuary is extremely turbid with very high suspended sediment concentrations and limited light penetration through the water column. It has large areas of intertidal mudflat which are of major conservation importance. Hence, it is protected under several European legislative directives and has a number of international designations. Due to its high tidal range, it is an ideal location for the installation of a tidal barrage, making the estuary a major candidate for large scale commercial exploitation of tidal renewable energy resource for electricity generation in the UK. However, there is considerable uncertainty as to how a tidal barrage would affect water quality in the estuary and its water management strategies. This study aims to address this research gap by combining laboratory and numerical modelling investigations to assess the potential impacts of a tidal barrage on water quality in the Severn Estuary, with particular emphasis on salinity and phosphate levels. Salinity at high water was found to reduce by 1 – 2 ppt downstream and upstream of the barrage, with up to 5 ppt reduction further upstream. However, only a slight reduction of 0.5 - 1 ppt was predicted downstream and upstream of the barrage at low water. Phosphate adsorption to suspended sediments was found to increase with decreasing salinity. The partition coefficient, K_d, of phosphate as a function of salinity was empirically described for incorporation into the model to further refine the model predictions.

INTRODUCTION

There are strong indications that the growing interest in tidal energy will lead to the implementation of several tidal renewable energy structures and devices, such as barrages and tidal stream turbines, in the next few decades around the UK. Several numerical modelling studies have shown that these schemes could have a range of impacts on the hydro-environment including changes to tidal currents, water levels, salinity and sediment transport concentrations due to alterations in the tidal flow characteristics [1 – 3]. However, the potential knock-on impacts on water quality, particularly nutrient levels, and eutrophication potential has received significantly less attention to date.

Nutrients are of significant importance in estuaries because excessive nutrient inputs could cause the prolific growth of algae, resulting in eutrophication. Eutrophication is defined as the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water column and to the quality of the water [4]. It leads to an array of changes including increased mortality of aquatic invertebrates and fish populations, reduction in dissolved oxygen and the overall deterioration of water quality [5].

In the water column, nutrients, and particularly phosphates, are present either in solution (i.e. dissolved phase) or adsorbed to suspended sediments (i.e. particulate phase) and the distribution between these two phases is of fundamental significance in environmental impact assessment modelling [6, 7]. In estuaries, the adsorption of phosphate to sediments is affected by estuarine controlling factors, such as salinity and temperature [8], hence it is a difficult task to predict the levels from theoretical considerations.

This study aims to combine a laboratory experimental study and numerical modelling using the three dimensional (3-D) Environmental Fluid Dynamics Code (EFDC) computational model in assessing the potential water quality impacts of tidal renewable energy schemes in the Severn Estuary, with particular emphasis on salinity and phosphate levels. The laboratory experiments were designed to obtain data on the effect of salinity on phosphate adsorption to suspended sediments, in order to refine the key coefficient which describes phosphate adsorption in the computational model. This will enable a more robust numerical modelling assessment which takes into account salinity effects on phosphate adsorption. Such model refinements are particularly important for tidal renewable energy schemes, in that when they are implemented at scales required to generate substantial amounts of electricity, they will inevitably lead to changes in salinity. This paper gives a brief description of the EFDC model and shows laboratory experimental results as well as numerical modelling results.

MATERIALS AND METHODS

Numerical model description

The EFDC model is composed of four major modules which include a hydrodynamic module, a water quality module, a sediment transport module, and a toxics module for simulating flow, transport, and biogeochemical processes in surface water systems, including estuaries. The hydrodynamic module is directly coupled to the water quality, sediment transport, and toxics modules. The model was originally developed at the Virginia Institute of Marine Science and has since been used in more than 60 modelling studies. The physical representation of the hydrodynamic model in EFDC is based on the Princeton Ocean Model (POM) [9]. It uses Cartesian, or curvilinear, orthogonal horizontal coordinates and a stretched or sigma vertical coordinate. The model's governing equations consist of the equations of: continuity, momentum and temperature/constituent transport, with the equations being solved using a second-order accurate spatial finite difference scheme on a staggered or C grid. A unique feature of the numerical solution method for the momentum equations is an internal-external mode splitting scheme, which reduces the computational time. The water quality module simulates spatial and temporal distributions of three algal groups, various components of carbon, nitrogen, phosphorus and silica cycles, faecal coliform bacteria and dissolved oxygen dynamics. The direct link of the water quality module to the hydrodynamic module eliminates numerical instability and modification of estuarine circulation during the water quality modelling [10]. Most of the kinetic processes included in the model are from the Chesapeake Bay three-dimensional water quality model, CE-QUAL-ICM [11, 12]. The EFDC model was refined to include a barrage module for simulating tidal flows through a renewable energy barrage structure, including sluice gates and turbines.

Adsorption experiment

Water samples were collected from the Severn Estuary. The collected water samples were filtered using 0.45 μm cellulose acetate filters and the suspended sediments were retained and air-dried for use in the experiments. The filtered seawater was diluted with deionised water to attain salinities of 1, 2, 5, 10 and 25 ppt. The diluted seawater was spiked with a phosphate standard (Sigma Aldrich, analytical grade) to achieve solutions with a final spiking concentration of 1 mgL^{-1}. The spiked solutions were added to suspended sediment to achieve suspended sediment concentrations of 0.001, 0.002 and 0.003 g mL^{-1}. The suspensions were shaken on a flatbed shaker at 250 rpm for 24 hours and filtered through a 0.45 μm cellulose acetate membrane filter. The filtrate and the sediment were analysed for adsorbed and dissolved phosphate as described in [13] and the partition coefficient (Kd) was calculated.

RESULTS AND DISCUSSION

Numerical modelling

The refined EFDC model with a barrage for the Severn Estuary was used to model the hydrodynamic and salinity processes in the Estuary and the model predictions generally agreed well with the field data [14].

The EFDC model was then applied to investigate the hydrodynamic processes in the estuary for a range of scenarios, both with and without the barrage, with the corresponding results showing that with the barrage the maximum water level would be significantly reduced in a large part of the Severn Estuary, especially upstream of the barrage. From the predicted minimum water depths, it has been shown that there would be a mean spring tide loss of 80.5 km^2 of intertidal habitats due to construction of the barrage. Meanwhile, the peak tidal currents would be considerably reduced, and by as much as a half in some areas along the main channel.

The comparisons for the predicted salinity concentrations between the cases with and without the barrage indicated that at high water, the salinity concentration would be reduced by 1-2 ppt downstream and upstream of the barrage and in the region near the Severn Crossing bridge, the value would be reduced by up to 5 ppt, and that at low water, salinity concentrations would be reduced by 0.5 – 1 ppt in the middle of the Bristol Channel and by 0.5 ppt and 1 ppt downstream and upstream of the barrage, respectively. The predicted results also indicated that the salinity concentration values downstream and upstream of the barrage would be under a relatively stable condition with slight oscillations due to the effect of the barrage.

Also, the results indicate that the reduction in the water volume and the maximum velocity entering the Severn Estuary would influence the transportation of suspended sediments, and the corresponding bacteria and other water quality indicator levels in the water column. The relative impacts on the environmental effects of these water quality parameters are being investigated currently using the EFDC model with the barrage module.

Adsorption experiment

A decrease was observed in the percentage of phosphate adsorbed with increasing salinity and this trend occurred in all the three suspended sediment concentrations used in the experiments as shown in [13]. The decrease in phosphate adsorption with increasing salinity observed in this study is consistent with previous studies which have examined the factors affecting phosphate adsorption to sediments [8, 15, 16] and can be attributed to competitive adsorption by seawater anions.

The partition coefficient (Kd) of phosphate as a function of salinity which is shown in [13] decreases with increasing salinity for the suspended sediment concentrations used in the experiments. This effect has been found for other types of sorbates, including metals and hydrophobic organic compounds, and for several types of sorbents, including clay, sediment, soil and sludge [17, 18]. These studies have proposed several hypotheses to explain this effect including adsorption to a third colloidal phase operationally defined as part of the dissolved fraction, reaction kinetics, particle-particle interactions, experimental artifacts and sorption reversibility. Given the data collected in this study, it is difficult to explain this effect but it is likely due to a combination of several physical and chemical mechanisms.

In order to embody this effect of salinity on phosphate adsorption into the EFDC model**, t**he partition coefficient, Kd, of phosphate as a function of salinity was empirically described by a power law function which is currently being used to further refine the EFDC model with the barrage module.

CONCLUSIONS

Globally, tidal renewable energy would play an important role in the generation of electricity in the future. However, the operation of tidal renewable energy schemes can have a significant impact on the hydro-environment. The overall aim of this study has been to combine a laboratory experimental study and numerical modeling, using the EFDC model, in assessing the potential impacts of tidal renewable energy schemes in the Severn Estuary on water quality with particular emphasis on salinity and phosphate levels. The numerical modelling investigation has shown that a tidal barrage would result in a reduction in salinity in the estuary. A comparison of the model predictions with a barrage and without a barrage indicated that, at high water, salinity would be reduced by 1- 2 ppt downstream and upstream of the barrage, with a further 5 ppt reduction further upstream, and that at low water, salinity would be reduced by only 0.5 - 1 ppt both upstream and downstream of the barrage. In addition, phosphate adsorption to suspended sediments was found to increase with decreasing salinity in the laboratory experimental study. The partition coefficient, Kd, of phosphate as a function of salinity was empirically described for incorporation into the EFDC model. This will allow for a more robust numerical modelling assessment, which embodies salinity effects on phosphate adsorption and ultimately assist environmentalists and planners involved in assessing the aquatic environmental risks and impacts of tidal renewable energy schemes.

REFERENCES

[1] Falconer R.A., Xia J., Lin B., Ahmadian R., The Severn Barrage and other tidal energy options: Hydrodynamic and power output modelling, Sci. China Ser. E-Tech. Sci. 52 (2009) 3413-3424.
[2] Xia J.Q., Falconer R.A., Lin B., Hydrodynamic impact of a tidal barrage in the Severn Estuary, UK, Renewable Energy 35 (2010) 1455-1468.
[3] Ahmadian R., Falconer R.A., Lin B., Hydro-environmental modelling of proposed Severn barrage, UK, Proc. of the ICE, Energy 163 (2010) 107-117.
[4] Comprehensive studies for the purposes of Article 6 and 8.5 of DIR 91/271 EEC, The Urban Waste Water Treatment Directive. Published for the Comprehensive Studies Task Team (CSTT) by Department for the Environment for Northern Ireland, Environment Agency, Scottish Environment Protection Agency and Water Services Association, 1997.
[5] Connell D.W., Basic concepts of environmental chemistry, CRC Press, Boca Raton, Florida, 2005.
[6] Sibley, T.H. and Myttenaere, C. (Eds.), Application of Distribution Coefficients to Radiological Assessment Models. Elsevier, London, (1986).
[7] van der Kooij, L.A., van de Meent, D., van Leeuwen, C.J. and Bruggeman, W.A., Deriving quality criteria for water and sediment from the results of aquatic toxicity tests and product standards: application of the equilibrium partitioning method. Water Res., 25, (1991), 697-705.
[8] Zhang J. and Huang X., Effect of Temperature and Salinity on Phosphate Sorption on Marine Sediments, Environ. Sci. Technol., 45 (2011), 6831-6837.
[9] Blumberg, A.F., Mellor, G.L., A description of a three-dimensional coastal ocean circulation model. In: Heaps, N.S. (Ed.), Three-Dimensional Coastal Ocean Models, Coastal and Estuarine Science, vol. 4. American Geophysical Union, Washington, DC, (1987).
[10] Zou, R., Carter, S., Shoemaker, L., Parker, A., and Henry, T., Integrated hydrodynamic and water quality modelling system to support nutrient total maximum daily load development for Wissahickon Creek, Pennsylvania, J. Environ. Eng., 132, (2006), 555–566.
[11] Cerco, C. F. & Cole, T. M., Three-dimensional eutrophication model of Chesapeake Bay: Volume 1, main report. Technical Report EL-94-4, US Army Engineer Waterways Experiment Station, Vicksburg, MS (1994).
[12] Cerco C.F., and Cole T., User's guide to the CE-QUAL-ICM: three-dimensional eutrophication model, US Army Corps of Engineers, Vicksburg, MS, Technical Report EL-95-1-5, (1995).
[13] Kadiri MO, Bockelmann-Evans BN, Zhou J, Falconer RA, Water quality model development for estuaries: A combined numerical and experimental approach. 10th International Conference on Hydroinformatics (HIC), Hamburg, Germany (2012).
[14] Zhou J, Falconer RA, Lin B, Refinements to the EFDC model for predicting the hydro-environmental impacts of a barrage across the Severn Estuary, Renewable Energy , 62 (2014) 490-505 ISSN 0960-1481 10.1016/j.renene.2013.08.012
[15] Suzumura M., Ueda S. and Sumi E., Control of phosphate concentration through adosprion and desorption processesin groundwater and seawater mixing at sandy beaches in Tokyo bay Japan, J. Oceano., 56, (2000) 667-673.
[16] Millero, F. Huang, F. Zhu, X. Liu and X. Zhang, J., Adsorption and Desorption of Phosphate on Calcite and Argonite in Seawater. Aquatic Geochemistry 7, (2000) 33-56.
[17] Owens RE, Balls PW, Price NB., Physicochemical processes and their effects on the composition of suspended particulate material in estuaries: implications for monitoring and modelling., Mar Pollut. Bull 34 (1997)51-60.
[18] Tye R, Jepsen R, Lick W., Effects of colloids, flocculation, particle size, and organic matter on the adsorption of hexachlorobenzene to sediments. Environ. Toxicol. Chem., 15 (1996) 643-651.