Severn Estuary Commission

Western Gateway | Porth y Gorllewin

Call for Information

Relevant Data and Research Relating to the Severn Estuary: Cardiff University Studies

Independent Information Report

Submitted by

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Information Submitted by Roger A. Falconer and Reza Ahmadian

Introduction

The information presented in this report is primarily based on the understanding and experience gained by the authors in leading research teams and projects (2000 to 2024) in the Hydro-environmental Research Centre, at Cardiff University, on tidal energy schemes located in the Severn Estuary and Bristol Channel. These studies primarily related to predicting the impact of various tidal energy schemes, including barrages and lagoon, on a range of hydrodynamic, water quality and sediment transport processes in the Severn Estuary and Bristol Channel, as well as investigating the far field impacts outside of the basin.

1. Relevant Bio-details

Roger Falconer is Emeritus Professor of Water and Environmental Engineering (Professor 1997-18), at Cardiff University and Director of Roger Falconer Water Consultancy Ltd. (2016-). He was previously Professor of Water Engineering (1987-97) and Head of the Department of Civil Engineering (1993-97) at the University of Bradford, and Lecturer at the University of Birmingham (1977-87). He has extensive experience of leading research studies on hydro-environmental modelling (including tidal renewable energy) for river, estuarine and coastal basins and has published and presented extensively in the field of tidal energy.

His past and current key role experience in tidal renewable energy is summarised below:

- Member: Government's Expert Panel for the Severn Tidal Power Feasibility Studies (2008-10)
- Member: Mersey Tidal Power Design Advisory Group (2010-11)
- Advisor: Corlan Hafren Ltd. - consortium of companies to develop Severn Barrage (2010-12)
- Member: Regional Committee and Expert Panel Member of Hafren Power Ltd. (2012-14)
- Consultant: ITP - providing technical support to Henry Review of Tidal Lagoons (2016)
- Member: Technical Advisory Board, Natural Energy Wyre Ltd. (2017-date)
- Director: Dragon River & Tidal Ltd. – responsible for developing a river and small tidal novel turbine (2017-23)
- Member: Welsh Government Hinkley Point C Expert Stakeholder Group (2020-date)
- Member: Liverpool City Region, Mersey Tidal Commission Steering Group (2020-date)
- Director: Tidal Engineering and Environmental Services Ltd. (2021-date)

Reza Ahmadian is Professor of Water and Environmental Engineering at Cardiff University. He has led and contributed to several research projects on hydro-environmental modelling, and particularly marine renewable energy. In particular, he currently leads the £1.2m EPSRC funded TARGET (TidAl Range schemes as configurable Grid-scale Energy sTorage facilities) project. He is also the Principal Investigator from Cardiff University on the UKRI SMART Grant project: 'Development of Very Low Head Tidal Turbine'. Over the past five years, he has also been Cardiff University's Principal Investigator on the EU funded EERES4WATER (Promoting Energy-Water nexus resource efficiency through renewable energy and energy efficiency) and the Marine Energy Engineering Centre of Excellence (MEECE).

2. Conflicts of Interest

Roger Falconer has two potential conflicts of interest to declare, including:

- Director of Tidal Engineering and Environmental Services Ltd. (TEES), which is primarily involved in designing and planning the West Somerset Lagoon tidal range energy project, i.e., an 80 km^2 semi-circular tidal impoundment, located in the Bristol channel, from Minehead to Watchet, and predicted to generate 6.5 TWh/yr.
- Advisor to Jacobs and Severn Estuary Tidal Bar Ltd. on the UKRI SMART grant project: 'Development of Very Low Head Tidal Turbine' (VLH turbines), relating to the development of a novel bi-directional turbine, using two counter-rotating blade arrays.

Reza Ahmadian has one potential conflicts of interest to declare, including:

- Contracted by Liverpool City Region to carry out optimisation and hydro-environmental modelling of different Mersey Schemes in 2020.

Comments on Western Gateway: Call for Information

In autumn 1997 Roger Falconer (RF) moved to Cardiff University (CU) as Professor of Water Management and founded the Hydro-environmental Research Centre (HRC), in the School of Engineering. Shortly after joining CU RF was awarded a joint NERC/Environment Agency grant (1997-99) to model the fate and impact of persistent contaminants in estuarine and coastal waters. This study involved setting up RF's hydrodynamic and water quality computational model for the Bristol Channel (i.e., from St. Govan's Head to Hartland Point) to the Prince of Wales Bridge in the Severn Estuary and included predicting tidal elevations and currents and faecal bacteria levels from several outfalls along the basin. This led to the first of many publications by staff and students in the HRC on modelling the hydro-environmental processes in the Bristol Channel and Severn Estuary[1] (hereinafter referred to as the Bristol-Severn Basin).

Following this first project and publication on predicting the hydro-environmental processes in the Bristol-Severn Basin, many more projects, publications and presentations were to follow, including funded projects from organisations, such as: EPSRC, NERC, the Royal Society, the Royal Academy of Engineering, Environment Agency, European Union, British Council, Welsh Government, INTERREG, Hyder Consulting, Halcrow Group, CH2M, Dragon River & Tidal Energy Ltd. etc. Computational and laboratory model studies (including field and experimental data acquisition) were continuously improved and refined for the Bristol-Severn Basin, including a small-scale physical model of the basin, and sited in the Hyder Hydraulics Laboratory at CU, with this physical model being used later to study the impact of a Severn Barrage[2,3], see Figure 1.

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[1] Lin, B., Falconer, R.A. 2001. Numerical modelling of 3-D tidal currents and water quality indicators in the Bristol Channel, *Proceedings of the ICE, Water and Maritime Engineering,* 148(3), 155-166.

[2] Brammer, J., Falconer, R.A., Ellis, C., Ahmadian, R. 2014. Physical and numerical modelling of the Severn Barrage. *Science China Technological Sciences,* 57(8), 1471-1481.

[3] Osei-Twumasi, A., Falconer, R.A. 2014. Diffuse source pollution studies in a physical model of the Severn Estuary, UK. Journal of Water Resource and Protection, 6(15), 1390-1403.

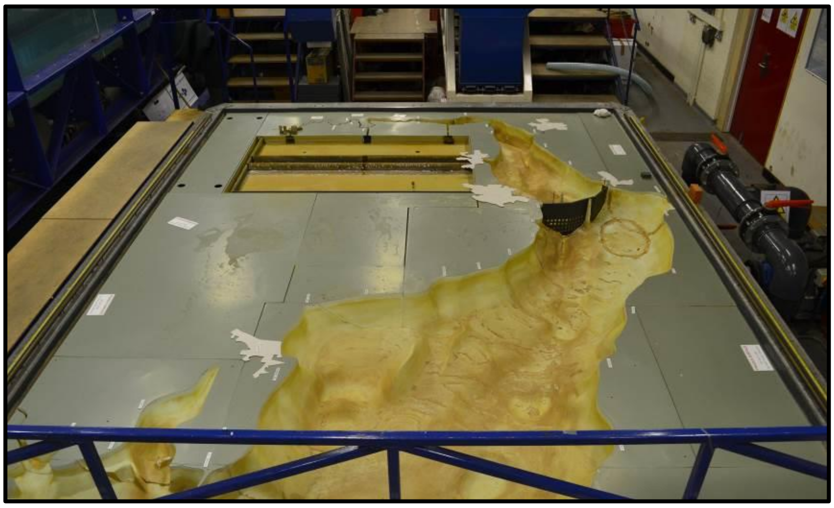

Fig. 1. Scaled physical model of the Bristol-Severn Basin in the Hydraulics at CU.

In 2000 RF received continuous sponsorship for his post at CU from the Halcrow Group Ltd. (becoming Halcrow Professor of Water Management), with part of this sponsorship being used continuously to support PhD students etc. on modelling the impact of a Severn Barrage (i.e., the original STPG design) on the hydro-environmental parameters in the Bristol-Severn Basin. This early research on the Bristol-Severn Basin led to a continuous stream of: (i) funded research projects (focused on continuously improving the accuracy of the processes and operational characteristics modelled), (ii) papers published primarily in leading international peer reviewed journals, (iii) presentations at leading international conferences, and (iv) over 200 presentations on the research findings to other universities, national and international learned societies, social groups (such as Rotary) etc. At the end of 2018 RF retired as an employee at CU and Prof. Reza Ahmadian (RA) now leads this research team, in the School of Engineering, at CU, with much of his work relating to all aspects of tidal range energy. RF continues to support the activities of RA's group in his capacity as Emeritus Professor, at CU.

The key comments below are in response to the points for information, as specified in the Western Gateway Call for Information, and primarily relate to the outcomes of the continuing research studies at CU, relating primarily to Point 1. The research study key findings are summarised in chronological order from about 2000 to date, with the key findings summarised in italics.

1. Effects on the estuary's hydraulic, geomorphological, and sedimentation regimes

The key initial development of the research studies undertaken at CU and relating to tidal range impacts on the hydro-environmental characteristics in the Bristol-Severn Basin was to re-model the hydrodynamics in the Basin using a state-of-the-art refinement to the DIVAST (Depth Integrated Velocities And Solute Transport) model, first developed by RF through a PhD study at Imperial College, 1974-76. This study[4] involved refining the model to use an unstructured finite volume grid in three dimensions and typical predictions of currents in the Bristol-Seven Basin are shown in Figure 2, using DIVAST-2DU, i.e. depth averaged velocities.

[4] Namin, M.M., Lin, B., Falconer, R.A. 2004. Modelling estuarine and coastal flows using an unstructured triangular finite volume algorithm. *Advances in Water Resources.* 27(12), 1179-1197.

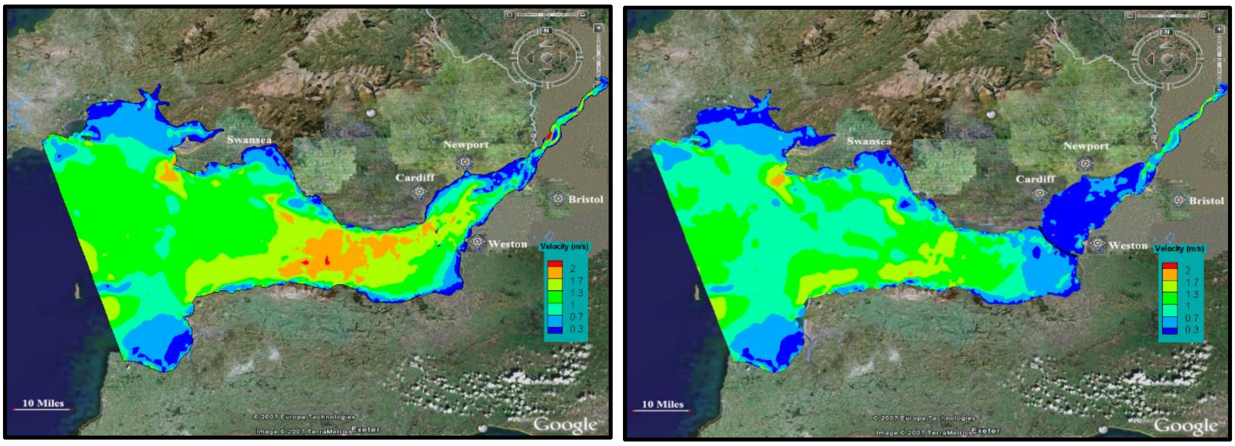

Fig. 2. Prediction of mean flood tidal currents in the Bristol-Severn Basin using DIVAST-2DU: (i) without a barrage (left), and (ii) with a barrage (right).

Key Finding 1: *An unstructured grid model allows much improved accuracy in the regions of interest and in representing complex bathymetries, meanders, basin shapes etc.*

The results of this study (in a presentation given in 2006 on the impacts of the STPG barrage) showed that the mean flood tide currents in the main Bristol-Severn Basin channel were much reduced, both upstream and downstream of the barrage, when operating in an ebb-only mode of generation. With such significant reductions in the tidal currents when a barrage was included, and bearing in mind that the suspended sediment load would be reduced by approximately the cube of the depth mean local current, then the consequences of a barrage operating in this mode of generation would be to reduce markedly the peak turbidity levels, particularly during spring tides. This decrease in the suspended sediment load would also increase the light penetration and potentially increase the bed biodiversity in the basin. Furthermore, ebb-only generation without pumping led to a predicted loss of inter-tidal habitats upstream of the barrage of about 120 km^2.

Key Finding 2: *Ebb-tide only generation leads to a much reduced tidal range upstream of an impoundment and a significant reduction in currents and suspended sediment or turbidity levels.*

At the time RF (with an engineering rather than ecology background) thought that the above barrage impact changes would be beneficial in terms of the eco-hydraulics and biodiversity characteristics of the estuary. However, following discussions and explanations with several NGO organisations, particularly Peter Jones of the RSPB, RF appreciated over time that it was the high suspended sediment and turbidity levels in the Severn Estuary that made this basin unique in terms of attracting rare bird species etc. RSPB encouraged RF and his team to investigate the impact of two-way generation on the tidal energy output and the hydro-environmental parameters, using a low head scheme similar at the time to that proposed by Evans Engineering Ltd. (now dissolved). However, with insufficient turbine details available the HRC team undertook several research studies to compare the impacts of ebb-only and two-way generation, with the general mode features being illustrated in Figure 3.

These two different modes of operation were studied in some detail for the Bristol-Severn Basin and showed several key benefits of two-way generation[5]. The studies assumed that the barrage consisted of double-regulated bulb turbines, with operational efficiencies being obtained from a widely used hill chart. More recent studies have also included studying the impacts of pumping at low and high tide, and under low head differences across the impoundment wall, i.e., using minimal energy to raise the head difference at high and low water for the next tide. The main findings from these studies have shown that: (i) ebb-only and two-way generation produce virtually the same energy output of 48 GWh over a lunar day and for spring tides; (ii) the loss of intertidal habitat is much reduced in the Severn Estuary when two-way energy generation is used; (iii) the upstream tidal level variations, currents and suspended sediment levels are much closer to the case without a barrage when two-way generation is used; and (iv) the benefits of two-way generation are further enhanced when pumping under low head is included, both at high water and low water.

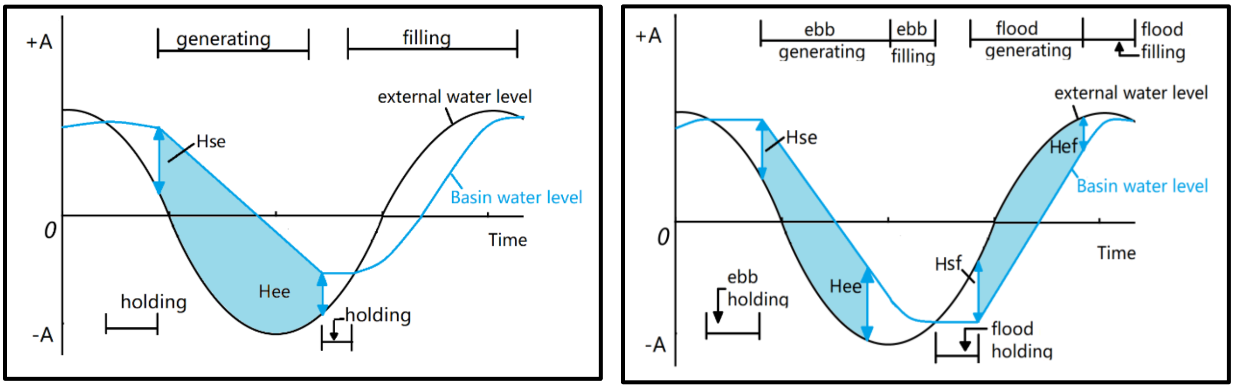

Fig. 3. Comparison of operating modes for: (i) ebb-only (left), and (ii) two-way generation, with ebb-only leading to a much-reduced tidal range upstream.

Key Finding 3: *Two-way generation has several hydro-ecological benefits when adopted in the Severn Estuary when compared to ebb-only and particularly with pumping at high and low tide.*

In the early studies undertaken within the HRC to predict the impacts of a barrage on the hydro-environmental impacts in the Bristol-Severn Basin the open boundary conditions were driven by water level variations along a boundary from St. Govan's head in Wales to Hartland Point in England, and with a Coriolis slope being included across this boundary. The inclusion of a Coriolis slope along an open sea boundary was found to be essential in much earlier studies, as without a Coriolis slope unrealistic circulation is generally generated along the open seaward boundary. The lack of inclusion of a Coriolis slope at such a long open boundary is often not included in commercial model studies and thereby could lead to inaccurate model predictions within the domain.

Model studies were then undertaken to study the effects of extending the open boundary location to cover the Irish Sea as shown in Figure 4 (right). The findings from these model predictions showed little impact of a Severn Barrage outside of the Bristol-Severn Basin. However, it was known that the reason that the tide amplifies within the basin is due to

[5] Xia, J., Falconer, R.A., Lin. B., 2010. Impact of different operating modes for a Severn Barrage on the tidal power and flood inundation in the Severn Estuary, UK. *Applied Energy,* 87(7), 2374-2391.

generation of the tidal characteristics from the Continental Shelf to the head of the estuary[6]. Studies were then undertaken to investigate the impact of a Severn Barrage on the peak water levels in the Irish Sea using the HRC's Irish Sea open boundary model and comparing this with a model driven by the boundary conditions generated at the Continental Shelf, Figure 4 (left)[7]. In comparing these results (i.e., Figure 4 left and right) significant differences can be observed in the predicted water levels in the Irish Sea, particularly in Cardigan Bay, along the North Wales coast, Liverpool Bay and Morecambe Bay. All these sites are vulnerable to significant impacts from sea level rise, with an additional 10 cm (yellow) being potentially significant at some key sites (e.g., Llandudno – a town vulnerable to sea level rise). Thus, the key finding from this study showed that for accurate predictions of the far field impacts of a barrage or lagoon sited in the Bristol-Severn Basin then it is desirable to drive any model using boundary conditions generated at the Continental Shelf. This finding is not surprising. Any barrage or, to a lesser extent, large lagoon sited in the Bristol-Severn Basin is potentially going to have an impact on the tidal resonant characteristics, created as a result of the tide generated at the Continental Shelf and then interacting with the basin up to the tidal limit. Furthermore, with the use of bulb turbines and their need to operate efficiently under a relatively high head, then the lost additional water in the basin at high and low tide has to go somewhere, as shown in Figure 4.

Key Finding 4: *For model studies undertaken to investigate the impact of a barrage or lagoon in the Bristol-Severn Basin it is desirable to extend the open boundary to the Continental Shelf.*

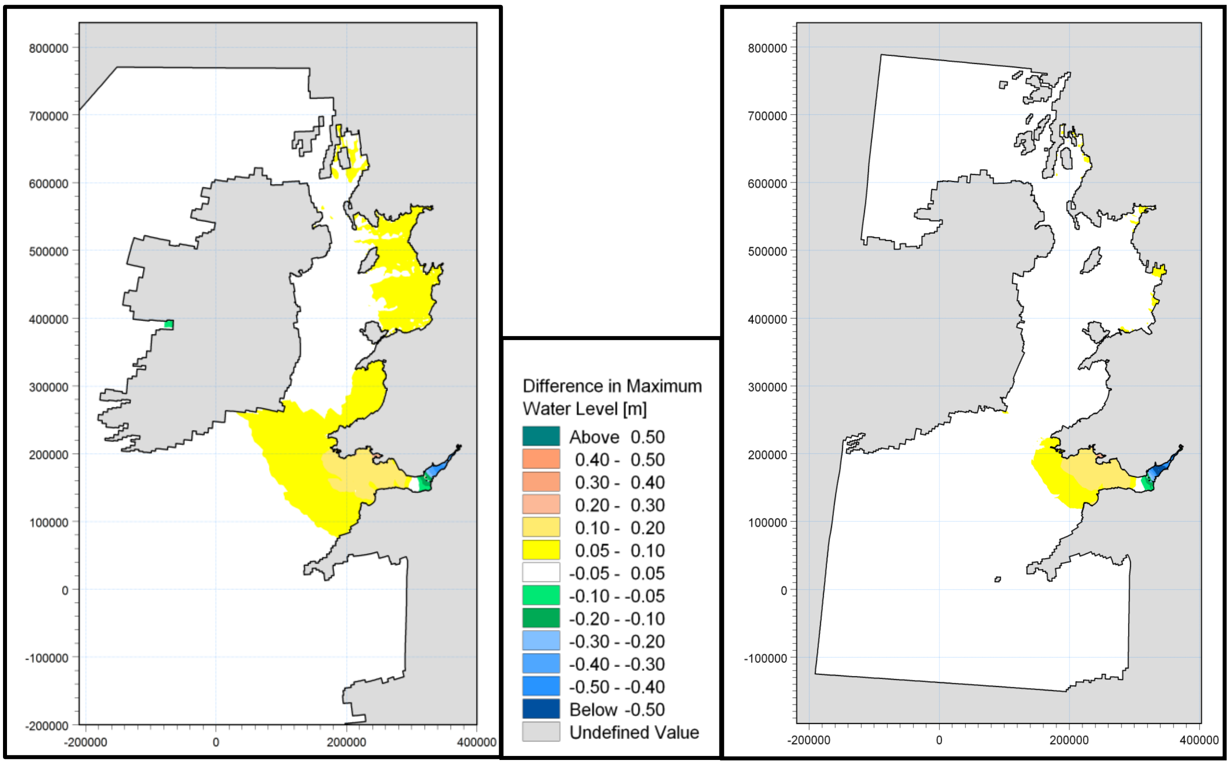

Fig. 4. Comparison of predicted peak water levels within the domain with different open boundary locations for: (i) Continental Shelf model (left), (ii) Irish Sea model (right).

[6] Liang, D., Xia, J., Falconer, R.A., Zhang, J. 2014. Study on tidal resonance in Severn Estuary and Bristol Channel. *Coastal Engineering Journal (World Scientific)*, 56(1), 1-18.

[7] Zhou, J., Pan, S., Falconer, R.A. 2014. Effects of open boundary location on the far-field hydrodynamics of a Severn Barrage. *Ocean Modelling*. 73, 19-29.

A series of hydrodynamic model studies were undertaken to establish the viability of siting tidal stream turbine arrays in the Bristol-Severn Basin[8]. It is generally considered necessary that for a tidal stream array to be commercially viable then a mean peak spring tidal current of at least 2 m/s is required, together with a minimum depth of 20 m at low spring tide. A typical example of the peak predicted spring tidal currents for the Bristol-Severn Basin is shown in Figure 5 and there are virtually no sites suitable where tidal stream turbines could be sited in the Severn Estuary, since the peak spring tide currents only exceed 2 m/s (i.e., coloured red) in parts of the navigation channel. Likewise, in the Bristol Channel there are very few sites outside of the main channel where the peak tidal current exceeds 2 m/s and the depth exceeds 20 m.

Key Finding 5: *Tidal stream turbines require hydrodynamic conditions greater than those in the Severn Estuary to deploy such turbines in the estuary, except in the navigation channel.*

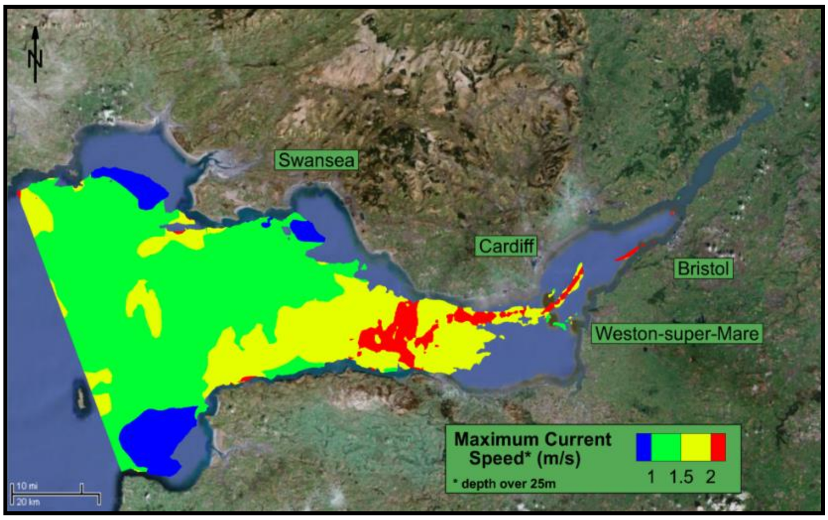

Fig. 5. Predicted peak tidal currents in the Bristol-Severn Basin, showing possible sites for tidal stream turbines (red).

Further key studies included investigating the impacts of sea level rise on the peak water levels in the Bristol-Severn Basin and these results generally predicted a uniform increase in the peak water levels along the basin, in line with the increase imposed at the outer seaward boundary[9]. Also, studies were undertaken to investigate the impact of a Severn Barrage on wave effects in the Bristol-Severn Basin[10], with the results indicating that the changes in wave heights would largely be small. The results predicted that the wave heights would be reduced by about 5% of the natural wave heights for most areas, and in areas where the effect is larger, then heights are less than 20% than the natural wave heights.

Key Finding 6: *The impact of climate change on peak tidal elevations in the Severn Estuary is predicted to be similar to the increased level assumed to occur at the open seaward boundary.*

[8] Xia, J., Falconer, R.A., Lin, B. 2010. Numerical model assessment of tidal stream energy resources in the Severn Estuary, UK. *Proceedings of the Institution of Mechanical Engineers, Part A: Power and Energy.* 224(7), 969-983.

[9] Ahmadian, R., Olbert, A.I., Hartnett, M., Falconer, R.A. 2014. Sea level rise in the Severn Estuary and Bristol Channel and impacts of a Severn Barrage. *Computers and Geosciences.* 66, May, 94-105.

[10] Fairley, I., Ahmadian, R., Falconer, R.A., Willis, M.R., Masters, I. 2014. The effects of a Severn Barrage on wave conditions in the Bristol Channel. *Renewable Energy.* 68, 428-442.

Key Finding 7: *The impact of a Severn Barrage wave heights is predicted to be small, i.e., less than 5% of the natural wave eight in most areas and less than 20% in some areas most affected.*

More recent studies have also been undertaken relating to the computational treatment of momentum conservation as the flow passes through the turbine diffusers. Although this may seem to be an academic point in many commercial model studies, full conservation of the momentum as the fluid enters and leaves the turbine ducts is critical in accurately determining the energy delivered and, in particular, the characteristics and size of the downstream wake. This has been studied in some detail in a recent study by Coz et al.[11] who compared several different model treatments of the momentum conservation through the turbine diffusers and included the algorithms in Delft3D. These refinements have since been included in the main model codes used by CU and the refinements show significant improvements in the predictions of turbine wakes. The refined model was applied to Swansea Bay Lagoon where the results showed that if the original design of 16 turbines and 8 sluice gates was adopted then large wakes were predicted inside of the lagoon and across the navigation channel into the marina on an ebb tide. However, if the turbine sluice blocks were split into three blocks of 8 turbines, 8 sluice gates and 8 turbines, then the wake intensity was markedly reduced, see Figure 6.

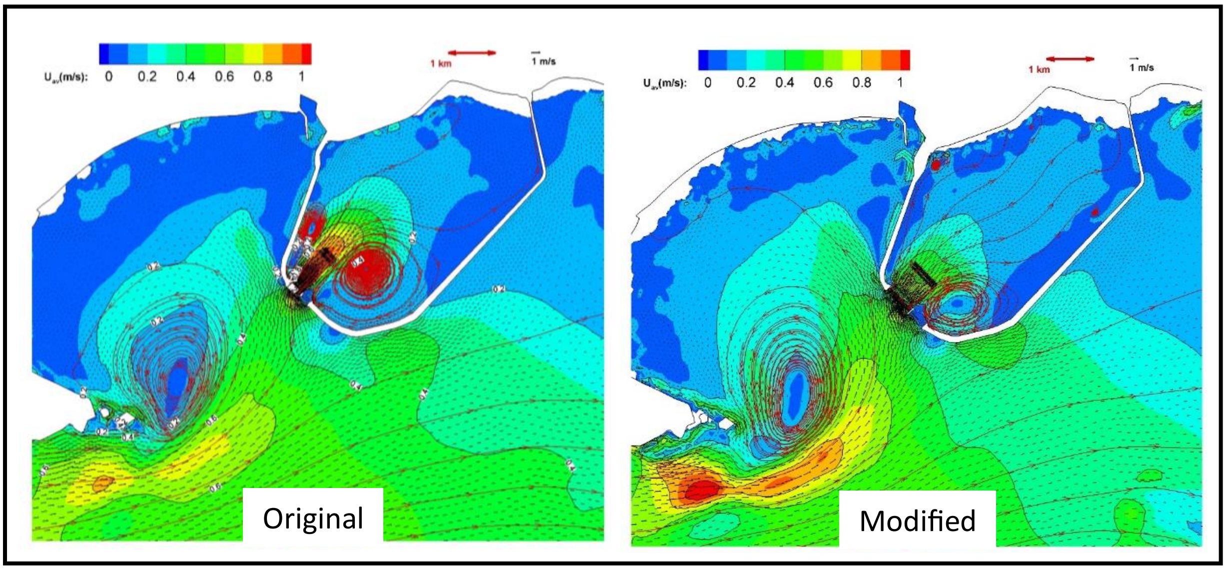

Fig. 6. Predicted wake characteristics in Swansea Bay Lagoon for different Turbine (T) and Sluice (S) configurations of: (i) 16T + 8S (left) and (ii) 8T + 8S + 8T (right).

This effect has been considered in the design of West Somerset Lagoon, with the turbine and sluice blocks distributed around the embankment wall to reduce the size and strength of the wakes, both within the lagoon and as the wake develops on the outside of the embankment wall, thereby minimising the impact on the tidal flow in the Bristol-Severn Basin[12], see Figure 7.

[11] Coz, N., Ahmadian, R., Falconer, R.A. 2019. Implementation of a full momentum conservative approach in modelling flow through tidal structures. *Water,* 11(9), 1917, 1-24.

[12] Guo, B., Ahmadian, R., Falconer, R.A. 2021. Refined hydro-environmental modelling for tidal energy generation: West Somerset Lagoon case study. *Renewable Energy.* 179, December, 2104-2123.

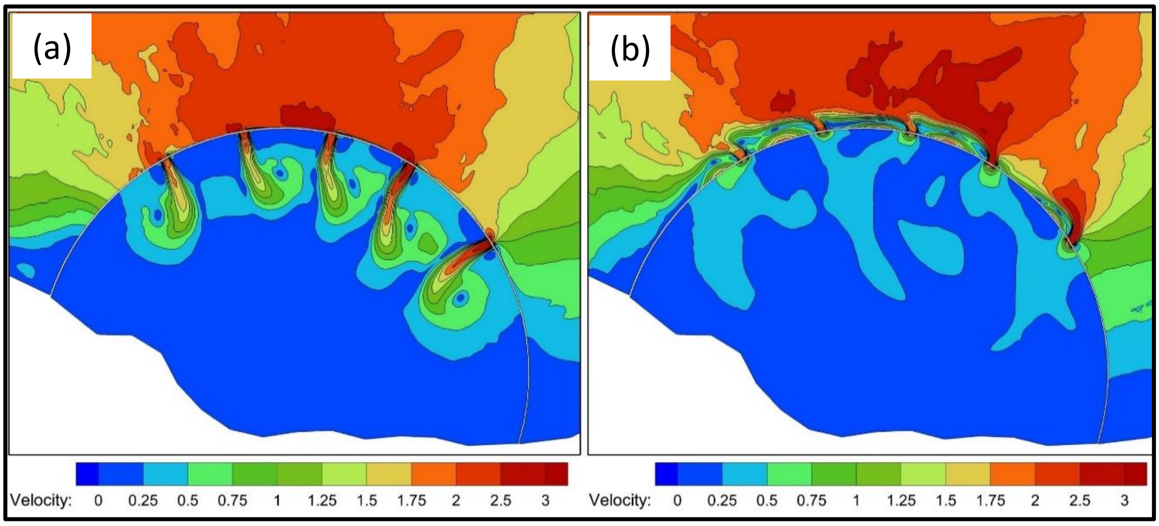

Fig. 7. Predicted spring tide currents in West Somerset Lagoon with momentum conservation and turbines around wall reducing wake sizes for: (i) flood (left), and (ii) ebb (right) tides.

Key Finding 8: *For accurate turbine wake predictions then momentum conservation is essential in diffuser representation and turbine blocks need to be spaced out to reduce wake strength.*

Since joining CU in 1997 RF has led a series of research studies on several proposed tidal range energy schemes, located in the Bristol-Severn Basin. Since 2019 RA has led further modelling research studies at CU on a range of new schemes, most notably the Mersey Barrage and West Somerset Lagoon. All these projects have been primarily funded through the Research Council and EU funding, along with funding from regulatory authorities, consulting companies, and industry. Two key studies that summarise some of the impact findings of the projects led by RF, include the hydro-environmental impacts on the Bristol-Severn Basin arising from: (i) the Severn Barrage, Fleming (or Welsh Grounds) Lagoon and the Shoots Barrage[13], and (ii) Swansea Bay Lagoon, Cardiff Lagoon, Newport Lagoon and the HRC Sever Barrage[14].

The first of several studies shows the maximum velocity predictions in Figure 8, with the main findings being that: (i) Welsh Grounds Lagoon would have little impact on the hydrodynamic processes in the Estuary, but sedimentation would be likely due to tidal pumping; and (ii) the barrages would have a greater environmental impact through water exchange and more pronounced intertidal habitat losses in the upper estuary. The predicted hydro-environmental impacts on the estuary were particularly pronounced for the STPG Cardiff– Weston Barrage.

The second study of several focused more on predicting the energy outputs and hydrodynamic interactions for the main proposed schemes sited within the Bristol-Severn Basin. These included: the original STPG Severn Barrage (ebb-only), the HRC Barrage (two-way) and the Swansea, Cardiff and Newport Lagoons, as proposed by Tidal Lagoon Power Ltd., with the velocity distributions for the lagoons being shown in Figure 9.

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[13] Xia, J., Falconer, R.A., Lin, B. 2010. Impact of different tidal renewable energy projects on the hydrodynamic processes in the Severn Estuary, UK. Ocean Modelling. 32(1-2), 86-104.

[14] Angeloudis, A., Falconer, R.A. 2017. Sensitivity of tidal lagoon and barrage hydrodynamic impacts and energy outputs to operational characteristics. Renewable Energy. 114, 337-351.

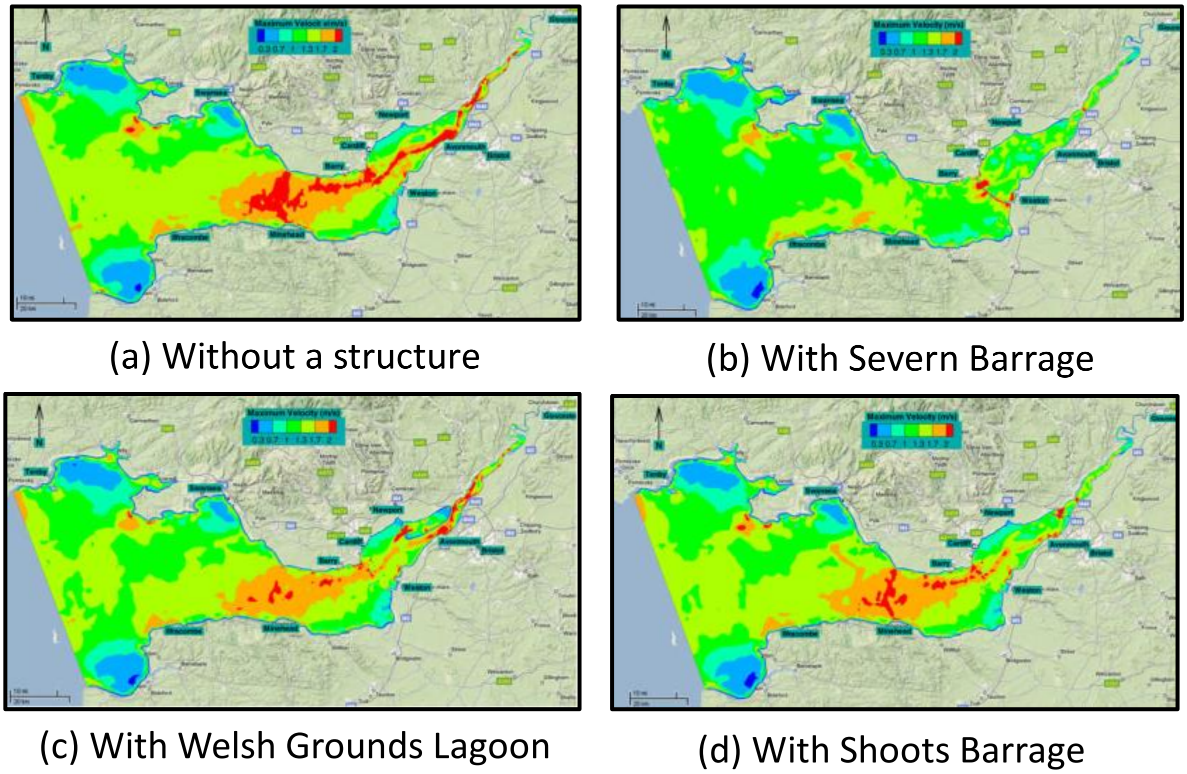

Fig. 8. Comparison of maximum tidal currents without (a) and with structures, including: (b) Severn Barrage, (c) Fleming Lagoon, and (d) Shoots Barrage.

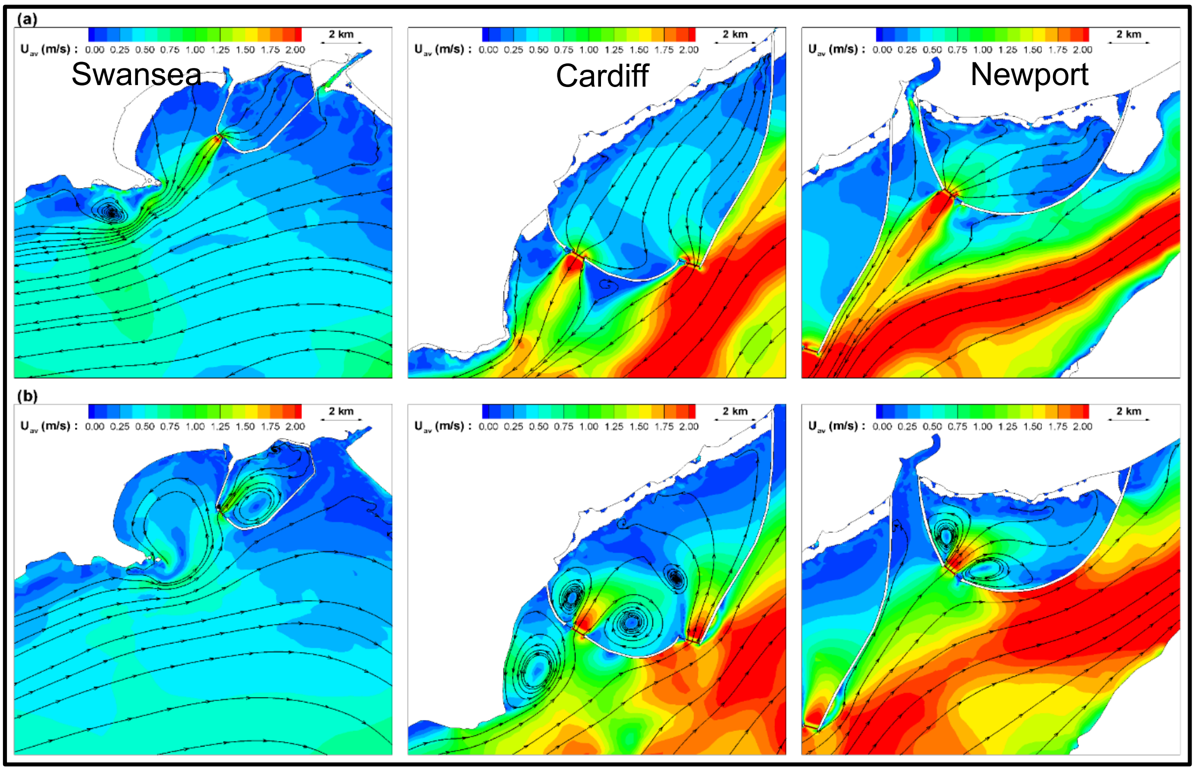

Fig. 9. Mean tide velocities and streamlines for the Swansea, Cardiff and Newport Lagoons for: (i) ebb tide (top), and (ii) flood tide (bottom).

The main finding from this study by Angeloudis and Falconer are given below. Tidal lagoons generally have less of an overall environmental impact on the Bristol-Severn Basin than barrage structures in the region. However, there are still noticeable impacts to the hydrodynamics in the basin, pronounced turbulent wakes close to the turbine/sluice structures, and pronounced recirculation zones within the lagoons, leading to a potential region of sedimentation. Lagoons in the Bristol-Severn Basin led to increased currents in the channel reaches, which would inevitably lead to increased turbidity in the region. Some implications on the tidal level maxima are reported, with relative reductions in the Severn Estuary and small increases in the levels in the Bristol Channel. The barrage options featured more pronounced hydro-environmental impacts, but a more significant annual energy production. Pumping was not considered in the studies reported above, but if included at low and high water then it would inevitably lead to a reduction in the degree of hydro-environmental change.

This study also included assessing all of the schemes for energy output, using both a 0-D (mass conservative only) and a 2-D hydrodynamic model (mass and momentum conservative). Such a comparison is considered crucial in validating and quantifying the uncertainty of simplified 0-D models, which are widely used for optimisation and evaluating the energy output of tidal range schemes. The results are given in Table 1, where it can be seen that the 0-D model provides a reasonably accurate estimate of energy output for the lagoons, but is much less accurate for a barrage, where the inherent assumption in the 0-D model is that the upstream water level slope is horizontal. This is a particularly inaccurate assumption for a Severn Barrage along the Cardiff-Weston line. The results also showed that a Severn Barrage would deliver ca. 6.8% of the UK's energy needs, whereas all the lagoons in operation together would only produce approximately 50% of the equivalent barrage output.

Table 1 Annual energy yield for the tidal range structures proposed in the Bristol-Severn Basin.

Numerical Simulations	Tidal Range Project Annual Energy (TWh/yr)					Hydrodynamic Impact (%)*					Total Energy (TWh/yr)
	Swansea Bay Lagoon (SBL)	Cardiff Lagoon (CL)	Newport Lagoon (NL)	Severn Barrage (STPG)	Severn Barrage (HRC)	SBL	CL	NL	STPG	HRC	
***EO: Ebb Generation :** h_{st} = 4.0m, h_{min}= 1.0m, t_h=2.2 h*											
0-D	*0.315*	*3.07*	*1.57*	*23.03*	*23.01*	-	-	-	-	-	-
2-D - SBL	0.292	-	-	-	-	-7.3	-	-	-	-	0.29
2-D - SBL,CL	0.291	2.89	-	-	-	-7.6	-5.9	-	-	-	3.18
2-D - SBL,CL,NL	0.290	2.77	1.25	-	-	-7.9	-9.8	-20.4	-	-	4.31
2-D - STPG	-	-	-	15.77	-	-	-	-	-31.5	-	15.77
2-D - HRC	-	-	-	-	16.35	-	-	-	-	-28.9	16.35
TW1: Two-way generation (1) - Max Power : Specifications of Table 5											
0-D	*0.615*	*5.28*	*3.05*	*25.01*	*36.06*	-	-	-	-	-	-
2-D - SBL	0.586	-	-	-	-	-4.8	-	-	-	-	**0.59**
2-D - SBL,CL	0.577	4.68	-	-	-	-6.2	-11.4	-	-	-	**5.26**
2-D - SBL,CL,NL	0.575	4.55	2.25	-	-	-6.5	-13.9	-26.3	-	-	**7.37**
2-D - STPG	-	-	-	15.31	-	-	-	-	-38.8	-	**15.31**
2-D - HRC	-	-	-	-	22.05	-	-	-	-	-38.9	**22.05**
***TW2: Two-way generation (2) - Reduced holding time::** h_{st} =2.5 m, h_{min} = 1.0m, t_h= 1.5 h,*											
0-D	*0.507*	*4.37*	*2.49*	*25.01*	*33.76*	-	-	-	-	-	-
2-D - SBL	0.474	-	-	-	-	-6.5	-	-	-	-	0.47
2-D - SBL,CL	0.464	3.94	-	-	-	-8.5	-9.9	-	-	-	4.40
2-D - SBL,CL,NL	0.462	3.87	1.73	-	-	-8.9	-11.4	-30.5	-	-	6.06
2-D - STPG	-	-	-	15.31	-	-	-	-	-38.8	-	15.31
2-D - HRC	-	-	-	-	21.53	-	-	-	-	-36.2	21.53
**The hydrodynamic impact refers to the deviation from 0-D annual energy results which discount the tidal impoundment impact on the hydro-environment*											

***Key Finding 9:** Lagoons will have less hydro-environmental impact in the Bristol-Severn Basin, but a barrage would deliver appreciably more energy.*

Key Finding 10: *0-D models provide reasonably accurate predictions of the energy output for lagoons, but for a long estuary then more accurate models are needed to predict energy output.*

Note: All the above studies were undertaken using double regulated bulb turbines and for which hill charts are available in the public domain. However, in the opinion of the writers, the current very low-head bi-directional counter-rotating turbine being developed by Jacobs and Severn Estuary Tidal Bar (SETB), and part-funded through a UKRI SMART Grant project, are likely to lead to increased power outputs and much reduced adverse hydro-environmental impacts.

More recent studies (i.e., post 2018) have been undertaken on modelling the power output and hydro-environmental impacts of tidal range schemes at CU, led by Prof. Ahmadian, and primarily focused on West Somerset Lagoon (WSL). The first of these studies has involved the development of a novel Genetic Algorithm designed to optimise the operation of lagoons and barrages for flexible starting and ending heads for each individual tide. This hydroinformatics tool has proven to be particularly attractive in terms of optimising the operation of tidal range schemes, through delivering ca. 10% more energy for the case of WSL[15].

Key Finding 11: *Optimising the operation of turbines using hydroinformatics technologies in tidal range schemes can increase the energy output appreciably through flexible driving heads.*

In parallel with the above study, research investigations have also been undertaken at CU on WSL to investigate the near-field and far-field impacts of the lagoon on a range of hydro-environmental parameters, both within the lagoon and in the Bristol-Severn Basin. These studies included investigating changes in the: hydrodynamic parameters (levels and currents), suspended sediment levels and morphology, tidal exchange and flushing, phytoplankton biomass and eutrophication potential[16,17].

In terms of water levels, the impact of WSL on the levels in the Bristol-Severn Basin is relatively small, as shown in Table 2. The results show that the peak reduction in the tidal range due to WSL would be about 0.35 m, which would have only a small effect on the potential energy generation from any future barrage or large lagoon scheme proposed elsewhere in the basin.

Regarding the main hydro-environmental parameters predicted in the above model studies[16], the key findings were that: (i) the decrease in the peak water elevations reduces the coastal flood risk, and (ii) the maximum velocity in the in the inner Bristol Channel increases by about 0.25-0.75 m/s with the operation of WSL, which improves the water renewal capacity and increases the maximum suspended sediment concentration in the Bristol Channel and Severn Estuary. The consequences of these changes in currents are that the risk of hyper-nutrification and eutrophication are reduced. The bed shear stress predictions and the indicative morphological modelling demonstrated potential erosion in the turbine wake regions, as expected, thereby influencing the general morphodynamic features during lagoon operation.

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[15] Xue, J., Ahmadian, R., Jones, O., Falconer, R.A. 2021. Design of tidal range energy generation schemes using a Genetic Algorithm model. *Applied Energy,* 286, 116056, 1-15.

[16] Guo, B., Ahmadian, R., Falconer, R.A. 2021. Refined hydro-environmental modelling for tidal energy generation: West Somerset Lagoon case study. *Renewable Energy,* 179, December, 2104-2123.

[17] Guo B. 2022. Hydro-environmental modelling and interaction of tidal lagoons around the UK coast. PhD thesis. Cardiff University, pp. 264.

Furthermore, the predictions show that WSL is likely to lead to some sediment deposition at the two sides of the lagoon impoundment, while increasing slightly the risk of scouring parts of the seabed in the inner Bristol Channel.

Table 2 Predicted peak tide level changes at key sites upstream for high water (HW) and low water (LW), spring (S) and neap (N) tides.

Site	**HWS (m)**	**LWS (m)**	**HWN (m)**	**LWN (m)**
Bridgwater Bay	-0.09	0.26	-0.04	0.14
Welsh Grounds	-0.15	0.11	-0.10	0.16
Slimbridge	-0.36	0.01	-0.28	0.01

Key Finding 12: *The impact of WSL, or any other large lagoon in the Bristol-Severn Basin is likely to lead to changes in water elevations upstream, but these changes are relatively small and would be unlikely to preclude the operation of a larger impoundment later.*

Finally, over the period reported a wide range of hydro-epidemiological modelling studies have been undertaken for a range of discharges in the Bristol-Severn Basin and including assessing the impacts of a barrage on the bathing water health risks associated with effluent discharges[18]. The results with the Severn Barrage[19] confirm that a barrage would reduce the tidal range and currents in the estuary significantly for ebb-tide generation, which would lead to reduced suspended sediment concentrations, more light penetration, more rapid decay within the water column and thereby leading to lower bacteria concentrations from the outfalls. These research studies have also focused more recently on refining the treatment of kinetic decay processes etc., wherein the decay rate in the models used at CU now include dependence of the decay on a range of parameters, including: temperature, salinity, sunlight irradiance etc. Studies using 3-D hydro-epidemiological modelling show significant differences between the surface and bed faecal bacteria levels in Swansea Bay[20], as shown in Figure 10, with these findings potentially highlighting the importance of needing 3-D modelling for some hydro-epidemiological modelling studies in considering any tidal range energy project to be developed in the Bristol-Severn Basin.

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[18] Gao, G., Falconer, R.A., Lin, B. 2013. Modelling importance of sediment effects on fate and transport of enterococci in the Severn Estuary, UK. *Marine Pollution Bulletin.* 67(1-2), 45-54.
[19] Gao, G., Falconer, R.A., Lin, B. 2013. Modelling effects of a tidal barrage on water quality indicator distribution in the Severn Estuary. *Frontiers of Environmental Science and Engineering.* 7(2), 211-218.
[20] Lam, M.Y., Ahmadian, R. 2024. Enhancing hydro-epidemiological modelling of nearshore coastal waters with source-receptor connectivity study. Environmental Pollution. 345, 123431,1-8.

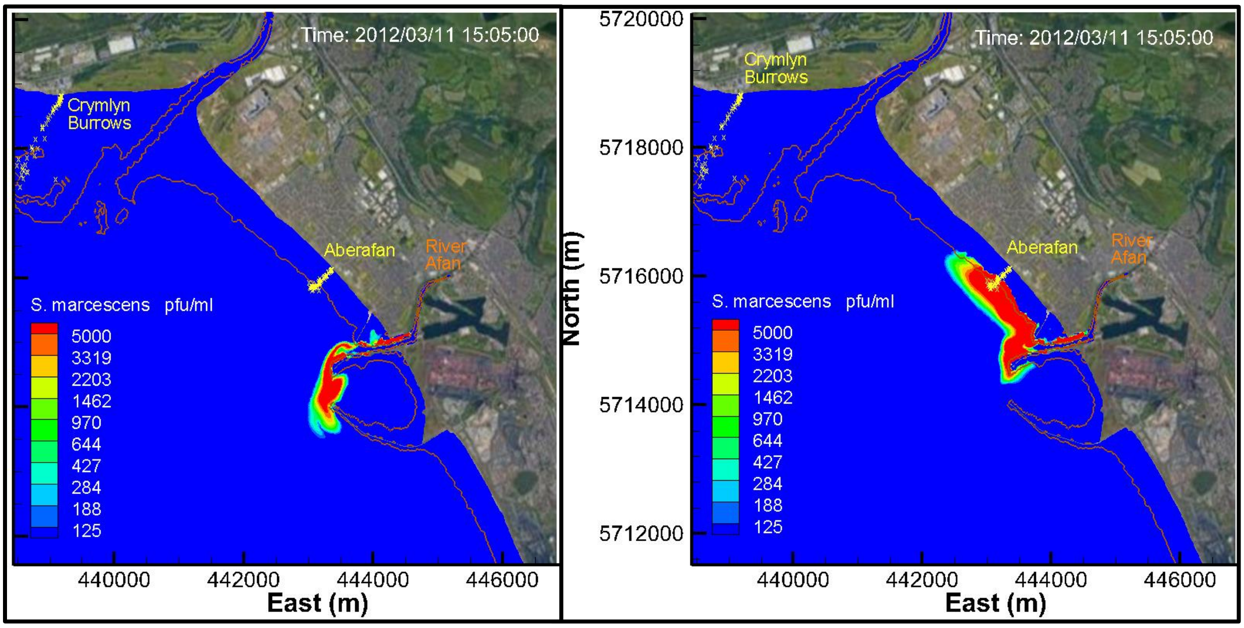


Fig. 10. Three-dimensional modelling of tide and wind induced freshwater tracer movement into Aberavon Bay for: (i) salinity excluded (left), and (ii) salinity included (right).

Key Finding 13: *Recent studies at CU have shown that the kinetics of faecal bacteria parameters is complex and requires 3-D modelling to predict accurately the key benthic concentrations.*

2. Associated sub-tidal and inter-tidal habitat and species changes

Based on the summary of the research undertaken at CU on the impacts of a range of proposed tidal range energy schemes, all schemes considered are likely to have an impact on the inter-tidal habitat areas and species changes in the Bristol-Channel Basin. These changes are predicted to be negligible for a small lagoon (area $\approx$ 10 km^2) to being moderate for a relatively large lagoon (area $\approx$ 80 km^2) and then significant for a barrage (area $\approx$ 500 km^2). The main impacts would relate to changes in the peak water levels and the corresponding loss of inter-tidal habitat areas. The other key hydro-environmental impact would be the corresponding change in the inter-tidal velocities and the small changes in sediment load and deposition or erosion. In terms of species changes RF is unable to comment as this is outside his field of experience.

Key Finding 14: *The impact of any tidal range energy scheme is likely to have an impact on the inter-tidal habitats in the Bristol-Severn Basin and particularly in the Severn Estuary. These impacts are likely to be dependent primarily on the size of the impoundment.*

3. Ornithological impacts, e.g. consequences of changes in inter-tidal habitats on bird populations

RF is unable to comment on this point as it is outside of his field of experience. However, in the past he has had fruitful conversations with members of various NGOs (particularly RSPB) and has learnt from them about the interactive link between the nature of birds feeding in the Severn Estuary and particularly on the inter-tidal habitats. He has regularly visited South Korea, where they have pioneered developing new and successful inter-tidal habitats for bird feeding etc.

4. Effects on water quality and surface and groundwater resources

The responses to point 1 of this report highlight the gross effects on water quality and surface and groundwater resources. However, more detailed discussions about the key water quality parameters that needed to be investigated in determining the hydro-environmental impact of barrages and/or lagoons on the Bristol-Severn Basin are summarised in two published papers by Kadiri et al.[21,22]. The first of these papers is based on a document produced by the writers for the Hafren Power team, who proposed a Severn Barrage scheme using VLH turbines, with counter-rotating blade arrays in 2012. The main parameters listed in the paper for investigation of water quality impacts included: sediment transport, salinity, dissolved oxygen (DO), trace metals, nutrients, and pathogens, with these parameters being included in water quality algorithm in the DIVAST-2DU model, as summarised in the biological process representation shown in Figure 11. The main conclusion from this paper reported “The significance and scale of the potential impacts of tidal renewable energy systems on water quality remains unclear and is likely to vary between estuaries and coastlines. Previous studies have shown that there can be positive hydro-environmental impacts associated with tidal renewable energy systems as well as the highly publicised adverse effects. More hydro-environmental modelling studies are needed as they provide a means of assessing the significance and scale of the impacts of proposed and future schemes on a site-specific basis and enable more definite predictions to be made.”

The second paper focuses on a model study to assess the impact of a Severn Barrage, operating in ebb-only and two-way generation, on the risk of eutrophication in the Bristol-Severn Basin.

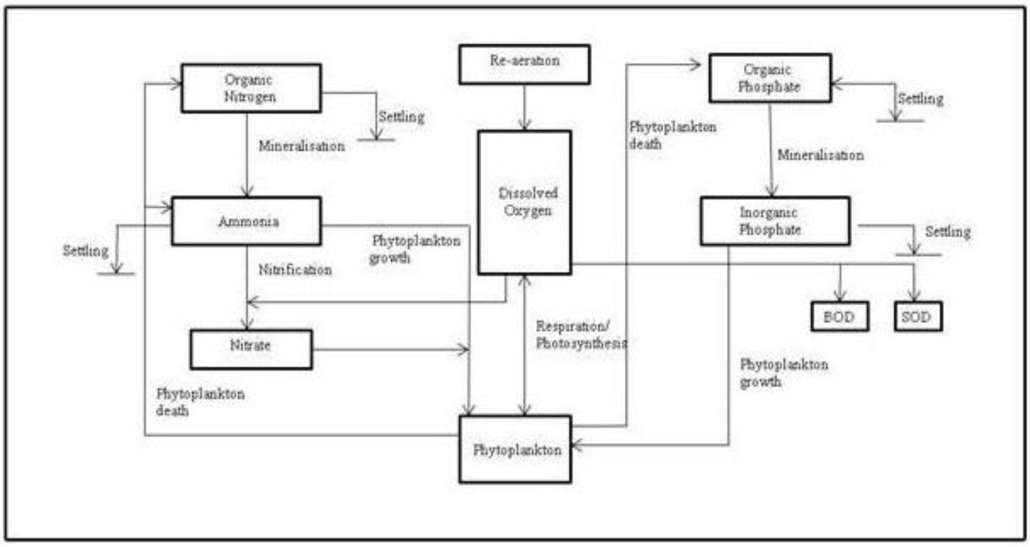


Fig. 11. Nutrient and phytoplankton cycles as represented in the DIVAST-2DU model.

[21] Kadiri, M., Ahmadian, R., Bochelmann-Evans, B., Rauen, W., Falconer, R.A. 2012. A review of the potential water quality impacts of tidal renewable energy systems. *Renewable and Sustainable Energy Reviews*. 16(1), 329-341.

[22] Kadiri, M., Ahmadian, R., Bockelmann-Evans, B., Falconer, R.A., Kay, D. 2014. An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn Estuary, UK. *Computers and Geosciences.* 71, 3-10.

The potential impacts of the two different modes of operation of the barrage (i.e. ebb-only and two-way generation) on the eutrophication potential of the Severn Estuary were assessed using the model for estimating the risk of eutrophication in estuarine and coastal waters. The predicted results indicated that the estuary was nutrient enriched and potentially eutrophic, with no net change in the status of the estuary following the operation of a barrage under either ebb-only or two-way operating modes. In addition, the model predictions also showed that there would be an increase in primary phytoplankton production under both ebb-only and two-way generation, because of the increased impounded water residence time and greater light availability in the enclosed basin behind the barrage. However, primary productivity was found to be significantly higher under ebb-only generation, as compared to two-way generation. This indicated more favourable conditions for phytoplankton production under ebb-only generation, with a decrease in the suspended sediment levels as compared to those for two-way generation, where a much smaller reduction in suspended sediment levels was predicted.

5. Effects on fish movements and spawning, arising from physical barriers, and changes in water chemistry

RF is unable to comment in any detail on this inquiry as it is outside of his field of experience. However, changes in the hydrodynamics, salinity levels and related water chemistry characteristics could affect fish movements in the Bristol-Severn Basin, as well as fish mortality possibly arising due to passage through a turbine or predation upstream due to exhaustion after passing through a turbine. VLH turbines should reduce the risk of fish mortality and predation due to the lower flow-through velocities and reduced pressure changes.

6. Flood risk management and land drainage implications

RF and his team at CU undertook several studies over the period to investigate the impact of various tidal range schemes on flood risk and, to a lesser extent, land drainage implications. Figure 12 below shows the predicted peak elevations in the Bristol-Severn Basin, both without and with a Severn Barrage. These model predictions are based on studies by Xia et al.[23] which are for the original STPG ebb-only scheme.

Whilst most barrage and lagoon schemes being consider now are based on two-way operation, and usually with pumping at low and high tide, the above results indicate a key benefit in terms of flood risk reduction of a barrage scheme across a large river. For ebb-only operation and no pumping the peak water level in the upper Severn Estuary is about 2 m less than for the case with no barrage. This would reduce flood risk to the river basin system upstream and reduce the time of tide-locking of drainage channels. However, with the low water level being raised appreciably for ebb-only operation then the groundwater levels on the surrounding floodplains would be raised, leading to more saturation of agricultural land. However, even with two-way operation and minimal pumping (if any) the peak water level is reduced upstream, thereby reducing flood risk and the period of tide locking through the tidal cycle. Furthermore, if it is predicted that there will be a significant storm and a high-risk level of flooding upstream then the turbines and sluice gates can be closed at low water, thereby increasing the hydraulic

[23] Xia, J., Falconer, R.A., Lin, B., Tan, G. 2011. Estimation of future coastal flood risk in the estuary due to the Severn Barrage. *Journal of Flood Risk Management*. 4(3), 247-259.

gradient upstream and appreciably reducing flood risk. However, whilst a barrage can be operated to reduce appreciably the flood risk level upstream, the lost water volume due to the structure has to go somewhere external to the impoundment, and this usually leads to a slight increase in flood risk on the seaward side, as shown in Figure 4 (left) for the more accurate Continental Shelf model predictions.

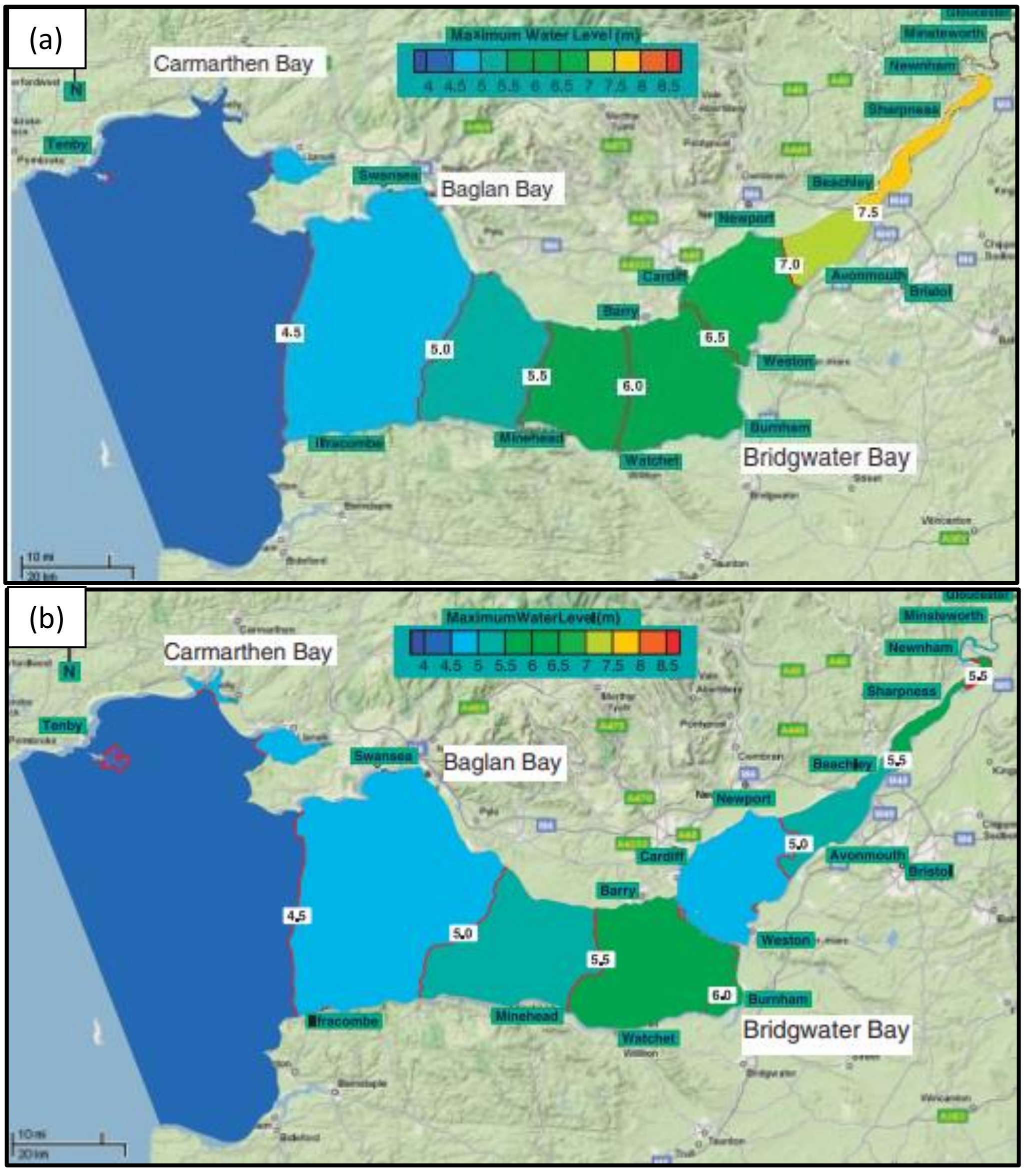


Fig. 12. Predicted distributions of maximum water levels: (i) without a barrage (top), and (ii) with a barrage (bottom).

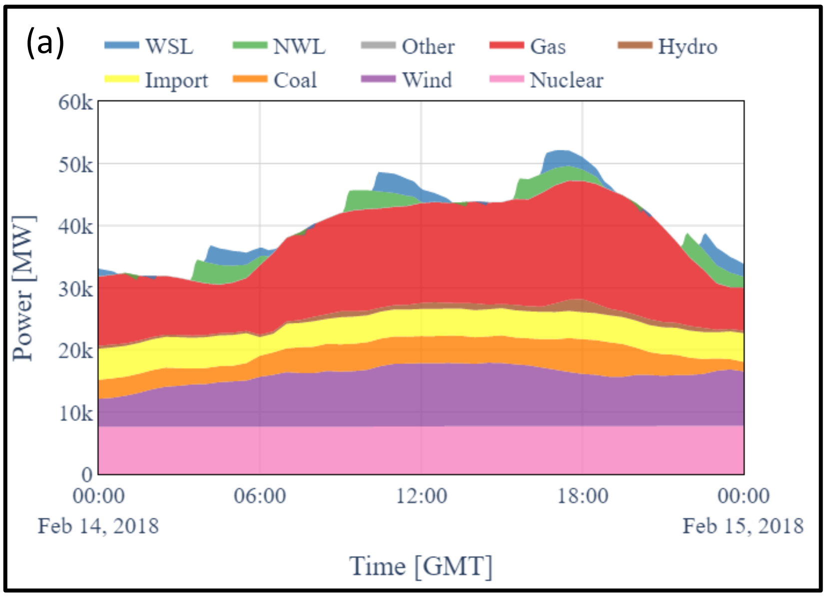
Key Finding 15: *Barrages and lagoons offer reduced coastal erosion and flood risk within the impounded area, with barrages potentially reducing the risk considerably if operated accordingly. However, there is a small risk of increased flooding outside of the barrage or lagoon.*

With regard to "Life Cycle Assessment" there is no particular reason why any tidal range structure needs to be decommissioned after its lifetime, particularly when considering sea level rise. These schemes will form part of the flood risk management of the area in the future. RA is currently leading the EPSRC TARGET project at CU where the life cycle assessment of Tidal Range Schemes and other renewable energy schemes are being carried out as a part of this project.

7. Current and future marine energy development

The advantage of barrage and lagoon schemes is that they offer the potential for other developments as well as predictable, and non-weather and sunlight dependent, renewable energy, such as flood and coastal erosion reduction, tourism, recreation etc. However, RF has links with many Far Eastern countries (particularly Korea, China, India and Malaysia) and was Vice President of the International Association for Coastal Reservoir Research until 2023, when the Association was moved into the International Water Association (IWA) as a Specialist Group on Sustainable Coastal and Estuarine Development (see: IWA Link). From RF's experience most of the Far Eastern countries with a relatively large tidal range (e.g. Korea and China) already have considerable internal expertise in the technology required to deliver tidal range schemes. However, in RF's experience the key opportunity for the future of UK technology to be promoted overseas is to develop the VLH turbine, now being developed by Jacobs and SETB, for markets where there is a growing interest in developing tidal range schemes, such as South Korea.

Another important benefit of tidal range schemes is that they can provide energy storage and other ancillary benefits to the energy system, in addition to generating low carbon energy. The predictability, dispatchability and potential of tidal range schemes can provide a unique opportunity for these schemes to store energy and provide a smoother delivery of energy to the grid, see Figure 13(a). A recent study led by RA and his team at CU has shown that the incorporation of multiple tidal range schemes can reduce the total operation cost to the power system, mainly through reducing the fuel cost, see Figure 13(b). The amount of cost reduction is greatly affected by the power demand and the renewable energy penetration level. For most supply/demand profiles, schemes such as West Somerset Lagoon and the Mersey Barrage could provide a daily cost reduction of more than £ 1.3 million[24]. This will also support migration to net zero by replacing services which are currently provided by combined cycle gas turbines.



[24] Zhang, T., Hanousek, N., Qadrdan, M., Ahmadian, R. 2023. A day-ahead scheduling model of power systems incorporating multiple tidal range power stations. *IEEE Transactions on Sustainable Energy.* 14(2), 826-836.

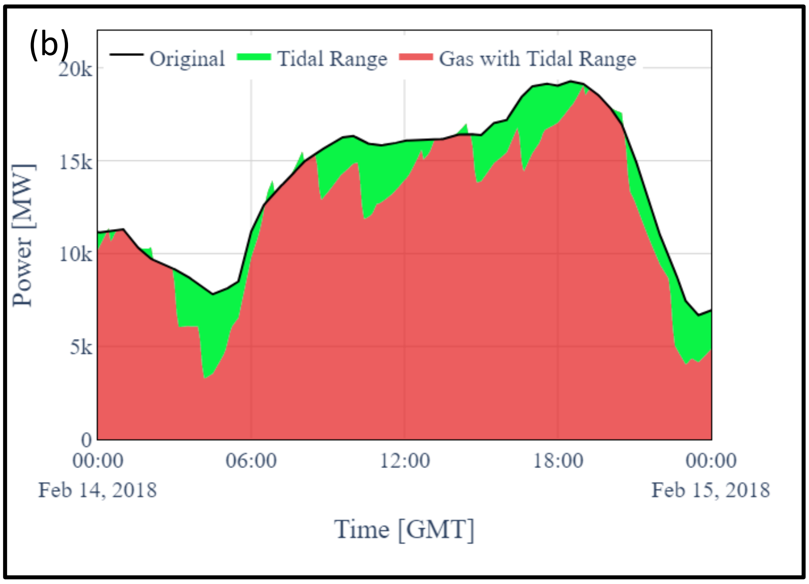


Fig. 13. Contribution of West Somerset Lagoon and North Wales Tidal Lagoon to UK energy system and migration to net zero: (a) contribution of optimised tidal range to energy mix on sample day; and (b) hypothetical reduction in gas generation on sample day due to tidal range.

Another opportunity for tidal energy development is retrofitting existing infrastructures, such as disused docks which can be repurposed as tidal range schemes. This is particularly important as the construction cost of such schemes is limited and they can provide significant storage capacity when used as energy storage systems. Furthermore, such infrastructures can be used as testing site for turbines or relevant technologies. RA's team at CU has studied potential sites around the UK and identified two docks around the Bristol Channel which are suitable for retrofitting[25], with a summary of the key sites being illustrated in Figure 14.

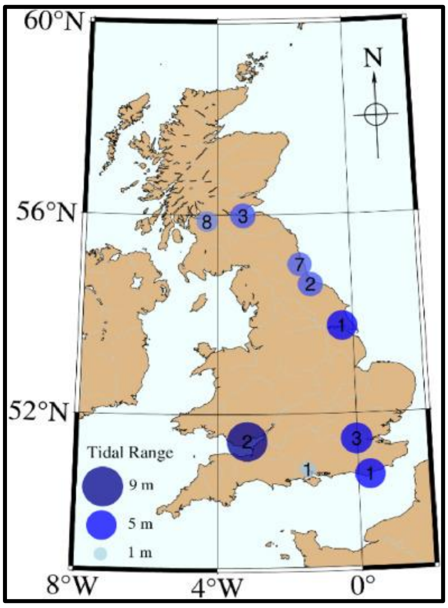


Fig. 14. Number of basins suitable for retrofitting identified around the UK.

[25] Hanousek, N., Ahmadian, R., Lesurf, E. 2023. Providing distributed electrical generation through retrofitting disused docks as tidal range energy schemes. Renewable Energy. 217, 119149, 1-10.

8. Other uses of the estuary and seabed

The Bristol-Severn Basin is an important water body for navigation to the ports of Bristol and Cardiff, with parts of the seabed also being important for aggregate dredging and the dumping of low level waste from sites such as Hinkley Point C in the future.

9. Effects arising from major structures

The effects arising from major structures, i.e. barrages and lagoons, has been covered in point 1 of this response.

10. Effects on navigation and commercial port trade

As outlined in point 8 above.

11. Sea disposal and marine aggregate dredging

As outlined in point 8 above.

12. Effects on commercial fishing

RF and RA have little knowledge on this topic and unable to comment further.

13. Landscape and seascape effects

RF and RA have little knowledge on this topic and unable to comment further.

14. Effects on areas identified as of potential archaeological and cultural heritage importance

RF and RA have little knowledge on this topic and unable to comment further.

15. Potential socio-economic costs and benefits

RF and RA have limited knowledge on this topic and others are better placed to comment further.

16. Carbon footprint, resource efficiency, and waste

RF and RA have limited knowledge on this topic and others are better placed to comment further.

Response from: **Roger A. Falconer**
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Note: Whilst the views and comments expressed in this report are based on studies led by Professor Falconer (1997-18) and Professor Ahmadian (2018-date), any views expressed do not necessarily reflect the views of Cardiff University.

Date: 01-05-2024

Appendix: Published Journal Papers on engineering and environmental research relating to the Severn Estuary and its potential for tidal energy

1. Lam, M.Y., Ahmadian, R. 2024. Enhancing hydro-epidemiological modelling of nearshore coastal waters with source-receptor connectivity study. Environmental Pollution, 345, 123431, 1-18.
2. Hanousek, N., Ahmadian, R., Lesurf, E. 2023. Providing distributed electrical generation through retrofitting disused docks as tidal range energy schemes. Renewable Energy, 217, 119149, 1-10.
3. Zhang, T., Hanousek, N., Qadrdan, M. and Ahmadian, R. 2023. A day-ahead scheduling model of power systems incorporating multiple tidal range power stations. IEEE Transactions on Sustainable Energy, 14(2), 826-836.
4. Abdulgawad, F., Teo, F.Y., Al-Qadami, E., Bockelmann-Evans, B., Falconer, R.A. 2023. Ammonium adsorption by surface sediments in the Loughor Estuary, UK. Journal of the Institution of Engineers, Malaysia, 84(1), June, 22-30.
5. Guo, B., Ahmadian, R., Falconer, R.A. 2021. Refined hydro-environmental modelling for tidal energy generation: West Somerset Lagoon case study. Renewable Energy, 179, December, 2104-2123.
6. King, J., Ahmadian, R., Falconer, R.A. 2021. Hydro-epidemiological modelling of bacterial transport and decay in nearshore coastal waters. Water Research, 196, 117049, 1-14. Free Access.
7. Xue, J., Ahmadian, R., Jones, O., Falconer, R.A. 2021. Design of tidal range energy generation schemes using a Genetic Algorithm model. Applied Energy, 286, 116056, 1-15.
8. Gao, G., Xia, J., Falconer, R.A., Wang Y. 2020. Modelling study of transport time scales for a hyper-tidal estuary. Water, 12(9), 2434, 1-14.
9. Guo, B., Ahmadian, R., Evans, P., Falconer, R.A. 2020. Studying the wake of an island in a macro-tidal estuary. Water, 12(5), 1225, 1-18.
10. Xue, J., Ahmadian, R., Jones, O. 2020. Genetic algorithm in tidal range schemes' optimisation. Energy, 200, 117496, 1-11.
11. Coz, N., Ahmadian, R., Falconer, R.A. 2019. Implementation of a full momentum conservative approach in modelling flow through tidal structures. Water, 11(9), 1917, 1-24.
12. Xue, J., Ahmadian, R., Falconer, R.A. 2019. Optimising the operation of tidal range schemes. Energies, 12(15), 2870, 1-23.
13. Guo, P., Xia, J., Zhou, M., Falconer, R.A., Chen, Q., Zhang, X. 2018. Selection of optimal escape routes in a flood-prone area. Journal of Hydroinformatics, 20(6), 1310-1322.
14. Huang, G., Falconer, R.A., Lin, B. 2018. Evaluation of E. coli losses in a tidal river network using a refined 1-D numerical model. Environmental Modelling and Software, 108, 91-101. Open Access.
15. Neill, S.P., Angeloudis, A., Robins, P.E., Walkington, I., Ward, S.L., Masters, I., Lewis, M.J., Piano, M., Avdis, A., Piggott, M.D., Aggidis, G., Evans, P., Adcock, T.A., Židonis, A., Ahmadian, R., Falconer, R.A. 2018. Tidal range energy resource and optimization - Past perspectives and future challenges. Renewable Energy, 127, 763-778.
16. Angeloudis, A., Falconer, R.A. 2017. Sensitivity of tidal lagoon and barrage hydrodynamic impacts and energy outputs to operational characteristics. Renewable Energy, 114, 337-351.
17. Bakar, A.A., Ahmadian, R., Falconer, R.A. 2017. Modelling the transport and decay processes of microbial tracers released in a macro-tidal estuary. Water Research, 123, 802-824.
18. Huang, G., Falconer, R.A., Lin, B. 2017. Integrated hydro-bacterial modelling for predicting bathing water quality. Estuarine, Coastal and Shelf Science, 188, 145-155.
19. Al-Enezi, E., Bockelmann-Evans, B., Falconer, R.A. 2016. Phosphorous adsorption/desorption processes of estuarine sediment: a case study - Loughor Estuary, U.K. Arabian Journal of Geosciences, 9(200), 1-9.

20. Angeloudis, A., Falconer, R.A., Bray, S., Ahmadian, R. 2016. Representation and operation of tidal energy impoundments in a coastal hydrodynamic model. Renewable Energy, 99, 1103-1115.
21. Harries, T., Kwan, A., Brammer, J., Falconer, R.A. 2016. Physical testing of performance characteristics of a novel drag-driven vertical axis tidal stream turbine; with comparisons to a conventional Savonius. International Journal of Marine Energy, 14, 215-228.
22. Bray, S., Ahmadian, R., Falconer, R.A. 2016. Impact of representation of hydraulic structures in modelling a Severn Barrage. Computers and Geosciences, 89, 96-106.
23. Angeloudis, A., Ahmadian, R., Falconer, R.A., Bockelmann-Evans, B. 2016. Numerical model simulations for optimisation of tidal lagoon schemes. Applied Energy, 165, 522-536.
24. Gao, G., Falconer, R.A., Lin, B. 2015. Modelling the fate and transport of faecal bacteria in estuarine and coastal waters. Marine Pollution Bulletin, 100(1), 162-168.
25. Huang, G., Falconer, R.A., Lin, B. 2015. Integrated river and coastal flow, sediment and Escherichia coli modelling for bathing water quality. Water, 7(9), 4752-4777.
26. Boye, B.A., Falconer, R.A., Akande, K. 2015. Integrated water quality modelling: Application to the Ribble Basin, U.K. Journal of Hydro-environment Research, 9(2), 187-199.
27. Osei-Twumasi, A., Falconer, R.A., Bockelmann-Evans, B. N. 2015. Experimental studies on water and solute transport processes in a hydraulic model of the Severn Estuary, UK. Water Resources Management, 29(6), 1731-1748.
28. Huang, G., Falconer, R.A., Boye, B.A., Lin, B. 2015. Cloud to coast: integrated assessment of environmental exposure, health impacts and risk perceptions of faecal organisms in coastal waters. International Journal of River Basin Management, 13(1), 73-86.
29. Osei-Twumasi, A., Falconer, R.A. 2014. Diffuse source pollution studies in a physical model of the Severn Estuary, UK. Journal of Water Resource and Protection, 6(15), 1390-1403.
30. Zhou, J., Pan, S., Falconer, R.A. 2014. Optimization modelling of the impacts of a Severn Barrage for a two-way generation scheme using a Continental Shelf model, Renewable Energy, 72, 415-427.
31. Ahmadian, R., Falconer, R.A., Bockelmann-Evans, B. 2014. Comparison of hydro-environmental impacts for ebb-only and two-way generation for a Severn Barrage. Computers and Geosciences, 71, 11-19.
32. Kadiri, M., Ahmadian, R., Bockelmann-Evans, B., Falconer, R.A., Kay, D. 2014. An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn Estuary, UK. Computers and Geosciences, 71, 3-10.
33. Brammer, J., Falconer, R.A., Ellis, C., Ahmadian, R. 2014. Physical and numerical modelling of the Severn Barrage. Science China Technological Sciences, 57(8), 1471-1481.
34. Angeloudis, A., Stoesser, T., Falconer, R.A. 2014. Predicting the disinfection efficiency range in chlorine contact tanks through a CFD-based approach. Water Research, 60, 118-129.
35. Liang, D., Xia, J., Falconer, R.A., Zhang, J. 2014. Study on tidal resonance in Severn Estuary and Bristol Channel. Coastal Engineering Journal (World Scientific), 56(1), 1-18.
36. Liang, D., Xia, J., Falconer, R.A., Zhang, J. 2014. On the refinement of a boundary-fitted shallow water model. Coastal Engineering Journal (World Scientific), 56(1), 1-19.
37. Fairley, I., Ahmadian, R., Falconer, R.A., Willis, M.R., Masters, I. 2014. The effects of a Severn Barrage on wave conditions in the Bristol Channel. Renewable Energy, 68, 428-442.
38. Ahmadian, R., Olbert, A.I., Hartnett, M., Falconer, R.A. 2014. Sea level rise in the Severn Estuary and Bristol Channel and impacts of a Severn Barrage. Computers and Geosciences, 66, 94-105.
39. Zhou, J., Pan, S., Falconer, R.A. 2014. Effects of open boundary location on the far-field hydrodynamics of a Severn Barrage. Ocean Modelling, 73, 19-29.

40. Zhou, J., Falconer, R.A., Lin, B. 2014. Refinements to the EFDC model for predicting the hydro-environmental impacts of a barrage across the Severn Estuary. Renewable Energy, 62, 490-505.
41. Sparks, T.D., Bockelmann-Evans, B.N., Falconer, R.A. 2013. Development and analytical verification of an integrated 2-D surface water-groundwater model. Water Resources Management, 27(8), 2989-3004.
42. Gao, G., Falconer, R.A., Lin, B. 2013. Modelling effects of a tidal barrage on water quality indicator distribution in the Severn Estuary. Frontiers of Environmental Science and Engineering, 7(2), 211-218.
43. Gao, G., Falconer, R.A., Lin, B. 2013. Modelling importance of sediment effects on fate and transport of enterococci in the Severn Estuary, UK. Marine Pollution Bulletin, 67(1-2), 45-54.
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