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Research paper

Impact of representation of hydraulic structures in modelling a Severn barrage

Samuel Bray, Reza Ahmadian, Roger A. Falconer

Hydro-environmental Research Centre, Cardiff School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK

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ABSTRACT

In this study, enhancements to the numerical representation of sluice gates and turbines were made to the hydro-environmental model Environmental Fluid Dynamics Code (EFDC), and applied to the Severn Tidal Power Group Cardiff–Weston Barrage.

The extended domain of the EFDC Continental Shelf Model (CSM) allows far-field hydrodynamic impact assessment of the Severn Barrage, pre- and post-enhancement, to demonstrate the importance of accurate hydraulic structure representation. The enhancements were found to significantly affect peak water levels in the Bristol Channel, reducing levels by nearly 1 m in some areas, and even affect predictions as far-field as the West Coast of Scotland, albeit to a far lesser extent.

The model was tested for sensitivity to changes in the discharge coefficient, C_d, used in calculating discharge through sluice gates and turbines. It was found that the performance of the Severn Barrage is not sensitive to changes to the C_d value, and is mitigated through the continual, rather than instantaneous, discharge across the structure.

The EFDC CSM can now be said to be more accurately predicting the impacts of tidal range proposals, and the investigation of sensitivity to C_d improves the confidence in the modelling results, despite the uncertainty in this coefficient.

1. Introduction

Enthusiasm for renewable energy has continued to grow in the UK, driven by an increasingly informed, environmentally-conscious, general public and a continued reliance on ever more expensive and depleting fossil fuels. Although renewable electricity generation in the second quarter of 2013 was up by 55% compared to the same period in the previous year, just 4.1% of the UK's energy consumption in 2012 came from renewable sources (DECC, 2013). The theoretical tidal range resource in the UK is between 25 and 30 GW (DECC, 2013), accounting for 50% of the available tidal resource in Europe (Hammons, 2011). There are no tidal range generation schemes in operation at present in the UK, but with the enormous resources available, and the added advantage of the predictability and reliability of tidal range power generation, it remains a sector with huge potential for growth and as such is the subject of continued government, industry and academic investigation.

For tidal barrages and lagoons, the power available is a function of the square of the level difference across the impoundment wall, and the area impounded by a structure. The Severn Estuary, located in the South-West of the UK, as shown in Fig. 1, has the second highest tidal range in the world, which is over 14 m, at spring tide. Moreover, its large funnel shape allows a relatively short structure of 16 km to impound a basin of around 500 km^2. These characteristics of the Severn Estuary make it a uniquely attractive site for tidal range power generation (Uncles, 2010; Owen, 1980), and it is estimated that a barrage across the estuary has the potential to produce 5% of the UK's electricity needs.

Due to the exceptional tidal range, the Severn Estuary has strong tidal currents, up to 2 m s^{-1} during spring tides, leading to thorough mixing of the water column and high suspended sediment levels (Manning et al., 2010). The large tidal range exposes vast areas of intertidal mudflats, an important feeding area for migratory birds, and, as such, the estuary is protected by several international designations. The estuary has a very high annual nutrient load, among the top five of UK estuaries (Nedwell et al., 2002), due to significant riverine nutrient inputs. Such levels of phosphate and nitrate could potentially put the estuary at risk of eutrophication, however, it is thought that the high turbidity limits the phytoplankton production and reduces the likelihood of harmful algal blooms (Kadiri et al., 2014).

The Severn Estuary's huge energy resource has led to many proposals for electricity generation over the decades. A number of these proposals have been considered by the UK government, including an ebb-only generation Severn Barrage and various tidal

E-mail address: brays@cardiff.ac.uk (S. Bray).

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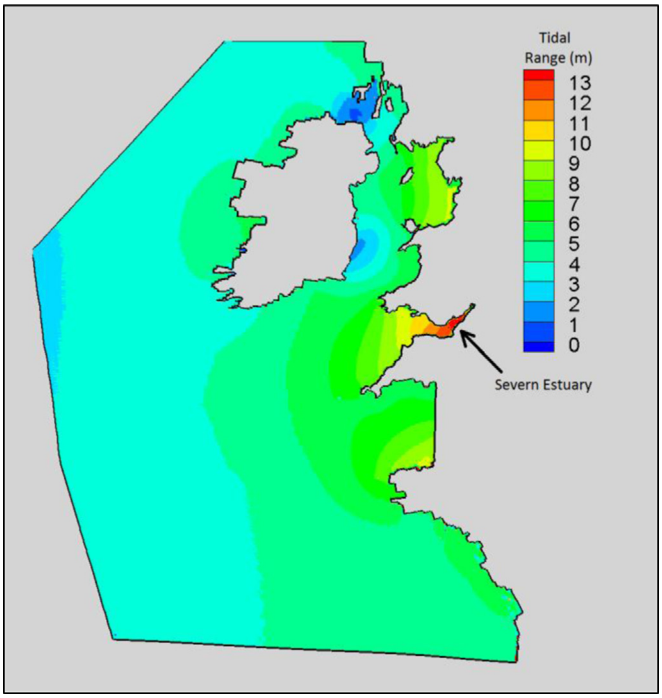

Fig. 1. Tidal range resource along the western coast of the UK and in the Severn Estuary.

lagoon options, shortlisted in the Department of Energy and Climate Change report (2010). More recently other schemes have been proposed, including a Severn Barrage that would generate power on both the incoming and outgoing tides (Xia et al., 2010a) and a coastally attached tidal impoundment at Swansea Bay (Tidal Lagoon, 2013). There are inevitable environmental implications of the construction and operation of a tidal barrage across the Severn Estuary, with some of the main effects being a change in the tidal range and regime, and a potential loss of intertidal zones. Currents within the estuary would be mainly reduced, which would cause a reduction in suspended sediment concentrations and turbidity, possibly leading to an increase and change in the primary productivity of the benthic flora and fauna (Kadiri et al., 2012). Whilst it is not implied that a new, more prolific ecosystem would be good or bad, it will inevitably be different, as observed at La Rance in Brittany (Kirby and Retière, 2009). The hydro-environmental impacts of a Severn Barrage under ebb-only generation were studied by Ahmadian et al. (2010), using the numerical model DIVAST, and it was predicted that power extraction from the estuary in this manner may come at the cost of a significant loss of intertidal habitat areas. These habitats are of special importance to wildlife, although the reduction in the maximum water levels upstream would offer some flood protection to the areas upstream of the impoundment. A barrage could also provide further flood protection benefits against forecasted sea level rise and climate change (Ahmadian et al., 2014a). The impact of a Severn Barrage under different operating modes was investigated by Xia et al. (2010b), where it was predicted that operating a Severn Barrage under two-way generation would reduce this intertidal loss at a minimal loss of electricity generation.

The conclusion of the Severn Barrage Committee (1981) was that an ebb-generating barrage would be the best scheme, due to higher head differentials being created, and fewer turbines being required, resulting in cheaper electricity generation. Studies since then (Xia et al., 2010a; Ahmadian et al., 2014b) have shown that a two-way generation scheme could generate almost as much electricity as an ebb-generation scheme. Two-way generation, however, carries the crucially important characteristic that the average basin water level is not raised, resulting in little change to the groundwater level upstream of the barrage structure, and resulting in the loss of considerably less intertidal habitat areas than for an ebb-only generating scheme. By operating at lower head differentials, and using VLH turbines as opposed to bulb-turbines, it is expected that the turbine tip-speed would result in significantly less fish mortality, although this requires more study, as reported in the Energy and Climate Change Select Committee Severn Barrage Report (Department of Energy and Climate Change, 2013).

A study on the far-field hydrodynamic impacts of a Severn Barrage was conducted by Zhou et al. (2013), in which it was found that the disturbance in the tidal regime caused by the inclusion of a Severn Barrage in a numerical model can reach the open boundary with smaller domains, and that when modelling the Severn Barrage it is necessary to extend the model domain out to beyond the Continental Shelf, West of Ireland. This dramatically increased domain size ensures that the disturbance to the tidal regime caused by the inclusion of the barrage does not affect the water elevations specified at the open boundaries, and also allows the investigation of hydrodynamic impacts outside of the Severn Estuary.

The representation of hydraulic structures is important in many hydrodynamic modelling scenarios: open channels and rivers, dams, locks, weirs, and in various hydropower applications. The reliability of the modelling of any project involving sluice gates or turbines is dependent upon the accuracy of the numerical representation of these hydraulic structures.

In the current study, the hydrodynamic model EFDC was used with a barrage module EFDC_B, developed by Zhou et al. (2014), to investigate the impacts of the treatment of hydraulic structure and barrage operation on the discharge and momentum across the structure. The predicted water levels, both near- and far-field, were also compared for this novel treatment, with the barrage being considered for operation using ebb-only generation. The model has been refined to include several improvements, such as using a Head-Discharge curve for the turbine flow during power generation, to more realistically represent the turbine operation, and to model the turbines and sluices as orifices of different areas during the filling stage for the impounded water basin. These refinements will affect the discharge across the structure during generation and during the re-filling of the basin between the generating phases, and as such will have an impact on the water levels in the estuary, particularly upstream of the barrage, and velocities in the immediate vicinity of the structure. In hydro-environmental modelling of marine renewable energy proposals, it is of vital importance that the hydraulic structures employed are modelled to as high a degree of accuracy as possible, so that accurate predictions can be made about the impacts of different schemes. Potential schemes can then be better evaluated and refined through the model to provide maximum power with minimal hydro-environmental impact.

The discharge through turbines and sluice gates is often described by the orifice equation, as demonstrated in Ahmadian et al. (2010), Zhou et al. (2014) and Xia et al. (2010a,b), and discussed further in the following section on Barrage Modelling. The orifice equation shows a directly proportional relationship between discharge and the discharge coefficient, a dimensionless factor of an orifice or valve, used to characterise the flow behaviour as shown in Eq. (2). While the other terms in the orifice equation are clear, there is limited guidance and some uncertainty regarding this coefficient (Xia et al., 2010c). Baker (2006) suggests a discharge coefficient value of 1, following the testing of a sluice gate prototype up to 2000 m^3/s (University of Bristol, 1981). Although it is not expected that the discharge coefficient value will vary widely from the suggested value of 1, since sluice gates are designed to transfer volume as efficiently as possible and not obstruct the flow,