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Research paper

Impact of representation of hydraulic structures in modelling a Severn barrage

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A R T I C L E I N F O

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A B S T R A C T

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

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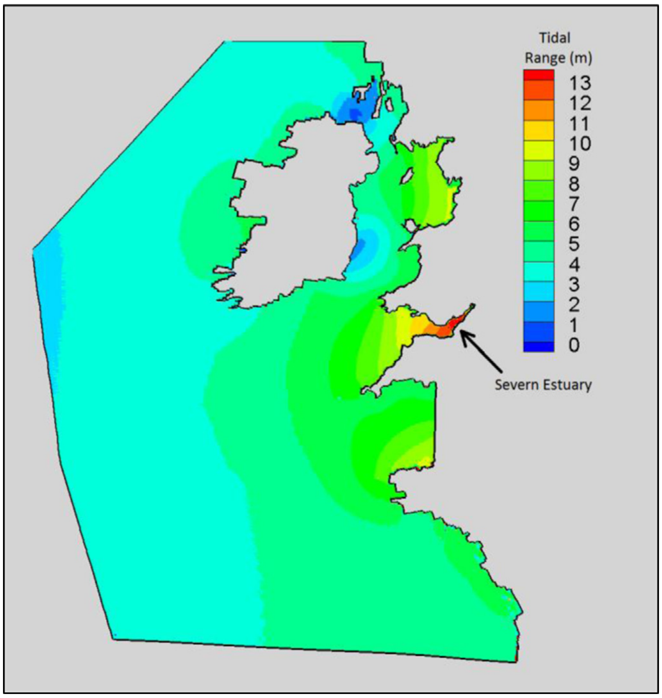

Fig. 1. Tidal range resource along the western coast of the UK and in the Severn Estuary.

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, the proportional relationship between discharge coefficient and discharge implies a potentially large impact from any uncertainty in the assumed value of 1 of C_d. As such, this paper investigates the sensitivity to limited changes in C_d, with the aim of assessing the importance of the coefficient and improving the confidence in the modelling.

In expectation of some performance loss from the barrage through a reduction in the C_d value, further scenarios were assessed in terms of power generation, in which the sluice area was increased in an attempt to mitigate the reduced discharge.

To summarise, the objectives of this article are as follows:

1) To demonstrate the importance of accurate hydraulic structure representation by applying refinements to the numerical representation of sluice gates and turbines to a case study – the Severn Barrage.
2) To update the predictions of far- and near-field water level impacts of the ebb-only generating STPG Severn Barrage.
3) To reduce uncertainty regarding the value of discharge coefficient used when modelling sluice gates in tidal power proposals such as barrages and lagoons, by quantifying the water level and power generation impact of changing this coefficient.
4) To determine whether performance change in a tidal range proposal, caused by uncertainty in the discharge coefficient value, can be mitigated by changing the sluice capacity of the structure.

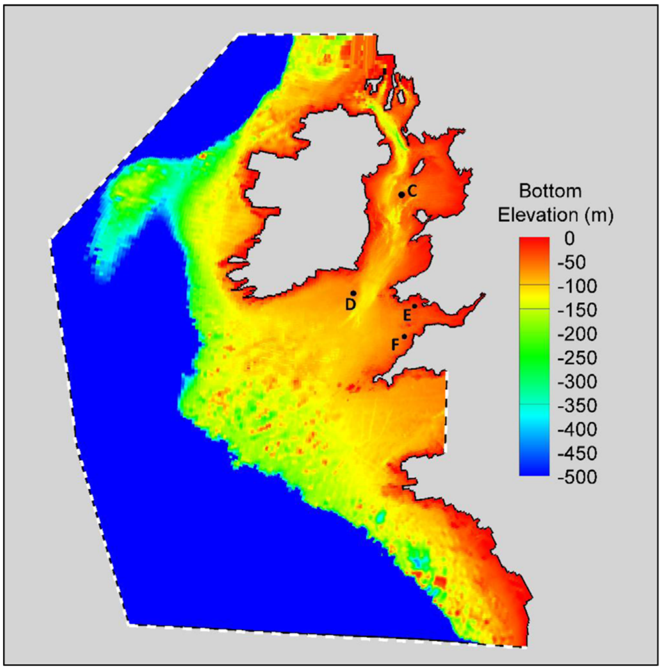

Fig. 2. Computational domain of modelling study, with black dots showing validation sites and dotted lines to indicate open boundaries.

2. Severn barrage modelling

The EFDC Model is an open-source hydrodynamic model developed by John Hamrick at the Virginia Institute of Marine Science. The model is based on a finite-difference alternating direction implicit solution of the Navier–Stokes equations for the hydrodynamic processes, and gives solutions of second-order accuracy on a space-staggered grid (Hamrick, 1992). EFDC allows for a Cartesian or a curvilinear grid, orthogonal in the horizontal, and a sigma coordinate grid in the vertical (EFDC, 2007). The EFDC model has been applied to more than 100 modelling studies worldwide, including to reservoirs, estuaries (Yang and Hamrick, 2003), both in hydrodynamic and water quality simulations (Liu and Huang, 2009).

The computational domain for the Severn Barrage studies is shown in Fig. 2, extending to beyond the Continental Shelf, to avoid impacts on the open boundary from the alteration to the tidal regime caused by the inclusion of a barrage. The grey area represents inactive or land cells, leaving a very large active area of simulation, approximately 846,000 km^2, with cells sizes ranging from 50 × 50 m^2 in the areas of specific interest, e.g. around the barrage, to 5000 × 5000 m^2 in the open ocean. The large active area is spread over a wide range of bottom elevations, from 5000 m below Ordnance Datum in deep water, to 5 m above Ordnance Datum in the Severn Estuary, along its narrower reaches.

A typical neap–spring tidal cycle for a period of 14 days, from 1 to 14 March 2005, was used for this study. The dotted lines in Fig. 2, demonstrate the open boundaries of the model domain, at which tidal elevations were specified. These open boundaries were split into a total of 1331 distinct sections, and elevations series for each section are specified along the model boundary. The tidal elevation used as the model boundaries were obtained from the MIKE21 global model (DHI Software, 2007).

One mode of barrage operation is investigated in this paper, the ebb-only generating barrage as originally proposed by the Severn Tidal Power Group (STPG, 1989). In this scheme, 166 large sluices and 216 bulb-turbines (as shown in Fig. 3) would allow the basin upstream of a 16 km barrage to fill with the incoming tide. Once high water is reached, the sluices and turbines are closed and a head difference either side of the barrage structure is caused by ebbing tide on the seaward side of the barrage. Once a sufficient head differential is achieved, the 216 × 40 MW bulb-turbines are opened for electricity generation, until the minimum head at which they can operate effectively is reached. The water is held at a constant level until the next flood tide causes the sea level outside of the barrage to rise above the basin water level, at which point the sluices and turbines are re-opened and the basin refilled.

The full details of EFDC_B, the module developed to include a barrage in the simulations, are included in Zhou et al. (2013) and so will only be briefly detailed herein to describe the various modes of barrage operation, refinements to structure representation and various scenarios. The changes to EFDC_B demonstrate the impact of the refinements to the numerical representation of the hydraulic structures. Sluice gates were initially represented in the model as cells which could be switched from open to closed, or wet to dry. During the filling phase, i.e. when the sluices are open, the velocities through the computational cells containing sluices were calculated as ordinary wet cells, with the velocities calculated as part of the EFDC solution. During the generating and holding phases, when the sluices are closed, zero velocity is set across the cell side, i.e. a no flow condition. The numerical representation was then updated, with sluice gates modelled as hydraulic structures, where the discharge through the hydraulic structure is calculated in a similar manner to evaluating the discharge through an orifice, as given by:

$$Q = C_d*A*(2*g*H)^{0.5} \tag{1}$$

where Q is discharge (m^3 s^{-1}), C_d is a discharge coefficient, A is flow-through area (m^2), g is gravitational acceleration, and H is water level difference either side of the cell (or sluice gate).

The discharge through the turbine cells is also represented in the model using two different methods. The first method uses the orifice equation above, and the second method using a Head-Discharge curve, or hill chart, typically obtained experimentally (Goldwag and Potts, 1989; Falconer et al., 2009). A hill chart used in this study is illustrated in Fig. 4. Discharges from the hill chart differ from discharges calculated using Eq. (1), especially at high

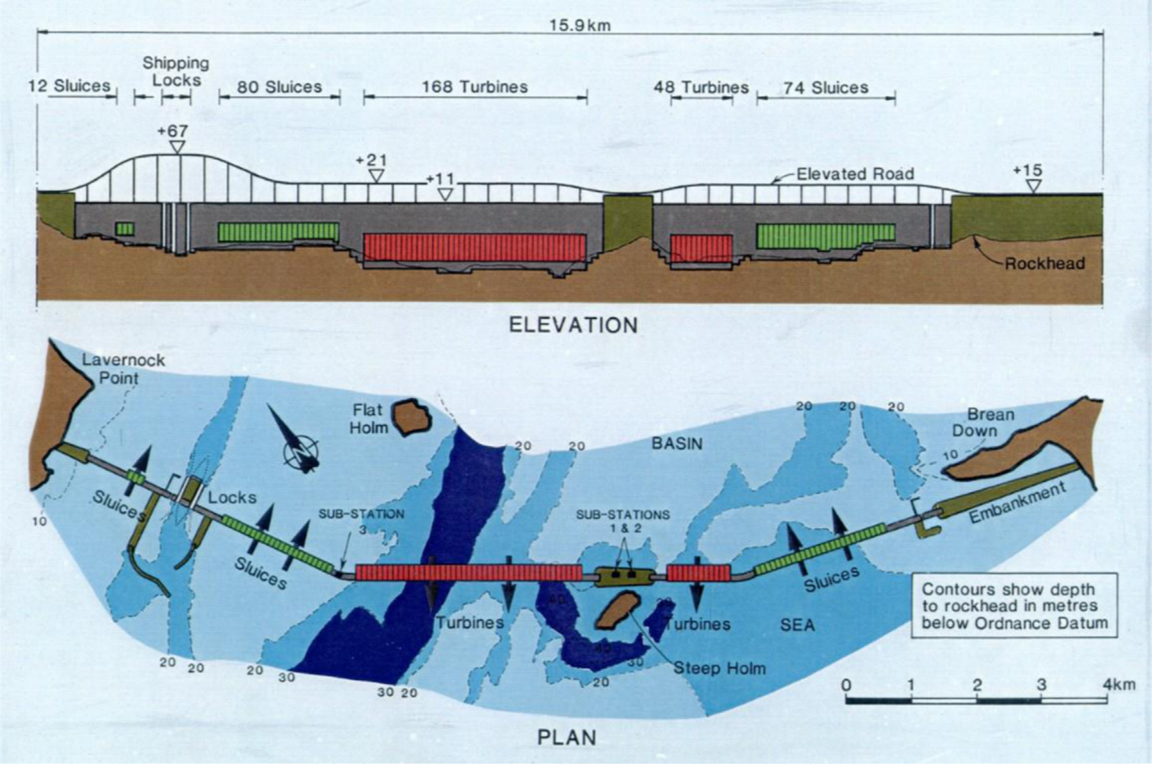

Fig. 3. Layout of STPG barrage (courtesy of Severn Tidal Power Group) (Department of Energy, 1989).

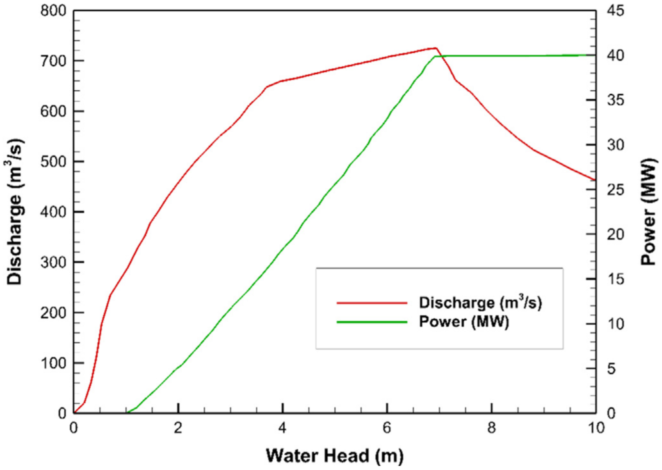

Fig. 4. Relationship between the water head, discharge and power output.

head differences where available power through flow is higher than the turbine maximum power capacity. Therefore, the discharge through the turbine is mechanically restricted to maintain a higher head difference and increase the total power generation over the generation phase. This is explained by Eq. (2), which expresses the formula for calculating the generation power P of each turbine:

$$P = \rho * g * Q * H * \eta \tag{2}$$

where ρ is specific density of sea water and η is efficiency coefficient of the turbine. As the head difference becomes very large, the turbine reaches its maximum power output (e.g. 40 MW in the case of the STPG proposal) and so discharge is restricted, so as not to waste potential energy. In calculating the power, using Eq. (2), the efficiency η was assumed to be 1, as suggested by Baker (2006).

Previous studies using the EFDC_B model have shown that there could be far-field effects of a Severn Barrage, however, the water levels predicted by EFDC_B are not in complete agreement with those previously reported in the literature, e.g. Ahmadian et al. (2010) and Xia et al. (2010b), where it is predicted that inclusion of a barrage in the model would reduce the water levels upstream of the proposed barrage by up to 1 m in some areas. Moreover, it is predicted that water levels upstream of the barrage would be lower than those predicted downstream of the structure.

The current study aims to demonstrate that the main cause of such a difference in the water levels predicted by EFDC_B was the representation of the turbines and sluices in the barrage, which was removed by improved representation of these hydraulic structures. The following scenarios were used to investigate the improved representation of the turbines and sluices for near- and far-field impacts of the ebb-generating Severn Barrage and to assess the sensitivity of the barrage to the discharge coefficient changes:

2.1. Scenarios 1 and 2 – Ebb-only generating barrage

In Scenario 1, the sluices were represented as wet cells during the filling phase, while they were switched to dry cells with a no-flow condition during the holding and generating phases. The turbines were set up to allow flow as computed from the orifice equation, both during the generating and filling phases, and allowing no flow through the turbines during holding phases. Scenario 2 included improvements that represented the barrage structure more appropriately, by modelling the sluices and turbines as orifices of different areas during the filling phase, and calculating the turbine flow during power generation from the bulb-turbine hill chart. The flow through sluice gates during the holding and generating phases was set to zero.

2.2. Scenarios 3–7 – Varying C_d values

The next set of scenarios used the refined hydraulic structure representations from Scenario 2, and varied the discharge

Table 1
Scenarios 3–7 detailing the different discharge coefficients used for each.

Scenario	Sluice area (m^2)	Discharge coefficient
3	35,000	0.9
4	35,000	0.95
5	35,000	1
6	35,000	1.05
7	35,000	1.1

coefficient to assess the sensitivity of the modelling of the barrage to this variable. A C_d value of 1 is recommended by Baker (2006), which was used as the base line, and with 5% and 10% changes made to this base value, to create the scenarios shown in Table 1.

2.3. Scenarios 8–12 – Adjusted sluice area to compensate for reduced/increased C_d values

It is expected that a reduction in the discharge coefficient would negatively impact on the performance of the barrage. The following scenarios were therefore set up to investigate whether changes in the sluice area could compensate for changes in the C_d values. This is of particular importance as it demonstrates whether changes in the design of the sluices, which may result in a lower C_d value, could be compensated for by adding more sluices. In these scenarios, the power generated by the Severn Barrage was assessed when the sluice area is increased/reduced by the same proportion that the discharge coefficient is reduced/increased, e.g. a 10% increase in sluice area is used with a C_d value of 0.9 (Table 2).

All of the different methods of computing the discharge and also employ a ramp function to represent the gradual opening and closing of the sluice gates and turbines. This representation is more realistic than turning the sluice gates and turbines on or off and remove the numerical oscillations caused by instant opening of the hydraulic structures, as suggested by Ahmadian et al. (2010). This ramp function is expressed in the form of a half-sinusoidal function, where an opening or closing time is set according to the expected operation times, i.e. typically in the region of 10–20 min.

3. Model validation

The original model was run for 14 days, over a neap–spring tidal cycle, and the predicted results were compared with measured field data from Admiralty Charts at locations in the Irish Sea, Celtic Sea and Bristol Channel.

Fig. 5 shows the typical validation results for 4 sites, as displayed in Fig. 2, with similar comparisons observed at other validation sites. To measure the predictive capability of the EFDC Continental Shelf Model, the Nash–Sutcliffe model efficiency coefficient (NSE) was used. The NSE, presented by Nash and Sutcliffe (1970), is based on the following equation:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Oi - Si)^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2} \tag{3}$$

Table 2
Scenarios 8–12 detailing different sluice areas and discharge coefficients.

Scenario	Sluice area (m^2)	Discharge coefficient
8	38,500	0.9
9	36,750	0.95
10	35,000	1
11	33,250	1.05
12	31,500	1.1

where Oi is the observed data, Si is the simulated data, and $\bar{O}$ is the mean of the observed data. The NSE result can range from $-\infty$ to 1, where an efficiency of 1 corresponds to an exact match between predicted and observed data, and 0 indicates that the mean of the observed data is as good a predictor as the model.

The NSE for the model predictions for current direction were excellent, with an efficiency of 0.86. The efficiencies for the spring and neap tide velocities were 0.82 and 0.86 respectively. These very high NSE results indicate that the model is a strong predictor for tidal directions and velocities in the Continental Shelf Domain, allowing for the inclusion of the barrage module so that the changes brought about by modifications to the hydraulic structure representation can be assessed.

4. Model application

After validating the Continental Shelf Model, the effects of the barrage modifications were investigated by comparing Scenarios 1 and 2, and the scenarios for a changed coefficient of discharge. Fig. 6 shows points A and B, each of which is 6 km either side of the barrage structure. Water elevations at A and B were compared for Scenarios 1 and 2, as shown in Figs. 7 and 8. These points are of particular importance as they are used to determine the operational phase of the barrage in the model.

It is clear that for Scenario 1 the barrage has had a large impact on the tidal regime upstream of the barrage, substantially raising the minimum water levels. The upstream maximum water levels were not significantly affected, and are higher than the maximum water levels found downstream.

In Scenario 2, which is a refined version of Scenario 1, the maximum water levels upstream are about 0.75 m lower than the prediction levels from Scenario 1; the levels are also lower than the predicted maximum water levels downstream. The minimum water levels upstream are almost unaffected by the changes to turbine and sluice representation. The maximum and minimum upstream water levels predicted for Scenario 2 were similar to those values reported in the literature (Ahmadian et al., 2010). Fig. 9 shows the impact of the refinements on the water levels at Point A, over a 7-day period.

An examination of the maximum water levels throughout the domain demonstrated that a Severn Barrage operating under ebb-only generation can have water level impacts as far-field as the West-Coast of Scotland, but that the refinements reduced the far-field effects, as shown in Figs. 10 and 11. Fig. 12 shows the impact of the refinements in the Severn Estuary and Bristol Channel.

The refinements have had a significant impact; they have raised the maximum water levels downstream of the Barrage by up to 0.25 m in some areas, and reduced the maximum water levels upstream by up to 0.75 m in much of the region. This is caused mainly by the change in the discharge through the structures as a result of the refinements; flow through the sluices during filling was significantly reduced in Scenario 2 compared to Scenario 1, resulting in the basin water level not getting so high.

5. Sensitivity to discharge coefficient

The maximum water levels for Scenarios 3–5 were compared to assess the impact of a change in the discharge coefficient. Figs. 12 and 13 show the changes in the maximum water levels brought about by a 10% and 5% reduction in the C_d values respectively.

The changes to the maximum water levels occur only within the Severn Estuary and Bristol Channel, so a reduced view of the domain is shown in Figs. 13 and 14, although the results are extracted from the full CSM domain. When the C_d value is reduced, then as expected the

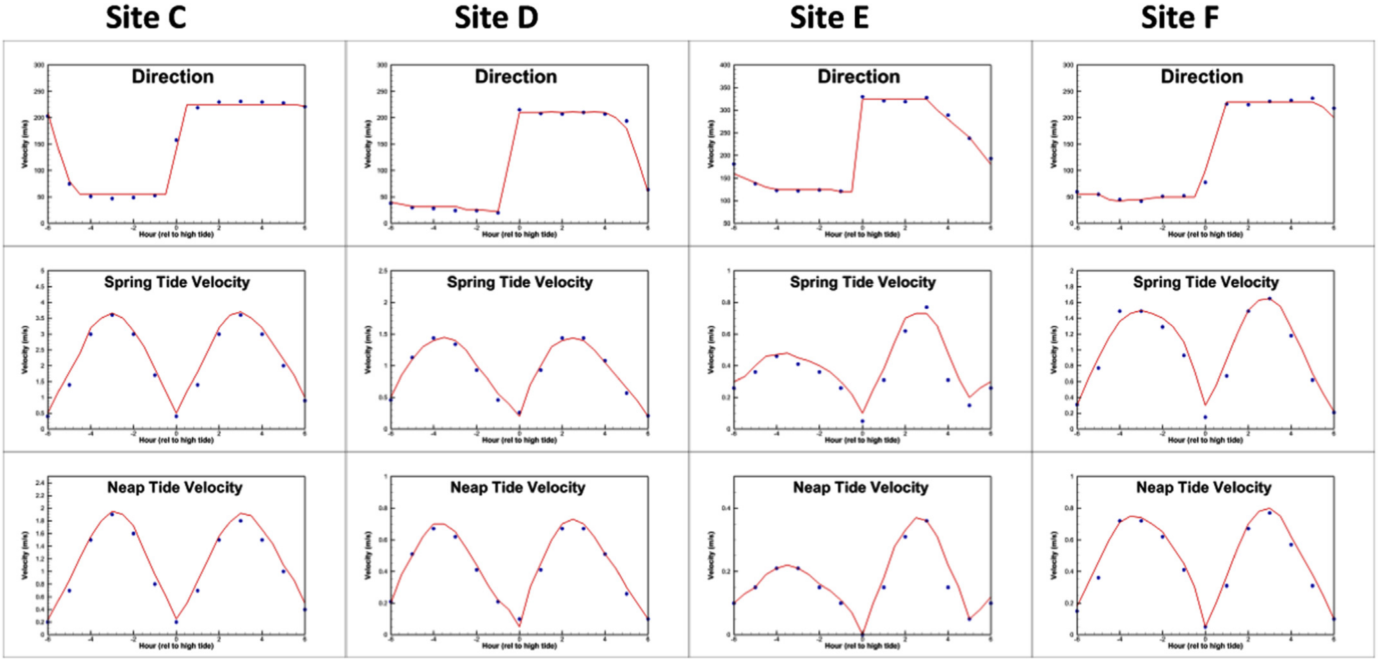

Fig. 5. Comparisons between observed (blue dots) and calculated (red lines) tidal stream current speeds and directions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

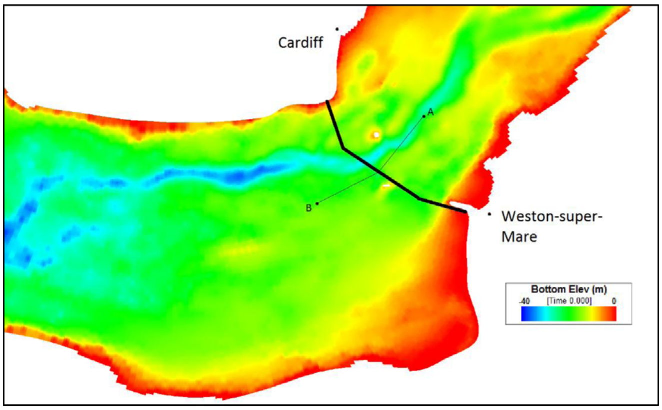

Fig. 6. Barrage location and Points A and B, used to demonstrate effects of refinements.

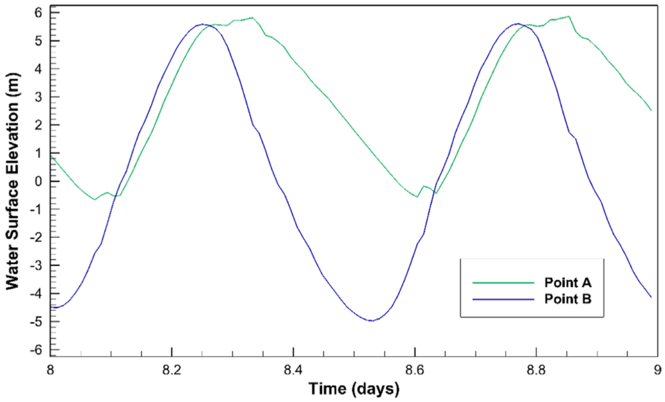

Fig. 7. Upstream (green) and downstream (blue) water levels for Scenario 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

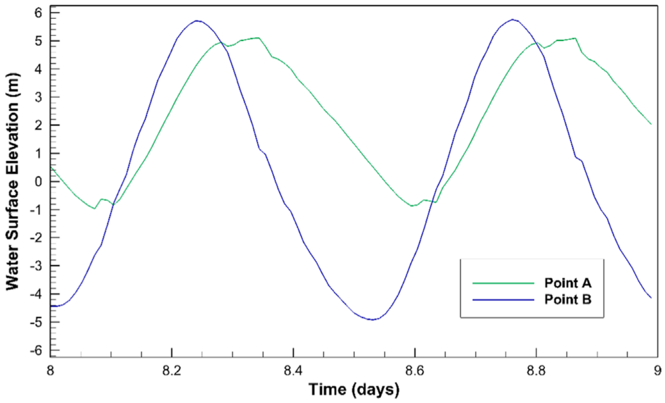

Fig. 8. Upstream (green) and downstream (blue) water levels for Scenario 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

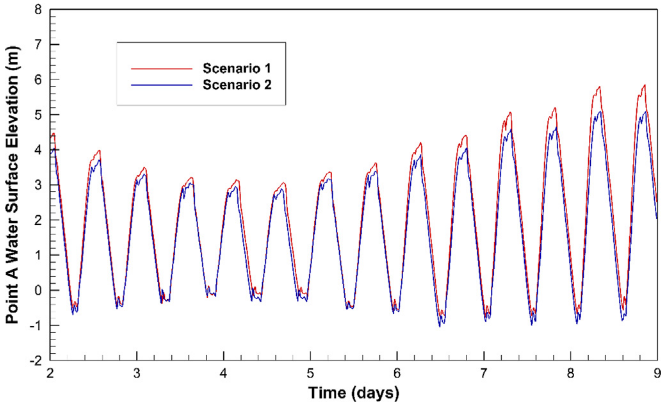

Fig. 9. -Impact of hydraulic structure refinements on water levels at Point A.

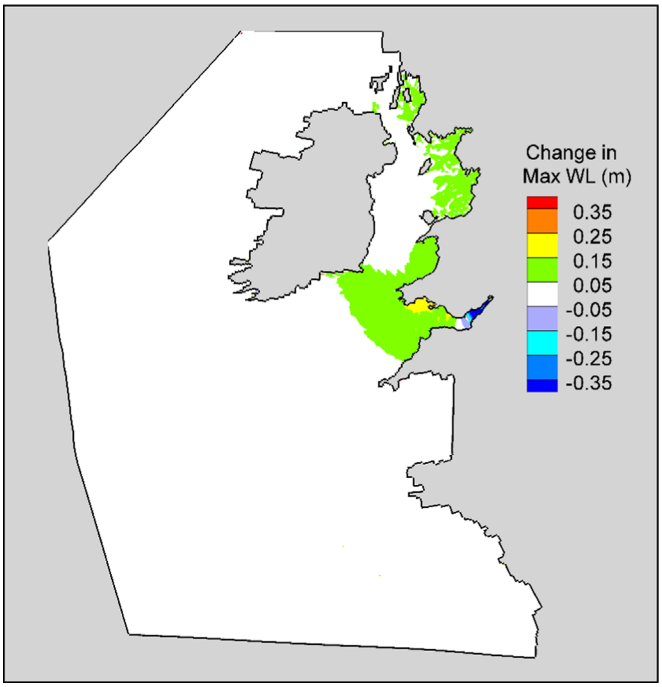

Fig. 10. Domain-wide maximum water level changes caused by barrage Scenario 1.

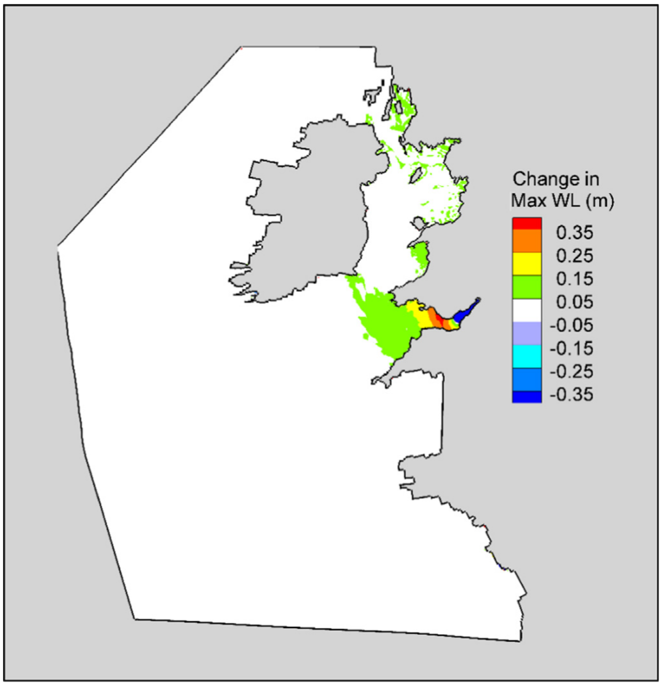

Fig. 11. Domain-wide maximum water level changes caused by barrage Scenario 2.

maximum water levels upstream are also reduced, due to the reduction in discharge through the sluice gates during the filling stage.

The power generated by the barrage when varying the discharge coefficient is compared in Fig. 15. It is clear that the power generated is only slightly affected by a reduction in the C_d, but a reduction in C_d causes a reduction in the power output due to lower head differences across the structure.

6. Mitigation through increased sluice capacity

To assess if the reduced power caused by lowering the discharge coefficient could be mitigated, Scenarios 8–12 were then compared for increased sluice areas. It can be seen that the differences in power generated due to a change in the C_d were reduced significantly when matched by a corresponding increase in the sluice area.

7. Discussion

Changes in the representation of sluices and turbines within the numerical model of the Severn Barrage can be seen to have a large impact on water levels within the estuary. When the sluices gates were only modelled as wet cells, i.e. in Scenario 1, the upstream water levels were only slightly lower than if the barrage was not included in the simulation. This is not consistent with the operation schemes suggested by Baker (2006) for the Severn Barrage and for the La Rance barrage, where higher upstream than downstream water levels are achieved only through pumping (Retiere, 1994; Hammons, 1993). For Scenario 2, where hydraulic structures were accurately simulated, the water levels upstream of the barrage were reduced by nearly 1 m in comparison. For the latter case the water levels were in much better agreement with the predictions reported in the literature, e.g. Ahmadian et al. (2010, 2014a, 2014b), Falconer et al. (2009) and Xia et al. (2010b), in which upstream water levels are also significantly reduced by the inclusion of a barrage, lowering the peak levels to below those found immediately downstream of the structure. The predictions cannot be statistically compared to demonstrate this agreement due to different boundary conditions being used, however, the comparison of peak water levels upstream and downstream demonstrate the concurrence of the prediction from Scenario 2 with the predictions from several other models. Scenario 1's predictions are in contrast to this, with upstream peak water levels remaining higher than those downstream, likely due to the insufficient resistance to flow offered by unrealistic physical representation of the hydraulic structures, as seen in Brammer et al. (2014). The refinements included in Scenario 2 are a more physical representation of the process of discharge through a sluice gate, and as such, coupled with the close agreement in water levels with predictions from other models, the updated prediction from Scenario 2 supersedes the prior results.

The reduced maximum water levels upstream are caused by more realistic filling of the basin. In Scenario 2, there is an added resistance to flow caused by modelling the sluices as orifices rather than wet cells, thereby effectively reducing the flow-through area. The rate of volume transfer is reduced, as can be seen in Fig. 8, where the gradient in the increase in the upstream water level is less steep than in Fig. 7. This slower rate of volume transfer during filling results in the upstream basin not reaching the water level that it would without the barrage, and in this sense would offer significant flood protection to floodplain areas.

In Scenario 2, the resistance to flow, and consequently the reduction in discharge through the sluices, causes an increase in the discharge through the turbine cells during filling, despite their numerical representation for filling being identical in Scenarios 1 and 2. Where previously, in Scenario 1, the sluice cells offered a route of significantly less resistance to flow, this disparity in resistance to flow was reduced by modelling both as orifices in Scenario 2, albeit with different flow-through areas.

The lower water levels upstream also have the effect of reducing the head difference across the structure for power generation. During the spring–tide cycle, the head difference in Scenario 1 was often higher than 7 m, at which point, according to the Head-Discharge curve used for the 40 MW turbines used in this study, the discharge would be limited as the turbines would have reached their maximum power output. In Scenario 2, the reduction in head difference was sufficient that the discharge would not

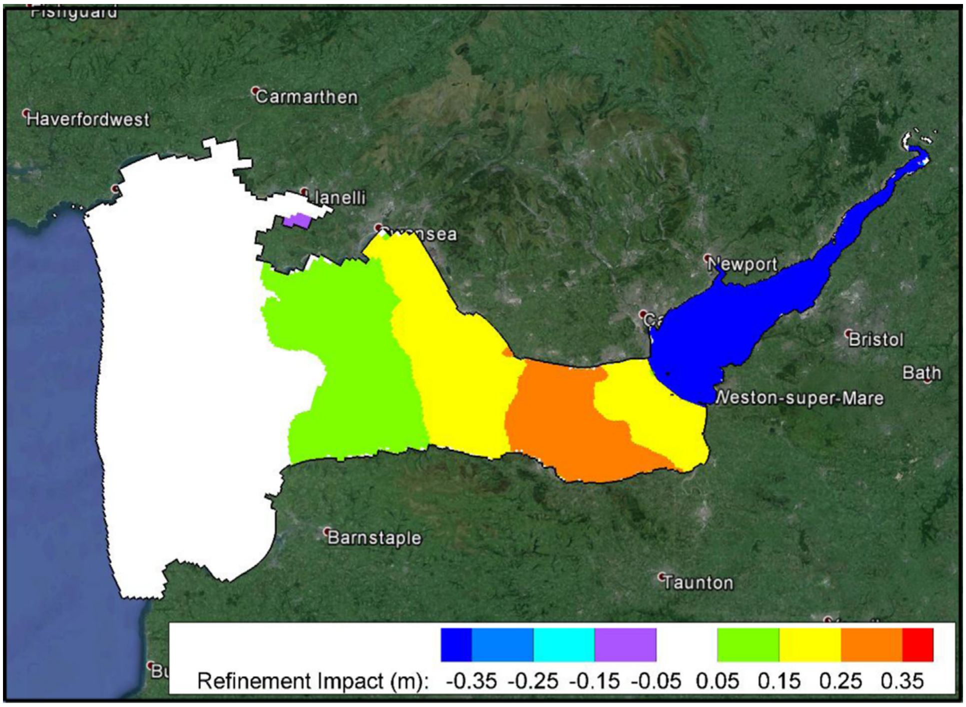

Fig. 12. Impact of hydraulic structure refinements on maximum water levels in the Severn Estuary and Bristol Channel.

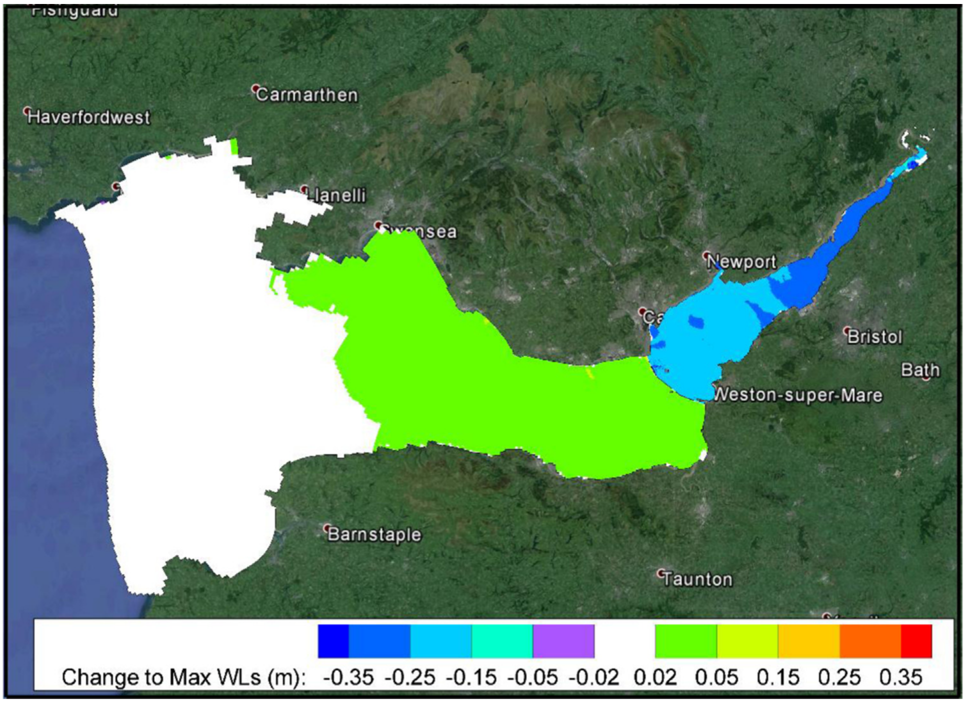

Fig. 13. Maximum water level changes caused by a 10% reduction in the C_d value predicted by the refined CSM (no change was observed outside the Severn Estuary and Bristol Channel).

have needed to be restricted, allowing the 40 MW turbines proposed for this scheme to operate as intended.

In assessing the sensitivity of the maximum water levels to changes in C_d, it can be seen that the impacts are contained entirely within the Severn Estuary, with no effects seen outside of this basin. A reduction in C_d caused some reduction in the discharge through the sluice gates and turbines during the filling phase of the barrage operation, causing the basin to fill more slowly and not reach the same water level as for the case with a higher discharge coefficient. Reducing the C_d value by 10%, i.e. from 1 to 0.9, caused an average reduction in the maximum water levels upstream of 3.8%. A 5% reduction in the C_d value caused an average 2.3% reduction in the maximum water levels upstream. Despite the instantaneous discharge being directly proportional to the C_d value, the continual nature of the filling the basin, and the increased head difference at each succeeding time step caused by the reduced discharge, has mitigated the effect of lowering the C_d value. This has, therefore, caused smaller changes to the water

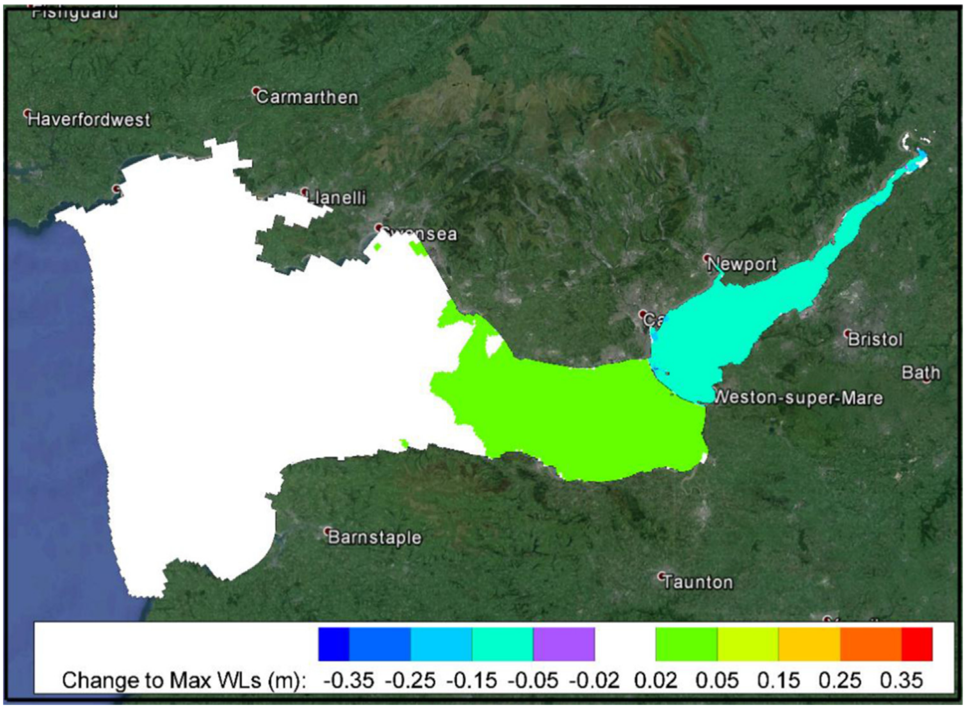

Fig. 14. Maximum water level changes caused by a 5% reduction in the C_d value predicted by the refined CSM (no change was observed outside the Severn Estuary and Bristol Channel).

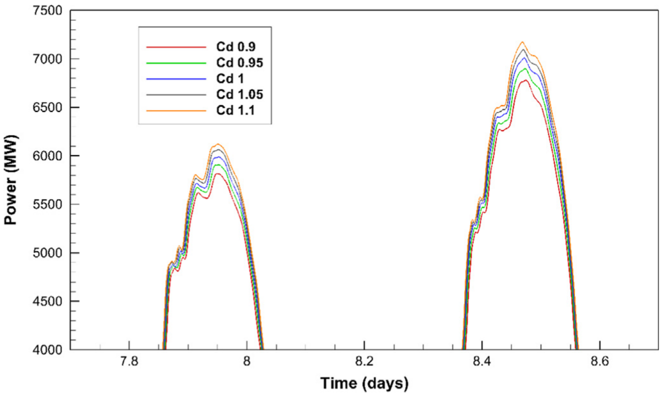

Fig. 15. Power generated by the barrage when varying C_d over one day.

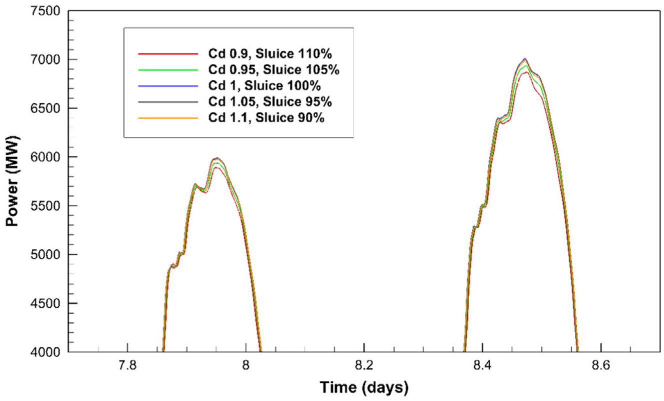

Fig. 16. Power generated by the barrage when varying C_d and sluice capacity.

Table 3
Power generation comparison.

Scenario	Discharge coefficient	Energy (14 days, MWh)	Energy per annum (TWh)	% of STPG C_d 1
3	0.9	629,617	16.4	95.77
4	0.95	644,270	16.8	97.99
5	1	657,431	17.1	100
6	1.05	666,885	17.4	101.43
7	1.1	676,627	17.6	102.91

Table 4
Power generation comparison.

Scheme	Discharge coefficient	Sluice capacity	Energy per annum (TWh)	% of STPG C_d 1
8	0.9	110% (38,500 m^2)	16.61	97.14
9	0.95	105% (36,750 m^2)	16.93	99.00
10	1	100% (35,000 m^2)	17.1	100
11	1.05	95% (33,250 m^2)	17.1	99.9
12	1.1	90% (31,500 m^2)	17.1	99.6

levels, discharge and power generation. This is further evidenced by the power generation statistics given in Table 3.

Table 3 demonstrates that a 10% reduction in the discharge coefficient causes a 4% decrease in predicted annual energy generation. Likewise, an increase in the discharge coefficient causes a proportionally smaller increase in energy generation.

Despite being mitigated by the continual nature of filling the basin, there are some power losses caused by a reduction in the discharge coefficient. Fig. 16 demonstrates that this power loss can be reduced by adding further sluicing capacity to the barrage and that, in fact, the power loss is negligible when an assumed discharge coefficient is matched by a proportional increase in the sluicing capacity. Table 4 compares the power output for scenarios 8–12.

8. Conclusion

In this paper, the numerical implementation of sluice gates and turbines has been refined within the EFDC model which includes modelling a Severn Barrage, i.e. using the EFCD_B model, to give an improved physical representation of the barrage. Following validation of the model against Admiralty Chart Data, and to identify the improvements as a result of the refinements, comparisons of the maximum water levels have been made for 2 main scenarios. Scenarios 1 and 2 investigated an ebb-only generating barrage by first modelling the sluices as a gap in the barrage, and then refined to be represented as a hydraulic structure where the discharge was computed from the orifice equation. Scenarios 3–7 compared the maximum water level impacts and power generation of the STPG Severn Barrage configuration using the refined hydraulic structure representations, but varying the discharge coefficient between 0.9 and 1.1. These scenarios enabled the sensitivity of the modelling to be investigated for changes in the value of the discharge coefficient, particularly since there is much uncertainty in the value of this coefficient.

Scenarios 1 and 2 have highlighted large differences in the predicted maximum water levels, particularly upstream of the barrage. The more realistic representation of the barrage, i.e. Scenario 2, showed a reduction of around 0.75 m in the maximum water levels upstream, bringing the levels into agreement with values reported in the literature using alternative hydrodynamic models. Scenario 2 demonstrated that an ebb-only Severn Barrage could reduce the maximum water levels upstream of the structure by as much as 1 m.

The results for Scenarios 3–7 demonstrate that a change in the discharge coefficient results in a significantly smaller change in the water levels, together with the discharge and power generated. This is explained by the continual, rather than instantaneous, nature in filling the basin, where a reduction in the value of C_d, which is directly proportional to the discharge, leads to an increased head difference across the structure during the filling period. A 10% reduction in C_d caused a 4% reduction in the maximum water levels upstream of the structure, and no notable changes elsewhere across the domain. The energy generation was also affected by 4%, for the same reduction in the C_d value. A 5% reduction in the C_d value changed the upstream water levels and energy generated by 2.3%, with similarly small changes in the water levels and energy generated being observed for proportional increases in the C_d values.

Increasing the sluice capacity of the barrage is shown to further mitigate any power losses caused by a reduction in the discharge coefficient, demonstrating that any power deficits caused by uncertainties in the value can be corrected through the simple addition of extra sluice gates.

The enhancements incorporated into Scenario 2 would have a significant effect on the hydro-environmental impact assessment of the renewable energy scheme, and highlight the importance of accurate numerical representation of hydraulic structures. As a result of these refinements, the updated EFDC model more accurately simulates the STPG Severn Barrage, and is better able to predict the hydrodynamic impacts of the scheme and other marine renewable energy proposals on the aquatic environment. The results of the sensitivity analysis to the discharge coefficient have improved confidence in the modelling, despite some likely uncertainty in the assumed value of the discharge coefficient, with the barrage performance being shown not to be significantly affected by changes in the value of this parameter. The small power losses caused by a change in the C_d value can be further mitigated by increasing the sluicing capacity of the structure.

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