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IMPACT OF THE SWANSEA BAY LAGOON ON STORM SURGES IN THE BRISTOL CHANNEL

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ABSTRACT

The proposed Swansea Bay tidal energy lagoon is an example of a relatively small-scale tidal barrage demonstrator project. A key concern with this technology is that such structures may exacerbate other environmental problems. However, such structures might also create beneficial environmental effects in some areas, such as mitigating the impact of storm surges. In this paper we model the hydrodynamics of the Swansea lagoon and surrounding area using a depth-averaged numerical model. We simulate a number of storm surge events from the past 40 years and analyse how the presence of the Swansea Lagoon (under various operating strategies) modifies the resulting water levels.

INTRODUCTION

Tidal energy is a clean and predictable way of generating power. There are two primary approaches: either using a free standing turbine, which must be placed in an area of fast flow, or using a tidal barrage. This paper looks at the latter case. Tidal barrages are an attractive technology in that most of the components are already used in other engineering applications. They suffer from a number of disadvantages such as cost, which we do not consider in this paper. However, a key issue with this technology is their environmental impact. One aspect of this is the impact on tidal hydrodynamics and on coastal flooding due to storm surges. See the review of tidal barrages and lagoons by Neill *et al.* [1] for further background.

In this paper we investigate the impact that a small tidal barrage has on storm surge. We base our case study on the proposed Swansea Bay Lagoon [2]. The proposed lagoon has a surface area of 11.5km^2 and its layout is given in Fig. 1. The project is predicted by the developer to produce an average power of 48MW. However, whilst of course a useful contribution, the primary purpose of the development appears to be as a prototype to inform the decision as to whether and how to construct larger facilities. At present the project appears to be on hold, primarily due to the cost.

The Swansea Bay lagoon is located in the Bristol Channel. This area is well known for having one of the largest tidal ranges in the world due to the combination of tidal resonance and the funnelling of estuary [3, 4]. Because of the large tidal range incidents of coastal flooding are relatively infrequent – flooding will only take place when an extreme meteorological event coincides with a high spring tide. There can also be some tide/surge interaction [5]. However, when these do coincide there is potential for very significant flooding partly due to the low-lying land around the estuary. As an example of this scenario, a major storm surge event occurred in 1607 which caused devastation in the area [6, 7].

There has been very little literature on the interaction of tidal barrages and storm surges. To our knowledge the only past study has been by Lyddon *et al.* [8]. Other studies such as Lewis *et al.* [9] have considered the impact on power production, albeit very simplistically. However, there will clearly be some impact on storm surge due to the deployment of a barrage and this needs to be understood before such a structure can be deployed.

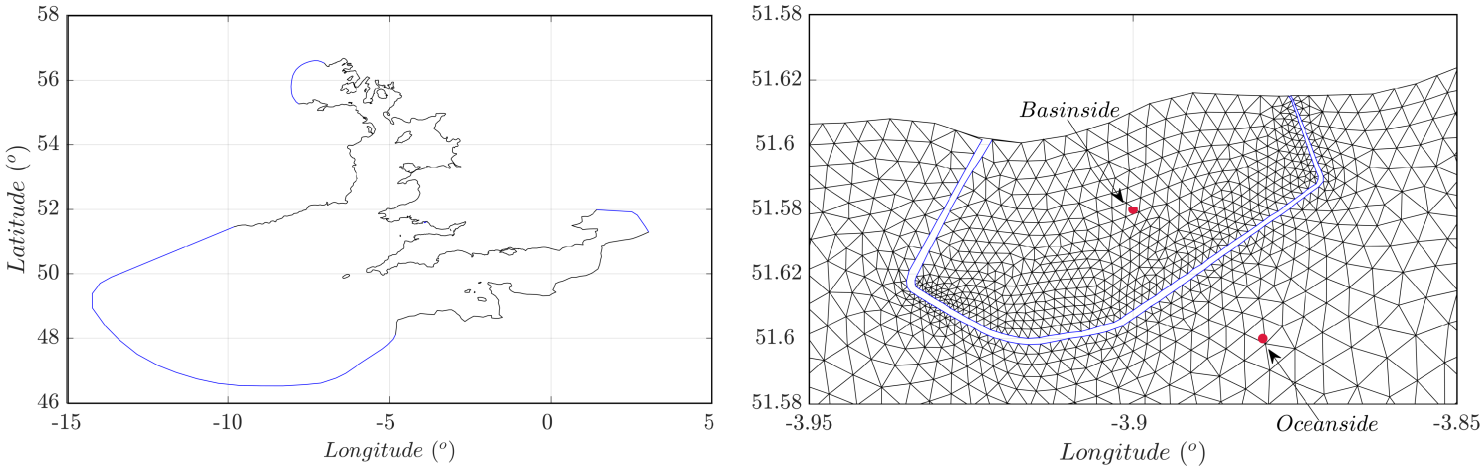

FIGURE 1: Model computational details: a) Model domain (left), blue lines show the ocean boundaries; b) Barrage layout for Swansea Bay Lagoon (right), the blue lines indicate the lagoon boundary.

In this paper we use a depth-averaged numerical model to investigate the tidal hydrodynamics in the Bristol Channel. Tides and storm surge events are simulated with and without the presence of the Swansea lagoon and the results analysed. Further, we investigate the impact of different operational strategies on the large scale hydrodynamics.

NUMERICAL MODEL

Tidal hydrodynamics can be modelled by the 2D shallow water equations assuming the absence of flow stratification [10]. The governing equations are [11]:

$$
\begin{aligned}
\frac{\partial \xi}{\partial t} + \frac{\partial (Du)}{\partial x} + \frac{\partial (Dv)}{\partial y} &= 0, \\
\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} + u\frac{\partial u}{\partial x} - fv &= -\frac{\partial \Omega}{\partial x} - \frac{1}{\rho}\left(\frac{\partial P}{\partial x} - \frac{\partial F}{\partial z}\right), \\
\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu &= -\frac{\partial \Omega}{\partial y} - \frac{1}{\rho}\left(\frac{\partial P}{\partial y} - \frac{\partial G}{\partial z}\right),
\end{aligned}
\tag{1}
$$

where u and v are depth-averaged horizontal velocities in the x- and y- directions; $f = 2\Omega \sin\Phi$ is the Coriolis parameter; Ω is Earth's angular speed; P is the atmospheric pressure; F is the total stress in the positive x-direction and G is the stress in the y-direction.

In this paper the shallow water equations are solved using the discontinuous Galerkin method version of the ADCIRC (DG-ADCIRC) [12–14] with unstructured triangular mesh. Fig. 1 depicts the domain of the model, which is based on that of Serhadlıoğlu [15, 16] with resolution improvement in some areas (convergence test has been conducted by Serhadlıoğlu). The model domain includes the Irish Sea, Celtic Sea, English Channel and Bristol Channel (the latter from the model of [17]), and is divided into 51,458 nodes and 98,278 elements of unstructured triangular cells for the mesh where there is no tidal lagoon (including a barrage structure requires minor remeshing and details on the mesh around the turbines can be found in [18]).

There are three open ocean boundaries as shown in the figure: the western boundary in the Celtic Sea, the eastern boundary in the English Channel and the northern boundary extending towards the Scottish Isles of Tiree and Coll. Tidal forcing has been specified on these ocean boundaries by the amplitude and phase of tidal constituents based on the Le Provost tidal database [19]. The three main tidal constituents in the Bristol Channel are the M_2, S_2 and N_2 tides (all semi-diurnal), which we use to force the model; smaller constituents are neglected for simplicity. When determining these boundaries, it is not practical to extend the model to the continental shelf in every direction. However, we believe they are sufficiently far from the Bristol Channel that they are not expected to cause significant error at the location of interest.

Representation of Storm Surges in the Model

Storm surges are generated as a result of strong winds and air pressure variations. A storm surge can last from several hours to one day with an approximate wavelength between 150 km and 800 km, which is classified as a long wave given the water depth of the ocean. In order to investigate the impact of the addition of a lagoon during storm surge events, meteorological data (i.e. wind stress and pressure variation) need to be applied as input for the storm surge simulations. The atmospheric surface pressure and 10-meter wind velocity and direction data have been captured from the ERA5 reanalysis data sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF) [20]. Another two datasets with different spatial and temporal resolutions, the ERA-Interim and the MÉRA dataset [21], have been examined as well for storm surge simulation in the Bristol Channel. However, the agreement between the surges predicted when using these alternative meteorological models and measured data are not as good as with the ERA5 model.

The original measured data from the ERA5 are distributed by latitude and longitude grid lines in hourly intervals. Data interpolation has been applied based on the distributed mesh data and meteorological input requirements of the ADCIRC. The pressure variations obtained are applied to the model directly. However, the wind speed need to be converted to a shear stress. This will be proportional to air density, ρ_a, and a dimensionless drag coefficient, C_d, between the wind and sea surface. The stress can be expressed as:

$$\tau_s = C_d \; \rho_a \; W^2, \tag{2}$$

where W is the wind velocity. There are various drag coefficient correlations with respect to varying wind speed as discussed by Bryant *et al.* [22]. The detailed consideration of different C_d correlations will be discussed with the model validation and calibration.

Representation of the Lagoon in the Model (Swansea Lagoon Proposal)

In order to include the effects of sluices and turbines in the tidal lagoon, this paper utilises a barrage boundary incorporated in DG-ADCIRC [18]. This barrage model was created based on a culvert model already present in DG-ADCIRC [14, 23], that adds an internal barrier into the finite element mesh. The internal barrier acts as a reflective boundary throughout its length (zero perpendicular velocity), except at the node pairs where hydraulic structures are simulated (Fig. 2). The flow through these node pairs is calculated from the water head developed between "front" and "back" sides.

For simulating sluice gates, the barrage model utilises the orifice equation, which relates head difference H_e to the flow Q_o through the boundary [24, 25].

$$Q_o(H) = C_d A_S \sqrt{2gH_e}, \tag{3}$$

where C_d is the discharge coefficient (equal to one in this study), A_S the sluice area and g the gravity constant.

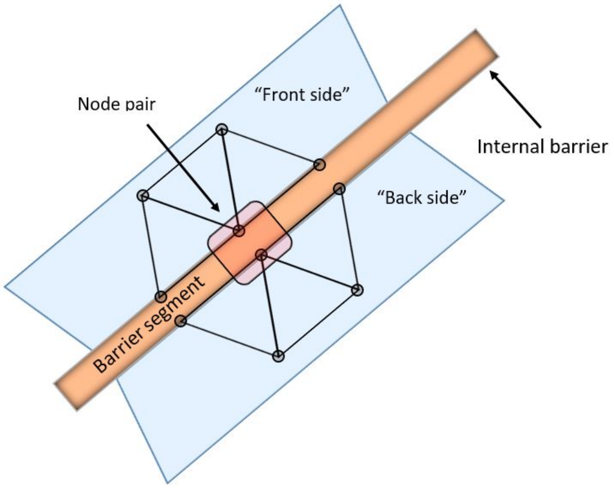

FIGURE 2: Top view of Internal barrier and triangular element representation (based on: [14, 18]).

The turbine's flow and power characteristics are obtained from a low head bulb turbine chart available by Andritz Hydro. [26, 27]. The Andritz chart used in this study is given in [18] and shows how turbine unit speed n_{11} and specific unit discharge Q_{11} (obtained experimentally) are related. The graph also shows wicket gate and running blade openings (in degrees) and efficiency curves E_f.

By specifying the parameters of the turbine: diameter D, number of generating poles G_p and grid frequency f, the turbine rotation S_p (rpm) can be obtained from $S_p = 120f/G_p$. From S_p, both unit speed n_{11} and specific discharge Q_{11} are calculated as:

$$n_{11} = \frac{S_p D}{\sqrt{H_e}}, \quad Q_{11} = \frac{Q_t}{D^2\sqrt{H_e}}. \tag{4}$$

Manipulating the specific discharge equation in Eqn. (4), the dimensional turbine flow-rate Q_t can be described as:

$$Q_t = Q_{11} D^2 \sqrt{H_e}. \tag{5}$$

When a forcing head is present, n_{11} is calculated from Eqn. (4), while Q_{11} is obtained by adjusting the opening of the wicket gate, the pitching of the runner blades and crossing the values with the obtained n_{11}. A parametrized curve of maximum power output is obtained by digitising the chart [26], and following the path where the product between E_f, Q and H_e is maximised (Eqn. (6)):

$$\begin{aligned} &Q_{11} = (0.0166)n_{11} + 0.4861; \; (\text{when } n_{11} =< 255) \\ &Q_{11} = 4.75; \; (\text{when } n_{11} > 255) \end{aligned} \tag{6}$$

Since n_{11} is acquired from the head difference, flow-rate trough the turbines can be calculated using Eqn. (5)-(6).

In order to choose appropriate parameters for designing the tidal lagoon, the current study follows previous research by [28, 29]. The chosen parameters are shown in Table 1.

	Swansea Lagoon Design
N^o of Turbines	16
N^o of Gp	95
Grid frequency (Hz)	50
Turbine Diameter (m)	7.35
Sluice Area (m^2)	800

TABLE 1: Swansea Lagoon Design.

A more thorough analysis of the barrage boundary implementation and verification (considering power generation) can be found in [18].

VALIDATION AND SIMULATION OF STORM SURGE EVENTS

2D Model Storm Surge Calibration

Calibration of the model has been carried out with respect to the different bed friction coefficients, wind surface drag coefficients and applied parameters that are significant to the accuracy of the final results.

The calibration of the friction coefficient is undertaken using Admiralty Tide Tables data [30] for M_2 and S_2 tidal elevation amplitudes and phases at selected stations. By adjusting the bottom friction coefficient C_f until the model-predicted results and observed tidal amplitudes and phases are as similar as possible in value. In addition, the bed friction types, a hybrid nonlinear bottom friction and a constant quadratic one, are considered in the calibration process. The simulations are run for 30-day periods with tidal forcing but excluding meteorological inputs and lagoon implementation. The comparison of different C_f values (0.002, 0.0025, 0.003 and 0.004) and types indicate that the overall best fit between the observations and the model results is achieved by setting $C_f = 0.0025$ with the constant quadratic friction law.

In order to achieve the most accurate results, the storm surge model with meteorological inputs and without lagoon implementation is tuned by adjusting the wind surface drag coefficient C_d. The observed surge (residual) levels from field-measured data, captured by the British Oceanographic Data Centre (BODC) at various locations within the Bristol Channel, are utilised for calibration. The sea-level measurements can be separated into the combination of a tidal component and a non-tidal component. We use the residual (the non-tidal component) to represent the storm surge phenomenon in this project and the simulation residual is calculated by the difference between the surge-induced and the baseline (no surge input) tidal elevations. The storm surge event selected is the flooding at Avonmouth on the 13th December of 2000. Five different coefficient correlations, including those developed by Sheppard (1958), Deacon and Webb (1962), Wu (1967), Garratt (1977) and Smith (1980) (see [22]), are applied in the surge simulations. It is concluded from the calibration comparisons that the model results show a good agreement with the BODC observed data when applying the drag coefficient correlation from Wu (1967):

$$C_d = \begin{cases} 0.5\, U_{10}^{0.5}, & 1 < U_{10} < 15 \\ 2.6 \quad , & U_{10} < 15 \end{cases}, \qquad (7)$$

where U_{10} is the wind speed at 10m height [31].

2D Model Storm Surge Validation

Model validation is undertaken by comparing harmonic constituent-based field measurements taken from the TotalTide software, a numerical model by Davis and Jones [32], and the measurements during the surge events, at locations within and a little beyond the Bristol Channel region.

The tidal harmonic analysis is done by comparing DG-ADCIRC results against predictions from Davis and Jones' models for the whole model domain. The contours of the computed M_2, S_2 and N_2 tidal amplitudes and phases are compared with the co-tidal chart, and all of them are found to be in good agreement. Quantitative comparisons have been carried out for the M_2 and S_2 tidal constituents. The predicted simulation results are compared against the observations from the Admiralty Chart (2006) at several observation stations and the overall predictions appeared to be in a satisfactory agreement with the tidal dynamics in the channel region.

A comparison between the model prediction and observed tidal and residual data at Avonmouth (from the BODC) for the storm surge event on the 13th December of 2000 is considered. The observed surge level at Avonmouth was over 2 m during this event. Fig. 3 shows the simulated surge pattern with clear flooding risks at the head of the channel. Fig. 4 displays the ADCIRC predictions compared with the BODC field measurements. As can be seen in the figure, there are small phase shifts between the field data and the simulation, and reduced surge (residual) peaks can be observed from the simulation results.

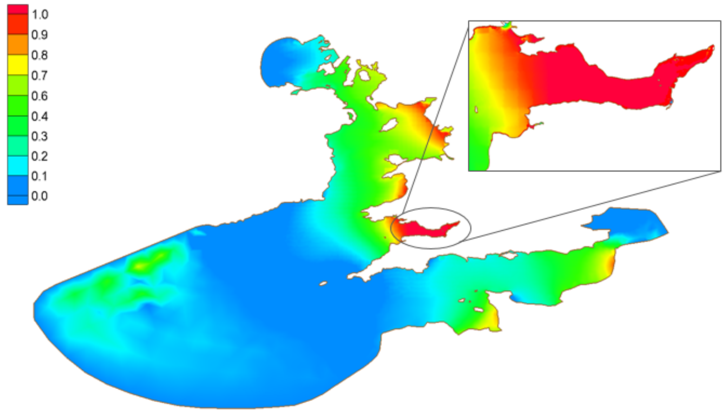

FIGURE 3: Simulation results of the surge residual during the storm surge events of 2000 for whole domain predicted and shown by DG-ADCIRC.

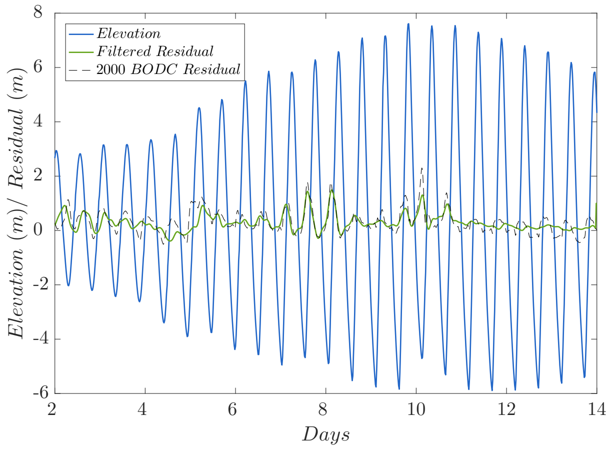

FIGURE 4: Simulation results of storm surge events of 2000 at Avonmouth predicted by DG-ADCIRC and compared with field measurements.

Whilst we consider these results acceptable, there are still discrepancies between measurement and model. A key reason for the discrepancy, which is considered in detail during this work, could be the inaccuracy in the meteorological inputs from the ERA5 dataset, which is evidenced by the poor estimation of the peak surge in the 2000 events. There are also a number of possible reasons in the simulation, including neglecting the contribution to water levels of wave set-up and river discharge. There are also, of course, many simplifications to the real physics inherent in using a depth-averaged model.

In this study we wish to explore the impact of a major flooding event in the Bristol Channel. Since there has not been a major event for the period which we have data, we have decided to focus on a synthetic event. The simulated scenario combines the surge predicted for a real meteorological event with the tides at the peak of the springs. In practice, this simply involves a small shift in the timing of either the meteorological or tidal records. Our synthetic storm has a maximum water elevation at the Swansea lagoon site of 5.57 m (without lagoon implemented).

RESULTS

Hydrodynamic Impact with Implementation of Lagoon

Before we consider its impact on storm surges, it is important to understand the impact of the Swansea Lagoon on the tidal hydrodynamics. On first consideration, the lagoon is small and might be expected to have only a small impact on the large-scale tidal hydrodynamics. However, the tidal hydrodynamics of the Bristol Channel are, as mentioned above, a resonant system [3] and such systems can change significantly with relatively small disturbances.

Case	Starting head (m)	Finishing head (m)
A	2.5	1.0
B	3.0	1.0
C	3.5	1.5
D	∞	0

TABLE 2: Lagoon operational scenarios with different starting heads and finishing heads.

In assessing the change to the naturally occurring hydrodynamics, we also need to consider different operational strategies. Becker *et al.* [33] found that using a low starting head had a significantly smaller impact on the tide and hence the environmental impact. In the present study we consider a number of different operational scenarios set out in Table. 2 (see standard works such as Prandle [24] for discussion of starting and finishing head).

The final case, ‘D’, is essentially a closed lagoon. The simulation is carried out with a time period of 30 days and the harmonic analysis is considered for the last 24 days of the simulation to avoid the initial transient response of the model. We consider the observation sites at the basin- and ocean- side, as seen in Fig. 1, for the results display.

We find that, despite the tidal resonance, there is very little impact on the tides outside of the Swansea Lagoon for any of the scenarios considered. The magnitude of the M_2 tidal constituent at Mumbles and Hinkey Point for the different scenarios is shown in Table. 3. The tidal amplitude outside the lagoon is

Case	Mumbles (m)	Hinkey Point (m)
No lagoon	3.09	3.97
A	3.08	3.95
B	3.08	3.95
C	3.08	3.95
D	3.08	3.95

TABLE 3: M_2 amplitude at selected measurement stations for different operation scenarios.

slightly reduced everywhere, see Fig. 5, with the biggest reduction occurring for the largest starting head. It is hard to identify whether this reduction is connected with the introduction of increased damping into the resonant system or whether it is to do with the change in channel geometry – these are of course interconnected. Although this reduction in tidal range is very small in percentage terms, this might have an impact on the return levels of an extreme flooding event.

Inside the lagoon it is not appropriate to use simple harmonic analysis as the water level is no longer well-approximated by a simple sinusoid (the water level remains unchanged during the holding stage as shown in Fig. 5). Whilst we can use an alternative quantitative comparison, for brevity here, we conclude that reducing the starting head does lead to a reduced impact on the tidal range within the lagoon — as would be expected.

2D Modelling of Storm Surge Interacting with the Lagoon

As stated in the previous section, the implementation of a lagoon would reduce the tidal elevation, thus possibly providing a small flood prevention function in the Severn Estuary. We apply the modified storm surge event from the year 2000, described above, and the lagoon is normally operated with a starting head of 2.5 m. Fig. 6 illustrates the simulation results of the lagoon implementation during the storm surge event at the aforementioned sites. The elevation results indicate the significance of flooding risk while the residual shows the deviation between the water level with and without meteorological forcing. Considering the ocean side, there is an overall small water elevation decrease, up to 0.90% at the peak of the surge, which is similar to the results of the tide-only phenomenon discussed previously. No clear difference can be observed for residual of the case with the lagoon compared with the no lagoon case. Within the lagoon, from the figure, we can see that water elevation has dropped significantly from lagoon operation and by 9.37% at the surge peak. Also there is some phase lag of approximately two hours. Regarding the residual, even though there is less reduction in the amplitude by 7.06%, the residual peak time has been delayed again for about two hours. We also find the same features of peak residual delay at some regions near the lagoon site. Bearing in mind that the typical storm surge event occurring in the Bristol Channel is about five hours, the delayed surge event would be a clear benefit for flooding risk management.

Another useful feature of the lagoon is that it appears to reduce the area susceptible to flooding, at least for our example event. Here we consider the surge residual during the storm surge events and compare the flooding affected regions (around the lagoon site) between the original "no lagoon" case and the case with lagoon implementation. Fig. 7 shows the comparison of results around the lagoon site captured at the beginning of the storm surge event with respect to residual. The surge condition is considered severe when the residual get to over 1m. From the figure we can see the regions are well protected within lagoon. For the regions around, the high risk areas are reduced as well due to the lagoon implementation. This is a relatively localised feature and this might not be the case for all coastal flooding scenarios.

Even though there exists small or even no impact of water rise on the ocean side during the surge event, for the basin side, there are clear benefits of flooding control with the lagoon implementation. In the present study, only a small area of Swansea would be protected; however, the design of a bigger lagoon or barrage can clearly protect a larger area.

2D Modelling of Different Lagoon Operation Scenarios

In this section we examine whether different lagoon operations during a storm surge can alter its performance.

An extreme case in lagoon operation is where, when a surge is imminent, the turbines and sluices are closed to prevent any water from entering the lagoon. To simulate this, we make a minor modification to the meteorological forcing; as the application of wind shear stress to the small enclosed water in the lagoon clearly gives non-physical results (probably due to insufficient dissipation in the lagoon), we therefore do not apply the wind shear stress within the lagoon area. Thus the results within the lagoon are not really meaningful. Outside the lagoon, shutting it off completely leads to a lower decrease in the water level of 0.01 m. Therefore, shutting the lagoon off completely is seen to have a small effect of decreasing the water level elsewhere.

Two other scenarios are analysed to investigate whether controlling the lagoon during the surge event could give more overall flooding protection. Assuming the knowledge of the time of the storm surge event and the hydrodynamics of the channel, the lagoon can be fully closed at the minimum water level in the basin and then reopened just before the surge, allowing water to flow through the lagoon. Two methods to reopen the lagoon have been considered: the complete opening of turbines and sluice gates (Case E), and the half-area opening of turbines and sluice gates to secure the basin regions (Case F). Based on the previous tidal hydrodynamics simulation results, the scenarios are designed to

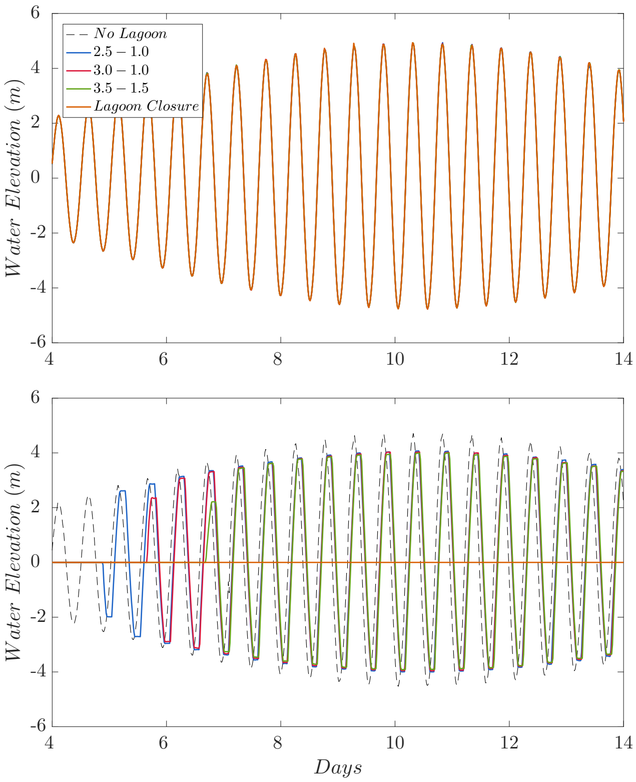

FIGURE 5: Impact of different operational heads on the water elevations: a) in the ocean side (top); b) in the basin side (bottom).

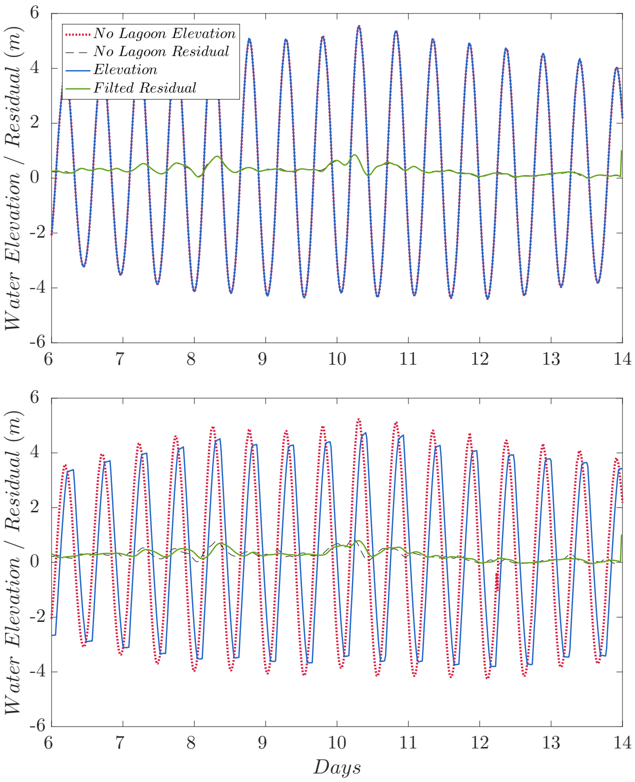

FIGURE 6: Interaction of lagoon implementation with storm surge: a) in the ocean side (top); b) in the basin side (bottom).

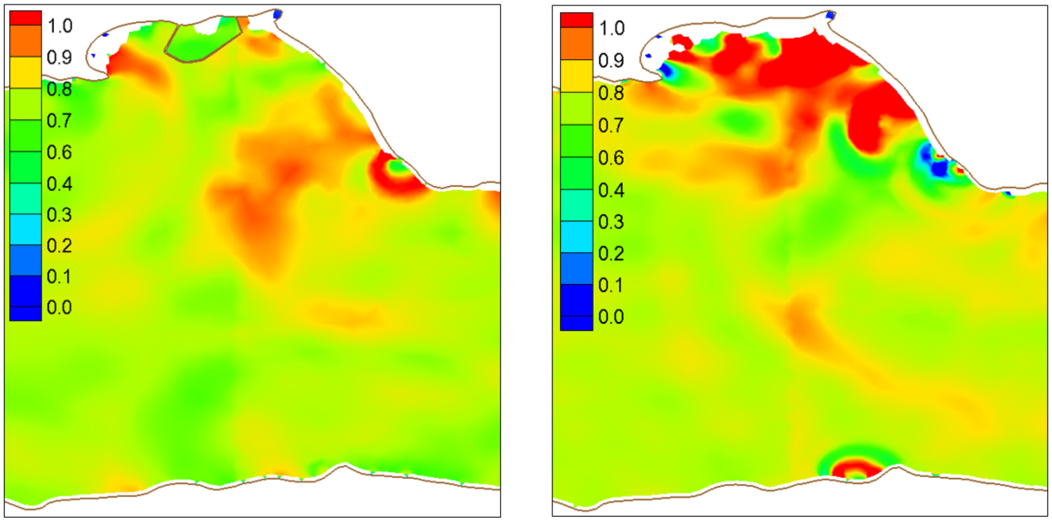

FIGURE 7: Comparison of residual simulation results around proposed lagoon site during the storm surge events displayed by SMS: a) lagoon implementation (left); b) original case (right).

close the lagoon at around 8 days in the simulation and reopen again at the time of 10 days, and then the lagoon is kept opened until the end of the simulation with a period of 14 days.

Comparison results of different cases are concluded in Table. 4, which are calculated based on the no lagoon case. The simulation results show that there are no clear timing benefits and only a small decrease of elevation or residual (within 1%) when compared with the original no lagoon case in the ocean regions (due to the small impact of lagoon implementation to the ocean region during surge events as discussed above). Thus it is more important to compare the different cases in regards to the basin region.

Considering the surge time delay for a surge event, as can be seen from the table, both cases E and F show more benefits than the case with normal lagoon implementation. For Case F especially, the time lag is approximately 3.84 hours with respect to the surge residual. In terms of water level, again more benefits can be observed by controlling lagoon operation. The water elevation decreases approximately 17.78% and 57.55% for case E and F respectively; for the residual, both cases indicate a level reduction over 20%.

Fig. 8 shows the lagoon impact with operation strategy Case F and clearly the basin region is well protected. The synthetic storm surge event introduced in this project coincides with the high tide, and the previous lagoon closure allows the water level within the basin to be at a minimum instead of nearly maximum and thus provides more flooding protection. Afterwards, the reopening of the lagoon during the surge allows storm water to flow into the basin and this has the small effect of reducing flooding outside the lagoon. For different lagoon reopening areas, even though the fully opened case has some benefits of more water elevation reduction in the ocean region, the water level decrease in the basin for the partially-opened case is significant. Therefore, lagoon operation Case F should be the most suitable overall strategy to choose for storm surge protection.

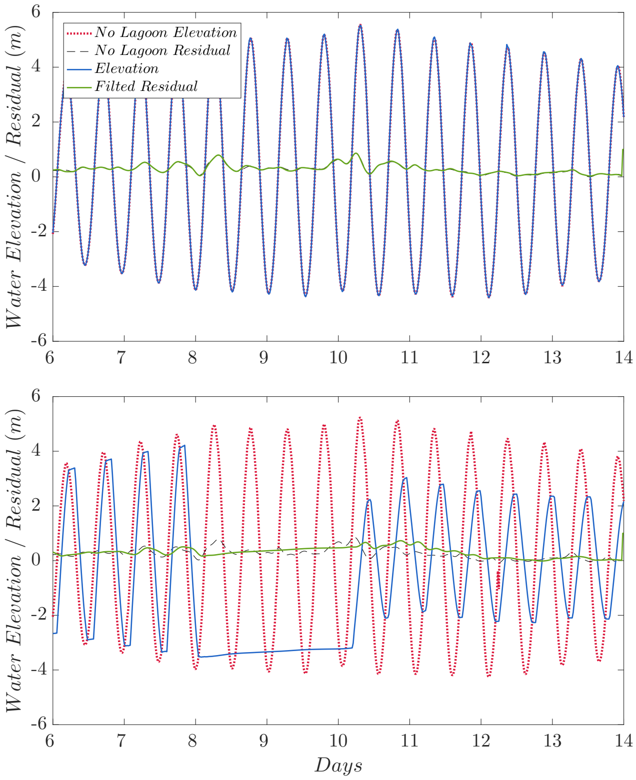

FIGURE 8: Interaction of lagoon implementation with storm surge with lagoon operation strategy Case F: a) in the ocean side (top); b) in the basin side (bottom).

CONCLUSIONS

In this paper, we developed and validated a two-dimensional numerical model to simulate storm surge events with the implementation of the Swansea Lagoon in the Bristol Channel. The results showed that limited hydrodynamic impacts would be expected from the construction of a small lagoon such as that proposed for Swansea Bay. Different lagoon operation strategies during a storm surge event were considered as well to achieve the most suitable operation that can provide a flood prevention function within and outside the lagoon. The comparisons indicated that operation case F, with the lagoon previously closed and partially reopening at the surge event, had the best performance with the flooding risk timing delayed up to 3.84 hours and water elevation reduced by 57.55%. Although the Swansea lagoon has a relatively small impact on coastal flooding, a bigger development, such as a Severn Barrage, would have a larger impact. We have shown herein that altering the operations of a lagoon does

Case	Normal lagoon case		Case E		Case F	
Parameter	Elevation	Residual	Elevation	Residual	Elevation	Residual
Timing delay (hr)	2.16	2.16	2.64	2.64	2.88	3.84
Decrease (%)	9.37	7.06	17.78	29.41	57.55	21.18

TABLE 4: Comparison of results of different cases for elevation and residual in the basin region base on the original results.

have some effect on the flooding. It will be important to consider this impact for larger tidal barrage developments.

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REFERENCES

[1] 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. A., Zidonis, A., Ahmadian, R., and Falconer, R., 2018. "Tidal range energy resource and optimization–past perspectives and future challenges". *Renewable energy,* ***127***, pp. 763–778.

[2] Baker, C., and Leach, P., 2006. *Tidal lagoon power generation scheme in Swansea Bay: A report on behalf of the Department of Trade and Industry and the Welsh Development Agency*. DTI London.

[3] Fong, S., and Heaps, N. S., 1978. "Note on quarter wave tidal resonance in the Bristol Channel".

[4] Gao, C., and Adcock, T. A. A., 2017. "On tidal resonance in the Bristol Channel". *International Journal of Offshore and Polar Engineering,* ***27***, pp. 177–183.

[5] Lyddon, C., Brown, J. M., Leonardi, N., and Plater, A. J., 2018. "Uncertainty in estuarine extreme water level predictions due to surge-tide interaction". *PloS one,* ***13***(10), p. e0206200.

[6] Horsburgh, K., and Horritt, M., 2006. "The Bristol Channel floods of 1607–reconstruction and analysis". *Weather,* ***61***(10), pp. 272–277.

[7] Gao, C., 2017. Analysis of Storm Surge and Tidal Resonance in the Bristol Channel. MSc thesis, University of Oxford.

[8] Lyddon, C., Plater, A., Brown, J., Prime, T., and Wolf, J., 2015. "The impact of tidal lagoons on future flood risk on the North Wirral and Conwy coastline, UK".

[9] Lewis, M. J., Angeloudis, A., Robins, P. E., Evans, P. S., and Neill, S. P., 2017. "Influence of storm surge on tidal range energy". *Energy,* ***122***, pp. 25–36.

[10] Dean, R. G., and Dalrymple, R. A., 1991. *Water Wave Mechanics for Engineers and Scientists*. Advanced series on ocean engineering. World Scientific.

[11] Pugh, D., 1996. *Tides, Surges and Mean Sea-Level.*

[12] Kubatko, E. J., Westerink, J. J., and Dawson, C., 2006. "hp discontinuous Galerkin methods for advection dominated problems in shallow water flow". *Computer Methods in Applied Mechanics and Engineering,* ***196***(1-3), pp. 437–451.

[13] Westerink, J. J., Luettich, R. A., Feyen, J. C., Atkinson, J. H., Dawson, C., Roberts, H. J., Powell, M. D., Dunion, J. P., Kubatko, E. J., and Pourtaheri, H., 2008. "A Basin- to Channel-Scale Unstructured Grid Hurricane Storm Surge Model Applied to Southern Louisiana". *Monthly Weather Review,* ***136***(3), pp. 833–864.

[14] Dawson, C., Kubatko, E. J., Westerink, J. J., Trahan, C., Mirabito, C., Michoski, C., and Panda, N., 2011. "Discontinuous Galerkin methods for modeling Hurricane storm surge". *Adv. Water Resour.,* ***34***(9), pp. 1165–1176.

[15] Serhadlıoğlu, S., Adcock, T. A. A., Houlsby, G. T., Draper, S., and Borthwick, A. G. L., 2013. "Tidal stream energy resource assessment of the anglesey skerries". *International Journal of Marine Energy,* ***3***, pp. e98–e111.

[16] Serhadlioglu, S., 2014. "Tidal Stream Resource Assessment of the Anglesey Skerries and the Bristol Channel". PhD thesis, University of Oxford.

[17] Adcock, T. A. A., and Draper, S., 2014. "On the tidal stream resource of two headland sites in the english channel: Portland Bill and Isle of Wight". *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE,* ***9A***, pp. 1–10.

[18] Schnabl, A. M., Moreira, T. M., Wood, D., Kubatko, E. J., Houlsby, G. T., and Adcock, T. A. A., 2019 – This Conference. "Implementation of Tidal Stream Turbines and Tidal Barrage Structures in DG-SWEM". *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE.*

[19] Le Provost, C., Genco, M.-L., and Lyard, F., 1995. "Modeling and predicting tides over the World Ocean". *Coast. Estuar. Stud.*, p. 175.

[20] Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., Mcnally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F., 2011. "The ERA-Interim reanalysis: Configuration and performance of the data assimilation system". *Q. J. R. Meteorol. Soc.,* ***137***(656), pp. 553–597.

[21] Éireann, M. MET ÉIREANN RE-ANALYSIS CLIMATE

RE-ANALYSIS.

[22] Bryant, K., and Akbar, M., 2016. "An Exploration of Wind Stress Calculation Techniques in Hurricane Storm Surge Modeling". *J. Mar. Sci. Eng.,* ***4***(3), p. 58.

[23] Westerink, J., Luettich, R., and Militello, A., 2001. Leaky Internal-Barrier Normal-Flow Boundaries in the ADCIRC Coastal Hydrodynamics Code. Chetn, US Army Corps of Engineers, June.

[24] Prandle, D., 1984. "Simple theory for designing tidal power schemes". *Advances in water resources,* ***7***(1), pp. 21–27.

[25] Baker, A. C., 1991. *Tidal Power*. Institution of Engineering and Technology (1711).

[26] Aggidis, G., and Feather, O., 2012. "Tidal range turbines and generation on the Solway Firth". *Renewable Energy,* ***43***, pp. 9–17.

[27] Petley, S., and Aggidis, G., 2016. "Swansea Bay tidal lagoon annual energy estimation". *Ocean Engineering,* ***111***, pp. 348–357.

[28] Angeloudis, A., Kramer, S., Avdis, A., and Piggott, M., 2018. "Optimising tidal range power plant operation". *Applied Energy,* ***212***, pp. 680–690.

[29] Angeloudis, A., Piggott, M., Kramer, S. C., Avdis, A., C. D., and Christou, M., 2017. "Comparison of 0-D, 1-D and 2-D model capabilities for tidal range energy resource assessments". *EarthArXiv*.

[30] Great Britain. Hydrographic Dept., 1997. *Admiralty tide tables. Volume 1, United Kingdom and Ireland, including European channel ports*, Vol. 1. [Taunton, Somerset] : The Hydrographer of the Navy.

[31] Wu, J., 1969. "Wind stress and surface roughness at airsea interface". *Journal of Geophysical Research,* ***74***(2), 1, pp. 444–455.

[32] Davies A.M. and Jones J.E., 1992. "A three dimensional model of the M2, S2, N2, K1 and O1 tides in the Celtic and Irish Seas". *Prog. Oceanogr.,* ***29***, pp. 197–234.

[33] Becker, A., Plater, A., and Wolf, J., 2017. The Energy River : Realising Energy Potential from the River Mersey. Tech. Rep. June, Liverpool City Council, Liverpool, UK.