Optimisation of Tidal Range Schemes

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Abstract— **There has been much interest in Marine Renewable Energy (MRE) schemes in the past decade, and across much of the globe, due to increasing interest in reducing CO_2 emissions and capturing the vast untapped resources of MRE. There have been several proposals to build a number of Tidal Range Schemes (TRSs), such as tidal lagoons and barrages, around the UK, and globally. It is estimated that the tidal range resource in the UK will be between 25 and 30 GW [1] and the independent Hendry Review commissioned by the UK government recommended construction of the world's first tidal lagoon in Swansea Bay, in the South West of the UK, in January 2017. One of the potential disadvantages of TRSs is their high capital cost, which consequently can lead to a high cost of electricity generation. However, TRSs have a significant advantage over many other forms of renewable energy generation in that they are based on a resource that is highly predictable. The predictability of TRSs provide us with the potential of active planning and optimising the operation of such schemes, which is not possible with less predictable sources. Optimisation of the operation could potentially result in higher electricity generation and lower hydro-environmental impacts and therefore lower electricity costs which therefore could lead to further schemes becoming economically viable. This study investigates the optimisation of TRSs and their operation by considering a number of structural variables, such as the number and capacity of the turbines and the area of sluice gates, besides a number of operational factors, including generation schemes and generation and sluicing opening and closing head differences. The hydro-environmental impacts of these scenarios are also considered to avoid significant adverse impacts of the optimised schemes.**

***Keywords*— Tidal Range Schemes, Tidal Lagoons, Tidal Barrages, Optimisation of Operation Schemes, Marine Renewable Energy, Swansea Bay Lagoon**

I. Introduction

There has been increasing interest in reducing CO_2 emission across the world and various governments have committed to reduce CO_2 emission by reducing reliance on fossil fuels and increasing electricity generation from renewable sources. Marine Renewable Energy (MRE) is one of the least exploited renewable sources and amongst MREs tidal schemes have gained significant interest due to their predictability. They are two major type of tidal renewable energy schemes: tidal stream and tidal range schemes. The power equations for each type of MREs highlight the main difference in resources for them. The power output of tidal stream turbines is calculated as follows [2]:

$$\boldsymbol{P = \frac{1}{2} C_p \rho A V^3} \qquad \textbf{(1)}$$

where P is the extracted power, C_p is the turbine power coefficient, ρ is the fluid density, A is the cross sectional area of the turbine and V is the fluid stream velocity. Potential power extracted by Tidal Range Schemes (TRSs) is calculated as follows:

$$\boldsymbol{P = \eta \rho g \Delta H Q} \qquad \textbf{(2)}$$

where η is efficiency coefficient for the turbines, g is gravitational acceleration, ΔH is head difference across the impoundment and Q is discharge through the turbines. Equations 1 and 2 show that the potential energy generated by tidal streams devices are mainly relative to the size of the device and the cube of the velocity. However, electricity generated by tidal range schemes is mainly relative to the head difference across the impoundments and total discharge through the turbines. Where total discharge depends on the tidal range and the plan surface area of the scheme.

It is estimated that the tidal range resource in the UK will be between 25 and 30 GW [1] and the independent Hendry Review commissioned by the UK government recommended construction of the world's first tidal lagoon in Swansea Bay, in the South West of the UK, in January 2017. Besides, the Swansea Bay Lagoon a number of other TRSs are proposed around the UK and particularly Severn Estuary and Bristol Channel as shown in Figure 1.

Since TRSs can be operated in different ways and this operation can influence ΔH and Q and therefore electricity generated. Number of researchers have studied TRSs using simplified 0-D models [3-6] and more sophisticated 2-D or 3-D models [7-11]. 0-D or flat-surface models, which require very limited computational power, are generally used for preliminary energy calculations. Fundamental theoretical research was carried out by Prandle [5] to provide a means to design TRSs at different locations using dimensionless parameters. He also utilised this approach on 3 schemes, namely La Rance, Bay of Fundy and the Bristol Channel and recommended a 2-way operation scheme [6]. Aggidis and Benzon [3] used 0-D models to evaluate energy generation in relation to varying trends in energy demand. Angeloudis et al. [4] compared refined 0-D and 2-D models in order to derive the optimum operation and found that a 0-D approach could be reliable for the design optimization in the initial stages of design. However, they demonstrated that 0-D models overestimated the potential energy compared with 2-D models for larger schemes, with a larger upstream plan surface area. Moreover, more sophisticated numerical models, such as 2-D or 3-D models, are required to investigate the environmental and ecological impacts. This study focuses on optimisation of the operation of TRSs to generate maximum electricity while the hydro-environmental impacts of such scheme are investigated.

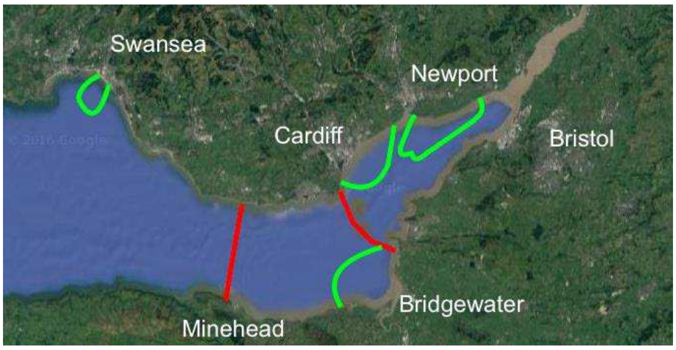

Fig. 1 Number of TRS proposals in the Severn Estuary and Bristol Channel (tidal lagoons in green, barrages in red) - Background picture: courtesy of Google

II. Tidal range Schemes

TRSs could be operated under various operation schemes. Two major operation schemes are ebb-only and 2-way generation. In ebb-only generation, starting from high water, the water is impounded in the basin at high tide (high water holding phase), until the head difference either side of the impoundment wall is high enough for optimised power generation (called starting maximum head here H_{max}). Then the generation phase starts by opening the turbines and directing the flow through the turbines, for energy generation. The generation phase will then continue until the head difference reaches the minimum head difference for power generation (called holding minimum head here H_{min}), and the second holding phase starts. The filling phase starts by opening both sluice gates and turbines when the water level on the seaward side of the impoundment is higher than the water level inside the impoundment. The filling phase would be followed by the holding phase when the water levels inside and outside of the impoundment are at the same level, around the high tide. Starting from high water, in the 2-way generation scheme, the water is held inside the impoundment by keeping the sluice gates and turbines closed. The high water holding phase continues until the head difference across the impoundment is large enough for power generation (called starting maximum head here H_{max}) and the ebb-generation phase starts. The generation continues until the head difference across the impoundment is not sufficient for power generation. At this stage, the sluice gates are also opened to facilitate emptying of the basin. This will continue until the water levels outside the impoundment are almost at the same level as the water levels inside. At this step, the second holding phase starts by closing both turbines and sluice gates. This closure continues until the water level difference between outside and inside the lagoon is higher than H_{max} and the flood generation phase starts. Flood generation is followed by sluicing phase which starts when the water level difference between outside and inside the lagoon is lower than H_{min}. Schematic illustrations of ebb-only and 2-way generation is shown in Figure 2.

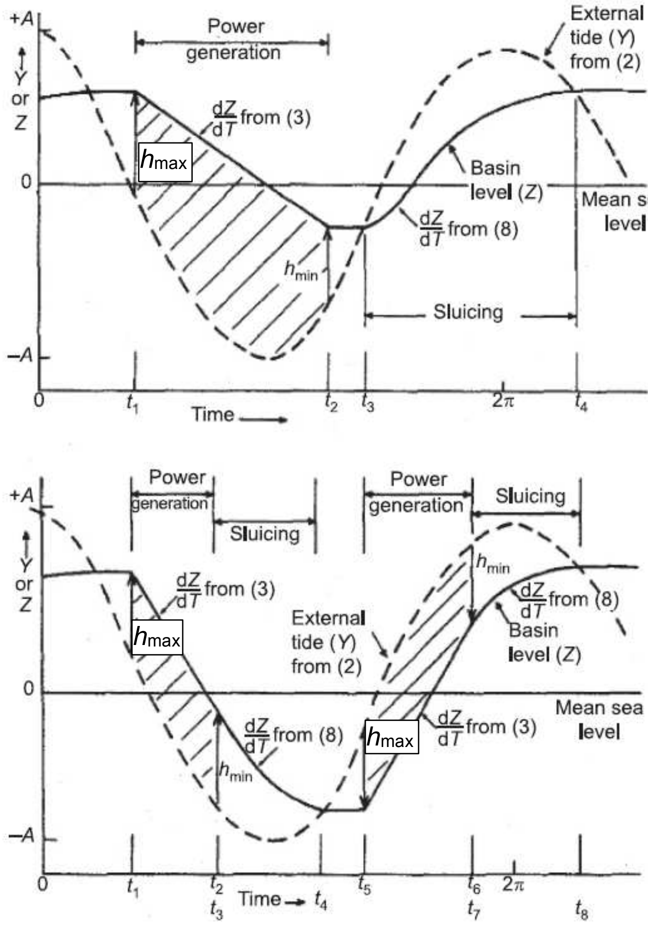

Fig. 2 Schematic representation of the operational mode of: (a) one-way ebb-generation; (b) a two-way tidal power plant. source: [6]

III. Methodology

A. 0-D modelling

A typical 0-D backward difference model is based on the continuity equation. The new upstream water level ($Z_{up,i+1}$) at any point in time can be calculated based on the upstream water level at the previous timestep ($Z_{up,i}$) and the downstream water levels ($Z_{dn,i}$) as follows:

$$Z_{up,i+1} = Z_{up,i} + \frac{Q(H)+Q_{in}}{A(Z_{up,i})}\Delta t \quad (3)$$

where Δt is the timestep, Q(H) is the total incoming or outgoing flow through the turbines and sluice gates, Q_{in} is the inflow/outflow to the lagoon through sources other than the impoundment, e.g. rivers or outflows and $A(Z_{up,i})$ is the plan surface area of the lagoon. The flow through the turbines can be calculated using a hill-chart by finding the discharge (Q) corresponding to the head difference (ΔH) on the Max Output line. A typical Hill-chart is shown in Figure 3 and further information on application of the Hill-Chart can be found in [12, 13].

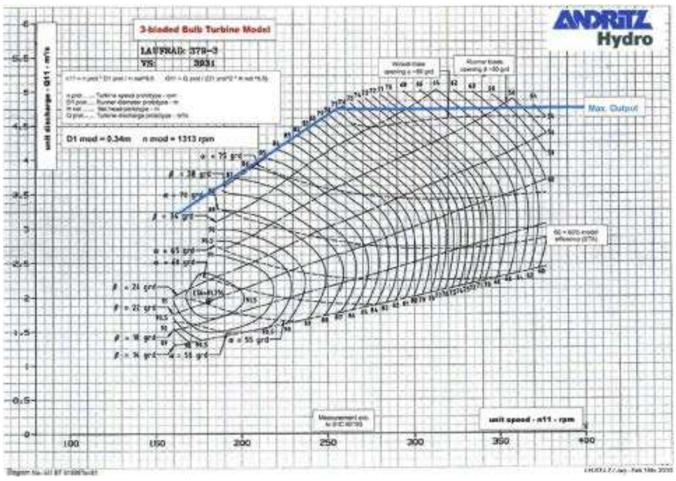

Fig. 3 Andritz Hydro 3-Blade low head bulb turbine unit [12]

Flow through the sluice gates can be calculated as follows [9, 13]:

$$Q = C_d A\sqrt{2g\Delta H} \tag{4}$$

where C_d is the discharge coefficient, assumed to be 1.0 at this preliminary stage, A is the sluice gate area and ΔH is the water level difference across the impoundment.

B. 2-D modelling

A 2-D hydro-environmental model, namely the DIVAST (Depth Averaged Velocity And Solute Transport) model, which has been widely used to model marine renewable energy schemes [4, 14-16] has been used for this study. The 2-D governing equations used in the model are briefly given below, with more details of the model being given in Falconer [17] and Kashefipour [18]. The 2-D depth-integrated equations were derived by integrating the governing 3-D equations over the depth to give for the x-direction [19]:

$$\frac{\partial \xi}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial x} = 0 \tag{5}$$

$$\frac{\partial q_x}{\partial t} + \beta\left[\frac{\partial u q_x}{\partial x} + \frac{\partial v q_x}{\partial y}\right] = f q_y - gd\frac{\partial \xi}{\partial x} + \frac{\tau_{xw}}{\rho} - \frac{\tau_{xb}}{\rho} + \varepsilon\left[2\frac{\partial^2 q_x}{\partial x^2} + \frac{\partial^2 q_x}{\partial y^2} + \frac{\partial^2 q_y}{\partial x \partial y}\right] \tag{6}$$

$$\frac{\partial \phi d}{\partial t} + \frac{\partial \phi q_x}{\partial x} + \frac{\partial \phi q_x}{\partial y} - \frac{\partial}{\partial x}\left[dD_{xx}\frac{\partial \phi}{\partial x} + dD_{xy}\frac{\partial \phi}{\partial y}\right] - \frac{\partial}{\partial y}\left[dD_{yx}\frac{\partial \phi}{\partial x} + dD_{yy}\frac{\partial \phi}{\partial y}\right] = d\sum\Phi \tag{7}$$

where u, v = velocity in the x, y directions, ζ = water surface elevation above datum, d = total water depth, q_x, q_y = discharges per unit width in the x, y directions ($q=ud$), β= momentum correction factor for non-uniform vertical velocity profile, f = Coriolis parameter, g = gravitational acceleration, τ_{xw}, τ_{xb} = surface and bed shear stress components respectively in the x-direction, ε = depth averaged eddy viscosity, ϕ=depth average solute concentration, D_{xx}, D_{xy}, D_{yx}, D_{yy} = depth averaged dispersion-diffusion coefficients in the x, y directions respectively and ΣΦ = total depth average concentration of a source or sink solute. The momentum equation (equation 2) was derived by assuming the no-slip bed boundary condition and including other external forces such as: wind shear, bottom friction, and the earth's rotation.

IV. Optimisation of the Swansea Bay Lagoon

Tidal data which were used as the downstream water levels in the 0-D model were obtained from the Mumbles site of the UK Tide Gauge Network of the British Oceanographic Data Centre [20]. Figure 4 illustrates tidal data over a month.

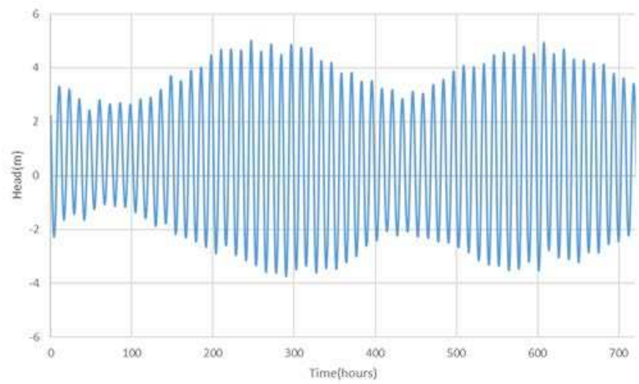

Fig. 4 Sample of tidal levels over 1 month near the lagoon location

In the absence of substantial wetting and drying, the wetted areas is generally assumed to be constant in 0-D models [5]. However, due to extensive flooding and drying in some regions such as Swansea Bay, the plan surface area of the impoundment could change significantly with the water level. Figure 5 shows the bathymetry of the area inside the lagoon while Figure 6 demonstrates the plan surface area of the lagoon for different water levels inside the lagoon which includes the impact of flooding and drying [4]. The impact of the water levels on the plan surface area of the lagoon is shown beyond the tidal range in Figure 6. This figure shows little changes in the plan surface area as a result of changes in water level up to about 2 m. However, most significant changes occur towards the low tide.

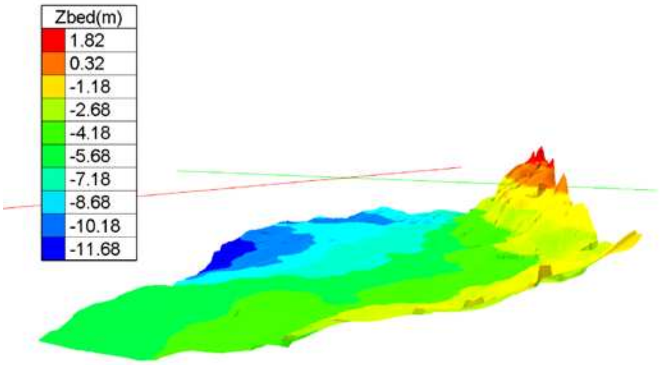

Fig. 5 Swansea Bay Lagoon bathymetry

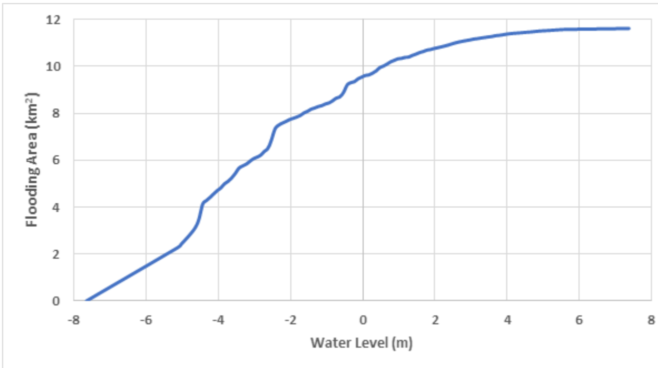

Fig. 6 Area versus water level

The model was run for a wide range of 2-way generation scenarios. These scenarios included a range of starting generation water elevations (H_{max}) from 0 to 4 m with 5 cm increments as well as a range of starting water levels for sluicing (H_{min}) from 0 to 2 m with 5 cm increments. Energy output maps excluding and including the impact of flooding and drying are demonstrated in Figures 7 and 8, respectively. It can be seen that highest energy is shown in the top left of the figures, which represents high Hmax and Hmin. Since the turbines are very inefficient at low heads, electricity generated at low heads are very negligible and close to zero. It was also seen that excluding the impact of flooding and drying had limited, less than 5%, impact on the energy output in this case. This is due to the reduction in A(z) with water levels as a result of flooding and drying in Equation 3. This in turn causes lower water level inside the lagoon at the next times step ($Z_{up,i+1}$) comparing to the scenario without flooding and drying. Lower water level inside the lagoon result in lower head difference and consequently lower discharge through the turbines and lower electricity generation. It is worth noting that changes in total electricity generation as a results of flooding and drying depends on the site and operation scheme, therefore the changes in electricity reported here is only valid for this specific site and operation scenario.

Using constant H_{max} and H_{min} regardless of the tidal condition causes very little generation at some stages. Therefore, the 0-D model developed here was modified to consider a variable H_{max} and H_{min} for each tide. For this purpose, the model considers the full range for each tide and finds the H_{max} and H_{min} which generates the maximum electricity for that particular tide regardless of the values of H_{max} and H_{min} during the previous tides. Using variable H_{max} and H_{min} for operation of the lagoon has resulted in more than 15% increase in electricity generation over a year.

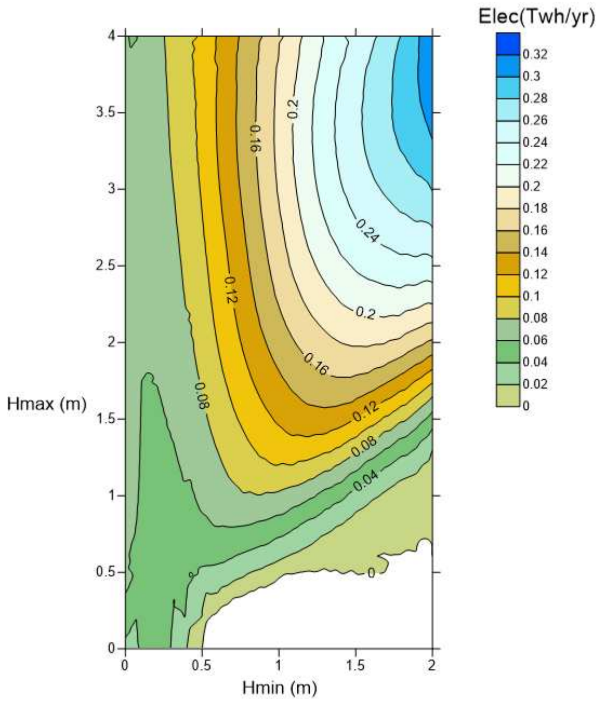

Fig. 7 Energy output with a constant area

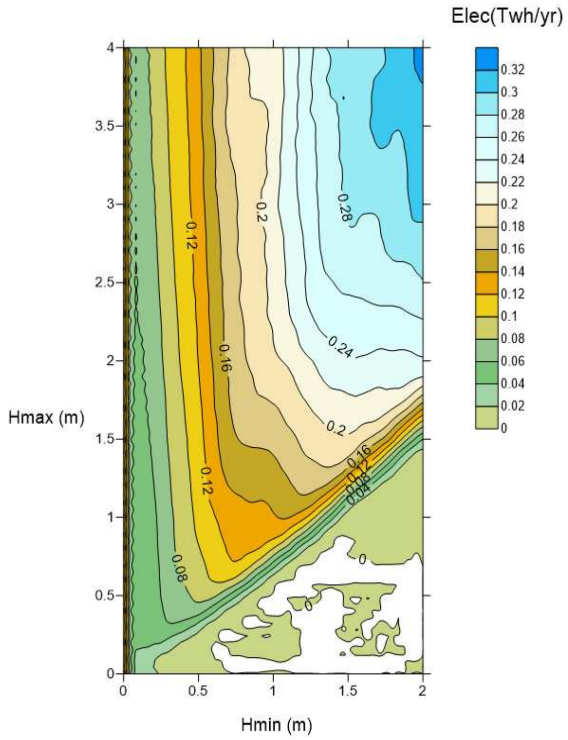

Fig. 8 Energy output with areas varying with water heights

V. Hydro-Environmental Modelling

In order to include the full hydro-environmental impact of the scheme and avoid potential interaction of the scheme with the boundary condition, the modelling domain is extended to cover the Severn Estuary and Bristol Channel. The model domain was extended to the River Severn tidal limit, located close to Gloucester, to the outer Bristol Channel, where the Channel joins the Irish Sea. The upstream boundary condition was set at a flow rate varying between 60 and 106 m3/s (i.e. the normal River Severn condition for the simulation period). The downstream water level boundary for the existing condition was obtained from the Proudman Oceanographic Laboratory (POL) [21] Irish Sea model, as implemented by Ahmadian and Falconer [22]. A 100m grid size and SeaZone digital bathymetry [23] were used in this study, while a grid dependency analysis showed no significant grid dependency [22]. The model was calibrated using values obtained from the Admiralty Charts, while model validation was undertaken using four data sets acquired and published by Stapleton et al. [24, 25] at two sites along the estuary as demonstrated by Ahmadian, Falconer [22] as well as British Oceanographic Data Centre (BODC) data [20]. Typical comparison of predicted and BODC measured water levels [20] at Mumbles site in Swansea Bay is shown in Figure 9.

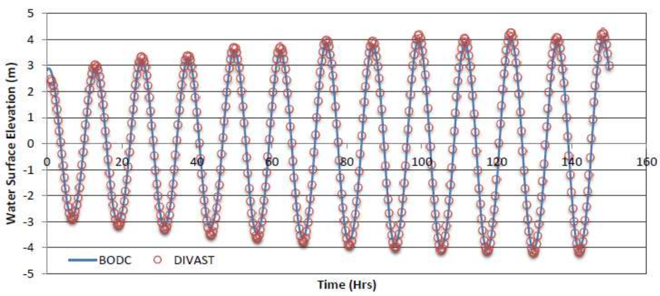

Fig. 9 Comparison of predicted and measured water levels at Mumbles

The optimised model derived by the 0-D model is incorporated with the 2-D model in order to make sure that the optimised operation scheme does not cause significant adverse impacts. These impacts include, impact on currents, loss of intertidal mudflats, sediment transport and flushing characteristics.

One of the main impacts of TRSs is expected to be the impact on sediment transport as a result of the impact on currents. The impact on currents and subsequently the impact on sediment transport could be influenced by the operation scheme. Figure 10 illustrates the potential changes in suspended sediment (SS) concentrations inside the domain under two-way generation.

This figure shows that suspended sediment levels could potentially increase at some locations as a result of construction of the lagoon. However, it should be noted that detailed sediment characteristics of the bed and suspended sediments are required for such a study. In the absence of such information, sediment characteristics from other sites in the Bristol Channel were used for the results presented here,

A conservative tracer was used to investigate the flushing characteristics of the lagoons. The concentration of the tracer inside the lagoon was set to 100 ppm while it was assumed that the tracer was not present outside of the lagoon. Distribution of the tracer inside and around the lagoon after 1 and 4 tidal cycles is demonstrated in Figure 11 and 12, respectively. This allows for an understanding of the water quality inside the lagoon and an investigation of the efficiency of different potential solutions to improve the water quality. The results reported in Figure 11 and 12 show that that the majority of the lagoon is flushed after 4 tides.

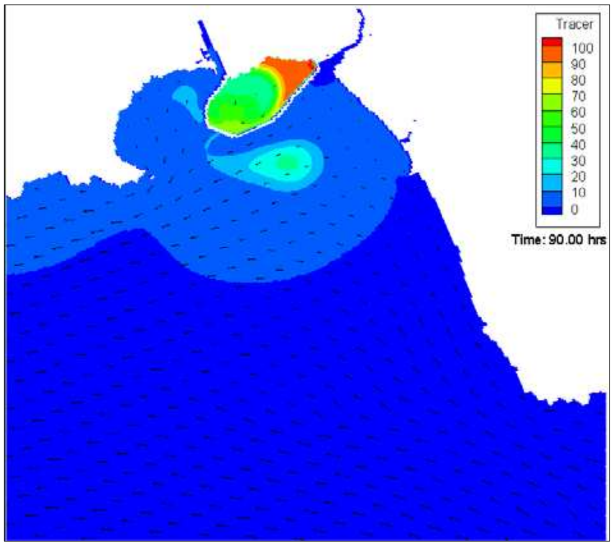

Fig. 11 Tracer levels in Swansea Bay Lagoon after 1 tidal cycles

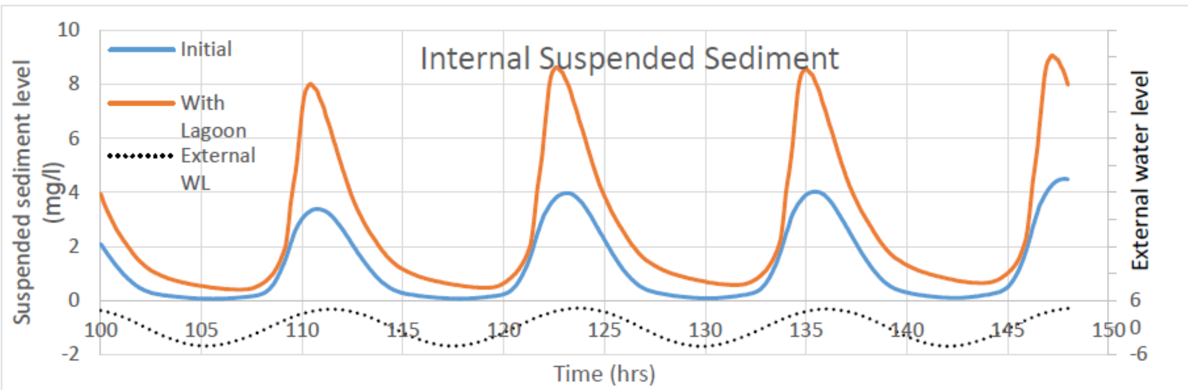

Fig. 10 Suspended sediment levels at a location inside the lagoon

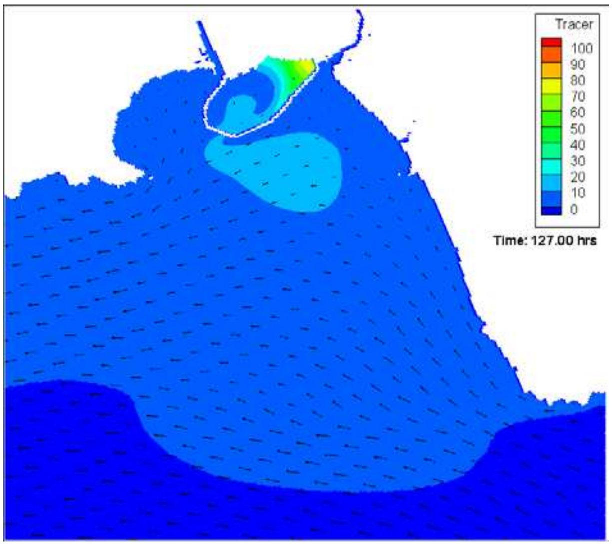

Fig. 12 Tracer levels in Swansea Bay Lagoon after 4 tidal cycle

VI. Conclusions

A 0-D model of Tidal Range Schemes (TRSs) has been developed and applied to Swansea Bay Lagoon for a range of operation scenarios. The impact of excluding flooding and drying in 0-D modelling was investigated and found to be less than 5% in this study. It is worth noting that changes in total electricity generation as a results of flooding and drying depends on the site and operation scheme and this effect should be investigated for each site. The operation of the lagoon was improved by considering variable H_{max} and H_{min} at each tide instead of considering constant values for all tides. Optimising H_{max} and H_{min} for each tide has resulted in more than 15% increase in electricity generation over a year.

The optimised operation should be utilized to evaluate flushing characteristics of the water inside such impoundments. For instance, the model results show that the majority of the lagoon will be flushed after 4 tidal cycle. Moreover, the impact of the structure on sediment transport has been considered and has shown changes in sediment levels inside the lagoon. This is the basis for future research.

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