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# Numerical model simulations for optimisation of tidal lagoon schemes

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## HIGHLIGHTS

- We discuss certain design aspects of tidal lagoons to inform future proposals.
- We demonstrate the tidal lagoon representation within a 0-D and 2-D hydrodynamic modelling framework.
- We examine the potential of simplified 0-D modelling techniques for operation optimisation.
- We highlight the extent where 2-D hydrodynamic model power predictions can deviate from 0-D modelling.

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## ABSTRACT

This study considers environmental impacts and the power production potential of a number of coastally attached tidal lagoons, proposed along the North Wales coast, UK. Initially, the impoundment shape, turbine and sluice gate locations were modified according to the regional bathymetric data. A refined 0-Dimensional approach was implemented to optimise the lagoon operation, based on given turbine and sluice gate specifications. In turn, a two-dimensional numerical model, based on an unstructured triangular mesh, has been refined to simulate the hydrodynamic processes, initially without and subsequently in the presence of the lagoons. The hydrodynamic model adopts a TVD finite volume method to solve the 2D shallow water equations, based on a second-order accurate spatial and temporal numerical scheme. An encouraging performance is apparent in reproducing the established conditions encountered in the region through comparisons against available data. The incorporation of tidal lagoons in the model appears to have a considerable effect on the flow structure in the region, by inducing high velocity accelerations near the sluices and turbines, depending on the stage of the tidal cycle. Considering a two-way generation regime, it is outlined that the loss of intertidal regions can be minimised, which is a major source of concern with regards to the environmental impact of such schemes through an ebb-generation operation. Particular focus is directed towards the comparisons between the 0-D and 2-D modelling results, an aspect which has not been reported previously. Predictions of the models diverge as the scale of the lagoon project increases, but it is highlighted that the 0-D methodology can be utilised for the optimisation of the processes in the initial stages of design before proceeding to more sophisticated numerical model simulations.



## 1. Introduction

The UK has a considerable opportunity to generate large quantities of renewable energy from some of the largest tides in the world. Practical estimates suggest that tidal energy systems can provide a significant proportion of national electricity demand, reliably and safely [1]. In the light of EU commitments to meet renewable energy targets, there is an emerging interest towards marine renewable energy schemes, seeking to harness the energy resource offered by the high tidal range reported around the UK. coastline. This can range from 6 to 10 m along the North Wales coast during spring tides while exceeding 14 m within the Severn Estuary [2–4].

Tidal range structures are constructed on the basis of creating an artificial tidal phase difference by impounding water, and then allowing it to flow through turbines to generate electricity when appropriate. It is known that these schemes can have a range of near- and far-field impacts on the hydro-environment, which can be positive and/or negative. These can occur mainly through alterations to the tidal flow characteristics, with changes to the hydrodynamic regime potentially having corresponding effects on the sediment transport rates, and the geomorphological, ecological and water quality processes in an estuary or along a coastline

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[3,5,6]. There are also numerous other factors, beyond the environmental impacts, to be taken into account before converging towards a reasonable tidal impoundment design. They span across a range of disciplines and can be of a geotechnical, electrical, mechanical or socio-economic nature. The influence of each of these challenges individually is beyond the scope of this paper, as they are the subject of associated studies (e.g. [3,6–11]).

For power generation, the prevalent technology currently reported for tidal range structures is the low head bulb turbine. The La Rance Barrage in France makes use of $24 \times 10$ MW bulb units of 5.35 m rotor diameter each [12]. More recently, as of 2011, the construction of Lake Sihwa tidal power station in South Korea came to completion where $10 \times 26$ MW bulb units, of 7.5 m diameter, are operated to harness the regional tidal power resource [13]. The majority of the options considered for the Severn Estuary also involve using bulb turbines as discussed by the Department of Energy and Climate Change (DECC) [14].

Tidal impoundments featuring the aforementioned turbine types have attracted interest amongst marine renewable energy experts and there have been numerous proposals to construct such schemes around Wales and the North West coast of England. Examples include the Severn Barrage [15,16] and the Swansea Bay lagoon [8], both encompassed within the Severn Estuary and Bristol Channel located in the South West of the UK. Numerical modelling techniques have been implemented widely to simulate flow and water quality processes during the operation of tidal range structures, with a view to assessing the feasibility of various proposals [4,6,17–19]. The application of numerical models on tidal range projects specifically around Wales has predominantly been focused on proposals across the Severn Estuary [4,20–25]. However, the theme of this work relates to the potential of tidal lagoon concepts along the North Wales coast.

The study of this area can be justified on the grounds of several of its characteristics, which could make such projects attractive in the near future, as also supported by preceding investigations reported in the literature [26–28]. Specifically, the flow along the coastline is subject to a tidal range exceeding 8 m during mean spring tides and therefore becomes suitable for the deployment of contemporary tidal range turbine technologies. Considering that power extraction from these schemes is predictable, but intermittent according to the tidal cycle, an additional incentive is that it could complement other tidal range projects in locations where the cycle is out of phase, such as a barrage in the Severn Estuary. Simultaneously, there is mounting concern over coastal flooding along the North Wales coast. Interest in reducing the flood risk has heightened over the impending detrimental effects of sea-level rise [29] that could substantially increase the severity of coastal flood damage unless properly addressed. Coastal flood protection can be provided on the upstream side of a lagoon since it acts as a barrier to wave impacts, high tides and surge effects along the impounded coastline. In addition, the appropriate regulation of flow control structures (i.e. turbines and sluices) facilitates a control mechanism for upstream peak water levels when necessary. Therefore, tidal-range marine renewable structures could play an important role in protecting susceptible regions, contributing to the benefits of such large-scale schemes.

The intention of this analysis is not specifically to suggest a particular lagoon design, but it is rather to inform future proposals in North Wales and beyond. Certain location characteristics are discussed with a view to demonstrate how they will invariably dictate the lagoon impoundment shape and annual energy output. Initially, a preliminary 0-D modelling approach was adopted to optimise and identify reasonable design and operational characteristics of 4 coastally-attached lagoon concepts in the vicinity of the North Wales coast. In turn, 2-D numerical model simulations are presented investigating the hydrodynamic flow structure developed during the tidal cycle, firstly without and subsequently in the presence of the tidal range schemes. A distinguished point of this investigation was to ascertain the correlation of the refined 0-D modelling of energy output against the more detailed 2-D numerical modelling, that accounts for the complex hydrodynamics close to impoundment hydraulic structures. The correlation of simplified 0-D model results against more elaborate 2-D hydrodynamic predictions has yet to be investigated, as outlined in the review of Adcock et al. [17] and is therefore a key aspect of this work. Thus, the objectives contemplated can be hitherto summarised as:

- Highlighting certain design aspects of tidal lagoons to be taken into account that can be used to inform future proposals.
- Reviewing the approach adopted to represent computationally the lagoon impoundment, sluices and turbines for a refined 0-D modelling strategy and the 2-D hydrodynamic models.
- Examining the potential of 0-D modelling techniques to provide optimum operational parameters, based on the given specifications of the turbine technology and sluices.
- Assessing the hydrodynamic impact of the tidal lagoon and demonstrating the extent where 2-D hydrodynamic model predictions can deviate from the 0-D modelling approach.

## 2. Research methodology

### 2.1. North Wales Bathymetry and lagoon design considerations

Fig. 1(a) provides an overview of the study area bathymetry, as contained by the seaward (Western and Northern) and land boundaries imposed for the hydrodynamic simulations. In terms of its characteristics, apart from the highly dynamic tidal flow conditions, the area is subject to strong wind effects as demonstrated by the presence of the Gwynt y Môr Offshore Wind Farm. The Colwyn Bay coastline has occasionally been subjected to extreme storm events which led to substantial coastal flooding in residential areas such as Towyn and Rhyl (e.g. 1990). There are also several inflows along this part of the coast which include the Menai Strait and the Conwy, Clwyd, Dee and Mersey rivers.

The bathymetric data was collated from a combination of UK admiralty charts (No. 1977 and 1978) and digitized data provided by Seazone Solutions with a resolution of 1 arc second, which was in turn used for the assessment of tidal lagoons through the 0-D and 2-D methodologies discussed subsequently. The bathymetric data were reduced to the level of Lowest Astronomical Tide (LAT) and are consistent with the UK Admiralty Chart No. 1978. Four tidal lagoons were selected to form the basis of the analysis herein and follow the conceptual designs of Anderson [30]. The principle of their design aims towards providing flood protection along the coast, whereas their shape attempts to take advantage of shallow parts of the coastal bathymetry. The impoundments extend to a sufficient depth to enable the introduction of turbines or sluices and the overall configuration can be observed in Fig. 1(b).

In the absence of further details for the operation of these lagoons, this study assumes that the power generation is conducted through 7.5 m rotor diameter low head bulb turbines, with a capacity of 25 MW as utilised in similar projects [13]. The power and the discharge through these turbines was represented according to Fig. 2(a). The hill chart of Fig. 2(a) relates the power *(P)*, water elevation difference *(H)* and discharge *(Q)* for 25 MW turbines. These specifications were adopted from the previous hydrodynamic study of Falconer et al. [20], taking into account the proven performance of bulb turbines in the existing tidal impoundments of La Rance and Lake Sihwa. In order to converge to a realistic turbine arrangement, it is of interest to highlight some influential characteristics of their design. Essentially, the minimum

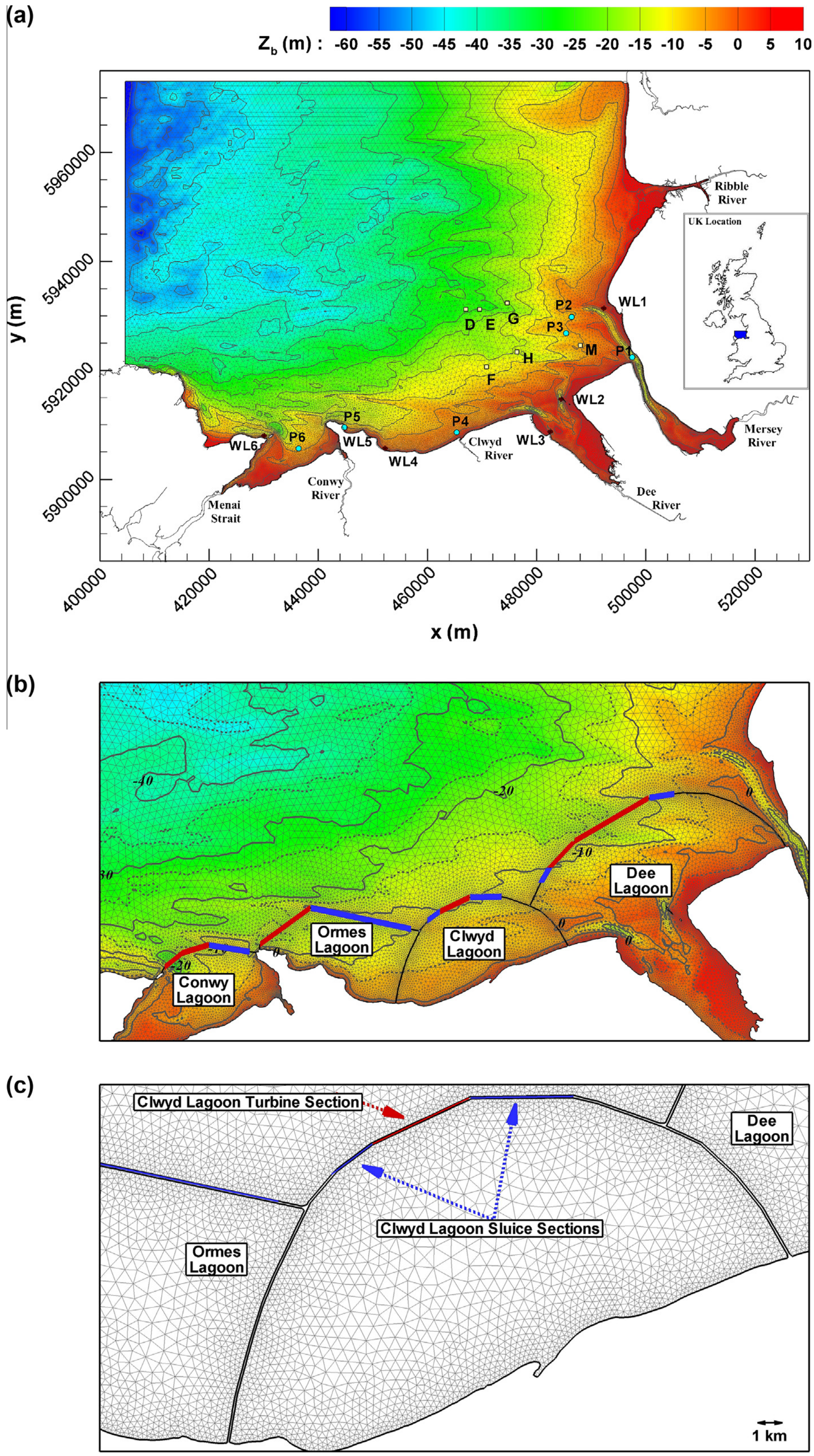


**Fig. 1.** (a) North Wales Bathymetry and a computational mesh considered for the hydrodynamic simulations, (b) Tidal Impoundment turbine (red line) and sluice (blue line) locations contemplated within this study and (c) an example of the mesh refinement close to an impoundment structure. Validation points for Water Levels (W.L.1-6), velocity magnitude and directions (D, E, F, G, H, M) and numerical model monitor points (P1–6) are highlighted across the domain. $Z_b$ corresponds to the Sea bed elevation according to the lowest astronomical tide datum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

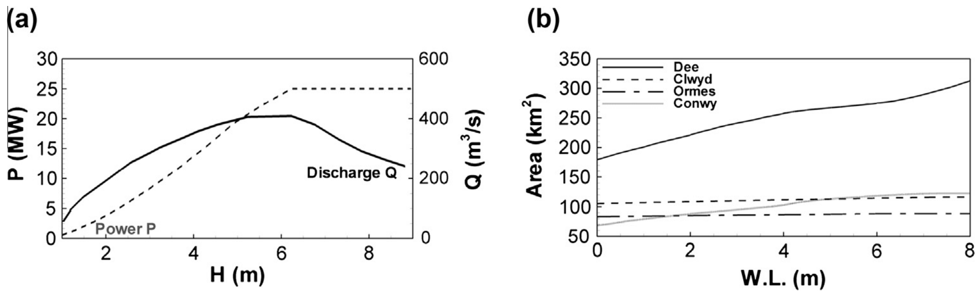


**Fig. 2.** (a) Hill Chart and (b) lagoon surface area against W.L. above chart datum.

water depth in the turbine region proximity should be sufficient to account for the dimensions of the hydraulic structure. The caisson support structure must ensure that the turbines are neither exposed to water surface weather and wave conditions, nor prone to sedimentation issues closer to the bottom of the water column. Consequently, a minimum depth of 10 m was preliminary estimated for the turbine locations to minimise any additional dredging costs. In this manner, impoundment sections available for turbine positioning are restricted to the highlighted areas of Fig. 1 on the grounds of the site bathymetry.

With regard to the distribution of the lagoon hydraulic structures, these are often concentrated within a small extent of the lagoon impoundment. The lack of sufficient water depth to place turbine caissons confines the power generation function of the lagoon to a relatively small space, along the deeper sections of the impoundment. This was apparent for the Welsh Grounds lagoon proposal [14]. However, in the hydrodynamic study of Falconer et al. [20], it was argued that the high concentration of turbines in a small section corresponded to the formation of large counter-rotating eddies along the turbine wake, which could have a significant impact on the hydro-ecology and the morphology. Ideally, turbines should be evenly spaced across the whole structure, enabling a smoother water transfer between the upstream and downstream side of the lagoon structure. It could be argued that smaller turbines should be placed on shallower sections, thus accommodating a more uniform distribution. However, these are characterised by greater rotor speeds and therefore could be accountable for greater mortality ratings towards marine life [31]. Minimising the impact of turbines on marine fauna remains a challenge for tidal impoundment operation and motivates optimisation efforts. Consequently, more research and technological advances could mitigate many of the associated issues in the near future as there is particular interest in developing environmentally-friendly designs.

Even though turbine caissons are constrained within specific areas, sluice gates can be employed in shallower parts of the structure. The maximisation of sluicing aides the transfer of water volume in the transitional periods between power generation modes while increasing the construction cost. It is postulated that 50 $m^2$ sluices can be introduced every 30 m at a minimum of 6 m depth. These assumptions reflect any structural and space constraints arising during the construction and manufacturing process and Fig. 1(b) indicates the potential sluice regions for all four lagoons. While the shape and configurations contemplated herein were based on the aforementioned constraints, they will be additionally influenced by factors such as the sea-bed geomorphology, shipping lanes, competing offshore projects and sedimentation processes which however were beyond the focus of this study.

Following construction, the manner in which power is extracted from the tides largely depends on the operation regime of the hydraulic structures [7]. In one-way ebb generation, the rising tide enters the enclosed basin through sluice gates and idling turbines. Once the maximum level in the lagoon is achieved, these gates are closed until a sufficient head ($h_{max}$) develops on the falling tide. Power is subsequently generated until a predetermined minimum head difference ($h_{min}$), when turbines are no longer operating efficiently. For flood generation the whole process is reversed to generate power during the rising tide. In two-way power generation, energy is extracted on both the ebb and flood tide with sluicing occurring around the times of high and low water [19,32]. Under a bi-directional regime, the duration of the generation is maximised and therefore it commences as soon as the optimum start-up head ($h_{start}$) is developed for the turbines to operate. A schematic representation of ebb and two-way generation modes of operation is shown in Fig. 3, highlighting the main trigger points during the tidal cycle that dictate the power generation. However, there are other variations of these regimes which are not discussed herein. For example, ebb generation can often be supplemented with pumping water through the turbines to increase even further the water head difference values as considered in the study of Aggidis and Benzon [26].

The design of a lagoon would invariably be affected by the default generation regime expected after construction. Low-head bulb turbines have the capacity to be bi-directional, but the power efficiency is dependent on their orientation. It is assumed in the analysis for simplicity that turbines are designed appropriately for ebb generation to maximise the energy extracted, whereas for two-way generation they are placed in an alternating manner to minimise the deviation of the energy extracted between ebb and flood generation periods. Consequently, during two-way generation, the power calculated is subject to a factor of 0.9, estimated to acknowledge the reduced efficiency of bulb turbines operating in reverse mode.

### 2.2. Numerical model description

The maximum potential energy, representing the instantaneous release of water from the lagoon at high water to low water during the falling or the opposite during the rising tide, corresponds to:

$$E_{max} = 4\rho g A_w h_a^2 \tag{1}$$

where $g$ is the gravitational acceleration (=9.807 m/s$^2$), $\rho$ the water density ($\approx$1025 kg/m$^3$), $h_a$ the tidal amplitude and $A_w$ the impounded basin wetted area [32]. The maximum extractable energy per tidal cycle corresponds to $0.27 \times E_{max}$ and $0.37 \times E_{max}$ for ebb and two-way generation respectively [27]. These findings were obtained based on Prandle's simplifications [32,33] outlined below:

(a) The external tide is sinusoidal and of amplitude $h_a$.
(b) The surface area $A_w$ remains unaltered.
(c) Flow through the turbines is at a constant rate $Q$.
(d) Power generation commences and stops at the same $h_{min}$.
(e) The water level within the basin is horizontal.

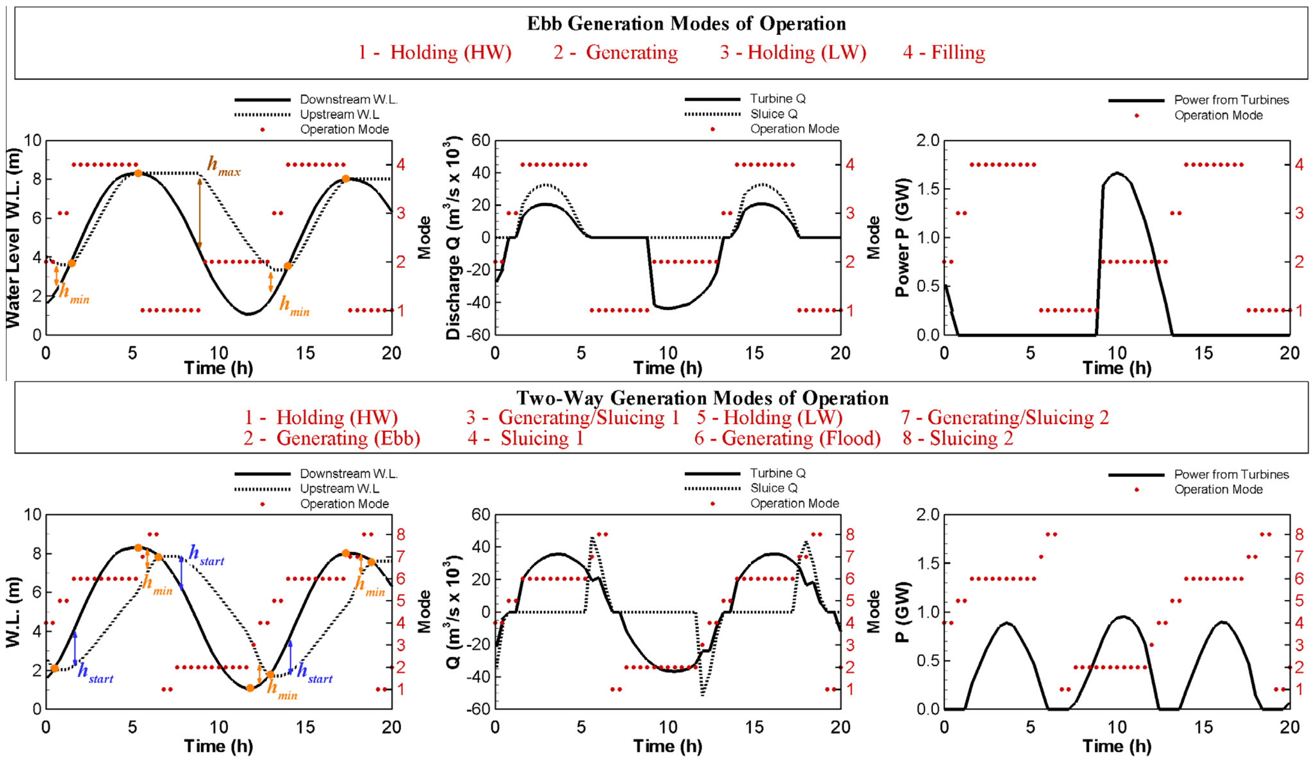


**Fig. 3.** Tidal lagoon operation for an: (a) ebb generation, and (b) two-way generation regime.

In order to obtain a more realistic approximation of the energy obtained from lagoons, the above assumptions should be addressed. The 0-D numerical modelling strategy accounts for Prandle's (a)–(d) assumptions, whereas the 2-D hydrodynamic modelling is not subject to any of the above assumptions.

### 2.2.1. 0-D numerical modelling

A 0-D numerical model was refined according to the principles of Burrows et al. [27,28] and Aggidis and Benzon [26]. It is a backward-difference numerical model developed according to the continuity equation. Specifically, given the downstream ($Z_{dn,i}$) and upstream ($Z_{up,i}$) water level at an instant, the upstream water level after a timestep of $\Delta t$ (in sec) was calculated as:

$$Z_{up,i+1} = Z_{up,i} + \frac{Q(H) + Q_{in}}{A(Z_{up,i})}\Delta t \tag{2}$$

where $A(Z_{up})$ is the wetted surface area of the lagoon for $Z_{up,i}$. In the absence of substantial wetting and drying, the wetted area can be assumed to remain constant as in Prandle [32], which is not typically applicable for coastally attached lagoons in estuarine environments. $Q_{in}$ is the inflow/outflow to the lagoon through sources other than the impoundment, e.g. rivers or outflows. The water elevation difference $H$ is defined as $Z_{up,i}$–$Z_{dn,i}$ and $Q(H)$ is a function determining the total discharge from the turbines and sluices. Essentially, the flow through a hydraulic structure can be estimated as [8]:

$$Q = C_d A\sqrt{2gH} \tag{3}$$

where $C_d$ is a discharge coefficient, equal to 1.0 for this preliminary stage of the investigation, and $A$ is the flow area through the structure. Eq. (3) was used to calculate the flow through sluices and idling turbines. An alternative approach was followed for the turbine operation, since discharge and power generated were computed using a hill chart, as in Falconer et al. [20].

A ramp function was also introduced to alter the flow volume calculated through the turbines and sluices, as in Zhou et al. [24], to represent the gradual opening and closing of turbines during transitional periods (e.g. between holding and power generation or, power generation and sluicing). The ramp function was expressed in a half sinusoidal form [24] when commencing the operation as $F_1(t) = sin(\pi t/2T)$, for $0 < t \leqslant T$, and a half cosine function as $F_2(t) = cos(\pi t/2T)$, for $0 < t \leqslant T$ when closing turbines and sluices. The ramp up time was given the value of $T = 20$ min and were triggered accordingly as soon the lagoon operation mode was altered. The function ($F_1$ or $F_2$) values were in turn multiplied with the discharge and power to account for any additional losses during these stages of the operation.

The 0-D numerical models required as input a water level time series close to the turbines for a sufficient time to simulate the lagoon operation during both spring and neap tidal cycles. The time series was directly used to represent the water level downstream of the structure and the $Z_{dn}$ values were calculated for each time step ($\Delta t$) through linear interpolation from the time series. In practise, these values would be based on the observed water level variation over time at the turbine sections of each individual lagoon. For the purposes of this study these were predicted from the North Wales hydrodynamic model, simulating the established flow conditions discussed in the following section. In turn, depending on the lagoon considered, the Area vs W.L. (Water Level) curves of Fig. 2(b) were imported to describe how the wetted surface area would be altered for the calculation of $Z_{up,i+1}$ from Eq. (2). The operation mode was therefore dictated by the given hydraulic structure operation parameters ($h_{max}$, $h_{min}$ and $h_{start}$) and the sequence associated with either the ebb or two-way generation as graphically illustrated in Fig. 3. The $Q(H)$ function was accordingly solved for the particular operation mode to yield the discharge inflow/outflow from the lagoons.

During power generation, the discharge and power extracted from each turbine was calculated according to the hill chart of

Fig. 2(a) and then multiplied by the number of turbines specified to provide $Q(H)$ and the cumulative generated power $P$. Similarly, under a sluicing mode, the discharge through the sluices and idling turbines calculated from Eq. (3) was multiplied by the number of sluices and turbines respectively and summed to yield the total $Q(H)$ through the impoundment. During *holding* (Fig. 3) periods, $Q(H)$ was set to $0\ m^3/s$, as there would be no discharge through the hydraulic structures. A drawback of the 0-D methodology explained so far is that: (a) it does not take into account the impact of the impoundment structure itself on the tidal flow, and (b) it assumes a horizontal water level on both sides of the impoundments. These simplifications motivated the analysis to expand towards more sophisticated 2-D hydrodynamic models of the lagoons.

### 2.2.2. 2-D hydrodynamic modelling

In coastal waters where the flow is primarily contained within a horizontal plane, in the absence of stratification or extensive three-dimensionality, the 2D shallow water equations can be sufficient for the description of the established flow conditions. These equations can be written as:

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial G}{\partial y}=\frac{\partial \widetilde{E}}{\partial x}+\frac{\partial \widetilde{G}}{\partial y}+S \tag{4}$$

where $U$ is the vector of conserved variables, $E$ and $G$ are the convective flux vectors in the $x$ and $y$ direction respectively, $\widetilde{E}$ and $\widetilde{G}$ are diffusive vectors in the $x$ and $y$ directions, and $S$ is a source term, that includes the effects of bed friction, bed slope and the Coriolis force. Eq. (4) can be expressed in detail as:

$$U=\begin{bmatrix} h \\ hu \\ hv \end{bmatrix},\quad E=\begin{bmatrix} hu \\ hu^2+\frac{1}{2}gh^2 \\ huv \end{bmatrix},\quad G=\begin{bmatrix} hv \\ huv \\ hv^2+\frac{1}{2}gh^2 \end{bmatrix},$$
$$\widetilde{E}=\begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \end{bmatrix},\quad \widetilde{G}=\begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \end{bmatrix},\quad S=\begin{bmatrix} q_s \\ +hfv+gh(S_{bx}-S_{fx}) \\ -hfu+gh(S_{by}-S_{fy}) \end{bmatrix} \tag{5}$$

where $u$, $v$ are depth-averaged velocities (m/s) in the $x$ and $y$ direction respectively, $h$ is the total water depth (m), and $q_s$ is the source discharge per unit area. The variables $\tau_{xx}$, $\tau_{xy}$, $\tau_{yx}$ and $\tau_{yy}$ represent components of the turbulent shear stresses over the plane. With regards to the source term $S$, the variable $f$ refers to the Coriolis accelerations, where $f = 2\omega\sin\varphi$. In turn, $\omega$ is the earth's angular velocity (=$7.29\times10^{-5}$ rad/s) and $\varphi$ the latitude of the domain (in this case 53°). The bed and friction slopes are denoted for the $x$ and $y$ directions as $S_{bx}$, $S_{by}$ and $S_{fx}$, $S_{fy}$ respectively.

The computational domain of Fig. 1 was divided into a set of triangular cells, with a view to forming an unstructured mesh, and adopting a cell-centred Finite Volume Method (FVM). Roe's approximate Riemann solver, combined with a monotone upstream scheme for conservation laws (MUSCL) is implemented to resolve the normal fluxes across each cell interface, by following a procedure known as the predictor–corrector time stepping to yield second-order accuracy in time and space. A thin film algorithm for the treatment of wetting and drying fronts was employed [34] since this phenomenon is prevalent in highly tidal coastal regions. In terms of stability, the numerical model is based on the Total Variation Diminishing scheme, which is an explicit algorithm and is therefore intrinsically stable provided the Courant–F riedrichs–Lewy (CFL) number is less than unity. Using this scheme the predicted hydrodynamic parameters are not prone to the generation of non-physical solutions. The maximum CFL number was consistently <0.8 for the current simulations, using a timestep of $\Delta t = 1$ s.

Computational meshes were created according to the domains of Fig. 1. Initially, a numerical model was generated to simulate the established tidal flow regime for validation purposes and to produce the necessary water level time series for the 0-D model. The associated hydrodynamic model boundary conditions were classified into land and open boundaries and their treatment (i.e. water level and discharge boundaries) has been described in more detail by Xia et al. [21]. For further information on the overall numerical methodology, the interested reader is directed to the work of Sanders [35], Sleigh et al. [36], Anastasiou and Chan [37].

The Western seaward boundary was set up as a water level boundary according to the tidal flow conditions in the region, which were provided by the National Oceanographic Centre for a duration of 720 h, to cover both spring and neap tide conditions. The tidal harmonics are consistent and in line with the Continental Shelf Model of Zhou et al. [24,25]. Based on the same model, the northern boundary was defined assuming no fluxes across it. The boundary closely follows a streamline for this region and hence it is driven by the water levels and an assumed free-slip tangential velocity condition as the flow normal to this boundary is essentially small. With regards to land boundaries, it was hypothesized that the tidal flow from the Menai strait (Fig. 1) would be blocked in order to make the operation of the Conwy Lagoon feasible. River flowrates in most cases were considered negligible towards the lagoon operation, either due to their relatively low flow rate (Conwy, Clwyd), or their distance from areas of interest (Mersey). However, a mean flow rate of $30\ m^3/s$ was imposed for the Dee River throughout the simulations in accordance with the UK National River Flow Archive data.

The numerical model simulations were driven by the tidal flow conditions and the operation of the lagoons was considered independent of regional wave and wind conditions. This assumption is in line with the findings of Fairley et al. [38] suggesting an insignificant impact of a tidal range project to regional wave conditions downstream, and a reduction upstream. As for effects of wind action on the tidal flow, and by extension to the tidal range structure operation, these were considered relatively small and therefore omitted for the purposes of this study.

The resulting computational meshes span an area of approximately $6000\ km^2$ and encompass an average water volume of $120\ km^3$, depending on the tidal phase. The grids were refined locally to give a higher resolution close to the coast and the lagoon sites (Fig. 1(b) and (c)), since the flow pattern developed in these regions was of particular interest and is where the typical element side length was approximately 100 m. In some areas, however, the resolution was even finer, with side lengths of 50 m due to the presence of narrow sections such as along the Mersey channel. On the other hand, the mesh was coarser further away from this region, so as to minimise the computational cost of the transient simulations. Indicatively, the maximum element side length was 1000 m and was typically encountered close to the Northern and Western boundaries of the domain. As a result the triangular cell area varied between approximately 1000 and $433{,}000\ m^2$ respectively. For the simulations combining all 4 lagoons, the mesh consisted of 29,601 nodes, 55,595 elements and a total of 85,193 edges.

A technique of domain decomposition was followed to efficiently address certain complex physical processes, such as the ones developed through the operation of turbines and sluices. The underlying principle of this technique is the subdivision of the domain into smaller parts, i.e. subdomains (Fig. 1(c)). Computations were conducted independently in the subdomains and were interconnected through open discharge boundaries. This technique was employed when considering the tidal impoundment by using two subdomains, one upstream of the impoundment, and another downstream of the structure (Fig. 1(b)). Open boundaries connecting the subdomains were specified in the region of impoundment flow control structures, e.g. the turbines. Subdomains were dynamically linked using a relationship between the discharge $Q$ and the water head difference $H$ at the boundary nodes in the same manner as explained for the 0-D modelling approach through Eq. (3) and the Hill chart of Fig. 2(a). As previously, the discharge and power calculated was coupled with a ramp function $f$ to ensure a smooth transition between the operation regime modes (Fig. 3).

It should be remarked that while the computational models were defined based on the available boundary data and may be suitable for the assessment of small lagoons, the accurate assessment of far-field effects from larger scale projects should be conducted with extended boundaries (e.g. [24]) to ensure that the impacts of the tidal lagoon structures do not influence the boundary conditions. On the other hand, since the primary focus herein is the comparison between 0-D and 2-D numerical model power predictions, the particular boundary extents were deemed sufficient.

## 3. Results and discussion

### 3.1. Numerical prediction validation

Apart from the high tidal range, the model domain (Fig. 1(a)) is characterised by steep seabed elevation gradients and an irregular land boundary around the coast, combined with large areas subjected to wetting and drying over the course of the tidal cycle. Consequently, the established conditions result in a challenge for any numerical model capabilities. In order to ensure the reliability of the predictions, a validation study was conducted through comparisons against observations of tidal level, current magnitude and flow direction, available from Admiralty Chart No. 1978 (i.e. covering the area from Great Ormes Head to Liverpool). The water level and current observation points are indicated in Fig. 1. The North Wales tidal flow reproduction simulations were initially calibrated for average spring tide conditions with respect to the sea bed Manning's number $n$, where a value of 0.022 yielded good agreement. In turn, the simulation was validated by simulating average neap tide conditions. Fig. 4 compares velocity magnitudes and flow direction predictions from the 2-D model against previously measured data during spring and neap tides. Table 1 summarises the predicted and observed values for the maximum and minimum water levels under spring and neap tidal ranges. The reproduction of water level conditions by the North Wales model was additionally compared against available tide gauge data for the conditions developed between the 6th and 13th of March 2005 as shown in Fig. 6. The associated correlation coefficients were 0.994, 0.994, 0.995 and 0.996 while the Root Mean Square Deviations (RMSD) were evaluated at 0.334, 0.345, 0.288, and 0.196 m for Fig. 6(a)–(c) and (e) respectively. An overall agreement is apparent for most sites and the degree of accuracy was acceptable, once taking into account the complexity of the flow structure for a numerical model of this size.

Further testament to the performance of the 2-D hydrodynamic model capacity to reproduce complex tidal flow can be found in the in-depth validation study of Xia et al. [4] for the Severn Estuary. Accordingly, the numerical modelling efforts along the North Wales coast would benefit from comparisons with more measurements obtained through field monitoring campaigns in the region, if tidal range schemes are to be considered. Nonetheless, the present numerical model performed within a satisfactory extent, with the overall hydrodynamic pattern being adequately reproduced.

Following the hydrodynamic model validation study, and an optimisation study through 0-D modelling, each of the lagoons was subsequently tested individually under a two-way and ebb-only generation regime (Fig. 3). In turn, a simulation was undertaken with all four lagoons operating concurrently to gauge the combined impact of the schemes.

Over the course of this study two methodologies were considered to model the lagoon operation, namely a generic 0-D and a more detailed 2-D hydrodynamic modelling approach, with both capable of calculating the power from the turbines at any instant, and therefore the electricity produced over a period of time.

### 3.2. Tidal lagoon optimisation

An initial challenge before embarking on the hydrodynamic modelling of the lagoons was to determine a suitable turbine and sluice number for their optimal operation, in a manner that accounted for the capabilities of the turbines and sluices, as well as the wetting and drying characteristics of the impounded areas. This was accomplished through a preliminary 0-D analysis.

The graphs of Fig. 5 were produced by iterative 0-D simulations run for a range of hydraulic structure and operational parameters as an example of the typical output that can be obtained through zero-dimensional modelling optimisation. Fig. 5(a) plots the annual electricity produced under ebb-only and two-way generation for each of the proposed lagoons, against an ascending number of 25 MW bulb turbines (1-400). The 0-D simulations consider the aid of the maximum number of sluice gates possible (Table 2), within the allocated space of Fig. 1(b). It is suggested in Fig. 5(a) that the introduction of turbines beyond a certain point becomes detrimental to the power production as the lagoon empties or fills too rapidly during the generation periods. Considering the typical hill chart of Fig. 2(a), it is desirable to maintain a high water head difference for as long as possible, as the turbines operate more efficiently. Therefore, a lower number of turbines corresponds to a reduced discharge during power generation, which facilitates a greater water head difference for longer, resulting in a superior performance. However, the optimum turbine number will vary upon the specifications of the hydraulic structures, the variation of the surface area within the lagoon due to wetting and drying, and the tidal range conditions at the particular site. It should be noted that for Fig. 5(a), it was assumed that $h_{min} = 1.5$ m, $h_{max} = 4.0$ m for ebb-only and $h_{start} = 2.5$ m for two-way generation respectively. On the other hand, variations in these operational parameters will also influence the performance, as shown by Fig. 5(b), assuming the turbine and sluice specifications of Table 2. Simultaneously, acknowledging that the construction and manufacturing process of the turbines will constitute the bulk of the investment, their numbers would be highly affected by cost-benefit analyses, an aspect beyond the focus of this work.

Table 2 summarises the specifications applied for each of the tidal lagoons used for further analysis through hydrodynamic modelling. The operational parameters $h_{max}$ and $h_{start}$ of Table 2 are rounded values that yield the maximum power as indicated in Fig. 5. On the other hand $h_{min}$ which is typically specific to the tidal turbine technology used values from previous studies [18,20]. For these configurations, the 0-D modelling predictions for annual power through ebb-only and two-way generation are outlined in Table 3, demonstrating a remarkable potential through tidal power in the region. An inspection of the water levels upstream at the peak of the spring tides suggests a reduction in the intertidal area, which, however, is less pronounced for a two-way generation regime (Table 3). Moreover, even though the power generation is less efficient, due to the orientation of the turbines, the two-way generation consistently yields more power compared to an ebb-only generation. With regard to the intertidal

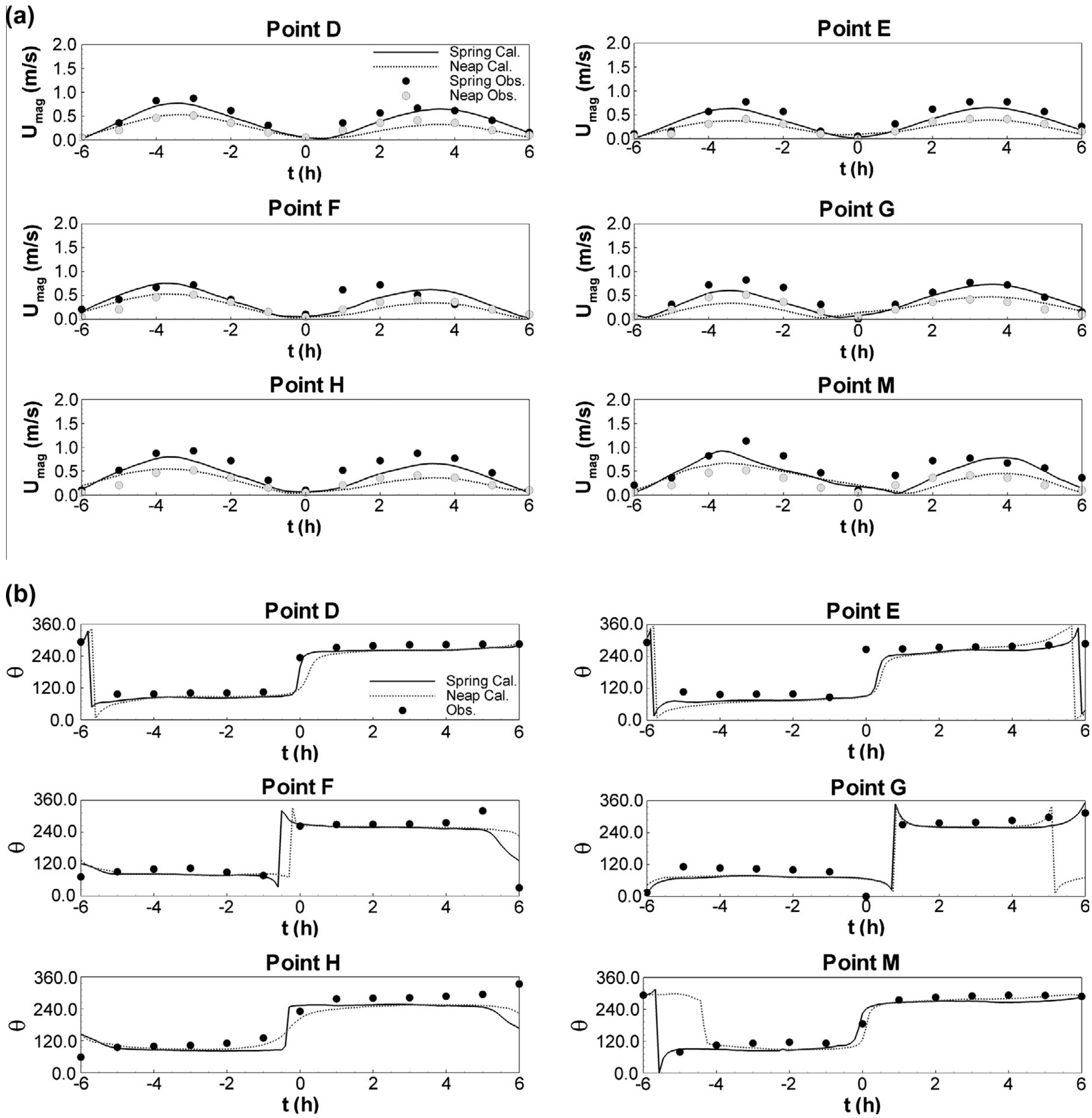

Fig. 4. (a) Velocity and (b) flow direction comparisons between simulated and observed data. The range of the x axis reflects the time before and after HW at the local validation point.

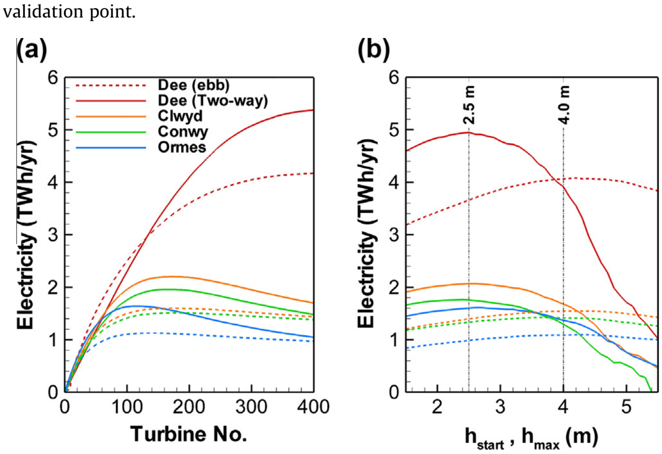

Fig. 5. Lagoon optimisation using 0-D modelling. Predicted power for each of the lagoons under ebb-only and two-way generation regime for: (a) increasing turbine number with maximum sluicing and (b) a variable $h_{start}/h_{max}$ head difference. The dashed lines correspond to rounded efficient driving head values for two-way generation ($h_{start}$ = 2.5 m) and ebb generation ($h_{max}$ = 4.0 m) respectively.

area losses, at first comparisons were made between the maximum and minimum upstream water levels against the status quo and then transformed to yield the intertidal area deviation through the W.L. vs Area curves of Fig. 2(b).

Once the turbine number and certain operational parameters were determined, 2-D simulations were performed to examine: (a) the impact on the established tidal flow structure, and (b) the corresponding effects on power production.

### 3.3. Hydrodynamic impact of the lagoon operation

An aspect of particular interest with regard to the operation of tidal range schemes is the potential significant impact on both the hydrodynamics in and around the lagoon, and the regional tidal flow conditions. Fig. 6, provides evidence of how the lagoons can interfere with the Water Levels established at various locations across the computational domain, assuming a combined operation with the configuration and operational specifications of Table 2.

**Table 1**
Water level comparison between simulated and observed data.

| No | Location | Latitude (N) | Longitude (W) | Spring tidal range | | | | Neap tidal range | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | HW obs. | HW cal. | LW obs. | LW cal. | HW obs. | HW cal. | LW obs. | LW cal. |
| 1 | Formby | 53°32′ | 3°07′ | 9.0 | 8.8 | 1.0 | 1.0 | 7.3 | 6.9 | 2.9 | 3.1 |
| 2 | Hilbre Island | 53°23′ | 3°14′ | 9.0 | 9.2 | 1.3 | 1.2 | 7.2 | 6.9 | 3.1 | 3.4 |
| 3 | Mostyn Docks | 53°19′ | 3°16′ | 8.9 | 8.9 | – | – | 7.1 | 6.9 | – | – |
| 4 | Colwyn Bay | 53°18′ | 3°43′ | 8.6 | 8.3 | – | – | 6.9 | 6.9 | – | – |
| 5 | Llandudno | 53°20′ | 3°50′ | 8.7 | 8.6 | 1.7 | 1.5 | 7.1 | 6.8 | 3.3 | 3.4 |
| 6 | Trwyn Dinmor | 53°19′ | 4°03′ | 8.4 | 8.3 | 1.4 | 1.4 | 6.8 | 6.7 | 3.4 | 3.4 |

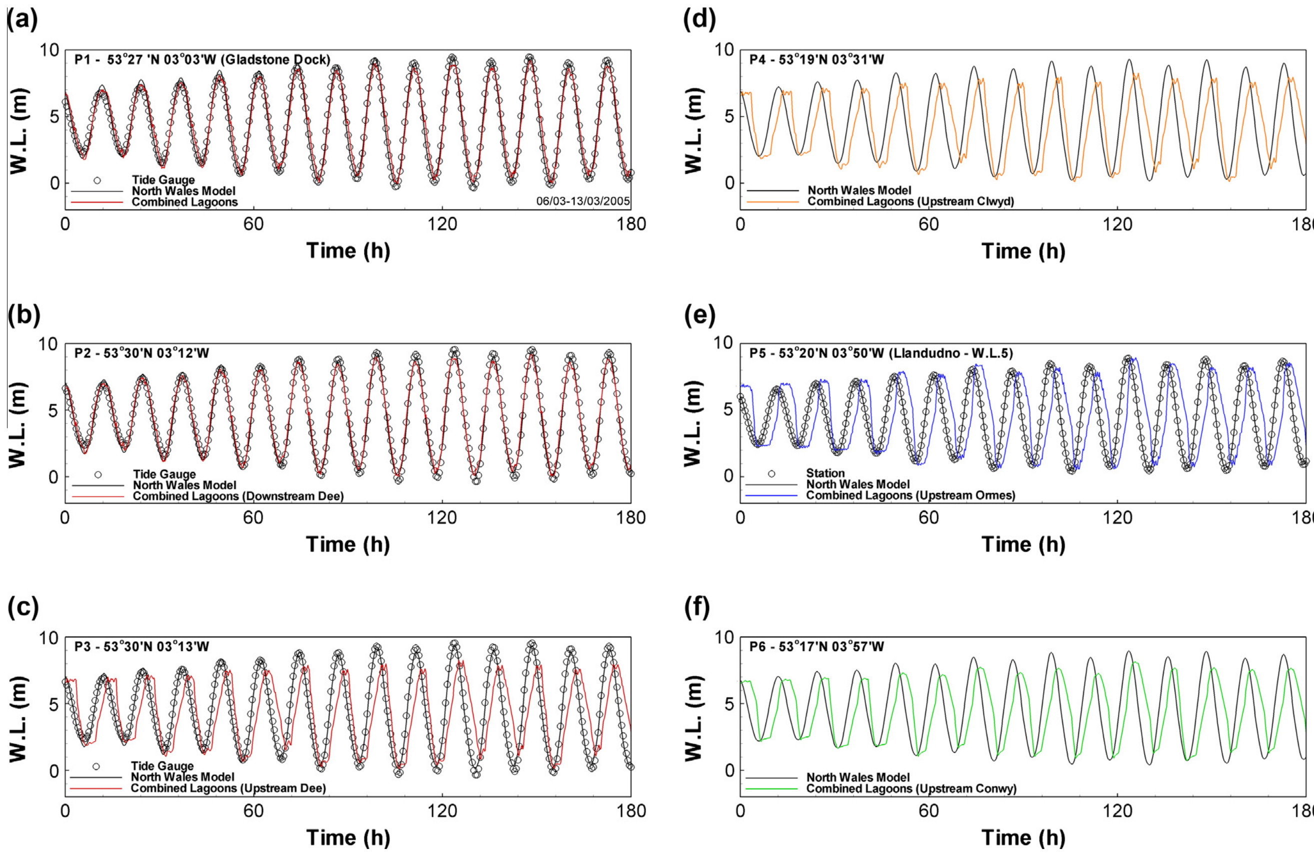


**Fig. 6.** Water level time series at monitor points across the computational domain (P1–6) according to tide gauge data, the North Wales model simulation and the combined lagoon simulation.

**Table 2**
Specifications of proposed lagoons considered for comparisons between a 0-D and 2-D analysis.

| Tidal lagoon | Maximum area ($km^2$) | Turbines (25 MW) | Sluices (50 $m^2$) | Operational parameters | | |
|---|---|---|---|---|---|---|
| | | | | $h_{max}$ (m) | $h_{start}$ (m) | $h_{min}$ (m) |
| Dee | 321 | 280 | 175 | 4.00 | 2.50 | 1.50 |
| Clwyd | 116 | 115 | 160 | 4.00 | 2.50 | 1.50 |
| Ormes | 88 | 90 | 370 | 4.00 | 2.50 | 1.50 |
| Conwy | 122 | 100 | 160 | 4.00 | 2.50 | 1.50 |

**Table 3**
Annual electricity production and impact on intertidal area through a 0-D assessment.

| | Annual Electricity (TW h/yr) | Intertidal area loss (%) | Intertidal area loss ($km^2$) | Maximum W.L. reduction (m) | Minimum W.L. increase (m) |
|---|---|---|---|---|---|
| *Two-way generation* | | | | | |
| Dee | 4.95 | 27 | 34.0 | 0.67 | 0.89 |
| Clwyd | 2.06 | 11 | 2.0 | 0.42 | 0.67 |
| Ormes | 1.69 | 13 | 0.3 | 0.19 | 0.23 |
| Conwy | 1.77 | 12 | 8.2 | 0.56 | 0.66 |
| *Ebb generation* | | | | | |
| Dee | 4.06 | 39 | 48.3 | 0.11 | 2.37 |
| Clwyd | 1.49 | 33 | 6.0 | 0.00 | 2.27 |
| Ormes | 1.00 | 63 | 1.5 | 0.00 | 2.43 |
| Conwy | 1.41 | 45 | 31.4 | 0.00 | 2.59 |

There is a noticeable impact on the water level time series both upstream and downstream of the impoundments. It is also highlighted by Fig. 6(e) that if a sufficient area of sluices is distributed across the impoundment wall as in the Ormes scheme, the upstream tidal range can be effectively preserved.

An indication is provided with regards to the maximum (Fig. 7(a)) and minimum water level (Fig. 7(b)) changes in the presence and simultaneous operation of the lagoons for a two-way generation regime. It should be noted that for a more accurate appreciation of the far-field impact of the structure on the water level maxima and minima, the boundaries of the numerical model should be extended to ensure that the hydrodynamic effect of the structures does not influence the model boundary conditions. However, since the focus of this work is more concerned with the comparison between 0-D and 2-D modelling predictions, it was considered beyond the scope of the current investigation.

The presence of the lagoons implies that due to the constraints of turbines and sluice operation, it is expected that a lesser water volume than previously will enter the impounded area. This volume displacement can lead to far-field effects such as water level rise in nearby regions downstream and thus increase their associated flood risk. This is the focus of far-field studies such as Zhou et al. [24,25]. The maximum water levels downstream of the structures noticeably increase in certain locations where there is an obvious deviation from the established flow. For instance, downstream of the Conwy impoundment, there is an elevation change of approximately 10–20 cm. These results suggest that if not designed properly, such schemes could increase the flood risk in nearby regions that might not previously have been susceptible to coastal flooding. A similar pattern arises with minimum water levels, where it can be deduced that the operation of tidal impoundments should be carefully monitored for their effects on the surrounding regions. With regard to the upstream water levels, for large lagoons, such as the ones contemplated in this analysis, the assumption of a flat water level in the 0-D analysis is far from reality. There was an obvious variation between the water elevation in the vicinity of the hydraulic structures, and closer to the coast of the impounded areas. This is more pronounced for the case when rivers and/or outfalls are discharging within the lagoon area (e.g. for the Dee lagoon). Nonetheless, there is an apparent reduction in the maximum upstream water levels on all but the Ormes lagoon, demonstrating the capacity of the impoundments to act as flood defence mechanisms. These water levels could be further reduced by the appropriate regulation of the turbines and sluices, thus providing the means to protect otherwise exposed communities upstream. As an example, without sluicing, the water body exchange between the downstream and upstream sides is predicted to be reduced even further, redirecting flood flow downstream to surrounding regions.

Apart from the impact on the tidal range, the construction of tidal lagoons would disturb the estuarine flow pattern along the two-dimensional plane considered as well as the velocity magnitude profile. Figs. 7(c) and 8 present a combination of contour and streamline plots, to provide an overview of the estuarine conditions before and after the lagoon construction.

By observation of the maximum relative velocity contour plot of Fig. 7(c), the magnitude of the velocities upstream of the structure appeared to be largely retained under a two-way generation regime, with significant accelerations close to the turbine and sluice wake if hydraulic structures are not widely distributed across the impoundment (e.g. Clwyd and Conwy lagoons.). However, during holding periods, the velocities upstream were reduced and the flow pattern comprised a series of large low-velocity recirculation zones, while the required head difference was developed for the turbines to operate in the next ebb or flood generation

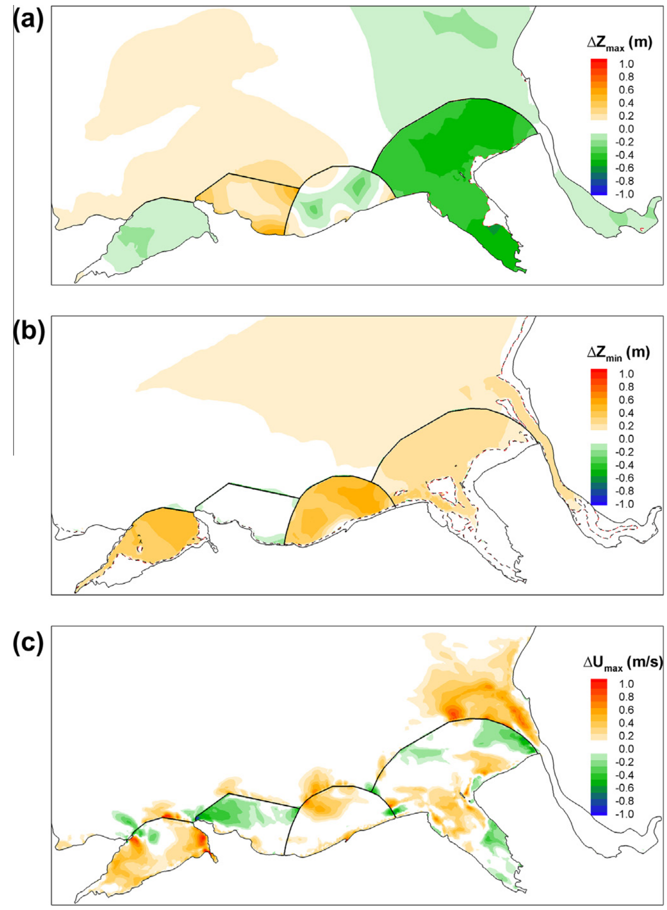


**Fig. 7.** Relative difference between the established conditions against the combined operation of the four lagoons in terms of (a) maximum water elevations, (b) minimum water elevations and (c) maximum velocity magnitude under a two-way generation regime assuming the specifications of Table 2.

period. This could lead towards a reduction in the suspended sediment levels and therefore deposition inside the lagoon. Moreover, reduced suspended sediment levels would also lead to increased light penetration, as predicted for the Severn Barrage by Ahmadian et al. [18]. However, these impacts are expected to be more complicated and require further studies. Simultaneously, schemes of this size can have a remarkable impact on the downstream side of the impoundments. For instance, in the particular simulations reported herein, the maximum magnitude of the incoming velocity from the west had been reduced slightly. Similarly, due to the design of the Dee impoundment, an acceleration in the currents entering the Mersey estuary was apparent (Fig. 7(c)).

Fig. 8(a) similarly depicts velocity magnitude and direction during the ebb generation phase as opposed to Fig. 8(b) that illustrates the flow pattern as developed on the flood part of the tide, while power is generated. As shown previously [4,21,22], for both cases there was an increase of the velocity in close proximity to the turbines during their operation. However, bearing in mind that it was opted during simulations to distribute the turbines as much as possible along the wall, the high magnitude water jet conditions resulting in counter-rotating eddies close to the turbines were not as prevalent as for the Welsh Grounds Lagoon study of Falconer et al. [20]. On the other hand, the formation of multiple larger recirculation zones was unavoidable during turbine operation (Fig. 8) as well as holding periods.

The discussion of the hydrodynamic impacts has so far concentrated on the two-way generation regime rather than ebb-only

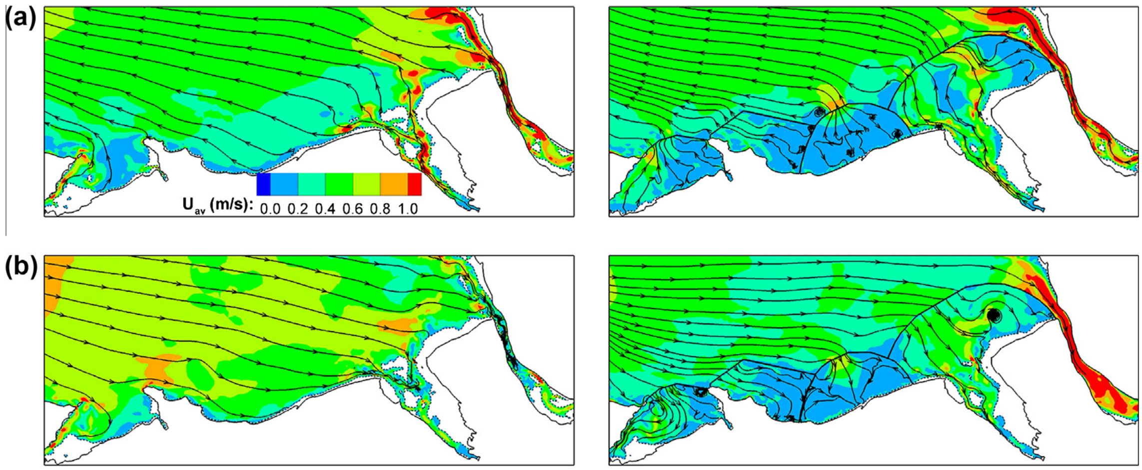


**Fig. 8.** Impact of tidal lagoons on established current conditions: (a) instantaneous flow pattern and velocity magnitude during ebb tide generation; and (b) instantaneous flow pattern and velocity magnitude during flood tide generation.

generation. This is because: (a) there is the potential to generate more electricity using this scheme, as shown by the theoretical studies of Prandle [32]; and (b) during a single tidal cycle there are two periods of generation instead of one. Therefore, the generated electricity can more easily be absorbed into the local electricity grid [8]. Moreover, a more comprehensive analysis of the hydrodynamic impacts of both ebb-only and two-way generation modes can be found in Xia et al. [22] and Ahmadian et al. [39]. On the other hand, ebb-generation power production results have also been produced for completeness and are discussed in the section below.

### 3.4. Power generation analysis

For the 0-D analysis, there were two short-comings as indicated from the previous section: (i) the impact of the impoundment structure and operation on the tidal flow was not acknowledged; and (ii) only a single lagoon could be modelled in each case, which indicates that the impact of regional tidal range schemes was also omitted. Therefore, in order to compare 0-D predictions with the hydrodynamic model predictions, all of the lagoons were initially modelled individually through the 2-D modelling technique. Subsequently, they were all incorporated into the same model, to observe the combined potential of the impoundments, while taking into account their accumulated impact on the tidal elevations and currents.

As an example, the energy extracted from the Clwyd impoundment predicted by the three approaches (0-D modelling, individual lagoon and combined lagoons using a 2-D hydrodynamic model) is plotted with respect to time in Fig. 9 under spring (Fig. 9(a)) and neap (Fig. 9(b)) tide conditions respectively. The power generated was maximised during peak spring tides, as the highest hydraulic head difference could be achieved under these tidal conditions. However, the operation of the lagoon during neap tides was far less efficient and in certain cases the required water level difference could not be achieved. Under these circumstances, the generating stage was directly skipped to sluicing (Fig. 9(b), $t > 175$ h) so as not to disrupt the dynamic tidal flow conditions. Apart from the tidal amplitude, which was held accountable for the majority of such anomalies, they were also induced in certain cases by the complex hydrodynamic flow very close to the turbines.

The overall pattern is reproduced quite well with both the 0-D and 2-D methods agreeing on the timeframe of the lagoon operation modes of Fig. 3. However, the 0-D modelling methodology consistently overestimated the power production through the turbines for a two-way generation regime. This is clearly reflected in the accumulated electricity calculated based on the power results such as in Fig. 9 over an extended simulation duration. While the deviation is acceptable in comparison to the 2-D modelling of individual lagoons (in this case approximately 5%), the overestimation becomes substantial once the four lagoons are operated simultaneously (≈30%). This phenomenon can be attributed to the impact of the lagoons on the tidal flow conditions. By observation of the water level time series (Figs. 6 and 9), this becomes apparent. The abrupt water jet on the wake of turbines and sluices at the beginning of generation and sluicing modes corresponded to local water level disturbances, both downstream and upstream of the impoundment (e.g. Figs. 6 and 9). When considering only a single lagoon (green[1] line) these fluctuations were not as dominant. As a result, the difference between the 0-D and 2-D modelling predictions is only minor and therefore the simplified approach can be useful and reliable during the preliminary design process. On the other hand, with multiple lagoons, the 0-D predictions were compromised by ignoring the water level difference oscillations close to the turbine sections.

The power generation over the longer duration of one month for both ebb and two-way generation is contemplated in Fig. 10. When modelled individually and in accordance with the aforementioned discussion, the power output of each individual lagoon was greater than if the lagoon was operated in combination with other lagoons under a similar two-way generation regime (Fig. 10(a) and (b)). For instance, the power peaks are reduced in many cases as clearly illustrated for the Dee impoundment. On the other hand, under an ebb-only generation regime (Fig. 10(c) and (d)), total power generated by the lagoons when they were utilised together is closer to the 0-D predictions for the same scenario. Moreover, when using 2-D models, the predicted power for each lagoon, when considered in combination with other lagoons, is close to the power predicted for that lagoon when only that individual lagoon was considered. For this case it is speculated that since there is a significant time interval between generation periods, the flow recovers to more uniform water level conditions and thus the oscillations discussed previously are less pronounced. In contrast, the more

[1] For interpretation of color in Figs. 6 and 9, the reader is referred to the web version of this article.

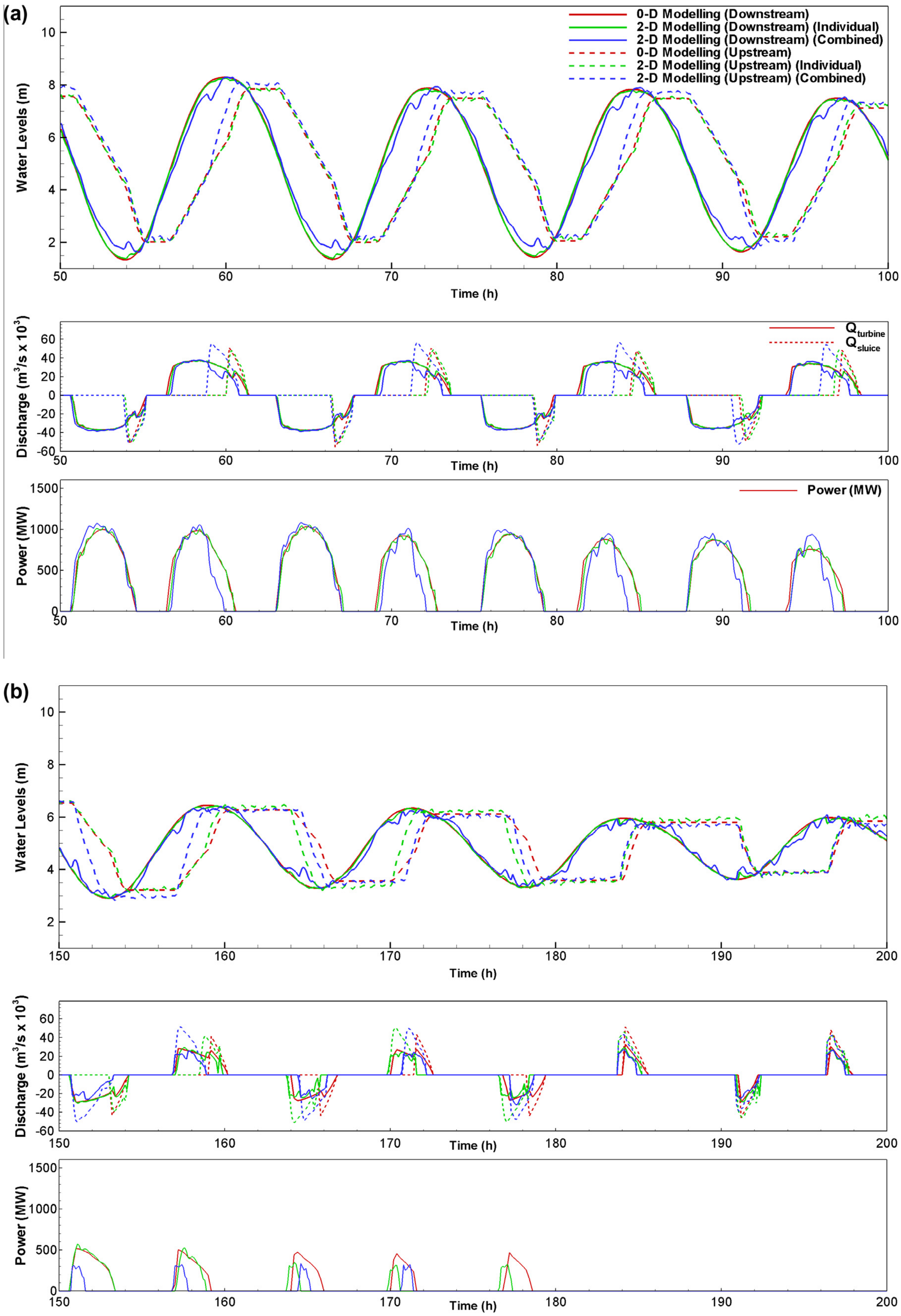


**Fig. 9.** Water levels adjacent to the impoundment, hydraulic structure discharge and power production for a two-way generation regime, as predicted using a 0-D and 2-D modelling analysis respectively for the Clwyd lagoon, for: (a) spring tide, and (b) neap tide conditions.

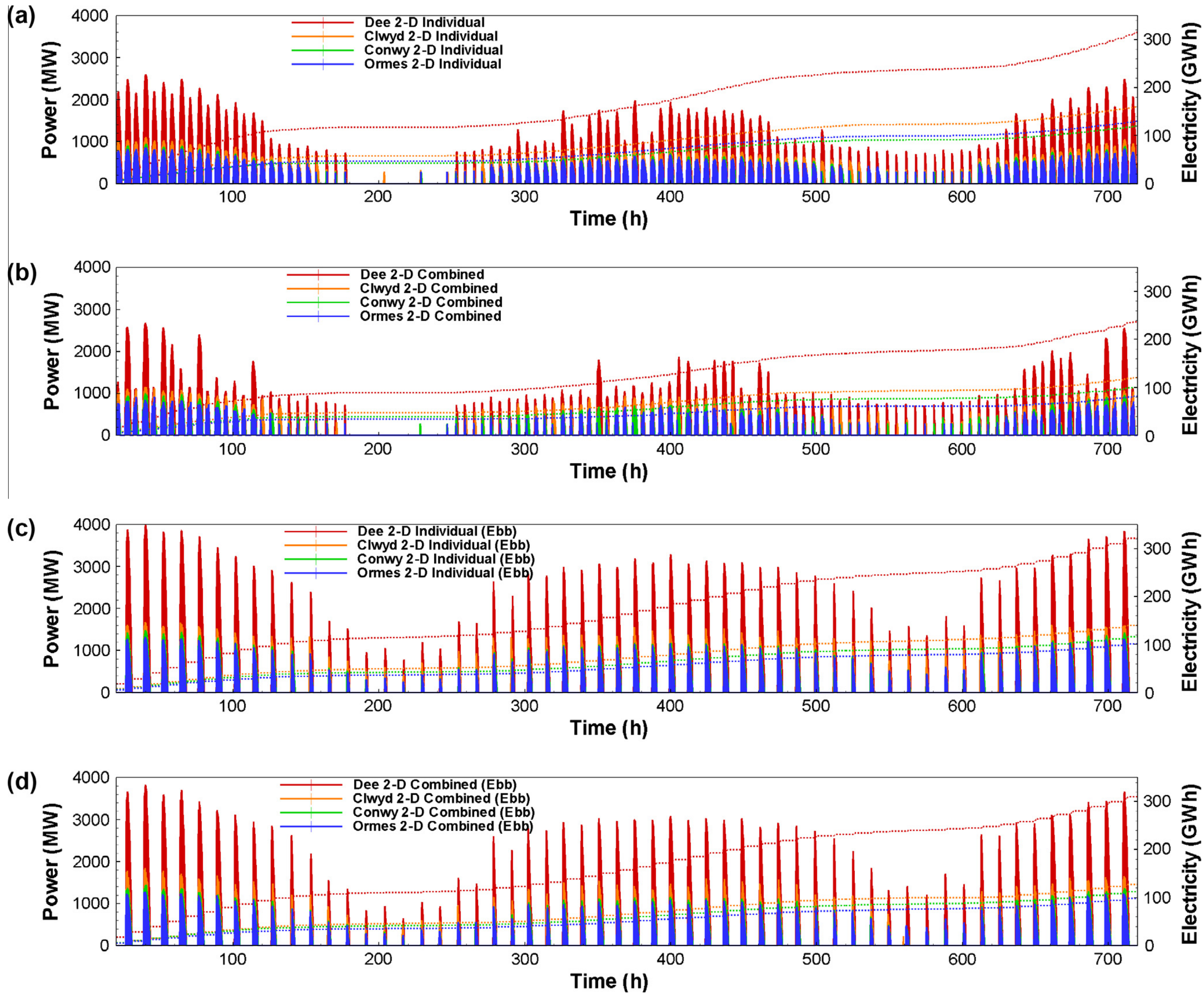


**Fig. 10.** Power production for two-way generation for each lagoon: (a) individually, (b) combined; and power production for ebb-only generation for each of the lagoons: (c) individually and (d) combined. The dashed lines indicate the cumulative electricity produced over the period of 720 h.

frequent operation of turbines in two-way generation may be responsible for the greater impact on the tidal elevations and currents and could be the justification for the reduction in power production for subsequent generation periods.

One of the most crucial aspects motivating the consideration of these schemes is the annual energy produced following their construction. Thus, the annual energy production estimation methodology should ideally be informed with economic and site-specific environmental considerations that may dictate a more conservative power-generating operation. Unfortunately, there is no established framework for their design and assessment, as they are as of yet in the planning process at best (e.g. Swansea Bay lagoon). Therefore, while the primary focus of this investigation was the numerical modelling combining the four lagoons, power production estimates of simpler approaches were also summarised in Table 4. Initially, the potential energy was estimated using

**Table 4**
Annual electricity production through the operation of the lagoons.

| Tidal lagoon | Theoretical approach | | 0-D modelling | | 2-D modelling (individual lagoons) | | 2-D modelling (combined lagoons) | |
|---|---|---|---|---|---|---|---|---|
| | Mean amplitude $h_a$ (m) | Potential energy $E_{max}$ (TW h/yr) | Ebb (TW h/yr) | Two-way (TW h/yr) | Ebb (TW h/yr) | Two-way (TW h/yr) | Ebb (TW h/yr) | Two-way (TW h/yr) |
| Dee | 2.25 | 12.755 | 4.06 | 4.95 | 3.91 | 3.83 | 3.77 | 2.88 |
| Clwyd | 2.00 | 3.658 | 1.49 | 2.06 | 1.70 | 1.95 | 1.55 | 1.46 |
| Ormes | 1.97 | 2.679 | 1.00 | 1.69 | 1.23 | 1.58 | 1.19 | 0.99 |
| Conwy | 1.90 | 3.472 | 1.41 | 1.77 | 1.41 | 1.46 | 1.36 | 1.22 |
| Total Electricity (TW h/yr) | | 22.565 | 7.961 | 10.471 | 8.245 | 8.810 | 7.871 | 6.554 |

Eq. (1) from Prandle [32], and in turn results from 0-D and 2-D approaches were outlined to estimate how much of the potential energy could be obtained. The sum of these from all four lagoons corresponds to the total potential energy to be extracted, which for this case was approximately 22.565 TW h/yr (Table 4). The 0-D modelling predictions which acknowledge the effects of wetting and drying, and the specifications associated with turbines and sluices, predict that only 35% and 46% of the potential energy can be harnessed through ebb-only and two-way generation respectively. For the 2-D modelling assessment of individual lagoons, results suggest that the altered tidal flow conditions will impair the 0-D modelling predictions, as only 37% and 39% of the overall potential energy would be extracted respectively. For ebb-only generation it appears that the tidal flow changes for the Clwyd and Ormes lagoons are actually beneficial for the power production. By extending the analysis to the simulation for combining the four lagoons, the power prediction estimates are reduced to 34% and 29% for ebb-only and two-way generation accordingly.

An interesting pattern emerged, where the two-way generation predictions were less efficient than the associated ebb-only generation. This is contrary to 0-D modelling predictions of Burrows et al. [27], as the disturbance on the regional hydrodynamic regime is not included in the calculations. In an attempt to improve the operational performance using two-way generation, a 2-D model simulation was undertaken where the $h_{start}$ value of 1.5 instead of 2.5 was applied. By reducing the starting operating head to $h_{min}$, the holding mode duration is minimised and thus the flow would be significantly closer to the tidal flow without any impoundment structures. The accumulated energy 0-D estimate for this value was 9.59 TW h/yr, according to Fig. 5, which is 8.5% less than when operating with $h_{start} = 2.5$ m ($\approx$ 10.471 TW h/yr). In contrast, the 2-D predictions yield 7.612 TW h/yr, i.e. a 16% improvement to the 6.554 TW h/yr. This would translate to 34% of the potential energy, i.e. to a level marginally inferior to that for ebb-only generation predictions.

These results indicate a distinctive lack of appreciation of the hydrodynamic impact of operating large-scale tidal range schemes through the simplified 0-D model. In the light of this, it is suggested that the optimisation of the lagoons is performed iteratively using both the 0-D and 2-D methods. As in the previous section, the 0-D modelling specifications should be fed to the 2-D model to provide water level time series that acknowledge the presence of the structures along the coastal flow. These series can in turn be used as input for the generic 0-D model and the process can be repeated until the analysis converges towards optimal specifications of the project.

## 4. Conclusions

In this paper details have been provided of two numerical methodologies (i.e. a simplified 0-D and a more comprehensive 2-D hydrodynamic model) used to model the hydrodynamic and power characteristics of tidal lagoons along the North Wales coast of the UK. In addition, an assessment was made of the interaction of a range of lagoons along the coastline. Initially, crucial considerations for the design of tidal lagoons were discussed, with particular focus on identifying suitable locations for the impoundment turbines and sluices. In turn, four proposed tidal impoundments were introduced in a 2-D numerical model to highlight the hydro-environmental impacts on the project site, the annual energy generation and reflect upon the contribution of the lagoon to flood risk mitigation upstream of the impoundments. A preliminary verification analysis suggested a promising performance of the model to reproduce measured data, which, however, would benefit from comparisons against more thorough field data, if such tidal range schemes are to be considered in the region. Therefore, undertaking field measurement campaigns could provide a greater insight to the conditions in the region, which could be invaluable towards the more detailed reproduction of the North Wales tidal flow.

The numerical model results indicate a range of impacts to the flow structure and tidal range upstream of the impoundment. It was shown that, depending on the location of the structure, the interpretation of the environmental impacts can vary significantly, as seen by the discussion associated with the changes of the upstream tidal range. It was highlighted that for lagoons in estuarine environments, a focal aspect of the design should be directed at the preservation of the benthic ecosystem and the minimisation of intertidal area losses through the optimisation of the lagoon operation. On the other hand, tidal lagoons should in addition be treated as flood protection schemes, since they have the capacity to regulate the water volume entering the lagoon, and thus protect otherwise vulnerable communities on the upstream side of the impoundments from coastal flooding.

The annual energy production was calculated through a range of techniques, beginning with theoretical approaches and gradually refining the methodology, with the specific details for each lagoon operation. While both 0-D and 2-D modelling approaches have been used to assess the potential of tidal range schemes, as suggested by the literature, these had not been compared directly. Results suggest that as the scale of the lagoon increases, so does the impact on the tidal flow conditions, which has a distinct effect on the overall energy output of the proposals. Specifically, only 34% of the potential energy could be extracted based on the given four lagoon configuration, through the hydrodynamic model using both two-way and ebb-only generation. On the other hand, without the consideration of the hydrodynamic conditions, more simplified approaches estimated the energy output to be as much as 46%, suggesting an overestimation in using 0-D modelling. Therefore, based on these results an iterative process is recommended that takes advantage of the low-computational cost of 0-D modelling, but makes use of the 2-D hydrodynamic model findings to produce input that acknowledges the effects of the impoundment structures on the water level time series for the 0-D models. However, it should be remarked that in the absence of extensive hydrodynamic impact in impoundments of a smaller scale, 0-D and 2-D modelling predictions can be in good agreement in terms of predicting the power output.

In the comparison between ebb-only and two-way generation, the analysis suggested that both regimes can yield similar annual electricity outputs. On the other hand, two-way generation can be superior as the power is generated over a greater duration of the tidal cycle, as also suggested by previous studies. This difference in the duration of power output also means that the power can be more readily absorbed by the electricity grid. At the same time, intertidal area losses are significantly reduced in comparison to ebb-only generation, as suggested by both the 0-D and 2-D simulation results, an invaluable prerequisite for the preservation of estuarine ecosystems.

With regard to the design of tidal lagoons, more research should focus on determining a suitable configuration and design of turbines that minimises undesirable consequences to the marine environment, water quality and sedimentation conditions upstream and downstream of the site. Additional studies of interest could aim towards the assessment and optimisation of different turbine operational schemes that perhaps enable power generation between lagoons to generate power during the entire tidal cycle. Far-field investigations, on the other hand, could look into the combined effects of tidal lagoons with other existing proposals along the North Wales coast and in the Severn Estuary. In particular, these studies could initially identify the full power generation potential in the region, as well as studying the effects of these proposals on the surrounding regions of the UK and Ireland.

## Acknowledgements

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