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The Impact of Tidal Lagoons on Regional Water Exchange

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ABSTRACT

The operation of a tidal lagoon (or barrage) involves impounding a substantial volume of water, creating a head difference across the impoundment wall, and converting the potential energy associated with the head difference into kinetic energy through turbines. Consequently, the functioning of a tidal lagoon facilitates the movement of substantial volumes of water between the water body and impounded basin, altering water exchange and tidal flushing patterns, which potentially affect water quality. In this study, three tidal lagoon schemes proposed in the UK, West Somerset Lagoon (WSL), Swansea Bay Lagoon (SBL), and North Wales Tidal Lagoon (NWTL), were investigated for their regional water renewal capacities under different operational schemes and tidal phase conditions within a comparative framework. The exchange processes were investigated by modeling tracer changes within a control domain, with and without the lagoon, under different operational procedures. The results revealed different tracer-exchange characteristics across all schemes. Regardless of the operation scheme, the exchange concentration distribution tended to converge to a near-steady-state distribution at the end of each tidal cycle over a longer timescale. This study indicated that although the tracer dispersion rate was not highly sensitive to the initial tidal conditions, the tracer concentration declined more rapidly when released during spring tides. The inclusion of the WSL significantly improved the water exchange capacity within the lagoon basin region and the Bristol Channel and Severn Estuary. By contrast, the SBL and NWTL schemes resulted in decreased water renewal capacity in the lagoon area.

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1. Introduction

With intensifying international concerns about energy security and the growing awareness and impacts of climate change, the need to explore effective approaches to renewable energy generation as a potential mitigation strategy is gaining increasing interest worldwide. The UK has substantial tidal range energy resources and is actively advancing the development of tidal range energy, particularly along the western coast [1,2]. Although tidal range energy offers the advantage of predictability relative to wind and solar energy [3], tidal range schemes (TRSs) face inherent challenges that have impeded their advancement, such as high upfront investment costs and potential negative hydro-environmental effects [4]. In particular, numerous proposed TRSs have been located within complex ecosystems that exhibit high sensitivity to fluctuations in regional physical and environmental parameters, such as the Severn Barrage and Severn Estuary [5].

The physical effects of a tidal lagoon on tidal elevation, currents, and water exchange are also likely to substantially influence solute and sediment transport processes as well as water quality, particularly within the impoundment region of the TRS [6]. The operation of a TRS tends to reduce the water exchange between the impoundment and the external water body [7]. For example, following the construction of the La Rance Barrage, the volume of water exchanged between the Rance Estuary and the ocean decreased by 30% [8]. Similarly, a 45% reduction in the flow rate into the Severn Estuary was predicted by model studies investigating the effect of constructing the original proposed Severn Barrage [9], resulting in a decrease of approximately 60% in the water exchange volume [10]. The hydrodynamic effects of TRSs, such as changes in water exchange volume and the formation of recirculation zones near the turbine and sluice gate wakes, can notably affect the dispersion and distribution of salinity, dissolved nutrients, fecal bacteria, other dissolved contaminants, and particulate organic matter [7,8,11,12].

A lower water renewal capacity, resulting from a reduced tidal flushing rate, can impede the dilution, transportation, and

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dispersal of these solutes, potentially failing to meet national or international water quality standards [6]. For example, the closure of the La Rance Barrage in the Rance Estuary led to a difference in the magnitude of fluvial and marine water inputs, increasing upstream salinity [8]. In contrast, the reduced water exchange upstream of the Severn Barrage was predicted to decrease the penetration of saline water into the basin [1]. Additionally, owing to the predicted reduced tidal flushing and increased water residence time within the Severn Estuary following the construction of the Severn Barrage, both nutrient concentrations and primary productivity of phytoplankton were expected to increase [13,14]. A study conducted on the Swansea Bay Lagoon (SBL) indicated that salinity levels within the lagoon basin were projected to experience a slight increase, whereas salinity levels outside the lagoon were primarily predicted to be influenced by local river discharge and the prevailing tidal current distribution patterns in the bay. In general, the predicted changes in salinity within Swansea Bay were considered insignificant and unlikely to result in negative effects [6]. Additionally, sufficient water renewal capacity is important to maintain water quality in the basin during pollutant spills, direct discharges from the TRS, antifouling coatings on hydraulic structures, or chemical leakage from gearboxes [15]. Notably, although a tidal lagoon and a barrage differ in the degree of water blockage, these two forms of TRS typically share the same operational procedures and are thus expected to produce comparable impacts. However, tidal lagoons are typically surrounded by seawater on all sides, creating complex hydro-environmental conditions that interact with freshwater fluxes in various ways.

Despite the potential negative hydro-environmental impacts, TRS operations can enhance regional water quality. These improvements have been reported for the Lake Sihwa tidal barrage in Republic of Korea, which aims to improve the quality of a polluted freshwater reservoir by increasing seawater circulation and reducing heavy metals and toxic organic contamination [16,17]. Similarly, the presence of the SBL was expected to increase the rate of water exchange in Swansea Bay, thereby decreasing nitrogen concentrations and having minimal effect on dissolved oxygen levels in the bay [6].

The tidal lagoon industry remains in its nascent stage and lacks specific environmental regulatory guidance. To secure the support of key stakeholders such as government regulatory agencies and conservationists, comprehensively understanding the impact of the scheme on the hydroenvironment in which the lagoon will be situated and addressing any predicted concerns is imperative. Although some preliminary studies have examined the effects of TRSs on water exchange, the impact of tidal lagoons on water renewal remains largely unexplored. Therefore, this study aimed to address this gap by examining how different lagoon scenarios and operational methods, including traditional fixed-head schemes and optimized flexible approaches, affect regional water exchange. The findings of this study are expected to contribute to expanding our understanding of the hydro-environmental impacts of tidal lagoons and to improving their design and operation to minimize these impacts.

2. Materials and methods

2.1. Hydrodynamic simulations

The TELEMAC-2D model (EDF Group, France) was selected for its balance between computational efficiency and accuracy, as well as its established applicability in tidal energy studies. Although a three-dimensional (3D) model provides a more detailed representation by capturing vertical transport, the Bristol Channel and Severn Estuary are shallow and well mixed owing to strong tidal

forcing, making horizontal advection and dispersion the dominant transport mechanisms [18–20]. Additionally, the tracer was released uniformly throughout the water column, reducing the need to explicitly resolve the vertical gradients. Therefore, the two-dimensional (2D) approach was considered sufficient and appropriate for this initial study. However, 3D modeling should be conducted to better understand the impact of tidal range structures on water renewal in the later stages of scheme design.

TELEMAC-2D is based on the Reynolds-averaged Navier–Stokes equations, as summarized below [21]:

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = S \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial Z}{\partial x} + \frac{1}{h} \nabla \cdot (h v_e \nabla u) + F_x \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial Z}{\partial y} + \frac{1}{h} \nabla \cdot (h v_e \nabla v) + F_y \quad (3)$$

where h is the depth of flow; t is the time; Z is the free-surface water elevation above the datum; g is the acceleration due to gravity; u and v are the depth-averaged velocity components in the x and y directions, respectively; v_e is the depth-averaged eddy viscosity; ∇ is a vector differential operator; S is the mass source term; and F_x and F_y are the momentum source terms, representing the effects of wind, Coriolis acceleration, bottom friction, and sources or sinks of momentum. The classic k - ε turbulence model (where k denotes turbulent kinetic energy and ε denotes the turbulent dissipation rate) was employed with a conjugate residual solver adopted, which has been applied and examined in other similar studies [22,23]. The TELEMAC-2D software suite enables the simulation of a passive tracer, which excludes physical parameters that do not interact directly with flow hydrodynamics. The tracer transport processes were computed using the depth-averaged advection–diffusion equation coupled with the hydrodynamic model as follows:

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} - \frac{1}{h} \nabla \cdot (h v_T \nabla T) = \frac{(T_{sce} - T)S_h}{h} \quad (4)$$

where T is the value of the tracer; v_T is the dispersion coefficient of tracer, which is computed from the depth-averaged turbulence k - ε model; T_{sce} is the source value of the tracer; and S_h is the flow source.

To achieve the key research objectives efficiently, two hydrodynamic models were developed: the Severn Estuary and Bristol Channel (SEBC) and Continental Shelf (CS) models [24,25]. The SEBC model was used to compute the hydrodynamic processes in the Severn Estuary and Bristol Channel, whereas the CS model covered a much broader modeling domain, including the entire Irish Sea and a substantial portion of the Celtic Sea (Fig. 1).

Most model parameters were consistent between the two models. The classic k - ε turbulence model was solved using a conjugate residual solver, and a Manning's roughness coefficient of 0.025 was applied following calibration. A spin-up period of two days was used for the SEBC model before analyzing the predictions, whereas the CS model required four days because of its larger domain. The applied boundary conditions differed, and the tidal time series of water levels were applied on the boundary of the SEBC model, while spatially varying tidal elevations and velocities from the TPX07.2 database were used as the driving force at the seaward open boundary for the CS model. Both model domains used unstructured triangular meshes with spatially varying resolutions: in the CS model, the resolution ranged from 9 km near the open boundary to 35 km in the central domain and was refined to 700 m along the coastline, while in the SEBC model it varied from

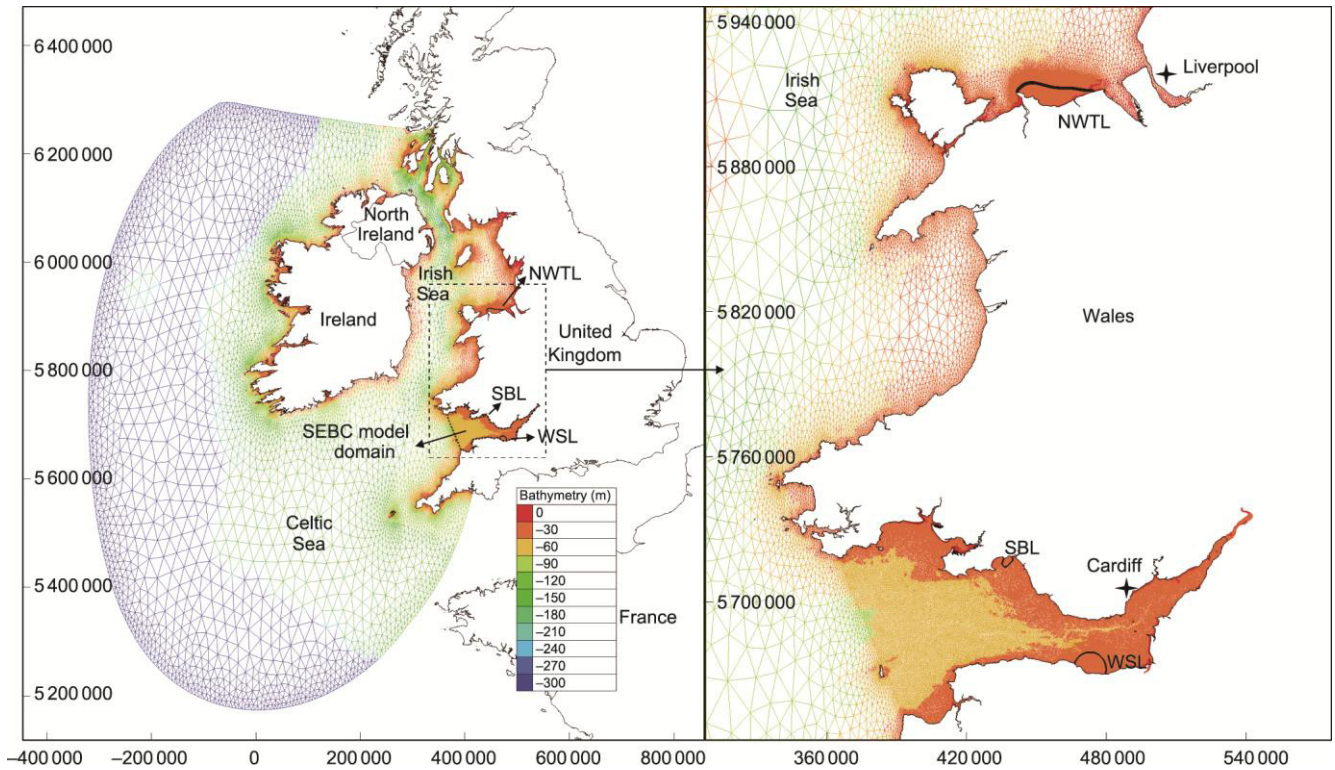


Fig. 1. Domains of the CS and SEBC models, shown in the universal transverse Mercator (UTM) coordinate format, including the location of the tidal lagoons. WSL: West Somerset Lagoon; NWTL: North Wales Tidal Lagoon.

50 m near the lagoon structures to 800 m towards the seaward open boundary. Freshwater inputs were included only from the main rivers near the studied tidal lagoons: seven in the Bristol Channel model, including Taff, Usk, Wye, Severn, Avon, Parrett, and Tawe, and four in the Colwyn Bay and Liverpool Bay region, including Dee, Mersey, Ribble, and Colwyn. Both models were thoroughly validated against tidal gauge water levels and acoustic Doppler current profiler (ADCP) velocity data, and the validation results are summarized in the Appendix A. The coefficient of determination R^2 values for the water level comparisons were all above 0.96, whereas the average root mean square error (RMSE) was 0.213 m for the CS model and 0.338 m for the SEBC model. These are considered satisfactory results owing to the large tidal ranges in these areas, with average spring tidal ranges of 6.61 m at the CS model validation sites and 9.61 m for the SEBC model.

2.2. Tidal lagoons introduction and modeling

The North Wales Tidal Lagoon (NWTL), West Somerset Lagoon (WSL), and SBL, each with unique designs and located in distinct regions, as shown in Fig. 2, are currently under investigation for TRS development. For example, the SBL was designed with concentrated turbines and sluice gates, whereas the NWTL and WSL had turbines and sluice gates dispersed around the breakwater walls. Additionally, the SBL and WSL are situated in the semi-enclosed hypertidal environment of the Bristol Channel, while the NWTL faces the open sea directly. The SBL was simulated using the SEBC model owing to its smaller construction scale, whereas the NWTL was simulated using the CS model. The CS model was used to investigate the influence of WSL on water exchange times across the entire Bristol Channel and Severn Estuary owing to the extensive volume of the water body under study. The SEBC model was employed to specifically study water exchange within the WSL lagoon.

The tidal lagoons were incorporated into the model using a mesh decomposition approach, in which the lagoon embankment

was treated as a solid, impermeable boundary. The turbines and sluice gates were represented as culverts connecting the two sides of the subdomains, and the discharge and power outputs were computed based on predefined formulae. Further refinements were introduced to improve the accuracy of the model, such as complete momentum conservation between the subdomains and independent operation of the turbine and sluice gate units. The specific details on the numerical settings for these tidal lagoons and their corresponding basic hydrodynamic impacts have been previously described [24,26,27].

The basic operational procedures for tidal lagoons include one- and two-way generation. These schemes can be further enhanced by a pumping function, in which turbines pump water from the lower- to the higher-water-level side, thereby consuming electricity during the process, as shown in Fig. 3 for the SBL scheme. The ebb operation scheme generated electricity only during the ebb tide phase, whereas the sluice gates remained open during the flooding phase to accelerate and enhance the amount of water stored during the filling process. As shown in Fig. 3(b), the ebb-generation scheme yielded a significantly higher turbine working discharge and longer operating periods during the ebb tide compared to those of the ebb-generating portion of the two-way operation. Additionally, incorporating pumping into the operation of the tidal lagoon increases the volume of water exchanged during each tidal cycle, as shown in Fig. 3(b).

These operational schemes typically employ fixed values for the operational water head, assuming that the starting and ending heads of the turbine remain constant throughout the neap and spring-tide cycles. However, a more advanced operational scheme incorporating a flexible generation head for each tidal cycle was explored. This approach has the potential to completely harness tidal range energy and optimize the corresponding energy output [2].

A tidal lagoon can be designed to operate in various modes, considering the regional tidal features, environmental concerns,

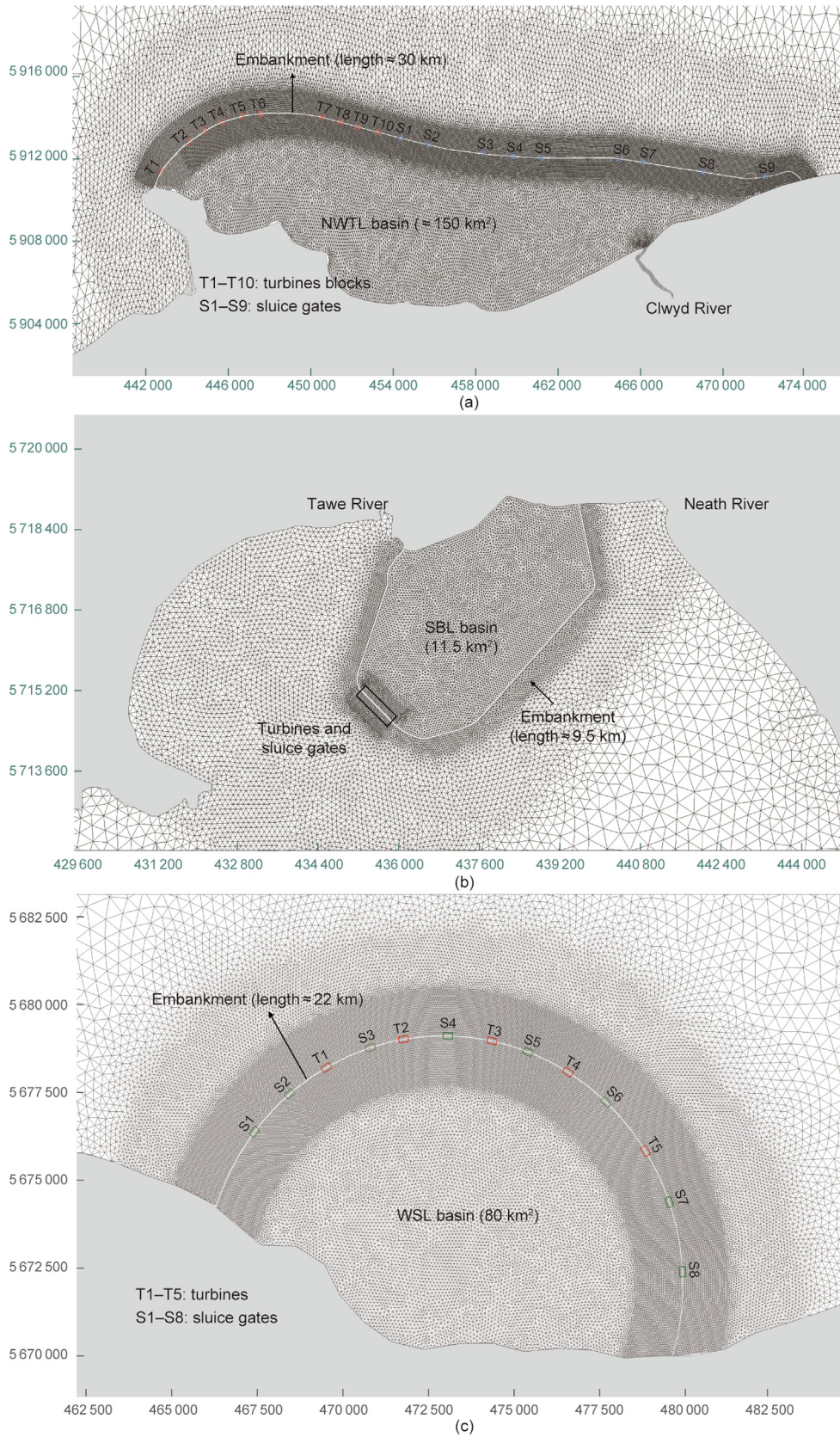


Fig. 2. Configuration of the (a) NWTL, (b) SBL, and (c) WSL.

national grid power connection capabilities, and cost control [28]. An optimal operational scheme should balance electricity generation and environmental impacts, achieving a trade-off that enables

sustainable energy production without compromising ecological integrity [5,29,30]. Previous studies of operational schemes have primarily focused on power output, while also addressing

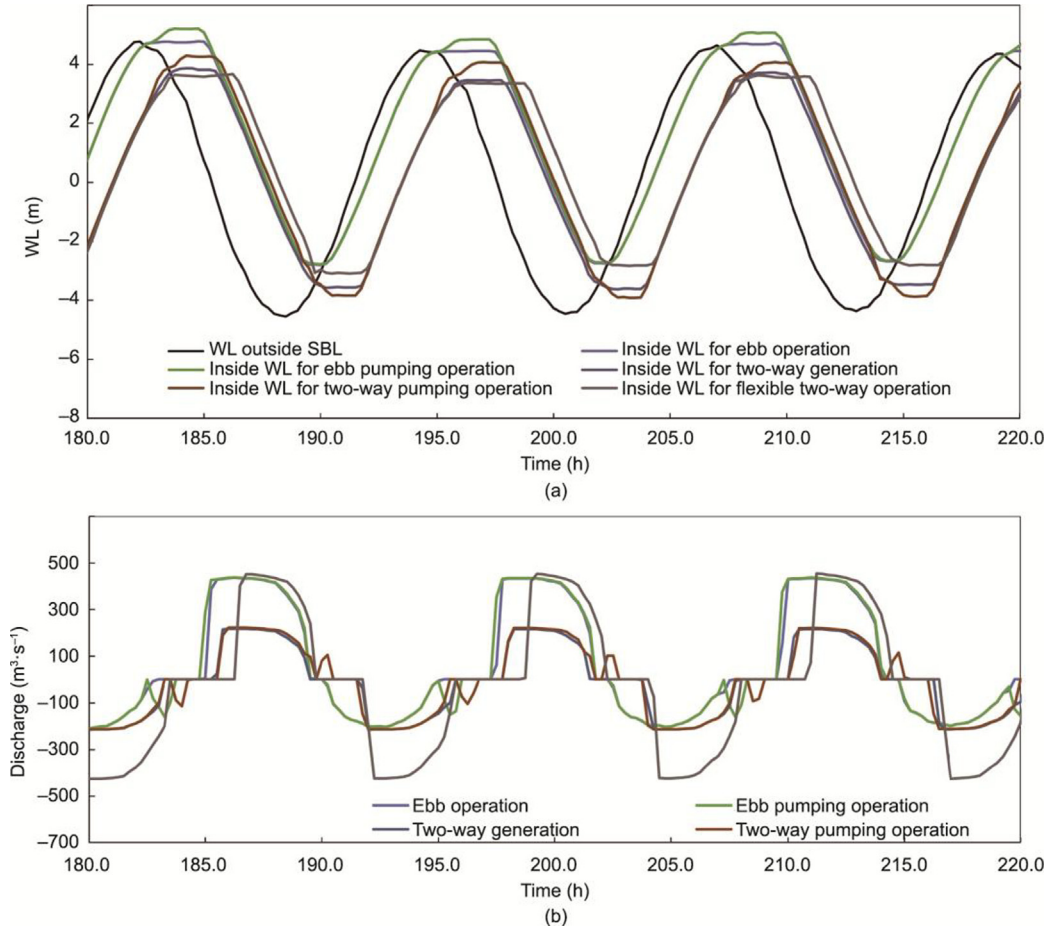


Fig. 3. (a) Predicted water levels (WL) on both sides of SBL and (b) corresponding total water discharges through the turbines for four different operational procedures, including ebb-only generation with and without pumping and two-way generation with and without pumping.

hydrodynamic impacts, particularly in relation to environmental assessments at a high level [9,29]. To improve our understanding of the cumulative environmental impacts of different lagoon operational procedures on the water renewal capacity, we conducted a systematic investigation across multiple tidal lagoons under a range of operational schemes.

2.3. Water renewal time

Various time scales are widely used to investigate the hydrodynamic processes that regulate the transport and removal of materials from water bodies, both in spatial and temporal variations. These include residence, flushing, renewal, and exposure times [12,31]. A universal quantification method to predict water residence time or water flushing time involves hydrodynamic modeling of the water body using either Eulerian or Lagrangian methods to investigate the time a fluid particle spends within a control water area [12,32]. However, these methods are primarily used to model water exchange in natural water bodies, which may not represent the water-flushing and renewal scales in artificial tidal lagoon-impounded water.

To quantify the effect of the operation of a tidal lagoon on sea-water renewal, the water renewal time was computed by tracking the evolution of a non-buoyant, mass-conservative tracer concentration introduced into the control domain surrounding a tidal lagoon. A tracer remnant function ($r(\cdot)$) was used to represent the ratio of the mass of the tracer within a control domain at a given time to the initial mass of the tracer, defined as follows [33,34]:

$$r(t) = \frac{M(t)}{M(t_0)} = \frac{\int_{\Omega} h(x, y, t) \cdot T(x, y, t) d\Omega}{\int_{\Omega} h(x, y, t_0) \cdot T(x, y, t_0) d\Omega} \quad (5)$$

where $M(t)$ is the total amount of tracer and t_0 is the initial time of tracer release; Ω is the spatial integration domain.

The renewal time in this study was determined using different thresholds across modeling scenarios. For example, a commonly used method for measuring time or flushing time is to define the “e-folding time,” which is the time it takes for the tracer concentration to reduce to $1/e$, or approximately 37%, of the initial concentration [12,22,35]. In this study, each numerical model cell was treated as a completely mixed reactor [34]; therefore, renewal times were recorded at each mesh point to generate a renewal time map, providing insights into the spatial heterogeneity of water renewal.

The lagoon impoundment area is of particular interest, as the advection, dispersion, and distribution of tracers are directly confined to the lagoon basin and are influenced by the lagoon structure and operation, for example, water jets from turbines and sluice gates [6,36]. For this purpose, the tracer was initially introduced into the lagoon domain and monitored over time to track temporal concentration changes. However, the tracer concentration in the lagoon basin exhibited a rapid initial decline following release, making the conventional $1/e$ threshold unsuitable for accurately estimating water renewal time. Consequently, to ascertain the renewal time in the lagoon basin, threshold values of 10% and 5% were used as previously employed in other studies [11,22]. Although applying different thresholds (10%, 5%, and $1/e$) for renewal time calculations can help assess changes within a given

project, this complicates direct comparisons across case studies. This represents a methodological compromise; however, future studies should use a unified or standardized threshold to facilitate cross-project comparisons.

Notably, the tracer-flushing concentration exhibited oscillations associated with the operational stage of the TRS and the ebb and flood phases of the tidal cycle. These oscillations have been eliminated in certain studies by averaging tracer concentrations over tidal cycles [22]. However, in this study, the original tracer concentration variations were presented, demonstrating the relationship between tracer flushing and the operational characteristics of the TRS throughout the tidal cycles. Additionally, the strength of the water jet through turbines notably affects the water renewal capacity. The results of conservative momentum formulation modeling indicated a 24% increase in the renewal time compared with that of a mass balance-only model [24]. In this study, the momentum term, including the source velocity, was applied at the end of the turbine diffuser because this approach is more representative of the realistic velocity field associated with turbines [24].

3. Results

3.1. Tracer flushing for different lagoon operation procedures

For each operation scheme, a tracer was introduced into the SBL domain at a low water level during a spring tide. The average tracer concentration in the lagoon impoundment area was monitored over time, as shown in Fig. 4, to provide insights into the flushing characteristics of the tracer within the lagoon for different operational procedures. The results showed that the tracer concentration decreased more rapidly in the ebb-only generation than in the two-way operation (Fig. 4), reaching 10% of its initial concentration after three to four tidal cycles. This can be attributed to the large volume of water exchange that occurs during the ebb-only generation and flooding-filling stages, which can be observed from the large water discharge through the turbine operation (Fig. 3(b)).

During the two-way operation, the tracer concentration declined markedly in the initial cycles, then decreased gradually over time. It took approximately 11.7 d for the tracer concentration to reach 10% of its initial value, after which the residual tracer value became stable over a longer timescale and decreased slowly as it approached zero.

Although both operational procedures benefited from pumping for tidal flushing, two-way generation particularly influenced flushing characteristics because of its bidirectional nature; that is, additional pumping with two-way generation facilitates greater water exchange in the basin during ebb tides as well as during flood tides. Overall, the inclusion of pumping in both operating procedures increased the volume of water exchange and facilitated more efficient water renewal in the lagoon.

Based on these findings, the impact of operational parameters was further investigated for WSL modeling scenarios, specifically focusing on two-way operation schemes with different turbine working heads. In the study, four traditional two-way operation schemes were tested with fixed turbine starting heads of 3.0, 3.5, 4.0, and 4.5 m, and all schemes ended at 2.0 m. Additionally, an optimized two-way operation scheme was implemented, utilizing an adaptive flexible generating head [24,37].

The tracer concentration in all four fixed generation schemes decreased to 10% of its initial value in approximately 7.2–7.3 d, whereas the optimized operation scheme achieved this reduction in approximately 5.2 d, as shown in Fig. 5. However, the tracer concentration evolution exhibited a similar trend across each two-way generation scheme during the low-concentration reduction period. For all the two-way generation schemes, it took approximately 17.1 d for the tracer concentration to decrease to 5% of its initial value.

A study conducted in the WSL basin showed that the reduction in tracer concentration was not significantly affected by variations in the turbine generation heads. Regardless of the specific generation head used, the tracer flushing process consistently converged as the concentration approached 5%–10% of its initial value. Based on these findings, future investigations will primarily focus on evaluating the performance of two-way operating schemes for all TRSs.

3.2. Tracer flushing sensitivity to release time

To understand the impact of the initial release tidal conditions on tracer transport, further investigations examined the sensitivity of tracer flushing to different tidal phases at the time of tracer release. This study specifically focused on typical tidal phases observed during semidiurnal and spring-neap tide cycles, including low and high water levels as well as the middle of the ebbing

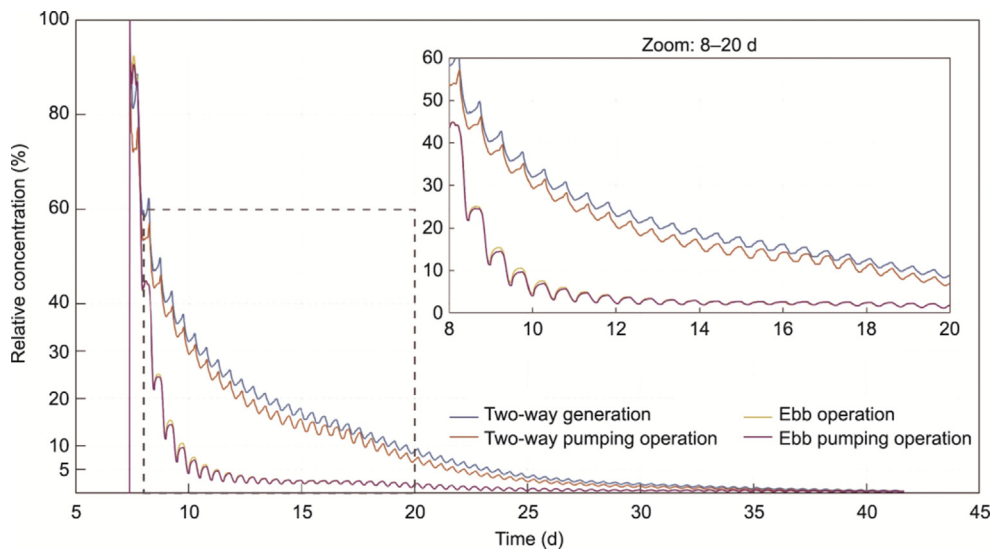


Fig. 4. Concentration variations of tracer released in the SBL basin with different operation schemes—relative concentration is calculated from the Eq. (5).

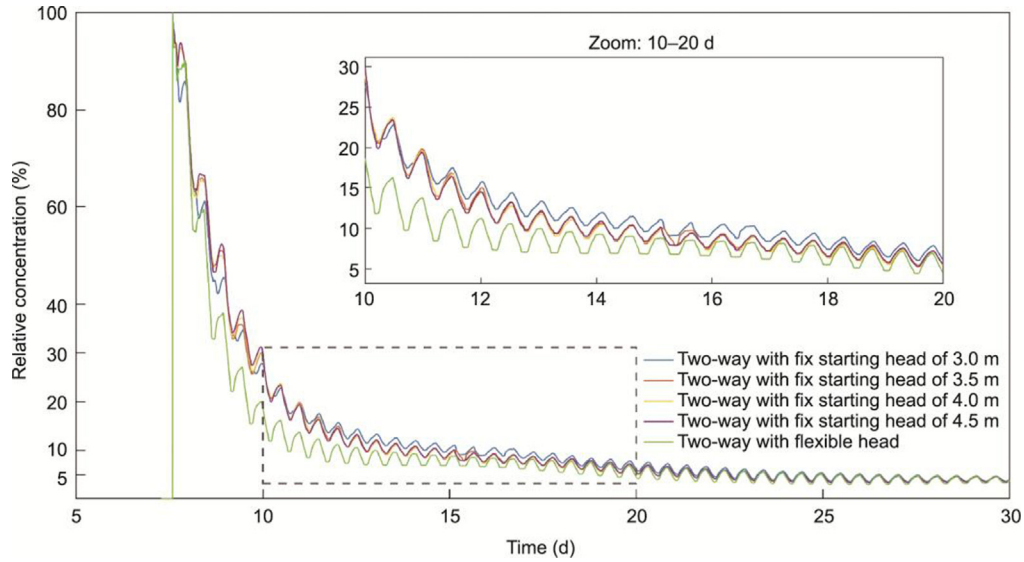


Fig. 5. Concentration variations of tracer released in the WSL basin for different operational schemes.

tide and flooding of neap and spring tides (Fig. 6). The impounded water in the WSL basin was chosen as the primary scenario for this study because of its significant influence on tidal dynamics [24].

Despite some initial discrepancies in tracer flushing during the preliminary tidal cycles, renewal times remained consistent across different tidal phases within a semidiurnal tidal cycle (Fig. 6). The consistent renewal times for tracers released in the low- and high-water-level scenarios indicate that the injected tracer mass has a minimal influence on the renewal time calculation. However, the predicted renewal times, based on either 5% or 10% of the initial concentration, differed between spring and neap tides at the time of tracer release. Specifically, for the remaining 5% tracer concentration, the renewal time for a tracer released during neap tides was approximately 17.2 d, whereas for a tracer released during spring tides, the renewal time was approximately 15.4 d. Therefore, increased tide velocities during spring tides enhance the

advection and dispersion of the reduced tracer concentration, resulting in increased water renewal capacity.

3.3. Effect of SBL operation on regional water renewal

The effect of the SBL operation on impounded water renewal was investigated by assessing the tracer flushing processes for the pre- and post-SBL construction scenarios, with the tracer released in the planned lagoon area at a low water level during the spring tide, as shown in Fig. 7(a). In addition, this study examined the water renewal capacity of the entire Swansea Bay. This broader investigation was motivated by the considerable pollution challenges experienced in the area during the last two decades of the 20th century, which were partly attributed to inadequate long-sea outfall sewage discharge locations and low water exchange rates [5,38]. Swansea Bay and Porthcawl, which are

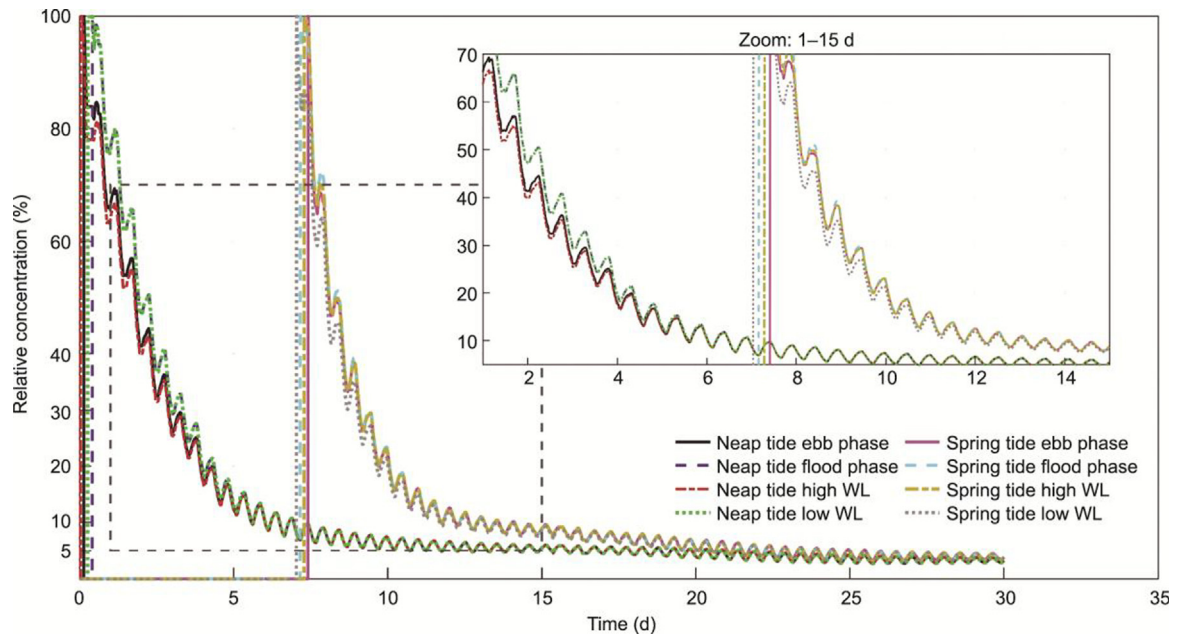


Fig. 6. Concentration variations of tracer released in the WSL basin at different tidal phases.

designated as “marine character areas” by the Welsh Government [39], were selected for the tracer initial release and subsequent monitoring to investigate the water renewal time, as shown in Fig. 8(a).

The evolution of the spatially averaged tracer concentration distributions in the study area is shown in Fig. 9. The renewal times for Swansea Bay and Porthcawl in the pre-SBL and post-SBL scenarios were 35.4 and 31.7 d, respectively, with a 10% tracer concentration threshold. These results indicate that the operation of the SBL enhanced water renewal in Swansea Bay and Porthcawl, which can be attributed to the increased flow dynamics in the area resulting from the operation of the SBL, as evidenced by the changes in the maximum tidal velocity magnitudes post-SBL (Fig. S3(a) in Appendix A).

When the tracer was released in the impounded area of SBL, the operation of SBL initially slowed down the water exchange rate, as evidenced by the renewal times of 11.7 and 12.2 d for pre- and post-SBL construction, respectively. Furthermore, as tracer flushing progressed, these differences were negligible. The duration for which the tracer concentration decreased below 5% of the initially released concentration in the control domain was approximately the same regardless of the operation of the SBL. This result is consistent with the changes in the average tidal velocity magnitudes (Fig. S3(b) in Appendix A) because the variations are limited in extent and are mainly confined to the turbine and sluicing areas.

The remaining tracer distributions at the end of the simulation period, when the average concentration decreased to 10%, are shown in Figs. 7 and 8. The decreased water renewal time suggests

that the coastal area of Swansea Bay, or the landward part of the SBL, could serve as a water retention area. This conclusion is further supported by the post-SBL tidal current change analysis (Figs. S3(a) and (b)), which shows that although the water velocity increased notably within the turbine wake zone, much of the surrounding area exhibited similar or even lower velocity magnitudes. A comparison of Figs. 7(b) and (c) reveal that the presence of the SBL leads to a lower water renewal capacity in the landward part of the SBL impoundment. Similarly, a comparison of Figs. 8(b) and (c) demonstrate that the SBL accelerates the water exchange rate in the region to its west while reducing it to the east.

3.4. Effect of NWTL operation on impounded water renewal

The effect of the NWTL operation on impounded water renewal was also investigated. The study revealed that the tracer concentration required 11.36 and 16.55 d to decrease to 10% of its initial concentration under pre- and post-NWTL conditions, respectively, as shown in Fig. 10.

The impact of the NWTL on water renewal can be attributed to asymmetric tides in the region and higher residual currents in the planning area, as indicated by the lower oscillation range of the tracer concentration shown in Fig. 10. Furthermore, Figs. S3(e) and (f) in Appendix A show that although short-lived, localized accelerations occur owing to the NWTL, the cycle-averaged tidal velocity, which represents the longer-term tidal magnitude, remains largely unchanged or even slightly reduced. Therefore, the observed decrease in water renewal time within the NWTL

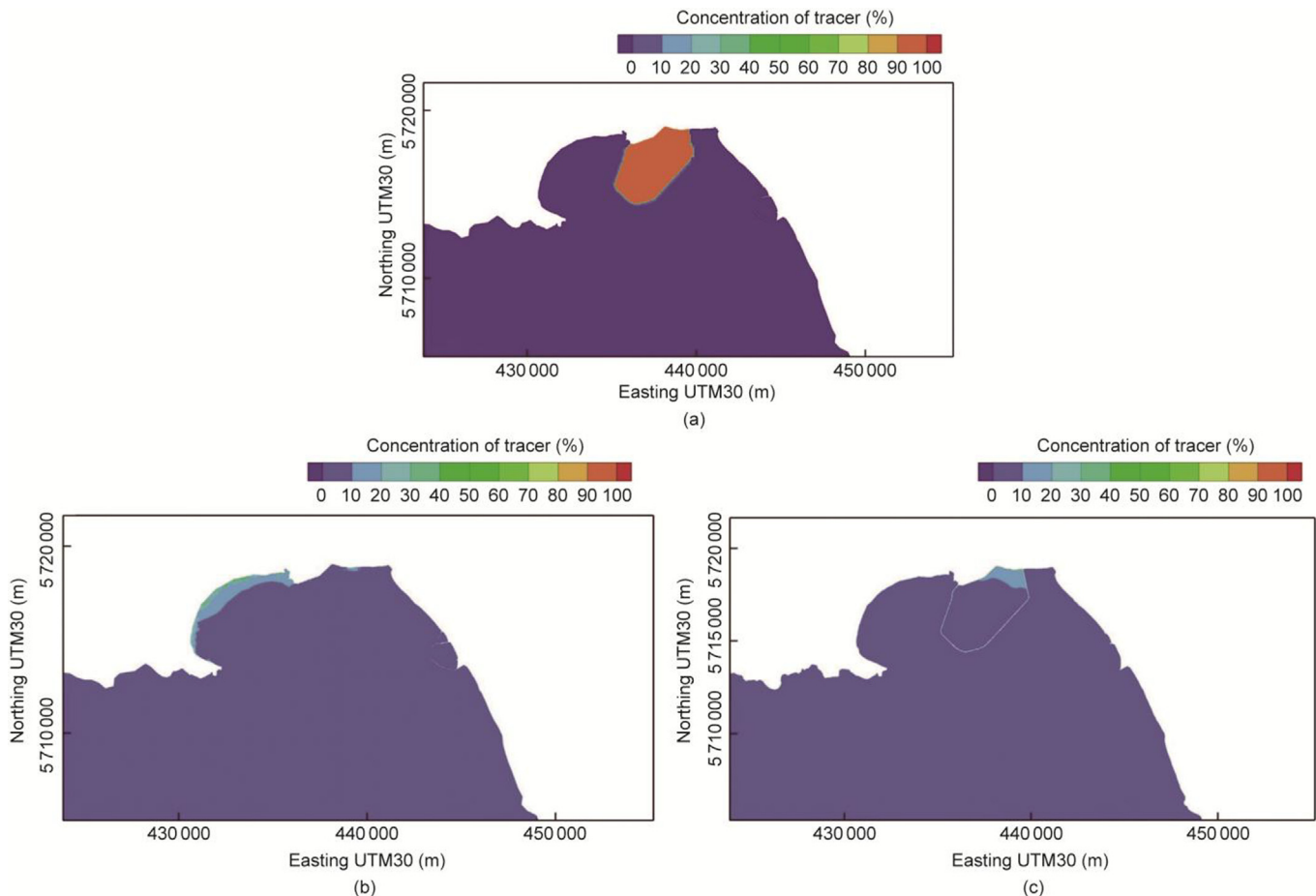


Fig. 7. Instantaneous tracer concentration distributions at the (a) initial releasing moment with a release area of SBL impoundment, (b) end of renewal time for the natural condition, and (c) end of renewal time for the post-SBL condition.

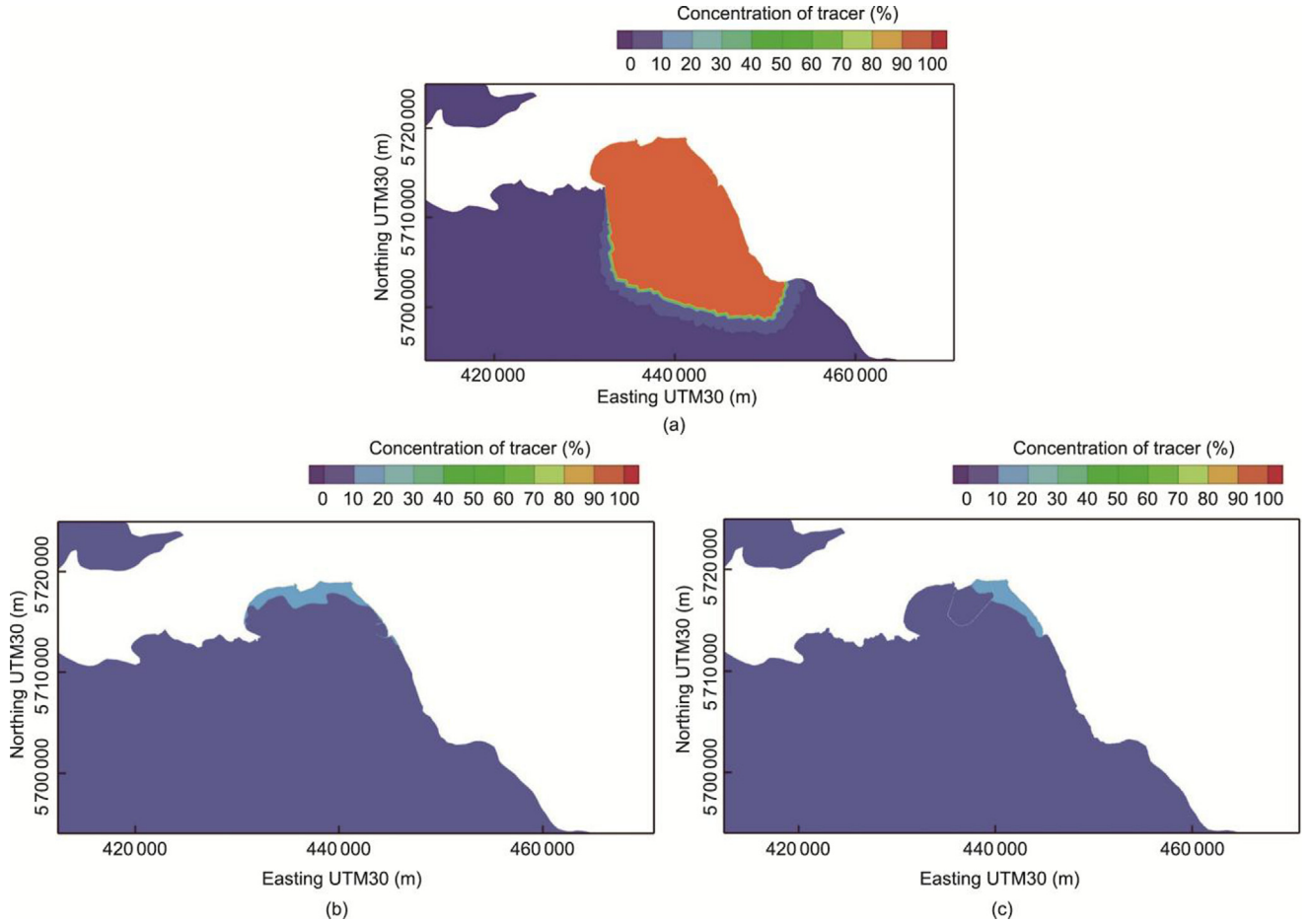


Fig. 8. Instantaneous tracer concentration distributions at the (a) initial release for Swansea Bay and Porthcawl, (b) end of renewal time for the natural condition, and (c) end of renewal time post-SBL condition.

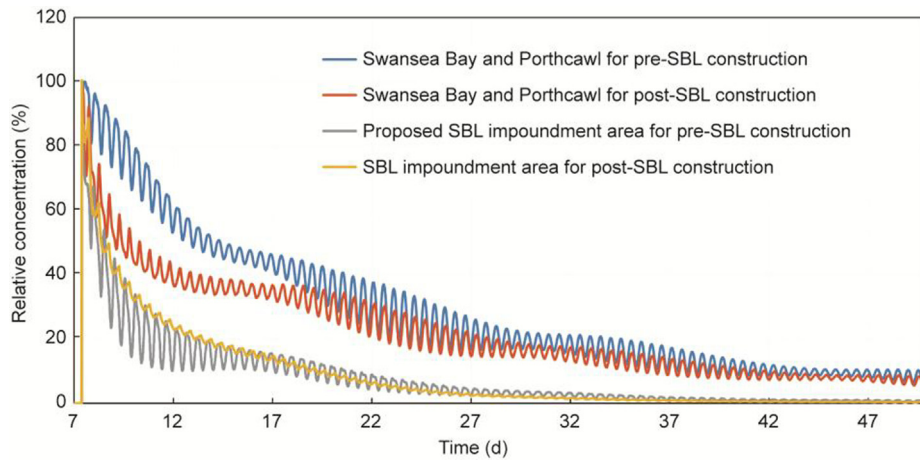


Fig. 9. Concentration variations of tracer in the Swansea Bay and Porthcawl and the proposed SBL impoundment area for pre-SBL and post-SBL, respectively.

region is consistent with the trend in the average tidal velocity magnitude changes.

Compared with the natural renewal time of 22.4 d in the WSL impoundment area [24], the NWTL site exhibited a much higher natural renewal capacity of 11.36 d, despite its larger basin, highlighting the efficiency of water exchange under natural conditions. Although the NWTL operation increased the maximum tidal velocity within the basin (Fig. S3(e)), the changes in the averaged tidal

velocity remained unchanged or even decreased slightly (Fig. S3(f)), indicating an increased natural averaged tide velocity in this area as well as the obstructive role of the NWTL in natural water flow.

The renewal times for each computational point were calculated and plotted as contour maps, showing the spatially heterogeneous water renewal capacity and clearly marked flushing pathways, as shown in Fig. 11. Notably, the threshold for renewal

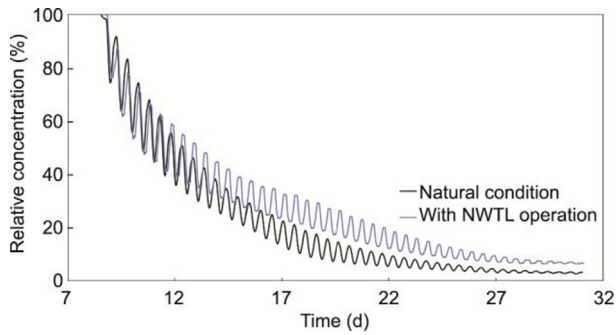


Fig. 10. Tracer concentration variations in the proposed NWTL impoundment area for pre- and post-NWTL scenarios.

times is the classical value of $1/e$, which effectively demonstrates the tracer-flushing feature and retention areas. High water exchange rates were observed on the west side of the NWTL-impounded area, which was a direct result of strong wakes from turbine blocks T1–T9. The wakes from the turbines advect the tracer towards the western side of the lagoon, where the water exchange rate between the impounded area and the sea is lower.

The typical discharges for the turbines and sluice gates of the NWTL are shown in Fig. 12, providing insights into the operational conditions of the NWTL. Evidently, although the sluice gates also exhibited high discharge rates per unit time, their operational duration was relatively short compared with that of the turbines. Because of the brief opening duration of the sluice gates, the sluice gates generated a lower discharge volume and a smaller wake scale. This could explain the lower water exchange observed in the eastern part of the NWTL impoundment area. However, as the primary purpose of sluice gates is to expedite the filling or emptying phase of a TRS to enhance electricity generation [40], the performance of the sluice gates shown in Fig. 12 meets this design requirement. Moreover, during ebb generation, the tracer discharged from the NWTL system was flushed towards the eastern side of the NWTL area during the flooding phase. Subsequently, a portion of this tracer returned to the NWTL during the filling phase of the sluice gates. This phenomenon could also partly contribute to the longer renewal time observed in the eastern region of the NWTL. The tracer flushing patterns indicate that, although the new water renewal capacity remains higher than that in many natural regions (West Somerset, as shown earlier), water renewal can be enhanced by optimizing the number, position, and operational method of turbines and sluice gates. For example, the number and positioning of turbines and sluice gate blocks can be adjusted to enhance water exchange and reduce retention zones. A mixed distribution of turbines and sluice gates, similar to that used in the WSL design, may also create increased variation in flow, promoting more effective mixing within the lagoon basin. Similarly, operational strategies could be refined to improve exchange efficiency, such as extending sluice-gate opening periods or lengthening turbine idle periods. However, these measures require detailed hydraulic design studies together with comprehensive economic and environmental assessments to evaluate their feasibility and effectiveness under various operating conditions.

3.5. Effect of WSL operation on water renewal of Bristol Channel and Severn Estuary

Previous studies examined the impact of WSL on water renewal in impounded areas, revealing a significant improvement in basin water renewal [24]. However, the Severn Estuary has been identified as one of the top five UK estuaries with the highest annual

nutrient load [41], highlighting the importance of investigating the impact of WSL operations on the water renewal capacity in the estuary and Bristol Channel. To enhance our understanding of the influence of WSL on water renewal capacity in various regions [34], tracers were introduced in three distinct regions based on geographical division: the Severn Estuary to the outer Bristol Channel (Fig. 13(a)), Severn Estuary to the inner Bristol Channel (Fig. 13(b)), and Severn Estuary (Fig. 13(c)).

The spatially averaged renewal times for all modeling scenarios are presented in Table 1, with the threshold taken as $1/e$ of the original tracer concentration. The results highlight the positive impact of WSL operation on water renewal capacity across all studied scenarios. The entire Bristol Channel and Severn Estuary region demonstrated a 43% reduction in renewal time, indicating a notable improvement in water exchange. Additionally, the inner Bristol Channel experienced a 20% decrease in renewal time, whereas the Severn Estuary showed a 13% reduction. These findings indicate that the WSL exerts a stronger influence on enhancing the water renewal capacity in the Bristol Channel than in the Severn Estuary. This was closely aligned with the post-WSL tidal velocity changes as the tidal current magnitude increased noticeably in the inner Bristol Channel because of the blockage effect associated with the WSL location (Figs. S3(c) and (d) in Appendix A), whereas the effect on tidal velocity was less pronounced in the Severn Estuary. Consequently, the operation of WSL accelerated pollution mitigation and attenuation in these areas, which is a meaningful consideration for the future design of similar treatment and retention systems with potential pollution and health risks.

The spatial distributions of the renewal time (threshold at $1/e$) for the pre- and post-WSL scenarios were also calculated to present the spatial non-uniformity of the water renewal capacity (Fig. 14). As shown in Figs. 14(a) and (b) the water near the mouth of the Bristol Channel underwent more rapid renewal owing to stronger mixing with seawater. However, the water adjacent to the release boundary in Figs. 14(c) and (d), that is, the inner Bristol Channel boundary, exhibited a slower renewal rate, primarily owing to tidal asymmetry in this area. The inner Bristol Channel and Severn Estuary are characterized by flood tide dominance over ebb tide [42,43], which results in the movement of the tracer up to the estuary.

Figs. 14(a) and (c) show that Bridgewater Bay had a higher renewal time than the other areas, suggesting slower water exchange owing to its shallow depth and weak currents. Notably, in the post-WSL scenario, the water exchange rate in Bridgewater Bay significantly improved, likely because of increased currents. River discharges enhance the water renewal capacity of estuaries; however, their impact is mainly confined to the river mouth and overshadowed by stronger tide-induced oscillatory discharges, as shown in Fig. 14. The observed improvement in water exchange from WSL operations can be attributed to two factors. First, the blockage effect of the WSL on the inner Bristol Channel increases the speed of the tidal currents, facilitating increased water currents and exchange upstream, as shown in Figs. S3(c) and (d). Second, the operation of the WSL introduced a disturbance in the area, contributing to enhanced water exchange within the region around the lagoon.

4. Discussion and conclusions

This study assessed the influence of tidal lagoon operational procedures on water renewal in the lagoon basin and surrounding coastal and estuarine waters. Various modeling scenarios have been used to investigate the effects of different lagoon operational procedures, tidal conditions, and spatial/temporal variations in the concentration distribution from a tracer release.

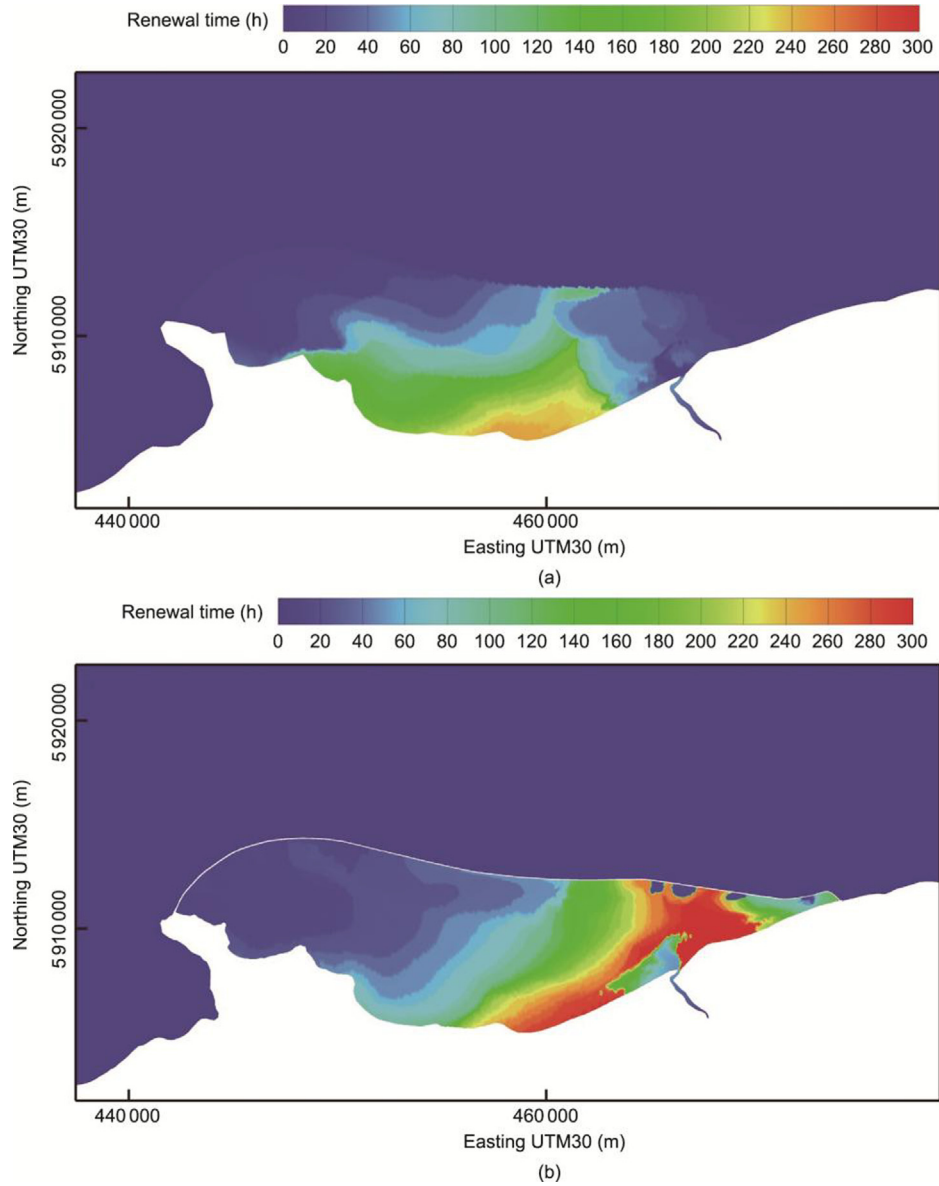


Fig. 11. Renewal time distribution for the (a) natural condition and (b) post-NWTL scenario.

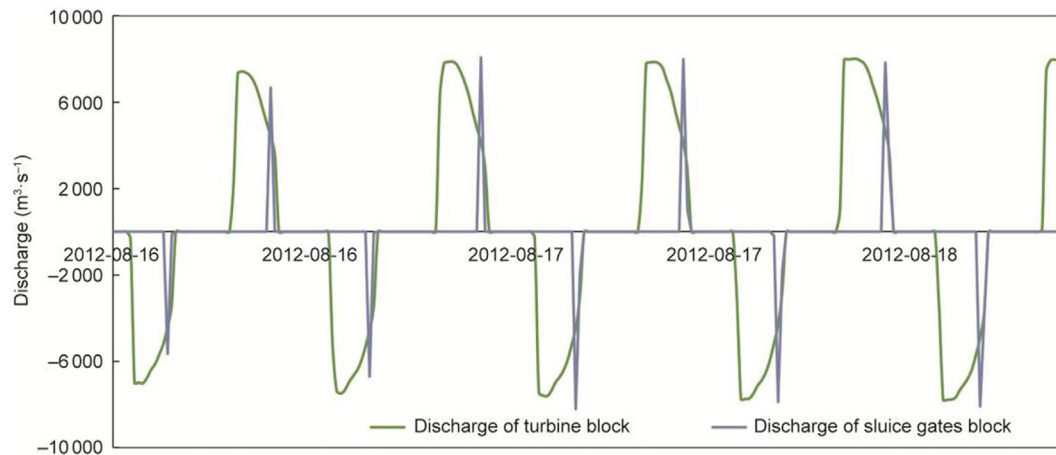


Fig. 12. The typical discharges of a turbine block and sluice gate block in NWTL.

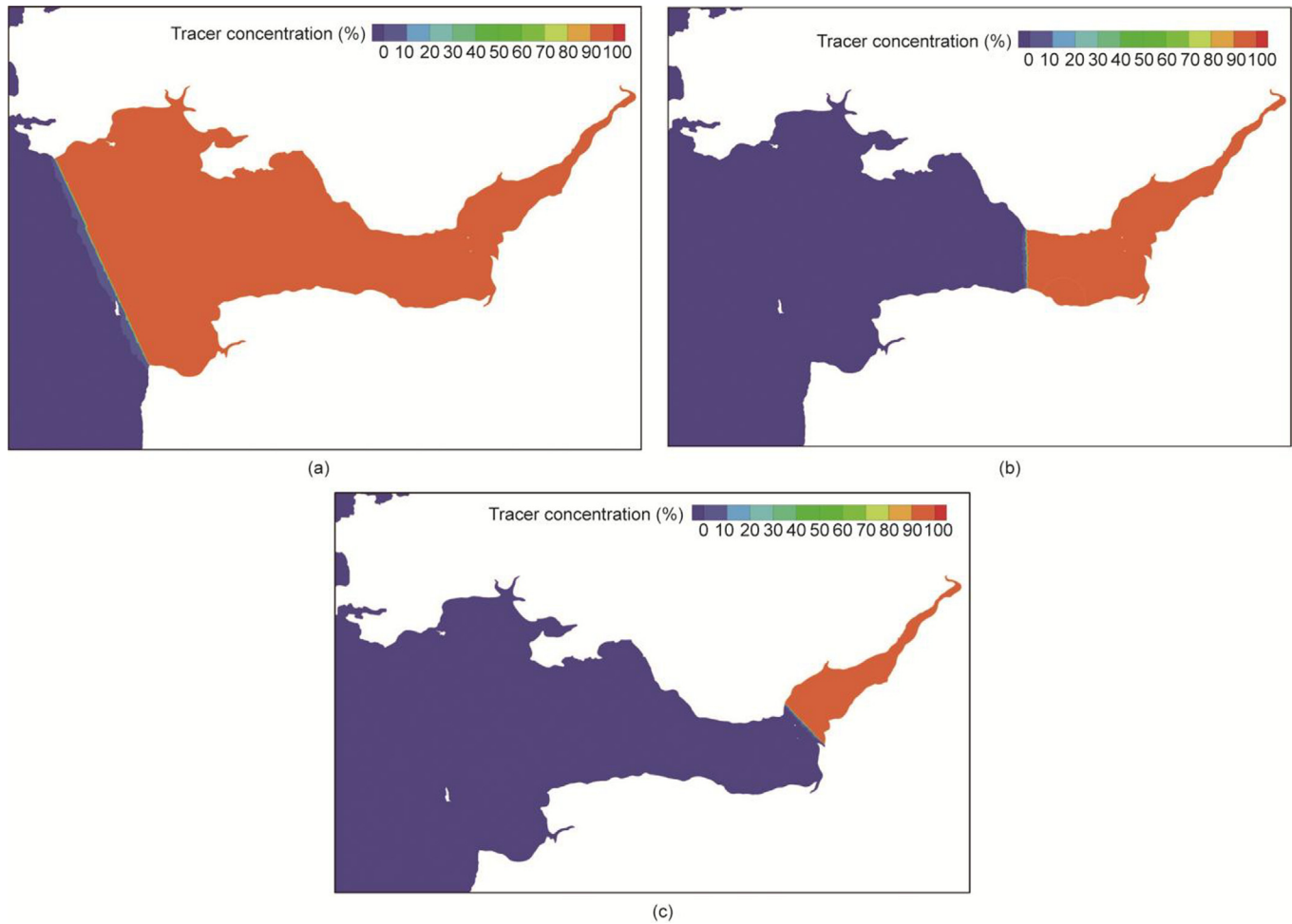


Fig. 13. Release area of tracer for the (a) Severn Estuary and outer Bristol Channel, (b) Severn Estuary and inner Bristol Channel, and (c) Severn Estuary.

Table 1
Spatially averaged renewal time in the study area.

Tracer release and tracking region	Post-WSL (d)	Pre-WSL (d)
Severn Estuary to outer Bristol Channel	65.45	113.96
Severn Estuary to inner Bristol Channel	49.46	62.04
Severn Estuary	20.64	23.70

Investigations of the impacts of various operational procedures have demonstrated that a notable relationship exists between the water exchange rate in a tidal lagoon impoundment area and the water discharge through both turbines and sluice gates. For the SBL, one-way generation showed greater water renewal capacity than two-way generation, and the addition of pumping had a marginal effect on water exchange. Additionally, tests on various two-way operation schemes for WSL indicated that tracer flushing was largely unaffected by different turbine generation heads within the same operation. However, optimized two-way operations with flexible generation heads showed a faster decrease in tracer concentration in the early stages than operations with fixed generation heads. The results also indicated that tracers released during spring tides exhibited greater concentration variability and shorter renewal times than those released during neap tides. However, the rate of tracer concentration reduction remained consistent across different tidal phases, regardless of the water level or tidal stage.

The water renewal exchange in the Bristol Channel and Severn Estuary was examined under both pre- and post-WSL conditions. The results showed a 43% reduction in renewal time across the

area, with reductions of 20% and 13% in the inner Bristol Channel and Severn Estuary, respectively, after WSL implementation. For the SBL, the renewal time decreased by 10.45% in Swansea Bay and Portcawl but increased by 4% within the SBL impoundment. In the NWTL basin, a 45.7% reduction was observed in the water renewal capacity owing to high natural exchange rates and limited sluice gate discharge on the eastern side of the lagoon.

Changes in water renewal capacity can substantially affect ecosystem processes, particularly in sensitive coastal areas such as the Bristol Channel and Severn Estuary, where most waters are classified as heavily modified under the European Union (EU) Water Framework Directive standards [44]. Following the construction of the WSL, faster water exchange rates in the Bristol Channel have been predicted to alter nutrient cycling by shortening the residence time of dissolved nutrients, potentially lowering the risk of eutrophication and reducing nutrient availability to primary producers [14]. Preliminary calculations indicate a slight decrease in equilibrium nutrient concentrations and phytoplankton biomass under the post-WSL scenario [27]. Additionally, increased flow-enhanced flushing in the Bristol Channel, which is the primary cause of enhanced flushing, is predicted to increase sediment resuspension and transport, with potential consequences for seabed morphology and turbidity within estuaries [29]. A suspended sediment transport analysis indicated an increased sediment-carrying capacity of tidal currents in the post-WSL scenario, particularly in the inner Bristol Channel, along with the risk of localized seabed erosion near the WSL site [27]. Post-WSL, stronger water renewal in the Bristol Channel may enhance water

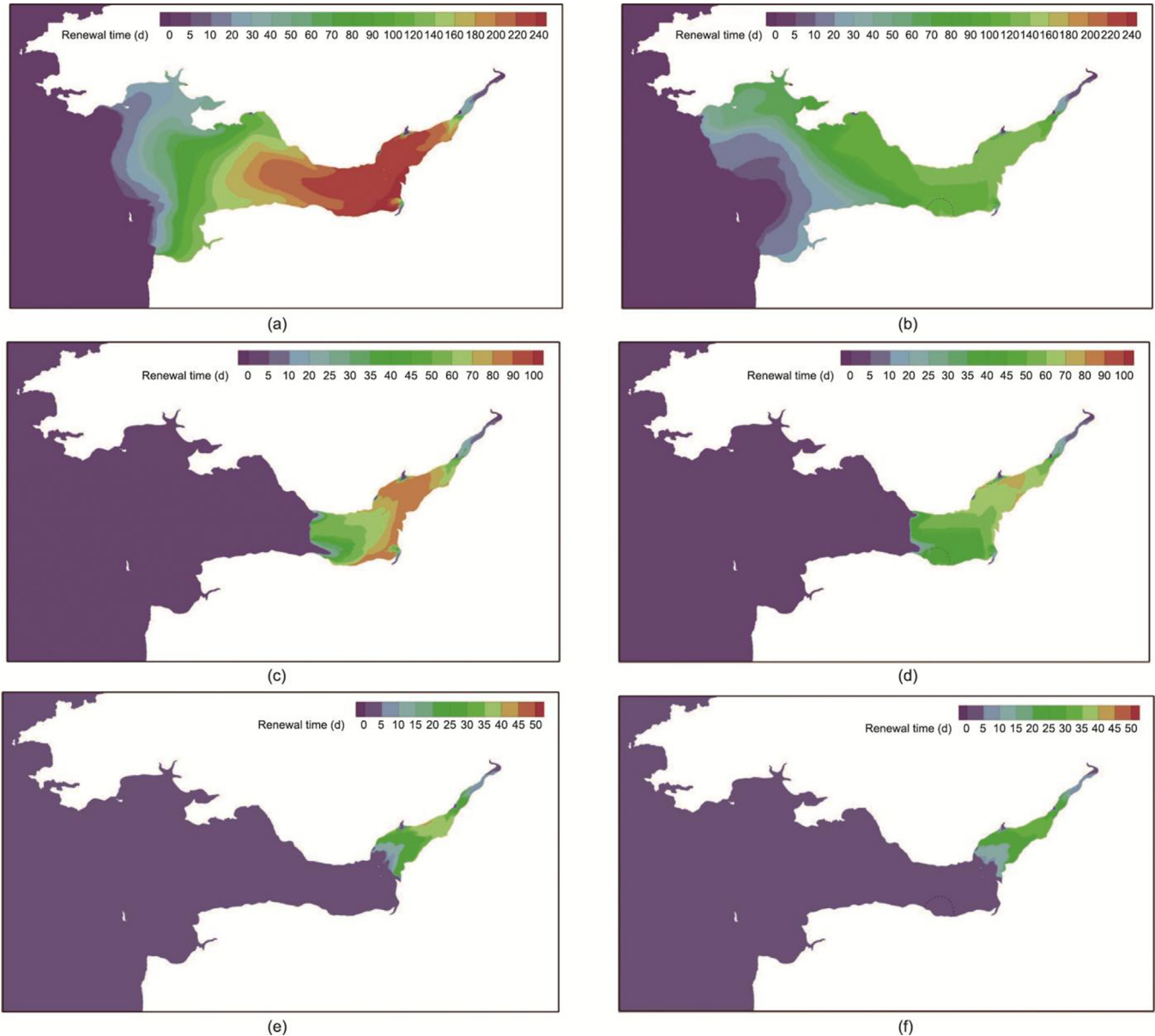


Fig. 14. Renewal time distributions for tracer release in (a, b) the Severn Estuary and Bristol Channel without and with WSL, (c, d) the Severn Estuary and inner Bristol Channel without and with WSL, and (e, f) the Severn Estuary without and with WSL.

quality by diluting pollutants and increasing oxygenation, potentially benefiting some mobile species; however, these changes could also disrupt conditions essential for benthic communities adapted to more stable or stratified environments. Notably, this preliminary study may not comprehensively capture the full extent of coastal ecosystem changes because ecosystem responses involve complex and dynamic interactions. This underscores the importance of implementing appropriate policies, conducting site-specific ecological assessments, and developing well-designed schemes that comprehensively address environmental and ecological impacts [45].

This study validated a methodology for assessing the impact of coastal infrastructures, such as tidal lagoons, on water renewal time and, consequently, water quality. The effects of tidal lagoons on regional water exchange depend on factors such as scale, location, and configuration, underscoring the need for tailored modeling and analysis for each scenario. Additionally, the findings highlight the importance of addressing stagnant zones within lagoon basins, as these areas may exhibit notably different water

quality compared to other regions within the impoundment, with pollution levels exceeding acceptable limits. These considerations are crucial for ensuring effective environmental management and protection during the design period. Future research should explore specific scenarios, such as salinity, dissolved oxygen, nutrient distribution, and pollution dilution, incorporating local inputs and characteristics.

Although the 2D depth-averaged model was considered suitable for the scope and objectives of this study, these models have inherent limitations in representing the vertical structure. In estuarine systems subjected to transient or seasonal stratification, 2D models may introduce bias into residence time estimates by failing to capture vertical shear, density-driven circulation, or slower-moving bottom waters. These processes, which are typically addressed only in 3D frameworks, can notably influence tracer retention and water renewal dynamics in stratified layers. Therefore, a 3D model is recommended for more accurate localized impact assessments in future studies. Although a non-buoyant, mass-conservative tracer provides a simple and robust approach

for quantifying water renewal without uncertainties from buoyancy or biogeochemical interactions, future applications would benefit from using process-oriented tracers such as salinity, temperature, nutrients, or chlorophyll to evaluate specific water quality indicators. Accurate simulation of these tracers requires thorough configuration of the advection–diffusion schemes, parameter coefficients, and degradation processes. However, these active tracers are more appropriately represented in 3D frameworks, where vertical mixing, stratification, and bathymetric influences can be resolved, provided that the vertical mixing and diffusion schemes are correctly specified.

CRediT authorship contribution statement

Bin Guo: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Roger A. Falconer:** Writing – review & editing, Conceptualization. **Reza Ahmadian:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The author is an Editorial Board Member for this journal and was not involved in the editorial review or the decision to publish this article.

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Data availability

The data underpinning this research are openly available at the Cardiff University Research Data Repository under reference <https://doi.org/10.17035/cardiff.30517808>.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eng.2026.02.003>.

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