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Modeling Dynamic Processes of Mondego Estuary and Óbidos Lagoon Using Delft3D

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Abstract: Estuarine systems currently face increasing pressure due to population growth, rapid economic development, and the effect of climate change, which threatens the deterioration of their water quality. This study uses an open-source model of high transferability (Delft3D), to investigate the physics and water quality dynamics, spatial variability, and interrelation of two estuarine systems of the Portuguese west coast: Mondego Estuary and Óbidos Lagoon. In this context, the Delft3D was successfully implemented and validated for both systems through model-observation comparisons and further explored using realistically forced and process-oriented experiments. Model results show (1) high accuracy to predict the local hydrodynamics and fair accuracy to predict the transport and water quality of both systems; (2) the importance of the local geomorphology and estuary dimensions in the tidal propagation and asymmetry; (3) Mondego Estuary (except for the south arm) has a higher water volume exchange with the adjacent ocean when compared to Óbidos Lagoon, resulting from the highest fluvial discharge that contributes to a better water renewal; (4) the dissolved oxygen (DO) varies with water temperature and salinity differently for both systems. On the one hand, for Mondego Estuary during winter the DO levels mainly fluctuate with salinity. On the other hand, for Óbidos Lagoon, DO distribution is determined by both water temperature and salinity. During summer, the high residence time and water temperature limit the DO levels in both systems. The high transferability and superior stability of Delft3D make this model a foundation for realistic simulation and research of distinct estuarine systems, giving support to their maintenance and restoration.

Keywords: Delft3D; hydrodynamic/water quality models; tide; salinity; water temperature; dissolved oxygen; residence time; Mondego Estuary; Óbidos Lagoon

1. Introduction

Estuarine systems are characterized as being highly productive with great biodiversity, which makes them environments of special interest. They are characterized as transitional environments, connecting marine and terrestrial environments, from where they receive a great number of nutrients and organic matter [1]. Their importance is recognized not only by the scientific community but also by the populations that live nearby these areas, which are about 60% of the global population [2] since they provide natural conditions for economic activities, aquaculture exploitation, navigation, and recreation.

Likewise, these areas are facing increasing pressure due to population growth, rapid economic development and climate change effects, leading to the deterioration of water quality [3,4]. These problems might include eutrophication due to high loads of nutrients or pollutants dispersal, strongly affecting the fauna and flora and further causing habitat and ecosystem services loss [1,5]. Therefore, the knowledge of estuarine systems water quality is of utmost importance in terms of scientific, socioeconomic, and political interest [6], being essential for their maintenance and restoration. The water quality of estuaries is strongly

dependent on their hydrodynamic and hydrography, which in turn are influenced by tides (asymmetries between flood and ebb) and freshwater inflow. Tidal asymmetries [7] and freshwater inflow [8] strongly influence nutrient and sediment loads, pollutants transport and water renewal by changing circulation patterns. Therefore, the understanding of the processes linked to tidal propagation and freshwater inflow in estuaries is crucial for the management of these systems.

Due to the lack of continuous in situ data, physical and water quality models arise as important tools for the prediction and characterization of estuarine systems. Indeed, in the last decades, there has been a growing demand for modeling tools to support water quality management in estuarine areas. For example, the authors of [9] applied a physical and water quality model to a shallow lagoon (Ria de Aveiro) to understand the primary production dependence on abiotic factors; [10] modeled the impact of extreme river discharge on the nutrient dynamics and dissolved oxygen in two adjacent estuaries (Lima and Minho Estuaries); [11] applied a 3D hydrodynamic and water quality model to comprehend the parameters that affect the dissolved oxygen and nutrient distributions throughout the Danshuei River estuarine system; among others.

The present study focuses on the application of a physical and water quality model on two estuarine systems located on the west Portuguese coast: Mondego Estuary and Óbidos Lagoon. Despite both systems being geographically close, they are subjected to different environmental and oceanographic conditions. According to the European Water Framework Directive, Mondego Estuary has significant oceanic and river contributions and therefore is characterized as a transitional well-mixed water body, whilst Óbidos Lagoon, due to the low freshwater inflow is considered a coastal semienclosed lagoon. Both estuaries are characterized by narrow inlets, however, while for Mondego estuary it is fixed and artificial, for Óbidos Lagoon the inlet undergoes severe migration on monthly time scales [12]. This research was performed using the Delft3D [13,14], a highly transferable open source model that consists of several integrated modules. These modules together allow the simulation of hydrodynamic flow (under shallow water assumption), the calculation of heat and salt transport, and the modeling of ecological processes and water quality variables.

Both Mondego Estuary and Óbidos Lagoon have been the subject of study of several works on a variety of topics. For example, in [15] the authors applied two different methodologies for the calculation of water residence time in the Mondego Estuary and results indicated that the main factor influencing it is the freshwater inflow; the authors of [16] mapped the potential aquaculture sites in Mondego Estuary; in [17] a numerical model was applied to simulate the morphological evolution of the Mondego Estuary inlet, considering several dredging scenarios. At Óbidos lagoon, the authors of [12] studied the effect of morphological changes on the hydrodynamics and flushing properties, and results showed that the residence time at the lagoon is heavily dependent on morphologic changes associated with both dredging operations and inlet migration; later, in [18] the bathymetric changes on the hydrodynamic and residence time were studied; in [19] the authors analyzed hydrodynamic role, tide, and waves, on the physical advection of properties.

In both systems, water quality problems have been reported. For Mondego Estuary, they started at the beginning of the 1990s, at the upstream connection between the two arms of the estuary that naturally closed due to sedimentary aggradations [15]. For Óbidos Lagoon, these originated from the discharge of domestic effluents to the River Cal (no longer occurring), generating the eutrophication of the eastern branch of the lagoon [20].

Although some characteristics of both estuarine systems are documented, the relation between the hydrodynamic, hydrographic, and water quality features are not fully understood nor quantified. Therefore, the present study aims to research the relation between the tidal dynamics (tidal propagation and asymmetry, residence time) and the spatial distribution of water properties throughout both systems, which are crucial in driving ecological and biological processes in estuaries, through numerical modeling. Further, it is intended to portray how physically distinct estuarine systems behave, Mondego and Óbidos estuarine systems, as well as the influence of its hydrodynamics in the advection of water properties.

The distribution, patterns and seasonality of salinity, water temperature and dissolved oxygen and their relation with hydrodynamics are very important to improve knowledge about these two important estuaries that are currently under-studied, and therefore, will have a significant impact on the characterization and research of local processes. Moreover, this research aims to demonstrate how Delft3D model software behaves in simulating environmental changes in estuarine systems with distinct features and intends to act as a starting point for further research in modeling water quality, improving models, and promoting in situ measurements.

2. Study Area

2.1. Mondego Estuary

The Mondego estuary (Figure 1A) is a relatively small system (16 km^2) located on the Atlantic coast, in the central region of Portugal (40°8′ N 8°50′ W). This is a warm temperate and polyhaline estuary, consisting of two arms (north and south), separated by Murraceira Island [21], with physical distinctions between them. The water depth ranges from 5 to 10 m at the northern arm and from 2 to 4 m at the southern arm during high tide and the tidal range varies between 0.35 and 3.3 m relative to the mean sea level [15].
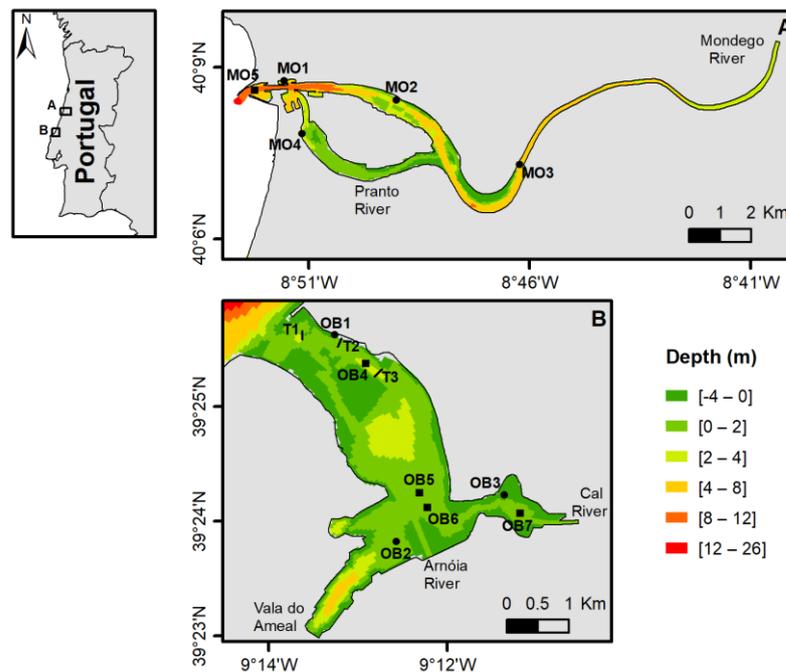

Figure 1. Bathymetry of Mondego Estuary (**A**) and Óbidos Lagoon (**B**), with the location of the sampling stations for hydrodynamic variables (black dots) and water quality variables (black squares).

The northern arm receives the majority of freshwater discharge from the Mondego River, and consequently, the south arm water circulation is mainly due to tides, wind, and the usually small freshwater input of the Pranto River [22]. According to [23], the annual mean discharges, which are controlled artificially by a sluice [22,24], are 340 m^3/s (Mondego river) and 5.1 m^3/s (Pranto River).

The Mondego estuary comprises an area of 8.452 km^2 of salt marshes, with a high potential for aquaculture farming. In the Mondego Estuary, fish farming increased when Portugal became an EEC/EU member as a result of the attribution of subsidies for aquaculture development [16].

2.2. Óbidos Lagoon

The Óbidos Lagoon (Figure 1B) is a shallow coastal system with 2 m average depth, occupying a surface area of 4.4 km^2 at mean sea level and 8.0 km^2 at high spring tide [12].

The lower lagoon is connected to the Atlantic Ocean by an inlet and composed of several channels [25]. The position of the inlet and the configuration of the channels in the lower lagoon have naturally changed in the last decades [12]. The water flows by the main channel, called the northern channel, where current velocities often exceed 1 m s^{-1} and reaching 1.6 m s^{-1} in the inlet [18,19]. The upper lagoon consists of a shallow basin, elongated arms (Barrosa and Bom Sucesso), and a small embayment in the south (Poça das Ferrarias, [12]). In the lagoon arms, current velocities of about 0.4 m s^{-1} are observed [18,19].

The main freshwater sources to the lagoon are Cal and Arnóia rivers (two main river discharges) and Vala do Ameal (a drainage creek). Cal river enters the lagoon at the Barrosa arm and Vala do Ameal at the Bom Sucesso arm (Figure 1B). Arnóia river enters the lagoon between both arms, contributing with 90% of the freshwater fluxes into the lagoon. Arnóia River is the primary source of sediments, whose deposition has created an extensive sandbank between the lagoon arms [19].

The lagoon is well-mixed, strongly influenced by semidiurnal tides and in a small extension by storm waves (wave height values ranging between 3 and 7 m). Freshwater input plays a minor role, with average flow rates of the order of $3\text{ m}^3\text{s}^{-1}$, which is less than 5% of the average tidal prism scaled by the M_2 period [26].

3. Methods and Data

3.1. Field Data Source

In the frame of this study two field surveys were performed (26/11/2014 and 12/12/2014) for Mondego Estuary, in order to measure in situ data concerning water level and temperature (MO1, MO2, MO3, and MO4) and salinity (MO1, MO3, and MO4) for the model calibration. The dissolved oxygen concentration data was acquired through a buoy located at Figueira da Foz harbor (MO5) in the year 2011.

Concerning Óbidos Lagoon data, water level data from OB1, OB2, and OB3 derive from the Portuguese Hydrographic Institute (IH), with a 6 min time resolution, for the period of 18/07/2001–06/08/2001. The current velocity calibration was performed on T1, T2, and T3 transepts and derive from an ADCP from IH, covering a tidal cycle on 03/07/2001. The salinity and water temperature calibration was performed on 10/05/2001 and 14/11/2001, covering a tidal cycle (OB1, OB2, and OB3). Lastly, the observational data concerning DO for Óbidos Lagoon system was downloaded from Sistema Nacional de Informação de Recursos Hídricos (SNIRH) for the year 2001 (OB5, OB6, OB7, OB8, and OB9).

3.2. Model Implementation and Boundaries Definition

The Delft3D modeling suite developed for coastal, river, and estuarine areas was implemented in Mondego Estuary and Óbidos Lagoon including the hydrodynamic with salt and heat transport (Delft3D FLOW) and water quality (Delft3D WAQ) modules. The FLOW module solves the 3D baroclinic Navier–Stokes and transport equations under the Boussinesq assumption and the WAQ solves the advection–diffusion–reaction equation for a wide range of model substances and seeks the hydrodynamic information from FLOW module. A detailed description of both modules can be found in [13,14].

In the present research, curvilinear grids were developed for both systems allowing a variable resolution, depending on the region of interest. For Mondego Estuary, the grid has a coarser resolution at the offshore boundary (60–300 m) and a finer resolution inside the estuary (25–50 m). For Óbidos Lagoon, the grid resolution ranges from 70 to 300 m at the offshore boundary and between 10 and 40 m inside the lagoon. The implementations consider a 2D depth-averaged approximation since both systems are usually considered vertically homogeneous [18,22,27].

The offshore bathymetries result from the interpolation of the Digital Model Terrain, EMODnet data, with a resolution of approximately 300×300 m for Mondego Estuary and 115×115 m for Óbidos Lagoon, while inside the estuaries, the bathymetric data come from IH (1964–2009) for Mondego estuary and IH (2000–2001) for Óbidos Lagoon. For Mondego

Estuary, the bathymetric data inside the estuary was complemented by the one provided by Figueira da Foz harbor administration.

Regarding the open ocean boundary for each estuarine implementation, the model uses 13 harmonic constituents gathered from OSU TOPEX/Poseidon Global Inverse Solution (https://sealevel.jpl.nasa.gov/missions/topex/ [28]) along with water temperature, salinity, pH, chlorophyll, nutrients, and DO concentration from the Atlantic Iberian Biscay Irish Ocean model provided by Copernicus Marine Environment Monitoring Service (CMEMS–https://marine.copernicus.eu/ [29]). For Mondego Estuary, two freshwater sources were considered, the Mondego River and the Pranto River, while for Óbidos Lagoon, three were considered: Vala do Ameal, Arnóia River, and Cal River. The discharges and water properties considered correspond to the climatology computed for 30 years provided by the watershed model of the SNIRH (https://snirh.apambiente.pt/ [30]). The atmospheric forcing imposed at the air–sea interface in both cases consists of surface air temperature, relative humidity, and net solar radiation gathered from the European Centre for Medium-Range Weather Forecasts (ECMWF, www.ecmwf.int [31]), which provides global reanalysis. Regarding the FLOW module, computational time steps of 0.5 min were chosen for both estuaries, to guarantee the stability and accuracy of the numerical results. For the WAQ module, a time step of 1 and 10 min were used for Mondego Estuary and Óbidos Lagoon, respectively.

Delft3D-WAQ presents a wide range of processes and substances to be modeled. Taking into account the balance between computational cost and quality of the predictions as well as available information to use as input, in this work the processes and substances used are listed in Table 1.

Table 1. Processes and substances used in Delft3D-WAQ module.

Processes	Substance
Reaeration	Dissolved oxygen Saturation oxygen concentration
Primary production	Dissolved oxygen Algae Ammonium (NH_4) Nitrate (NO_3) Orto-phosphate (PO_4)
Calculation of pH	Total inorganic carbonate Alkalinity
Nitrification	Dissolved oxygen Ammonium (NH_4) Nitrate (NO_3)
Denitrification	Dissolved oxygen Nitrate (NO_3)

3.3. Model Calibration

The field data previously described were used to compare with model results, with the objective of evaluating the model performance and adjusting the model-free parameters until achieving the best fit between model and data. The accuracy of the model was quantified through the root mean square error (RMSE). Regarding the FLOW module, the bottom roughness was the main parameter used to optimize the fitting between model results and in situ data. According to [32] the hydrodynamic roughness of the bed is a primary calibration variable for all coastal and estuarine models. For both estuaries, a constant manning value was assumed for bottom roughness: 0.025 for Mondego Estuary and 0.024 for Óbidos Lagoon. For the WAQ module, the main parameters used to obtain the best model results accuracy are the production, respiration, and mortality rates, whose values are depicted in Table 2.

Table 2. Parameters used in WAQ module.

Parameter	Value		Unit
	Mondego	**Óbidos**	
Maximum Production Rate Greens	0.6–1.5	0.6	d^{-1}
Maintenance respiration greens	0.045	0.045	d^{-1}
Growth respiration factor greens	0.15	0.15	–
Mortality rate constant greens	0.35	0.30	d^{-1}

3.4. Estuaries Characterization

The main semidiurnal (M_2, S_2) and quarter-diurnal (M_4) tidal constituents were computed using the t_tide matlab® package of Pawlowicz [33] and mapped for both Mondego Estuary and Óbidos Lagoon. Additionally, to understand the tidal distortion and dominance (ebb or flood), the tidal asymmetry and the tidal prism were evaluated. The tidal asymmetry was evaluated through the Amplitude Ratio ($Ar = AM_4/AM_2$) and the Relative Phase ($\varphi = 2\theta M_2 - \theta M_4$), where AM_4 and AM_2 are the amplitude and θM_4 and θM_2 are the phase of the respective tidal constituents. The tidal prism was also computed for a cross-section located at the estuaries' mouth in a flooding/ebbing cycle, during spring and neap tides.

Additionally, the mean residence time and the freshwater fraction were computed and mapped in each grid cell for winter (December, January, February: DJF) and summer (June, July, and August: JJA) seasons. The mean residence time was computed through the methodology used in previous works [6,34,35]. According to these authors, the mean residence time represents the necessary time for the conservative tracers' concentration, in the interest domain, to decrease to $1/e$ (approximately 37%) of its initial concentration.

The freshwater fraction ($F = (S_0 - S)/S_0$) was calculated by comparing the estuarine salinity (S) with the salinity of seawater (S_0) [36]. The salinity of seawater was set as the average values imposed in the open boundaries provided by CMEMS, following the methodology of [6].

Finally, a spatial characterization was performed through the assessment of the water temperature, salinity, and DO variability. The seasonal mean of these variables was computed considering winter (DJF), spring (March, April, May: MAM), summer (JJA), and autumn (September, November, October: SON) for each grid cell. Additionally, the relation between water temperature, salinity, DO, and residence time was accessed, for wet (DJF) and dry seasons (JJA) and correlation coefficients (CC) between these variables were computed.

4. Results

4.1. Model Calibration

The field data previously described was used for calibration purposes. In a first step, a comparison between model results and observed hydrodynamic variables (SSE and current velocity when available) was performed in order to evaluate the model accuracy in the reproduction of the tidal propagation. Secondly, the model accuracy in reproducing the hydrographic (water temperature and salinity) and water quality variables (DO concentration) was assessed.

In this context, for Mondego Estuary, as previously referred to, data of SSE, water temperature, and salinity for neap and spring tidal regimes are available for comparison. As an example, only the results relative to the spring tide are shown (Figure 2), being the RMSE presented in Table 2 for both tidal regimes (ST—spring tide; NT—neap tide).
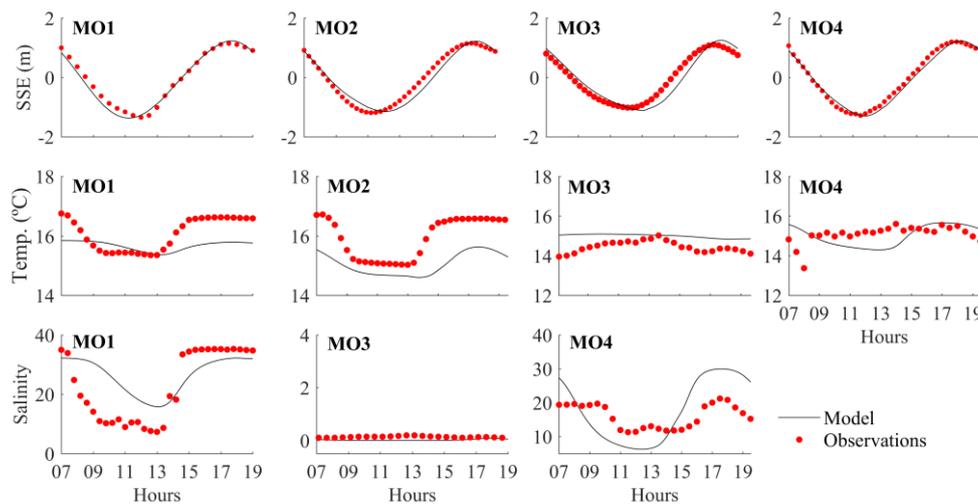
Figure 2. Comparison between model results and observations of sea surface elevation, water temperature, and salinity for MO1, MO2, MO3, and MO4 stations located at Mondego Estuary during the spring tide.

The results of SSE (Figure 2 top) suggest a good agreement between model results and observed data for all stations. According to Table 3, the lowest errors are found for MO1 (0.15 and 0.07 m) and MO4 (0.12 and 0.11 m) for spring and neap tide, contrasting with higher errors found on MO3 (0.25 and 0.21 m) for spring and neap tide.

Table 3. RMSE for Mondego estuary (MO1, MO2, MO3, MO4, MO5 stations); ST—spring tide; NT—neap tide.

Variable		MO1	MO2	MO3	MO4	MO5
SSE (m)	ST	0.15	0.21	0.25	0.12	–
	NT	0.07	0.14	0.21	0.11	–
Water temperature (°C)	ST	0.6	0.9	0.6	0.7	–
	NT	1.5	1.2	0.4	1.5	–
Salinity	ST	9.3	–	0.1	7.4	–
	NT	11.7	–	0.2	10.0	–
DO (g/m^3)		–	–	–	–	1.02

Regarding water temperature (Figure 2 center), the model reasonably represents the observations, with the RMSE ranging from 0.4 to 1.5 °C. The lower RMSE is found for MO2 during spring tide (0.97 °C), which represents 6% of mean local water temperature, and for the neap tide, an RMSE of 0.4 °C was obtained for MO3. Analyzing the highest RMSE, it was found for neap tide for MO1 and MO4 (1.5 °C). Generally, it can be noticed that higher RMSEs occur during neap tide. On the other hand, an RMSE lower than 1 °C can be found during spring tide measurements.

Analyzing the salinity variability along a tidal cycle, the model accurately reproduces the observations for MO3 with an RMSE of 0.1 and 0.2 for spring and neap tide, respectively. Although the model reproduces well the trends for MO1 and MO4, the RMSEs are considerable, of 9 and 11 for MO1 (spring and neap tide) and 7.4 and 10 for MO4 (spring and neap tide).

Regarding the comparison between the model results and observed DO concentration, whose best fit is represented in Figure 3 (MO5 station), the model represents well the annual trend, with an RMSE of 1.02 g/m^3, although it frequently overestimates the concentration observed.
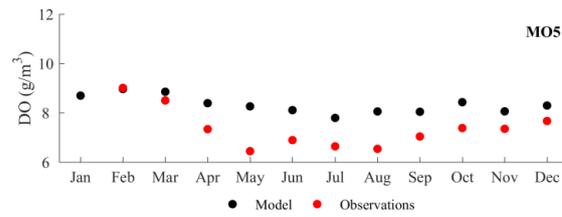
Figure 3. Comparison between model results and observed monthly means of dissolved oxygen for MO5 station located at Mondego Estuary.

Regarding the calibration for Óbidos Lagoon, results are presented in Figures 4 and 5, and the RMSE in Table 4. Concerning SSE, it can be verified that the model accurately represents the tide observed, with the best adjustment in the station close to the mouth (OB1) with a RMSE of 0.03 m. For OB2 and OB3, RMSEs of 0.07 and 0.13 m were found, where model results slightly differ from observed tidal amplitude. Data regarding the current velocity show that the model adequately represents the velocity module of the observed data, with the lowest RMSE of 0.07 m/s for T2 and the highest of 0.13 m/s for T1.
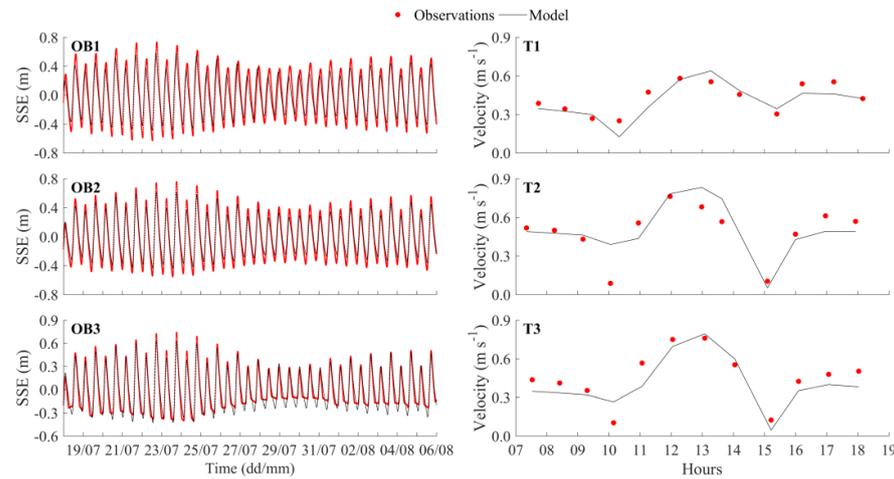

Figure 4. Comparison between model results and observations of sea surface elevation for OB1, OB2, and OB3 stations and current velocity for T1, T2, and T3 transects located at Óbidos Lagoon.
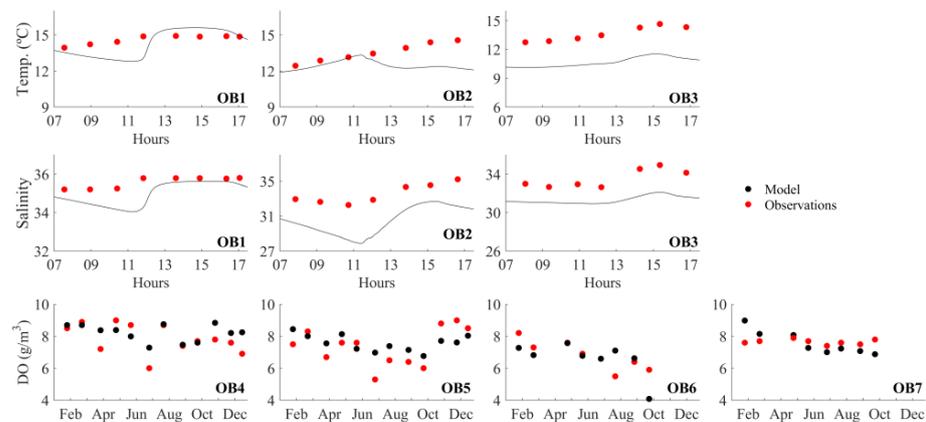

Figure 5. Comparison between model results and observations of water temperature, salinity, and dissolved oxygen concentration for stations OB1 to OB7 located at Óbidos lagoon. Data concerning November and December months are missing for stations OB6 and OB7.

Table 4. RMSE for Óbidos Lagoon (OB1, OB2, OB3, OB4, OB5, OB6, OB7, OB8) stations.

Variable	OB1	OB2	OB3	OB4	T1	T2	T3	OB5	OB6	OB7
SSE (m)	0.13	0.08	0.07	—	—	—	—	—	—	—
Velocity (m/s)	—	—	—	—	0.13	0.07	0.10	—	—	—
Temperature (°C)	1.02	1.36	2.93	—	—	—	—	—	—	—
Salinity	0.76	3.23	2.26	—	—	—	—	—	—	—
DO (g/m^3)	—	—	—	1.31	—	—	—	0.92	1.58	0.68

Regarding water temperature and salinity (Figure 5), an acceptable fit was achieved for the stations analyzed. For water temperature, the RMSE increases towards the end of the lagoon with RMSEs of 1.02, 1.36, and 2.93 °C for OB2, OB3, and OB4, respectively. For OB4 the model underestimates water temperature values, however, follows the general trend of temperature evolution over the tidal cycle.

For salinity, there is a good agreement for the station OB1 since the RMSE is 0.76, which corresponds to 2% of local mean salinity. Regarding OB2 and OB3, the RMSEs are 3.2 and 2.3, corresponding to 10% and 7% of local mean salinity. Although the model underestimates salinity for OB2 and OB3, the salinity trend over the tidal cycle is followed by model results.

Concerning the DO concentration, the minimum errors range from 0.68 g/m^3 in OB7 whilst the maximum errors are found for OB6 (1.58 g/m^3). The model reproduces the annual dissolved oxygen trend, except for June for all considered stations, where the observations are very low (around 3–6 g/m^3) whilst the model predictions are around 7 g/m^3.

4.2. Tidal Characterization

4.2.1. Tidal Constituents

To characterize the tidal propagation in Mondego Estuary and Óbidos Lagoon, the main tidal constituents observed at the Portuguese coast (M_2, S_2 and M_4) were computed in each grid point and are presented in Figure 6.

Generally, the results indicate that the amplitude of the main semidiurnal constituents decreases from the mouth of both systems to upstream, while the phase increases. Otherwise, both the amplitude and phase of the quarter-diurnal constituent increase upstream.

The M_2 constituent presents the highest amplitude for both estuarine systems, reaching 1 m at the estuaries inlet while decreasing until 0.90 and 0.25–0.30 m at the Mondego and Óbidos upstream regions, respectively. The phase of M_2 constituent increases from 70° at the mouth of both systems to 100° at Mondego and 150° at Óbidos upstream regions. These values mean a phase delay of approximately 60 min for Mondego Estuary and 160 min for Óbidos Lagoon.

The amplitude of S_2 constituent decreases from 0.36 m at the mouth of both estuaries to 0.30 and 0.09 m at Mondego Estuary and Óbidos Lagoon upper regions, respectively. The phase lag between the mouth and far end of the estuaries is 36° (70 min) for Mondego and 70° (140 min) for Óbidos.

Finally, the M_4 constituent, as expected, is higher in amplitude at Mondego Estuary, as it derives from M_2 decomposition. Indeed, its amplitude reaches maximum values of 0.14 m at the far end of Mondego channel and 0.16 m at the south branch. The phase of M_4 constituent reaches the maximum value after the estuary entrance (212°), decreasing towards the channel head (148°), which means a phase lag of 66 min.

Óbidos Lagoon presents the maximum M_4 amplitude in a specific region at the inlet (0.08 m) mainly due to the bathymetric characteristics. After this region, the amplitude of M_4 is approximately 0.06 m increasing towards the East branch of the lagoon. The phase of M_4 constituent increases from 136° at the mouth to 214° at the end of the main channel, reaching 230° at the end of the East branch, meaning a maximum delay of 95 min.
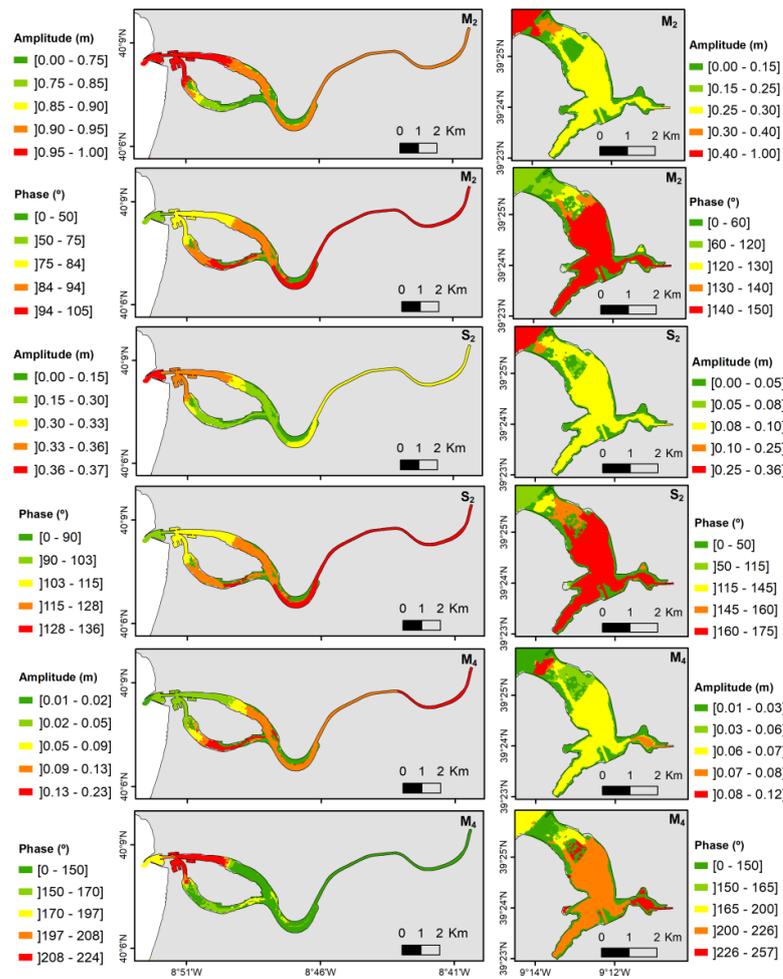
Figure 6. Amplitude (m) and phase (°) of the main tidal constituents for Mondego estuary (**left**) and Óbidos Lagoon (**right**).

4.2.2. Tidal Asymmetry and Tidal Prism

To evaluate the tidal distortion in both systems, the tidal asymmetry (amplitude ratio and relative phase) was computed in every grid cell and is mapped in Figure 7. Additionally, the tidal prism in a cross-section located in both estuaries' mouths was computed (Table 5).
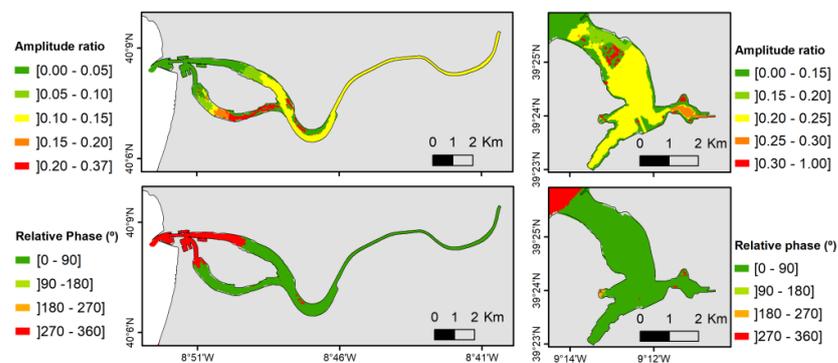

Figure 7. Amplitude ratio and relative phase (°) for Mondego Estuary (**left**) and Óbidos Lagoon (**right**).

Table 5. Tidal prism (m³) computed at the mouth channel section for Mondego Estuary and Óbidos lagoon.

	Mondego Estuary		Óbidos Lagoon	
	Flood	**Ebb**	**Flood**	**Ebb**
Spring Tide	2.30×10^7	2.40×10^7	1.80×10^7	0.99×10^7
Neap Tide	0.16×10^7	0.65×10^7	0.56×10^7	0.48×10^7

Results indicate that the tide presents a higher distortion at Óbidos Lagoon than at Mondego Estuary. Indeed, the amplitude ratio at the mouth of Óbidos Lagoon is approximately 0.2 increasing upstream, reaching a maximum at the end of the East branch (0.25). Since the relative phase in Óbidos Lagoon is comprehended between 0 and 180° and the flood tidal prism is higher than the ebb (either in spring or neap tides), the lagoon is considered flood-dominant.

For Mondego Estuary a gradual increase of the amplitude ratio between the mouth (0.02) and the upper areas (0.15) is noticed. It is important to note that the highest tidal distortion is registered at the end of the south arm, with values of 0.37. The adjacent area of Mondego Estuary mouth behaves as ebb-dominant as the relative phase ranges in 270 and 360° and the ebb-tidal prism is higher than the flood, the remaining estuary being considered flood-dominant.

Comparing the tidal prism for both estuaries (Table 5), it ranges in the same magnitude orders, with Mondego Estuary being superior in terms of volume (m³), except during the flood for the neap tide, where Óbidos is slightly superior. The values obtained for both estuaries are in line with the ones obtained by [37] for Mondego Estuary and [38] for Óbidos Lagoon.

4.3. Water Renewal Timescales: Residence Time and Freshwater Fraction

Aiming to evaluate if effective water renewal occurs in both estuaries and the effect of the distinct drivers (tide and river flush), the residence time and freshwater fraction were computed for Mondego Estuary and Óbidos Lagoon during winter and summer seasons (Figure 8).

Generally, for both systems, the residence time is lower during winter than during summer, due to the higher river discharge that promotes water exchange. Indeed, regarding Mondego Estuary, for winter, a residence time of 2 days is observed in the mouth region, decreasing upstream to less than 5 h (Figure 8A). For summer, the residence time at Mondego Estuary mouth is almost 5 days, while upstream is approximately 1.5 days (Figure 8C). It is noteworthy that, during the summer, the highest residence times (between 10 and 15 days) are observed in the central region, more precisely in the upstream connection between the two arms of the estuary.

For Óbidos Lagoon, during the winter period, the residence time ranges from 3–3.5 days in the first downstream half of the lagoon to 4–5 days in the second half, except for the West branch that registered a residence time higher than 7 days (Figure 8B). For summer, the residence time increases from 4 days at the inlet region to almost 12 days upstream (Figure 8D).

For both systems, the effect of the tide is perceived at the inlet as well as the river discharges upstream. Indeed, Mondego Estuary has a strong river influence, detected until the middle estuary for both seasons, with freshwater fractions near 1. Even though the river influence can be noticed more downstream in winter when compared to summer (Figure 8E,G).

For Óbidos Lagoon the freshwater fraction is substantially lower than for Mondego Estuary, since the freshwater flow is very low, which becomes noticeable during summer with mean freshwater fractions of 0.02 (Figure 8H). In winter, the freshwater fraction increases from the inlet (0.01) to the upstream regions, where a maximum of 0.1 is observed (Figure 8H).
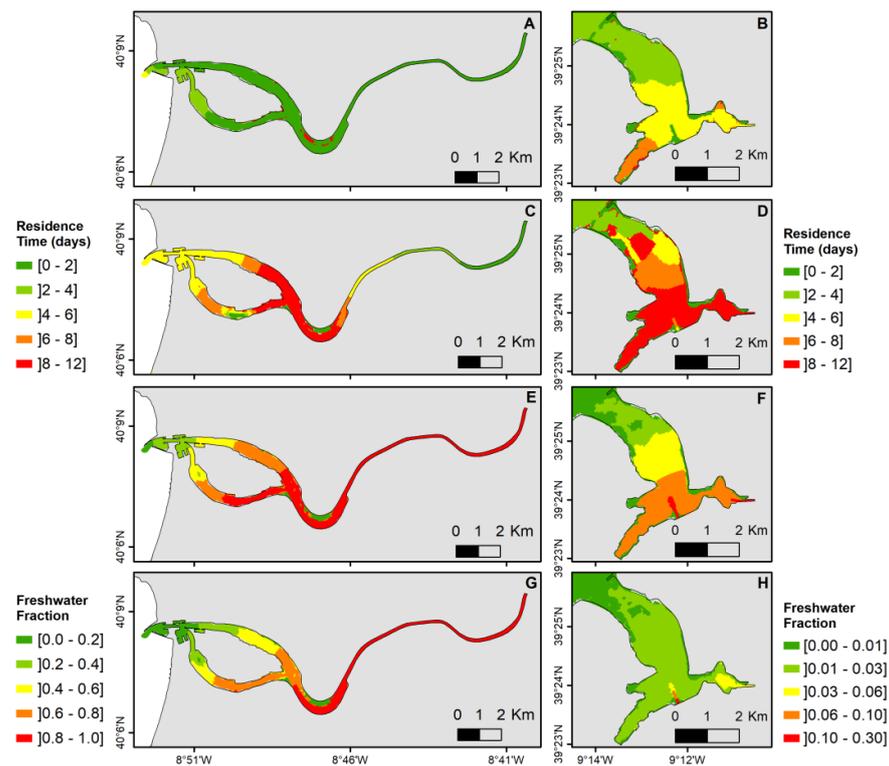
Figure 8. Residence time (days) for winter (**A**,**B**) and for summer (**C**,**D**) and freshwater fraction for winter (**E**,**F**) and summer (**G**,**H**) for Mondego Estuary (left) and Óbidos Lagoon (right).

4.4. Spatial Distribution of Water Temperature, Salinity, and DO

To characterize the physical and water quality variables for both estuarine systems the seasonal mean of water temperature, salinity, and DO are mapped and presented in Figure 9 for winter, spring, summer, and autumn. Generally, the distribution of salinity and water temperature is directly related to the intensity of the freshwater discharge. Overall, the seasonal mean water temperature shows a similar pattern for both estuaries, with higher temperatures in summer (reaching up to 24 °C—Figure 9E,F) contrasting with lower temperatures in winter (between 10 and 12 °C), showing the characteristic succession of winter minima and summer maxima (Figure 9A,B). At Mondego Estuary the mean winter water temperature is lowest at the middle estuary with values smaller than 12 °C, increasing towards the inlet (12 °C) and the upstream area (14 °C). Regarding Óbidos Lagoon, a longitudinal gradient is observed with higher values at the inlet (13 °C) and lower upstream (10 °C). Spring season is characterized by a uniform water temperature varying between 16 and 17 °C in Mondego Estuary and between 15 and 16 °C in Óbidos Lagoon. The summer season portrays the highest temperature (24 °C), as expected, and a clear increasing gradient from the mouth (19 °C) to the upstream area (24 °C) is observed for Óbidos Lagoon.

For Mondego Estuary, the mean summer water temperature pattern is different, showing the highest values in the middle estuary (22 °C), decreasing to 18 °C at the inlet and to 17 °C at the upstream area. The mean water temperature for autumn presents a uniform pattern throughout both estuaries with values of approximately 16 °C for Mondego Estuary and between 17 and 18 °C for Óbidos Lagoon.

Figure 10 presents the mean salinity for Mondego Estuary (left) and Óbidos Lagoon (right) for winter, spring, summer, and autumn. Generally, for both systems, a typical estuarine pattern is observed, with salinity decreasing from the estuaries' mouth to upstream.
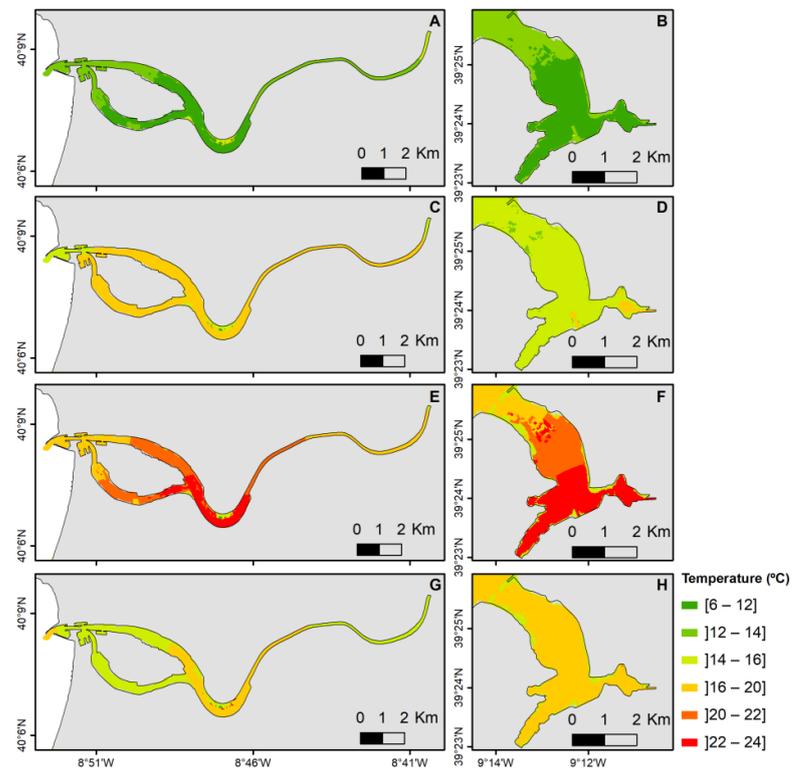
Figure 9. Seasonal mean of water temperature (°C) for Mondego Estuary (left) and Óbidos Lagoon (right): (**A**,**B**)—winter; (**C**,**D**)—spring; (**E**,**F**)—summer; (**G**,**H**)—autumn.
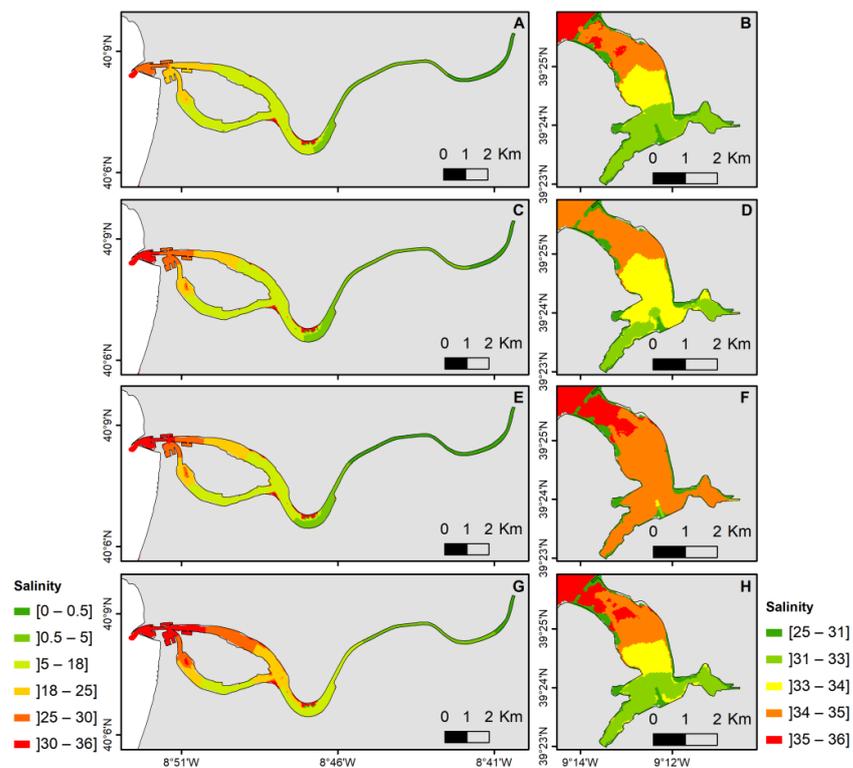
Figure 10. Seasonal mean of salinity for Mondego Estuary (left) and Óbidos Lagoon (right): (**A**,**B**)—winter; (**C**,**D**)—spring; (**E**,**F**)—summer; (**G**,**H**)—autumn.

There is a notable difference regarding both estuaries: while Mondego Estuary reaches lower salinity values of 0 (near riverine discharges), Óbidos Lagoon has the lowest salinity of 30. This difference may reflect the distinct freshwater contribution to each of the estuarine systems.

Regarding the Mondego Estuary, the influence of the oceanic waters is observed near the mouth, with salinity values higher than 30 for all the seasons. It should be noted that this saltier water mass extends further upstream in the summer and autumn seasons, which is expected due to the low river inflow that promotes the salt-wedge intrusion. The fluvial influence is also detected since low salinity values (<14) are observed from the middle estuary to the upper region. According to the Venice System zonation, generally, the Mondego Estuary presents a euhaline section ($S > 30$) at the estuary mouth and polihaline lower ($25 < S < 30$) and middle sections ($18 < S < 25$) in the upstream contiguous areas. A mesohaline ($5 < S < 18$) section is also visible in the central estuary followed by an oligohaline ($0.5 < S < 5$) and a limnetic ($S < 0.5$) section in the head of the estuary, due to the influence of Mondego River. The existence and extension of these sections vary seasonally in Mondego Estuary as observed in Figure 10.

Regarding Óbidos Lagoon (Figure 10), the salinity is always higher than 30, independently of the season. Even though, in winter and autumn, the mean salinity is below 32 in the East and West branches, while in spring and summer is near 33 and 32, respectively. Therefore, according to the Venice System zonation, it appears that practically the entire lagoon is considered euhaline ($S > 30$) during all the year, except for Arnóia River mouth that can be classified as polihaline lower ($25 < S < 30$) during winter and autumn. These results show the importance of the river contribution in the modulation of the salinity patterns throughout an estuarine system.

Figure 11 shows the dissolved oxygen horizontal distribution for Mondego Estuary (left) and Óbidos Lagoon (right), through winter, spring, summer, and autumn.
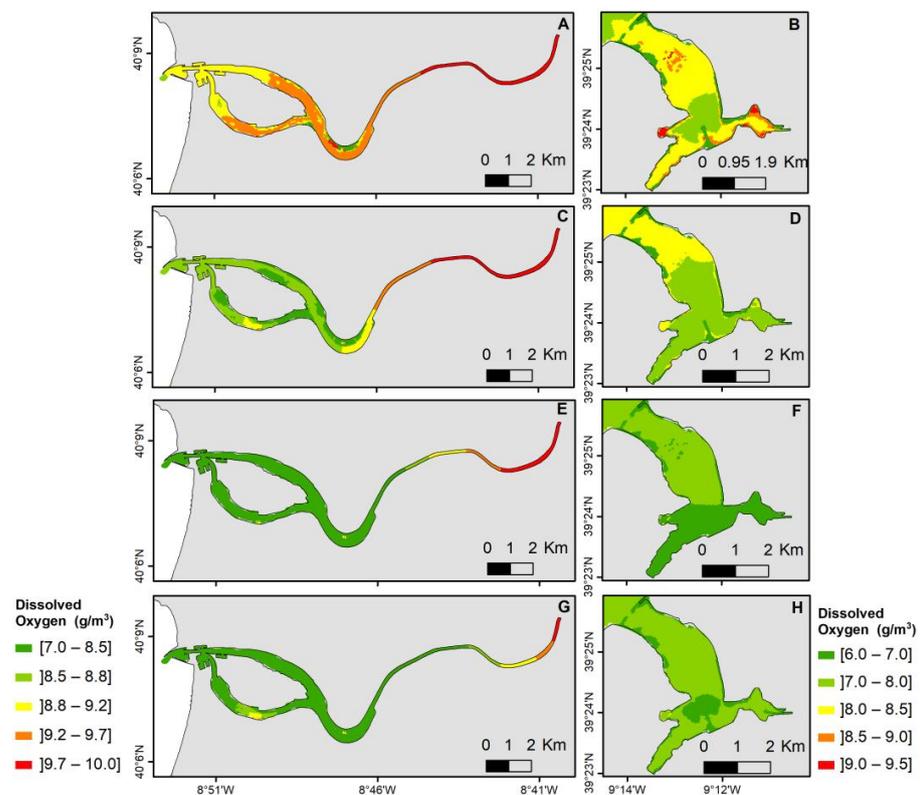

Figure 11. Seasonal mean of dissolved oxygen (g/m^3) for Mondego Estuary (left) and Óbidos Lagoon (right): (**A,B**)—winter; (**C,D**)—spring; (**E,F**)—summer; (**G,H**)—autumn.

For Mondego Estuary the DO has minimum concentrations on the shore, whilst presenting the greatest values at the main channel end, reaching 10 g/m^3. Generally, the lower DO concentration is observed during summer and autumn, with values ranging from 7.7 g/m^3 at the mouth and 9.5 g/m^3 in the upper region. For winter and spring, the DO concentration in the estuary head is approximately 10 g/m^3, decreasing to 9.5 and 8.8 g/m^3 in the middle estuary and 8.8 and 8.5 g/m^3 near the estuary mouth, respectively.

For the Óbidos Lagoon, a seasonal trend of DO concentration is also observed, however less marked than in Mondego Estuary. During winter and spring months a DO concentration of approximately 8 g/m^3 is observed at the inlet, decreasing landward for 7.6 g/m^3. For summer and autumn, the magnitude of the mean DO concentration is slightly lower and the landward decrease is still observed (7.6 g/m^3 at the inlet and 6.8 g/m^3 in the upper region).

4.4.1. Relation between Residence Time and DO, Water Temperature, and Salinity

To achieve complete knowledge about the dynamics of the variables under study (water temperature, salinity, and DO concentration) their relation with the residence time was assessed considering the values of each variable along the channels axis of both Mondego Estuary and Óbidos Lagoon, for winter and summer (Figure 12).
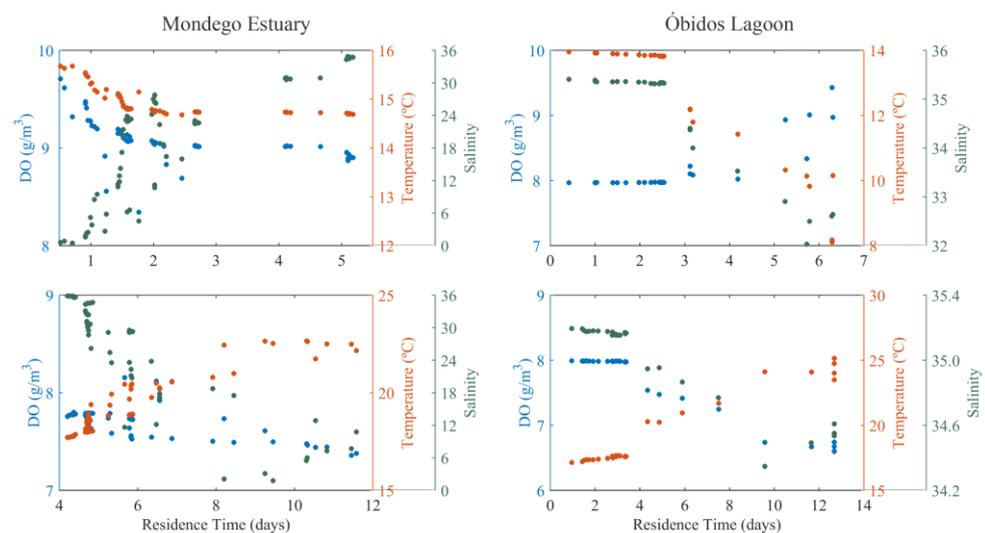

Figure 12. The relation between water temperature (°C), DO (g/m^3) and salinity with residence time for Mondego estuary (**left**) and Óbidos Lagoon (**right**), for winter (**top**) and summer (**bottom**).

For Mondego Estuary, results suggest that for winter the DO levels mainly fluctuate with salinity, since the mean water temperature is quite uniform throughout the estuary (14.5 and 15.5 °C). Low salinity values correspond to high DO levels that decrease with higher salinities. Additionally, the highest DO levels are found in regions with low residence times and with low salinity. For summer, it seems that an opposite trend between DO and water temperature is detected. The DO levels decay when water temperature increases and high residence times occur.

For Óbidos Lagoon, during winter the majority of the lagoon presents uniform patterns of DO levels, salinity, and water temperature, with low residence times (between 1 and 3 days). For residence times higher than 3 days (second upstream half of the lagoon) the DO levels increase with the water temperature and salinity decrease. For summer, a similar pattern to that of the Mondego Estuary is observed, where the increasing water temperature and decreasing salinity for high residence time results in a decrease of DO concentration (Figure 12).

5. Discussion

5.1. Model Calibration

The FLOW and WAQ modules of Delft3D were implemented and calibrated for both Mondego Estuary and Óbidos Lagoon. The model was successfully calibrated, proving its proficiency in reproducing the main physical and water quality features of both systems. Despite scarce and noncontinuous observations available, it can be concluded that the model accurately represents the hydrodynamic processes in both systems, whereas water temperature, salinity, and DO concentration results are acceptable.

Regarding the Mondego Estuary, the model results and observed SSE portrays very good agreement, however with increasing errors towards the end of the estuary. In general, the absolute RMSEs obtained for NT were smaller, however, when compared with local tide amplitude, the deviation presents the same order of magnitude for both periods (between 4% and 10% of the local amplitude). The higher errors found at stations furthest from the mouth (MO2 and MO3) may be attributed to bathymetric data uncertainties. The results obtained in the present study are in line with [27], which aimed to validate a hydrodynamic and morphodynamic model in the study region. Other studies in different systems reported similar RMSE [6,39–41]. Considering the water temperature and salinity, the model adequately reproduces the observed parameters considering both ST and NT regimes. Mondego Estuary has a significant freshwater flow during the year and therefore the water temperature and salinity throughout the estuary are very dependent on its value. Consequently, the errors between model results and observed variables are associated with uncertainties in the definition of landward boundary conditions. Nonetheless, a RMSE lower than 1 °C was achieved for all stations, which means a good representation of the water temperature in the Mondego Estuary. Regarding salinity, the highest errors found for stations MO1 and MO4 (near the estuary mouth) can be explained by numerous secondary freshwater effluents, including watersheds from agricultural activities that are not well documented nor considered in the present model implementation. In addition, the NT errors were higher when compared with ST, since during NT the volume of oceanic salty water that penetrates to the estuary is smaller, and therefore errors related to freshwater input inaccuracies might become more relevant.

Notwithstanding, and keeping in mind other implementations and validations found in literature it can be concluded that the implementation developed herein is a valid representation of the hydrography of the Mondego Estuary.

Regarding the DO (MO5) a fair agreement between model results and observed data was found, with a RMSE of 1.02 g/m^3. Although the model reproduces the annual DO variability (with lower values in summer months due to higher consumption), it frequently overestimates the oxygen water content. It should be noted that the lowest observations of DO occur in May, while the model lowest levels occur in August. This could be related to specific events that the model is not able to reproduce. For instance, the existence of agricultural fields along the Mondego Estuary margins may act as a source of nutrients, discharges of sewage effluents or illegal domestic discharges may also lead to the enrichment of nutrients in the water and consequently modify the DO oxygen levels in the water. Moreover, in the present implementation, the WAQ module only considers algae and primary producers, while neglecting other oxygen consumers, such as bacteria. The prediction of DO is particularly difficult since it depends on the physical and biological interaction, including vertical mixing, air–sea exchange, oxygen release by primary production, and oxygen consumption by respiration/mineralization [6]. This portrays the difficult operation in modeling water quality parameters.

Regarding the SSE in Óbidos Lagoon, the model accurately represents the phase and amplitude of the observed tide, with the best adjustment in the station close to the mouth (OB1). As the mouth configuration changes over time and the inlet sandbank migrates both in space and time, the morphological uncertainties inherently increase errors in the estimation of SSE. In the remaining stations, there is also a good fit between the model results and observations, however, with small differences in amplitude, where the model

tends to underestimate the observed values. The highest errors found for the inner stations are due to the propagation of tidal uncertainties towards areas where the bathymetric information is scarce. The highest RMSE at the OB2 station is associated with a phase lag between model results and observations, which is more evident during the neap tide. Comparing with similar studies, the implementation developed shows better agreement with observational data [42].

Regarding the current velocity, in general, the model represents adequately the temporal variation of data. For T2 section, the model is not able to reproduce the first minimum, overestimating the observed value. However, as there is a good fit between the remaining observations and the model results, both in this station and in the rest, it can conclude that the model reproduces the current velocity with high accuracy. Moreover, the errors between model results and observed current velocity are on average 0.1 m/s, which according to [32] expresses a good performance of the model.

For the water temperature and salinity calibration, an acceptable fit was achieved for the analyzed stations. Indeed, the model underestimates salinity in a few observing stations, reflecting the uncertainties related to freshwater inflow data as well as lack of continuous monitoring of river flow.

Regarding the DO concentration, the model fairly reproduces the observations, showing some discordant points. Some observations show very low DO content (around 3 g/m^3), which may indicate a hypoxia event. These events are difficult to predict due to their local origin and might have to do with sewage discharges that are not considered in the model implementation. Additionally, although the DO dataset covers one year, the fact that this data is not continuous may be a source of uncertainties. Therefore, the use of a more continuous dataset would be an asset for future studies.

Taking into account all the difficulties listed before, and considering the approximations performed in the governing equations, the outdated bathymetries available, as well as the frequent inaccuracy of data used as boundary conditions or to perform the model calibration, the models cannot represent perfectly the reality. Therefore, it is assumed by all estuarine modelers that the model's performance deteriorates from the hydrodynamics to the water temperature and salinity and finally to water quality predictions [9,43], due to the consecutive dependence of the solutions, the parametrizations used, and complexity of all the processes inherent to each one of those variables. Regarding Delft3D applications, the authors of [9] obtained errors between 7% and 16% of the local mean water temperature and between 10% and 50% of the local mean salinity for Ria de Aveiro. Regarding water quality parameters the authors refer that the model deviations are higher than those obtained for water temperature and salinity. In [44], the authors evaluated the performance of Delft3D in reproducing hydrodynamic and water quality parameters in Lake Eğirdir and found discrepancies between model results and data in the same order or higher than those found herein. Other examples of Delft3D implementations with similar errors are found in [6,10]. Comparing the results here obtained for both Mondego Estuary and Óbidos Lagoon, it seems that the Delft3D performance is similar to that found in the studies referred above. Moreover, the model's accuracy is similar for both cases, despite being subject to different human pressures, having different sources of data available to use as boundary conditions and to calibrate the models, as well as their general distinctive features.

5.2. Tidal Characterization and Water Renewal

For both Mondego Estuary and Óbidos Lagoon, tides are predominantly semidiurnal, and therefore the M_2 and S_2 are the most important constituents (Figure 6). For both estuaries, the amplitude of the semidiurnal constituents decreases towards the end of the channels, and the phase lag increases, due to bottom friction that becomes more significant in lower depth areas. The decrease in amplitude and the increase in phase are different among both estuaries. On the one hand, for Mondego Estuary this longitudinal gradient occurs gradually, while in Óbidos Lagoon it is more abrupt. Indeed, at the entrance of the Óbidos Lagoon a decrease of about 0.6 m (0.25 m) in the M_2 (S_2) amplitude and an

increase of 30° (40°) in the phase is observed (Figure 6), evidencing the importance of the bathymetry and configuration/width of the lagoon in the tidal propagation.

The results obtained for the M_4 constituent demonstrate that its amplitude is negligible in the coastal region, with an amplitude of 0.01 m, but increases rapidly inside both estuaries. As observed for both semidiurnal constituents, the amplitude of M_4 constituent at the Óbidos Lagoon entrance is quite high (0.08 m) when compared with the amplitude in Mondego Estuary (0.02 m), evidencing that M_4 is strongly influenced by changes in morphology and bathymetry. Indeed, the entrance of the lagoon is a very dynamic region with the mouth configuration changing over time. After the entrance of Óbidos Lagoon, in the tidal channels of the lower lagoon, the amplitude of M_4 decrease to 0.05 m, increasing upstream to 0.06 m. For Mondego Estuary there is an increase in the M_4 amplitude upstream, reaching 0.14 m in the head of the estuary and in the upstream area of the south arm, which is shallow and almost silted up [22]. Regarding the phase of M_4 constituent, a slight increase from the mouth to the upstream area is observed for Óbidos Lagoon (due to the almost constant depth of the upper lagoon), while for Mondego Estuary the M_4 phase rapidly intensifies as a result of an abrupt change in geomorphology (due to the location of the port and marina which correspond to areas with stronger geomorphologic changes). Therefore, the amplitude and phase variations occur predominantly in areas with significant modifications in morphology and bathymetry.

The generation of shallow-water overtides in shallow coastal areas with a large semidiurnal tidal range (dominated by M_2) leads to tidal distortion and, therefore, to changes in the advection of local properties.

Comparing both systems, in general, the tidal distortion is higher in Óbidos Lagoon than in Mondego Estuary (except for the south arm), evidencing the importance of the system bathymetry and configuration. Particularly, Mondego Estuary presents an ebb-tidal dominance in the central area (with the ebb-tidal prism higher than the flood for both spring and neap tides), revealing the potential to export sediments and other properties from this region to the ocean. Towards the end of the Mondego Estuary, a flood dominance is observed, underlying the potential to retain properties, with great expression in the south arm of the system (with an amplitude ratio higher than 0.3), due to its bathymetric characteristics. Several works [24,45,46] have reported eutrophication problems in the south arm of the system, due to human activities, nutrient and chemical discharge from agricultural lands, aquaculture farms, and industries. Indeed, this region presents high residence times, 12 days for summer dropping to 1.5 days for winter (Figure 8), meaning that the retention of water properties, such as nutrients and pollutants decreases the water quality.

Óbidos Lagoon revealed a flood dominance, with a flood tidal prism 1.8 times higher than the ebb in spring tide and similar during neap tide, promoting the inflow of sediments and properties into the lagoon. Indeed, the water remains for more than 6 days in winter and more than 10 days in summer in the upper lagoon, showing a low water renewal capacity. Otherwise, in the lower lagoon, the water exchange is more effective since the residence time is approximately 3 and 3.7 days for wet and dry seasons, respectively (Figure 8). This result evidenced that the freshwater input plays a minor role in Óbidos Lagoon (freshwater fraction of 0.08 in the upper lagoon in winter) since the average flow is less than 1% of the average tidal prism computed for both spring and neap tide. This value is below the one computed by [19], due to differences in the flood tidal prism computed for spring tide that is quite lower in the present study. This might be explained by differences in the period simulated, since the sandbank that exists in the lagoon entrance changes location over time, leading to changes in the total water volume flowing into the lagoon.

Results prove that Mondego Estuary has higher water volume exchange with the adjacent ocean when compared to Óbidos, as a result of the highest fluvial discharge (with a freshwater fraction higher than 0.8 in the upstream half of the estuary for both seasons), contributing to a better water renewal and preventing events of eutrophication or pollutants retention in the estuary (except for the south arm).

5.3. Water Temperature, Salinity DO, and Residence Time Relation

From the spatial distribution of water temperature (Figure 9), salinity (Figure 10), and DO (Figure 11), different patterns were found among both estuaries. These differences are mainly attributed to the physical processes driving the dynamics of both systems, such as the different freshwater inflow, which is much higher for Mondego Estuary, and the different geomorphological configurations.

For Mondego Estuary, the extreme water temperatures (highest in summer and lowest in winter) occur in the central estuary, including part of the north and south arms, whilst for Óbidos Lagoon the extreme water temperature is found in the lower lagoon. Additionally, although both systems present a typical estuarine pattern, the range of water salinity is much wider for Mondego Estuary ($0 < S < 36$) than for Óbidos Lagoon ($S > 25$), evidencing the different freshwater contribution for each system. The highest discharges for Mondego Estuary promote the aeration of the water column, since freshwater holds more oxygen than saltwater, and therefore the DO levels are much higher than in Óbidos Lagoon.

Indeed, according to the results (Figure 12), the amount of DO will vary depending on water temperature and salinity differently for both systems, which are related to the residence time.

For Mondego Estuary, the DO is mainly dependent on salinity distribution for winter since the water temperature is approximately constant (CC = -0.46 between salinity and DO). Indeed, during winter the river flow is high and the residence time is low (less than 3 days in most of the estuary) being the majority of the estuary filled with freshwater that presents high DO concentration (CC = 0.80 between salinity and RT and CC = -0.50 between DO and RT). In regions where the salinity is higher than 30 (near the mouth), a decay of the DO level is expected as well as an increase of residence time (Figure 12).

For Óbidos Lagoon, during winter the DO levels are influenced by both water temperature and salinity (CC = 0.96 between DO and salinity and CC = -0.94 between DO and water temperature). Since the tidal prism is higher than the freshwater input into the system, the regions with oceanic influence (higher than 35) present the lowest residence times and lower levels of DO (CC = 0.88 between RT and DO). Further upstream, where the residence time is higher than 4 days, an increase of DO content is expected in response to the decrease in water temperature and salinity.

During the summer, the relation between these variables is similar for both systems, where an increase of residence time leads to an increase in water temperature, with a CC of 0.92 and 0.97 for Mondego Estuary and Óbidos Lagoon, respectively. Consequently, a decay of DO concentrations occurs with high RT, being the CC between DO and RT equal to -0.65 and -0.97 for Mondego Estuary and Óbidos Lagoon, respectively. It seems that, for summer, the water temperature is determinant for the DO distribution in both systems, since a DO decrease is observed when the residence time is higher than 4/6 days along with water temperatures higher than 20 °C. Indeed, several studies reported the influence of water temperature in biological and physical processes that in turn influence DO levels [6,47–49].

6. Conclusions

The Delft-3D numerical model was used to study two estuarine systems in terms of their annual descriptive physical and water quality properties as well as their interrelationship. The study shows that the models developed simulate the hydrodynamics of both systems with high accuracy. Otherwise, the simulation of the temperature/salinity, and dissolved oxygen conditions has a fair accuracy, however, in line with other recent estuarine model applications. Therefore, the models developed are considered an acceptable representation of the system's characteristics and useful to improve the knowledge about two important estuaries currently under-studied.

The main difficulties found in this study are related with the calibration process, namely the lack of continuous in situ data, the poor definition of landward boundary conditions (use of climatology flow and water properties), the lack of recent bathymetric

data, or the unquantified sources of pollution reported in the literature, which could not be considered in the models.

Results suggest that the tidal propagation and asymmetry are mainly determined by the estuaries geomorphology as well as the inflow of freshwater into the systems. Therefore, the Óbidos Lagoon presents higher tidal distortion than Mondego Estuary and less effective water renewal, due to the low freshwater input.

According to the seasonal distribution of water temperature, salinity, and DO concentration, together with the residence time, a different response of each system was identified. For Mondego Estuary, in winter the salinity becomes the determinant factor affecting the DO levels since the freshwater input is high. For summer both systems present higher residence times than for winter and the water temperature is the main environmental factor affecting the DO contents in the water column.

Delft3D model software proves to be an efficient tool in reproducing the annual environmental fluctuations of the estuarine systems under research, showing a high capacity to simulate their dynamics under different conditions of human pressure. To conclude, the high transferability and stability of Delft3D make this model the ideal basis for realistic simulation and investigation of estuarine systems with different characteristics, supporting the definition of measures for its maintenance and restoration by the local authorities and stakeholders.

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