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Assessing Present and Future Ecological Status of Ria de Aveiro: A Modeling Study

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Abstract: Coastal lagoons hold significant ecological value due to their rich biodiversity and essential roles in supporting ecosystems. However, they are increasingly threatened by accelerated climate change, and it is crucial to assess these environments' ecological status for present and future conditions resulting from the impacts of climate change. In this context, the present work aims to evaluate the present and future ecological status of Ria de Aveiro through the application of the numerical model Delft3D. The model was validated, and the results demonstrate that it effectively captures the main characteristics of the lagoon dynamics, although achieving accurate water quality representation poses challenges due to interdependencies in solutions and the inherent complexity of associated processes. The model was explored to characterize the environmental factors of the lagoon and evaluate its ecological status through the computation of several indexes. According to the model results, the main environmental factors present seasonal variations consistent with temperate climates. Regarding the ecological status of Ria de Aveiro, the central channels of the lagoon mostly hold a Good/Moderate status, while regions near river inflows tend to exhibit Moderate to Poor conditions. In future conditions, water quality is expected to improve in winter and autumn due to reductions in river-borne pollutants resulting from the projected decrease in river flow. For spring and summer, a decline in water quality is projected mainly due to the increase in phosphate concentrations in the lagoon. This study provides valuable insights into the ecological dynamics of coastal lagoons under changing climatic conditions, contributing to improved management and mitigation strategies. The findings can guide future conservation efforts and help mitigate the adverse effects of climate change on these vital ecosystems.

Keywords: Delft3D; climate change; seasonal characterization; ecological status

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1. Introduction

Coastal systems play a key role in the Earth's ecosystems, offering a unique interface between terrestrial and marine environments, being among the most productive, biologically, and geochemically active and diverse systems on Earth [1–3]. Their significance lies not only in providing habitats for diverse flora and fauna, but also in offering valuable ecosystem services to human populations, such as fisheries, recreation, and coastal protection [4]. Additionally, coastal systems play a crucial role in processes like nutrient cycling, decomposition and transformation of organic matter, and the removal of pollutants (heavy metals, for instance) [5,6].

At the same time, these regions face direct threats due to intense human activities [7], including industrial and agricultural practices and littering, as well as to the wider impacts of global climate change [8,9], making them increasingly vulnerable. Indeed, the influx of nutrients from agricultural and industrial activities fosters accelerated algae growth, potentially disrupting the balance of aquatic organisms and compromising water quality [10]. Additionally, changes in sea levels, air/water temperature, and precipitation patterns, as well as ocean acidification, can disrupt the delicate balance of coastal ecosystems, posing additional challenges to marine and terrestrial life [11]. Therefore, the evaluation of the ecological status of these systems is of crucial importance, as it provides essential insights into their health and resilience, addressing present pressures and foreseeing future challenges. Understanding the current condition of these ecosystems allows for informed decision making to mitigate existing threats while enabling proactive measures to anticipate and adapt to emerging environmental stressors.

The ecological status of European surface water bodies is typically expressed as the Ecological Quality Ratio (EQR), which compares the measured value of a specific water body to a reference value established for an undisturbed site [12]. As an example of the application of the EQR, Cereja et al. [13] carried out a comprehensive assessment of the ecological status of the Tagus estuary, evaluating both physicochemical and biological indicators. Their study revealed that water bodies in the central estuary exhibited “Good” and “High” water quality classifications, while those in the upper estuary region showed poorer results. These authors also underscored the significance of potential climate change impacts on the spatial distribution of physicochemical and biological parameters within the Tagus estuary, emphasizing the potential consequences for water classifications.

Although research on the impact of climate change on coastal systems has gained considerable attention in the last years [5,14–17], there is currently a gap in studies specifically addressing the ecological classification within a climate context. Brito et al. [5] investigated the potential biogeochemical responses of a shallow-water coastal lagoon (Ria Formosa) to changes in water temperature and sea-level rise, and evaluated the implications of climate change in eutrophication events. These authors indicated that rising sea levels and global warming are likely to affect shallow coastal lagoons and increase their vulnerability to eutrophication. Other studies [14,15] evaluated the future challenges of aquaculture suitability in two different systems, the Sado Estuary and Ria de Alvor, through numerical modeling. Regarding the Sado Estuary, the results highlight an increase in the water temperature that contributed positively to the chlorophyll-*a* (Chl-*a*) availability and, therefore, to the estuary’s increased suitability for bivalve aquaculture. In Ria de Alvor, future projections suggested a decline in the Chl-*a* concentration and an increase in the water temperature due to climate change, which are significant factors posing threats to bivalve production. Liu et al. [16] implemented a coupled three-dimensional hydrodynamic and water quality model in the Danshuei River estuarine system to predict the influences of climate change on water quality. The results indicated that the dissolved oxygen concentration was projected to decrease, whereas nutrients will increase due to climate change. Cereja et al. [17] investigated how the reduction in river flow, the rise in mean sea level, and the increased nutrient input from human activities impact the Tagus estuary. The results suggested that reduced river flow and rising sea levels resulted in elevated salinities, alongside decreased concentrations of nutrients and chlorophyll-a in the middle and upper regions of the estuary. This decline in river-derived nutrients could potentially heighten the influence of anthropogenic nutrient sources on the spatial distribution of phytoplankton communities in the future.

The present study focuses on Ria de Aveiro, a coastal lagoon located on Portugal’s northwestern coast (Figure 1). Comprising diverse ecosystems, including beaches, dunes, mudflats, salt marshes, seagrasses, and narrow channels, Ria de Aveiro is recognized as a Natura 2000 site [18] and holds designations as a Special Protection Zone and a Site of Community Importance under the EU Birds and Habitats Directives. The lagoon plays an important ecological role, as it serves as the habitat for numerous species of flora and fauna whose existence is supported by the lagoon’s dynamics [19].

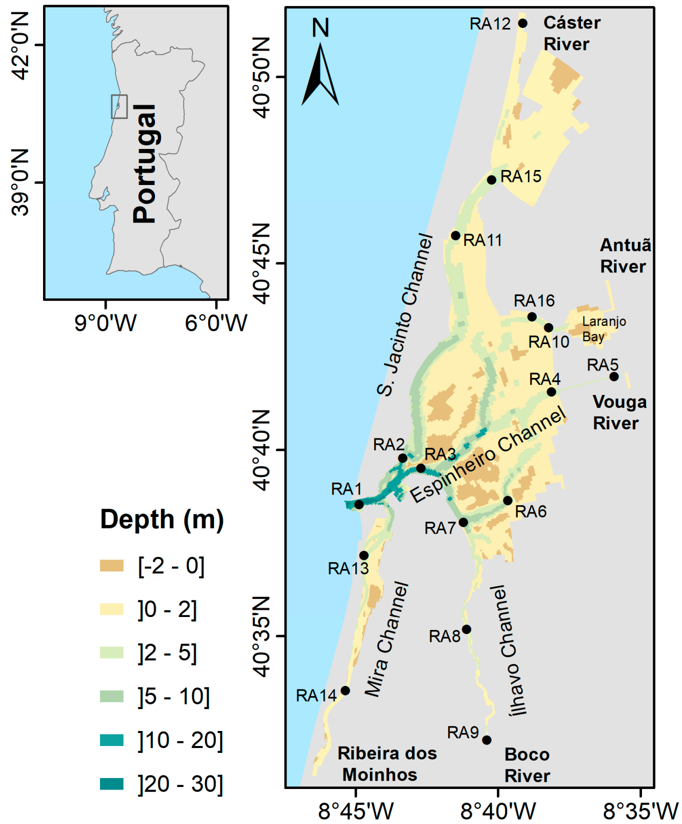

Figure 1. Bathymetry of Ria de Aveiro, with the location of the validation stations, main channels, and rivers.

With its rich biodiversity, the lagoon provides various ecosystem services linked to socio-economic activities of considerable economic importance. Notable examples include agriculture, livestock, heavy industry, traditional practices (such as salt production and bait digging), tourism, and recreation (including sailing and surfing). Additionally, maritime port operations, aquaculture, and commercial fishing contribute significantly to the regional economy and the Portuguese fisheries market, with the Aveiro region holding a key position [20,21]. Aligned with the global trend, Ria de Aveiro has also experienced multiple pressures, including urbanization, industrial activities, pollution, and climate change impacts. In this context, it is imperative to recognize the interconnection of physical, chemical, and biological aspects in order to implement effective conservation measures and ensure the continued health and resilience of Ria de Aveiro in the face of a changing climate.

While several studies have previously examined the water quality characteristics of Ria de Aveiro, these investigations have often been limited by the spatial and temporal coverage of in situ data, as well as the lack of continuous measurements. Additionally, most prior works have focused on current environmental conditions without providing a comprehensive assessment of how future climate change could impact the lagoon's water quality and ecological status.

Consequently, this work addresses these gaps, intending to contribute to a better understanding of how climate change may influence the ecological status of Ria de Aveiro, through the development and application of a numerical model implementation based on the Delft3D model suite. Therefore, the main goals of the present study are as follows: (1) characterize the present abiotic environmental conditions of Ria de Aveiro; (2) assess the lagoon's present water quality; and (3) project potential ecological shifts based on future changes in environmental conditions. By addressing these objectives, this research aims to enhance the understanding of Ria de Aveiro's ecological dynamics and provide valuable information for effective conservation and management strategies in a changing climate. Thus, this research's novelty lies in its integration of future climate scenarios and the application of a validated model to fill critical gaps in the prediction and management of estuarine water quality.

2. Study Area

Ria de Aveiro is a mesotidal coastal lagoon on the northwest coast of Portugal (Figure 1). It is distinguished by its extensive mudflats, salt marshes, and narrow channels, which connect to the Atlantic Ocean through a single, artificially stabilized inlet. The lagoon stretches 45 km in length and 10 km in width. During spring tide, its area is 89.2 km^2 at high tide and 64.9 km^2 at low tide [22]. The lagoon has an average depth of 0.8 m relative to the mean sea level [22]. The semidiurnal tide combined is the primary driver of circulation within the lagoon that combined with the freshwater inflow controls the water mass dynamics. Tide propagates from the lagoon's mouth, exhibiting similar characteristics to a damped progressive wave, with the amplitude decreasing from the mouth to upstream as the phase lag increases [23].

The lagoon has four main channels that connect to its mouth, namely the S. Jacinto, Espinheiro, Mira, and Ílhavo channels, which receive freshwater from five rivers: the Vouga, Antuã, Cáster, Boco, and Ribeira dos Moinhos (Figure 1). The Vouga River contributes an average flow of 80 m^3/s [22], accounting for approximately two-thirds of the freshwater entering the lagoon [24]. The average flows of the Antuã, Ribeira dos Moinhos, Boco, and Cáster rivers are significantly lower, at around 20, 10, 5, and 5 m^3/s, respectively [22]. These rivers transport nutrients from diffuse sources related to agricultural activities [25,26].

In 1998, the S. Jacinto Submarine Sea outfall was built to mitigate the negative impacts of the wastewater discharge into the lagoon [27]. It is located 3 km north of the lagoon inlet and 3.3 km offshore. Nowadays, it drains the treated effluent from the three wastewater treatment plants and from 10 municipalities, which account for over 300,000 inhabitants [28,29].

3. Materials and Methods

3.1. Model Setup

The numerical model Delft3D (version 4.0.2) was implemented for Ria de Aveiro, considering the FLOW and WAQ modules. The hydrodynamic module (FLOW) solves the 3D baroclinic Navier–Stokes and transport equations under the Boussinesq assumption. A comprehensive overview of the model is available in [30]. The WAQ is the water quality module, responsible for calculating the mass balance of state variables within each computational cell, while ensuring the mass conservation principle [31]. It accounts for mass transport driven by dispersion and advection, as the latter is derived from the FLOW hydrodynamic model.

The Delft3D-FLOW and WAQ modules were selected for their proven effectiveness in simulating complex hydrodynamic and water quality processes in estuarine environments like Ria de Aveiro [32–35]. These modules ensure reliable predictions of the lagoon's current and future ecological status, making them ideal for this study. Their successful application in similar studies and adaptability to climate change scenarios further support their use [14,15,36].

A curvilinear grid with 193 × 459 cells was used, with a horizontal resolution between 25 and 200 m inside the lagoon and 200 and 500 m in the coastal region. Bathymetric data from a general survey conducted in 1987/88 by the Hydrographic Institute of the Portuguese Navy were used in the entire lagoon. These data were then updated with more recent surveys, specifically in 2011 by Polis Litoral Ria de Aveiro in the main channels of the lagoon, and 2020 by the Aveiro Port Administration (APA) and University of Aveiro (UA) in the lagoon's inlet and port area [37].

At the open boundary, the amplitude and phase of 19 tidal constituents derived from the harmonic analysis of water-level observations at the lagoon's mouth (station RA1 in Figure 1) with a temporal resolution of 6 min were imposed. A correction factor was considered accounting for the distance between the open boundary and the tide gauge.

Additionally, at the open ocean boundary, the model also uses water temperature, salinity, pH, nutrient, Chl-*a*, and dissolved oxygen (DO) concentration obtained from the Atlantic Iberian Biscay Irish Ocean model provided by the Copernicus Marine Environment Monitoring Service (CMEMS) [38].

The atmospheric conditions applied at the ocean–atmosphere boundary include surface air temperature, relative humidity, and net solar radiation, calculated using data from ERA5 provided by the European Centre for Medium-Range Weather Forecasts [39]. Finally, the freshwater input (runoff and water properties) for the five main rivers obtained from the watershed model Soil and Water Integrated Model (SWIM) [40] were imposed as landward boundary conditions.

A 2D approximation was considered, due to the lagoon shallowness and the low freshwater input relative to the tidal prism. A time step of 30 s was selected for the hydrodynamic module (FLOW) and 2 min for the water quality (WAQ) to ensure the stability and accuracy of numerical outputs.

3.2. Model Performance

To assess the model's performance and ensure its reliability in replicating the physical and chemical characteristics of the lagoon, a series of simulations were conducted to test various model free parameters until stable solutions were obtained. Subsequently, for the calibration of the FLOW module, multiple simulations were executed, adjusting the bottom roughness until an optimal fit between the model outputs and in situ data was achieved. For Ria de Aveiro, the most accurate results were obtained using a dynamic coefficient of friction for bottom roughness, which is recalculated at each time step of the model [41]. In the WAQ module, key parameters for enhancing model accuracy included the total net primary production (set at 0.1 $gCm^{-2}day^{-1}$), maximum production rate (set at 1.4 day^{-1}), maintenance respiration (set at 0.5), growth respiration factor (set at 0.15), and mortality rate constant (set at 0.35 day^{-1}).

Attending the focus of this research, only the validation results enforcing the model skill in reproducing the observed variables will be further discussed.

To validate the hydrodynamic model, sea surface elevation data from 16 tide gauge stations for 2002/2003 and 2016 were used. These data sets were collected by the UA and APA, respectively. The sea levels of 2002/03 have an hourly temporal resolution, while the 2016 data have a 20 min periodicity.

Additionally, salinity and water temperature data for the year 2016 were also obtained and provided by the APA with a temporal resolution of 20 min. Regarding the water quality module's validation, data from several sources were used. The pH, Chl-*a*, and DO concentrations at stations RA8, RA13, and RA15 were obtained in 2013 and 2014 in the framework of the project BioChangeR: Biogeochemical Processes Induced by Climate and Anthropogenic Circulation Changes—The Case Study of Ria de Aveiro (Portugal), with a temporal resolution of one minute. Additionally, nutrient and Chl-*a* concentrations for 2000/2001 and 2002 were obtained by the UA. For the RA1 station, data were measured every 1.5 h throughout a tidal cycle, while for the RA4 station, data were collected on a quarterly basis.

The root mean square error (*RMSE*) and the predictive skill (*Skill*) metrics were calculated for sea surface elevation, water temperature, and salinity over a one-month time series to assess the model accuracy. For water quality parameters, only the *RMSE* was computed due to the limited data availability, which spans only 12 h. This short duration may not provide a sufficient range of variability required to accurately compute the *Skill* metric, which typically needs a longer data series to capture temporal trends and patterns effectively.

3.3. Climate Change Scenarios

To evaluate the impact of climate changes on the ecological water quality status of Ria de Aveiro, two simulations were performed: one considering the present scenario (baseline year 2018), with the model setup previously described, and the other based on the projections from the 6th Assessment Report (AR6) by the Intergovernmental Panel on Climate Change (IPCC) covering the period 2081–2100 relative to the baseline period of 1995–2014. The most pessimistic scenario SSP5-8.5 was considered, representing extremely high greenhouse gas emissions, with annual CO_2 emissions to triple by 2080.

The future scenario was incorporated into the model by changing the boundary inputs of the air temperature (AT), mean sea level (MSL), sea surface temperature (SST), salinity, Chl-*a* and DO concentrations, and pH, following the methodology of Picado et al. [15]. Specifically, the differences between the SSP5-8.5 future scenario and the present conditions (average changes from 2081 to 2100 relative to 1995 to 2014—Table 1) were applied to the ocean boundaries of the baseline simulation. This was performed instead of applying directly the projections from the AR6 because of the low temporal resolution of the models. This approach allowed for a projection of future conditions based on expected climate change.

Table 1. Projected average changes for the west coast of Portugal (near Ria de Aveiro).

Season	AT (°C)	MSL (m)	SST (°C)	Salinity	Chl-*a* (%)	DO (mg/L)	pH
DJF	+3.1	+0.73	+2.0	−0.8	−38	−0.34	−0.40
MAM	+3.7		+2.1		−59	−0.32	
JJA	+5.3		+2.2		+32	−0.18	
SON	+4.6		+2.5		−14	−0.27	

Table 1 shows the mean differences between future and baseline scenarios for the west coast of Portugal, considering four seasons: winter (December to February—DJF), spring (March to May—MAM), summer (June to August—JJA), and autumn (September to November—SON). A reduction of approximately 30% in the nutrient (NO_3, PO_4, and NH_4) concentration was considered according to the projections performed by Pereira et al. [14]. The MSL, SST, AT, and pH changes are available in [42], and the salinity, Chl-*a*, and DO were computed from an ensemble of CMIP6 models [43]. The watershed model SWIM [40] provided the main tributaries' inflow and water properties for the future period. Generally, a reduction in flow and nitrate concentration is predicted for the future, with the most significant changes expected during winter. Relative to the phosphate concentration, for the Antuã and Vouga rivers, the watershed model SWIM predicts an increase during the spring and summer months.

3.4. Seasonal Characterization of Environmental Factors

To perform the seasonal characterization of the abiotic environmental factors (water temperature, salinity, nitrate, phosphate, Chl-*a* concentration, and DO) for the present scenario, Deldt3D was used to conduct an annual simulation, with an initialization period of 6 months.

Regarding salinity, the zonation by the Venice System was conducted. The Venice System zonation considers 5 sections: limnetic (salinity below 0.5), oligohaline (salinity between 0.5 and 5), mesohaline (salinity between 5 and 18), polyhaline (salinity between 18 and 30), and euhaline (salinity above 30).

Additionally, the difference between the future and present scenarios was computed for all variables (water temperature, salinity, Chl-*a*, nitrate, phosphate, and DO) at five stations. The stations were chosen to represent the lagoon's mouth and each main channel.

3.5. Ecological Water Quality Indicators

The ecological water quality of Ria de Aveiro was also seasonally assessed both under the present conditions and for the projected future scenario. In this context, a set of ecological water quality indicators were computed based on the nutrient (nitrate and phosphate), DO, and Chl-*a* concentration. The nutrient and DO indicators were calculated following the recommendations of the Portuguese Environmental Agency [44], by calculating the ratio between the 90th percentile of the nutrient/oxygen concentrations during a year and reference values. These reference values were derived by [44] for Portuguese transitional waters taking into account four salinity classes (0–10, 10–20, 20–30, and >30). For DO, the results between 0.7 and 1.2 inclusive are considered Good, and for nutrients, the classification Good is attributed to the results lower than 2 inclusive. The Chl-*a* indicator was calculated following [44,45], which consists of computing the ratio between the reference value and the 90th percentile of the Chl-*a* concentration for an annual time series. The reference values were derived by [45] and consider two salinity ranges ($\leq$25, and >25). Results are then converted into Bad ([0–0.2]), Mediocre ([0.2–0.3]), Fair ([0.3–0.44]), Good ([0.44–0.67]), and Excellent ($\geq$0.67).

Additionally, the trophic index (*TRIX*) was calculated considering all the variables together according to the following equation [46]:

$$TRIX = [log(Chl - a \times |100 - \%DO| \times NID \times PT) + 1.5]/1.2 \quad (1)$$

where $Chl - a$ is the chlorophyll-*a* concentration (µg/L), $|100 - \%DO|$ the absolute percentage deviation from oxygen saturation (%), NID the concentration of dissolved inorganic nitrogen (µg/L), and PT the total phosphorus concentration (phosphate concentration in µg/L was used in this study). The coefficients 1.2 and 1.5 are used to establish the index lower limits and the scale interval between 0 and 10. Results were converted into the classification of High ([0–4]), Good ([4–5]), Moderate ([5–6]), and Poor ([6–10]) water quality.

4. Results

This section presents the model validation, which involves comparing the in situ data described before and the model results of the hydrodynamic and water quality variables. Also, a seasonal characterization of the water temperature, salinity, DO, Chl-*a*, nitrate, and phosphate concentrations are outlined for the present scenario, and differences with the future were also computed. The ecological water quality indicators were also computed and mapped seasonally for present and future scenarios.

4.1. Model Validation

Table 2 presents the *RMSE* obtained by comparing a one-month water-level time series for 16 stations (RA1 to RA16 in Figure 1). Generally, it is found to be a good fit between the model results and observations. For the station located at the lagoon's mouth (RA1), the *RMSE* for the water level is approximately 0.05 m for 2002/2003 and 0.06 m for 2016, representing about 3% of the local tidal range. The highest errors were found at stations RA9 and RA12, with an *RMSE* of 0.26 m and a *Skill* of 0.93 and 0.90 m. These two stations are in the head of the Íllhavo and S. Jacinto channels, respectively, and the disagreements may be related to local bathymetric uncertainties. Regarding the Íllhavo channel, it should be noted that it is characterized by very narrow sections, where strong current velocities occur, making it a particularly difficult region for accurate representation by the model. Nevertheless, these results are in line with previous studies [23] and, therefore, it can be considered that the model can accurately reproduce the evolution of the sea surface elevation in all the lagoon stations. Regarding the quantitative evaluation using the *Skill* parameter, in general, the results are quite good, since almost all stations present values higher than 0.95 (except for stations RA9 and RA12 previously mentioned).

Concerning the water temperature, the results suggest adequate reproduction at all stations since the *RMSE* is less than 1 °C. The *Skill* parameter is higher than 0.95 at stations RA8, RA15, and RA16, revealing high model accuracy (Table 3). However, for stations RA4 and RA14, the *Skill* is 0.81 and 0.94, respectively. Regarding salinity, in general, there is a fair fit between the model results and observations, with an adequate reproduction of the maximum and minimum values. It is also verified (Table 3) that the highest *RMSEs* are found in stations RA4 and RA8 (5.90 and 6.40, respectively), while the *RMSE* is less than 4 for the other stations. Indeed, the water temperature and salinity are strongly influenced by river discharge, and therefore less accurate definition of flow and freshwater properties may compromise the results, especially at stations located upstream. Thus, the errors obtained may be due to the fact that, in the present implementation, data from a watershed model for the five freshwater sources are used as a boundary condition as a consequence of the lack of in situ data. However, the results are in agreement with previous works [23] and it can be considered that the model adequately simulates the salt and heat transport in Ria de Aveiro.

Table 2. *RMSE* and *Skill* for a one-month water-level time series.

Stations	2002/2003		2016	
	***RMSE* (m)**	***Skill***	***RMSE* (m)**	***Skill***
RA1	0.05	0.999	0.06	0.998
RA2	0.08	0.997	–	–
RA3	0.13	0.993	–	–
RA4	0.12	0.991	0.09	0.995
RA5	0.17	0.976	–	–
RA6	0.09	0.996	–	–
RA7	0.07	0.998	–	–
RA8	0.23	0.955	0.20	0.967
RA9	0.26	0.929	–	–
RA10	0.14	0.987	–	–
RA11	0.07	0.995	–	–
RA12	0.26	0.900	–	–
RA13	0.12	0.994	–	–
RA14	0.19	0.972	0.10	0.993
RA15	–	–	0.11	0.991
RA16	–	–	0.11	0.992

Table 3. *RMSE* and *Skill* for water temperature and salinity time series, for the year 2016.

Stations	Water Temperature		Salinity	
	***RMSE* (°C)**	***Skill***	***RMSE***	***Skill***
RA4	0.57	0.807	5.90	0.89
RA8	0.62	0.976	6.40	0.76
RA14	0.72	0.939	3.75	0.89
RA15	0.83	0.965	3.33	0.62
RA16	0.75	0.962	2.77	0.92

The model results for the pH, Chl-*a* concentration, and oxygen saturation for 2013 and 2014 were validated through a comparison with data collected at stations RA8, RA13, and RA15. An example of the comparison between the predicted and in situ data is presented in Figure 2 and the *RMSE* in Table 4. Additionally, Figures 3 and 4 show the comparison between the nitrate, phosphate, ammonium, and Chl-*a* concentration for stations RA1 and RA4, measured during a tidal cycle of 2002 and quarterly for 2000/2001, respectively.

Table 4. *RMSE* for pH, Chl-*a* concentration, and oxygen saturation for the year 2013/2014.

		RA8	**RA13**	**RA15**
Summer	pH	0.24	0.15	0.13
	Chl-*a* (µg/L)	1.53	1.31	1.37
	Oxygen sat. (%)	17.40	-	22.30
Autumn	pH	0.32	0.37	0.63
	Chl-*a* (µg/L)	1.83	1.40	2.86
	Oxygen sat. (%)	9.09	13.70	12.16
Winter	pH	0.24	0.19	0.31
	Chl-*a* (µg/L)	3.60	1.59	4.37
	Oxygen sat. (%)	12.98	5.00	11.78

Table 4. *Cont.*

		RA8	RA13	RA15
Spring	pH	-	0.05	-
	Chl-*a* (μg/L)	-	2.01	-
	Oxygen sat. (%)	-	6.74	-

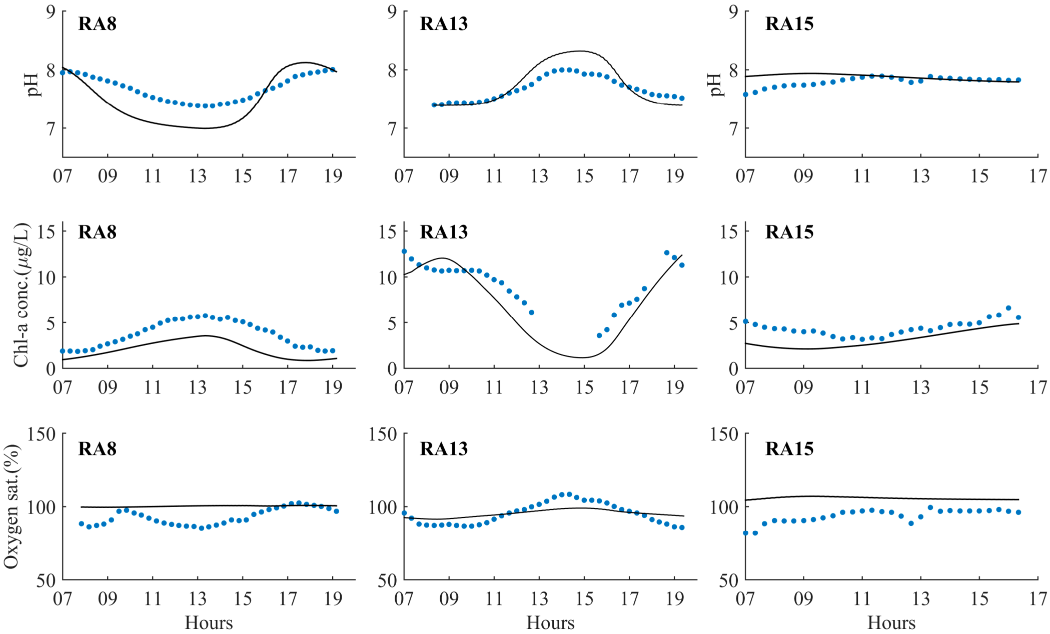

Figure 2. Comparison between model results (black line) and observations (blue dots) of pH, Chl-*a* concentration, and oxygen saturation for stations RA8, RA13, and RA15. Although the data were collected in one-minute intervals, for visualization purposes, it is presented here in 20 min intervals.

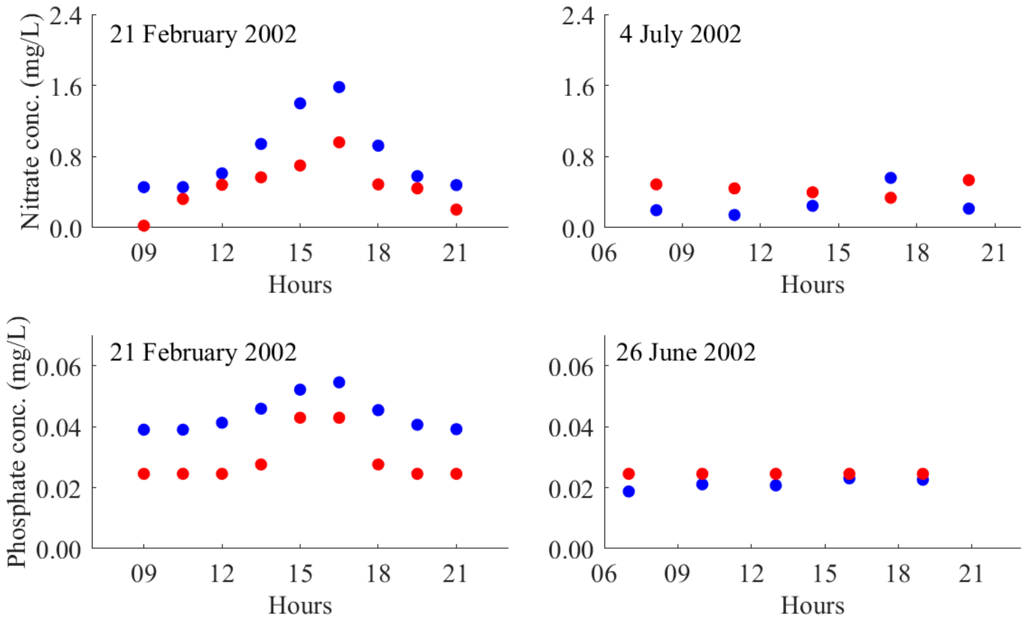

Figure 3. Comparison between model results (blue dots) and observations (red dots) of nitrate and phosphate concentrations (mg/L) at station RA1 for two distinct periods.

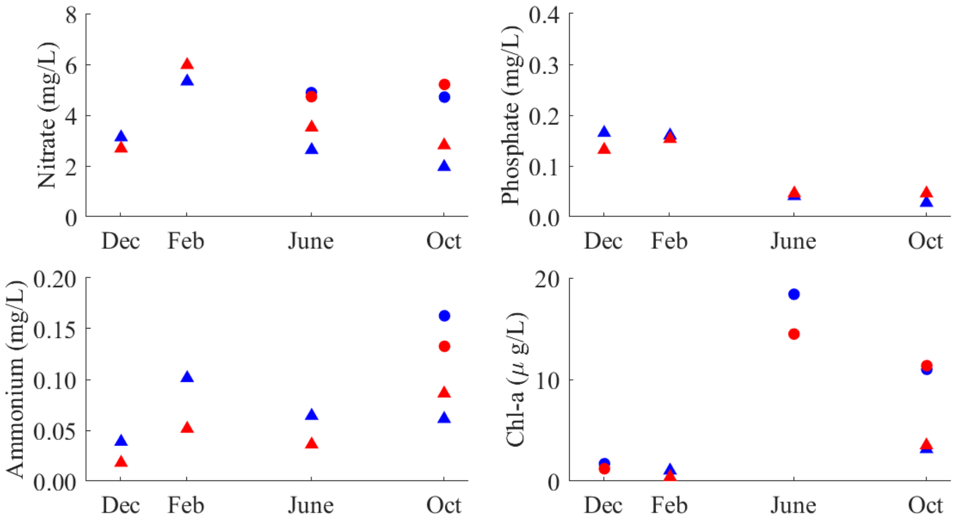

Figure 4. Comparison between model results (blue dot/triangles) and observations (red dots/triangles) of nitrate, phosphate, ammonium, and Chl-*a* concentrations (mg/L) at station RA4 during 2000/2001. Dots referred to low tide instant and triangles to high tide instant.

Generally, there is a reasonable fit between the model results and the observations, especially considering that the water quality variables are extremely difficult to simulate, particularly in such a complex and dynamic system as Ria de Aveiro.

Concerning the pH, it is found that the model can adequately reproduce the instants in which the maxima and minima occur at all stations analyzed. The *RMSE* varies between 0.10 at station RA13 in the summer period and 0.53 at station RA15 in the winter, corresponding to 1 and 6% of the local average, respectively. Concerning the oxygen saturation, for station RA8, the highest *RMSE* is obtained in winter (approximately 20%), and the lowest in summer (8.9%), which can be justified by the uncertainty of the water properties coming from the rivers.

Regarding the nitrate and phosphate concentrations at station RA1 (Figure 3), it is observed that the model overestimates the concentrations in winter, while slightly underestimating them in summer. The *RMSE* for nitrate is 0.41 mg/L in winter and 0.27 mg/L in summer, while for phosphate, it is 0.015 mg/L in winter and 0.004 mg/L in summer. At station RA4 (Figure 4), only a few measurements are available; however, it is observed that the model adequately represents the data. The *RMSEs* are 0.55, 0.014, 0.026 mg/L, and 1.43 µg/L for nitrate, phosphate, ammonium, and Chl-*a*, respectively.

4.2. Seasonal Abiotic Characterization

The seasonal characterization of the environmental abiotic factors in Ria de Aveiro are represented in Figures 5–7.

Generally, throughout the year, the water temperature and salinity (Figure 5) exhibit a well-defined seasonal pattern, characterized by higher water temperatures and salinities during the summer and autumn months (JJA and SON—Figure 5) and lower water temperatures and salinities during winter and spring (DJF and MAM—Figure 5). These seasonal variations reflect river dynamics' significant role in shaping the ecosystem's overall hydrological and environmental conditions throughout the year.

During the winter months (DJF), reduced solar radiation, colder air temperatures, and increased river flow lead to cooling of the water body, resulting in lower water temperatures. Indeed, in winter, the mean water temperature decreases from 12 °C at the lagoon mouth to approximately 10 °C at the end of the Espinheiro channel due to the Vouga and Antuã rivers' influence. Also, at the end of the Mira, Ílhavo, and S. Jacinto channels, the water temperature decreases to 11 °C, revealing river discharges' influence. Regarding the salinity, a typical estuarine pattern is observed. According to the Venice System zonation, the lagoon is classified as euhaline (red in Figure 5) in the inlet channel, polyhaline (orange in Figure 5), and mesohaline (yellow in Figure 5) in the regions immediately upstream, and oligohaline and limnetic (green) in the head of the main channels.

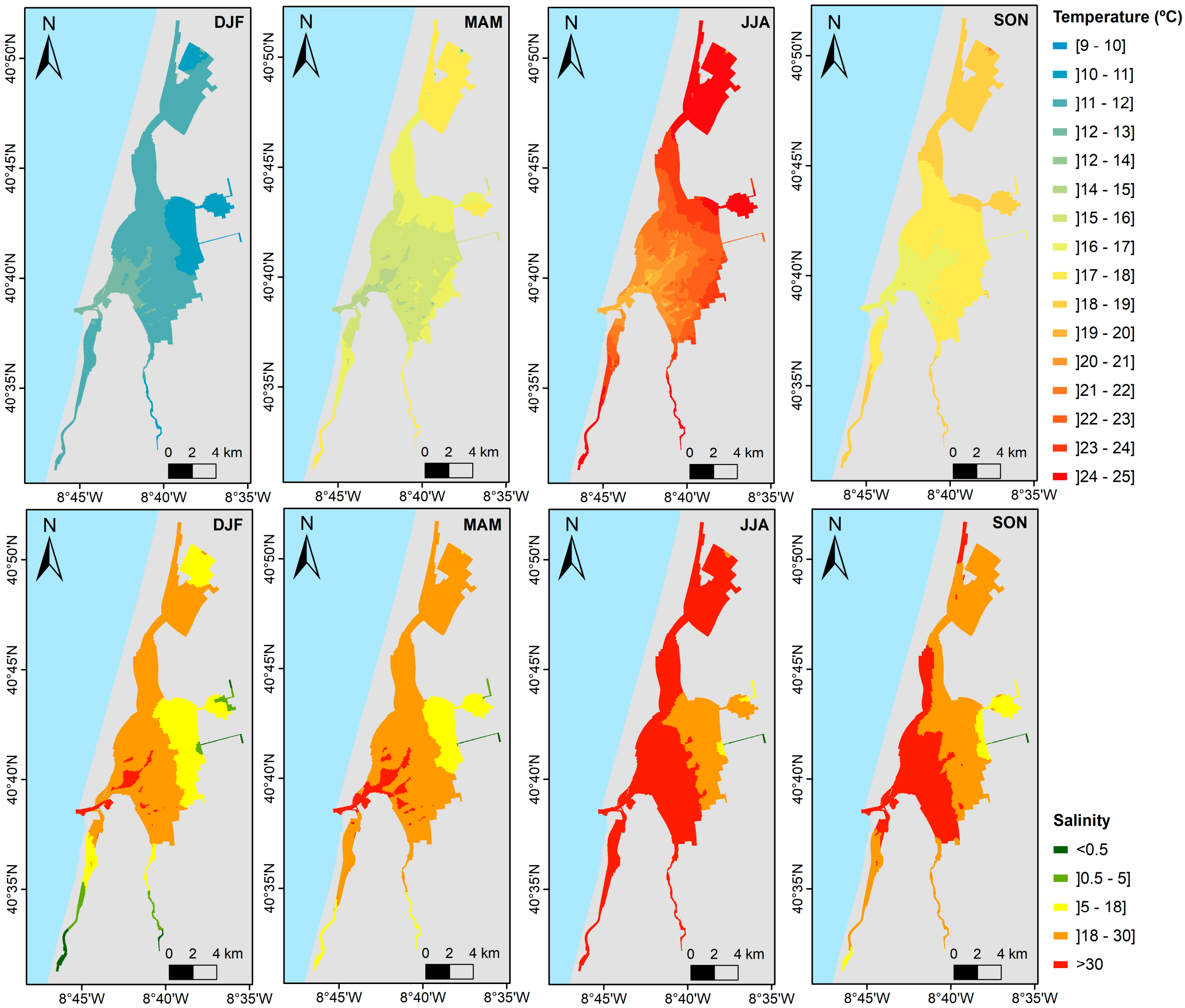

Figure 5. Water temperature (°C) and salinity seasonal averages for the present scenario.

For spring (MAM), the mean water temperature increases, reaching approximately 14.7 °C at the lagoon mouth, 15.5 °C in the central region, and 16.4–17.0 °C upstream.

As for the salinity patterns, the Venice System zonation is similar to that of winter; however, at the end of the Mira, Ílhavo, and S. Jacinto channels, it is classified as mesohaline due to lower river contributions compared to winter. The Vouga and Antuã channels are characterized as limnetic and oligohaline, respectively, as they constitute the primary sources of freshwater into the lagoon.

Throughout the summer (JJA—Figure 5), increased solar radiation and warmer air temperatures contribute to increased water temperatures promoting biological activity. Generally, the water temperature shows a positive longitudinal gradient, with water temperature ranging from 19 °C at the lagoon mouth to 25 °C upstream.

As river discharge decreases, the salinity of the lagoon increases. Indeed, during summer, the majority of the lagoon becomes euhaline, except for the upstream region of the Antuã and Vouga rivers, which is characterized as polyhaline. Locally, in the Vouga and Antuã channels, the salinity is less than 0.5 (limnetic) and approximately 8 (mesohaline), respectively.

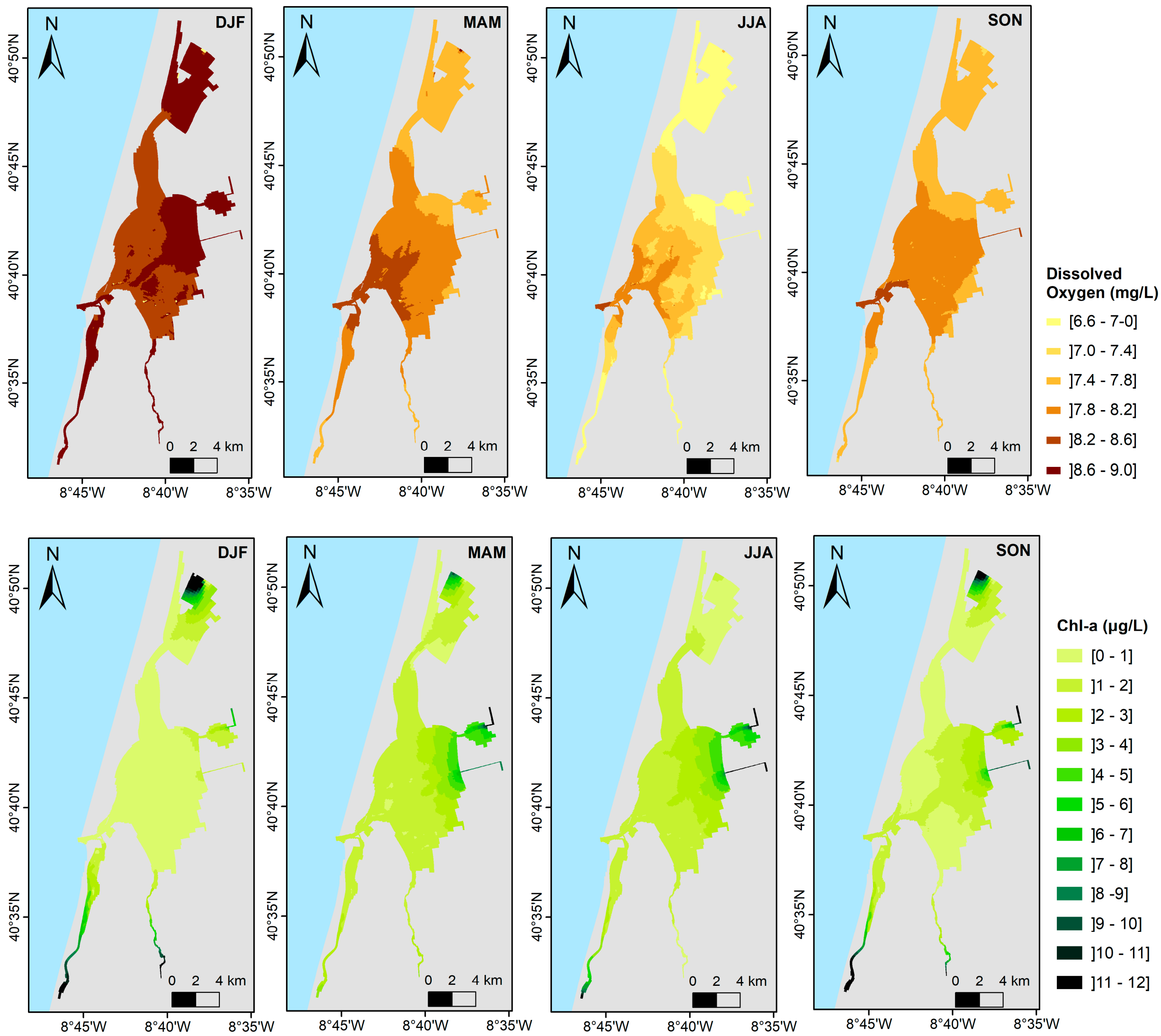

Figure 6. DO (mg/L) and Chl-*a* (µg/L) seasonal averages for the present scenario.

In response to a decrease in air temperature and an increase in freshwater discharges in autumn (SON—Figure 5), the water temperature decreases compared to summer, ranging from 16 °C in the lagoon's mouth and central area to 18.5 °C upstream. Salinity classification is similar to the summer months; however, the euhaline region decreases, leading to an increase in the polyhaline area.

Figure 6 presents the seasonal distribution of DO and Chl-*a* at Ria de Aveiro, while Figure 7 presents the nitrate and phosphate concentrations. Generally, DO exhibits a well-defined seasonal pattern, with higher values during winter and spring and lower during summer and autumn (Figure 6). This pattern is closely related to the water temperature pattern, as colder water holds more dissolved oxygen than warmer water. Conversely, the Chl-*a* concentration typically follows an inverse pattern to that of DO. Regarding nutrient availability (Figure 7), a seasonal pattern is also observed. Specifically, the nutrient concentration (nitrate and phosphate) is higher in winter months and close to the river's mouth.

During winter, the levels of DO consistently exceed 8.5 mg/L throughout the entire lagoon, with the highest concentrations observed in proximity to the lagoon's mouth (8.6 mg/L) and freshwater sources (8.9 mg/L). The Chl-*a* concentration during winter is approximately 0.7 µg/L in the majority of the lagoon, presenting values higher than 9 µg/L in the head of the S. Jacinto, Mira, and Ílhavo channels and 1 µg/L in the Espinheiro channel head. The higher Chl-*a* concentration observed in the head of the Mira and Ílhavo channels, when compared to the Espinheiro channel, can be attributed to several factors. The shallower depth of these regions combined with reduced turbulence (lower runoff) plays a significant role, since shallower regions typically receive more sunlight and lower turbulence allows an effective sunlight penetration in the water column, further supporting the growth of photosynthetic organisms. Also, in winter, high nutrient concentrations in the Mira, Ílhavo, and S. Jacinto channels' head (2, 0.5, and 3 mg/L for nitrate, and 0.04, 0.01, and 0.10 mg/L for phosphate, respectively) are observed, leading to increased phytoplankton growth and subsequently a higher Chl-*a* concentration. At the end of the Espinheiro channel, where the Vouga River discharges (the highest contribution of freshwater into the system), the Chl-*a* concentration is notably low in winter, despite the abundance of nutrients (>8 mg/L of nitrate and 0.3 mg/L of phosphate). This may be attributed to limited light availability, a critical factor influencing photosynthesis and, consequently, the Chl-*a* concentration. Indeed, in areas where high freshwater inputs lead to increased turbidity or sedimentation, light penetration into the water column may be limited, inhibiting the growth of phytoplankton and resulting in lower Chl-*a* concentrations.

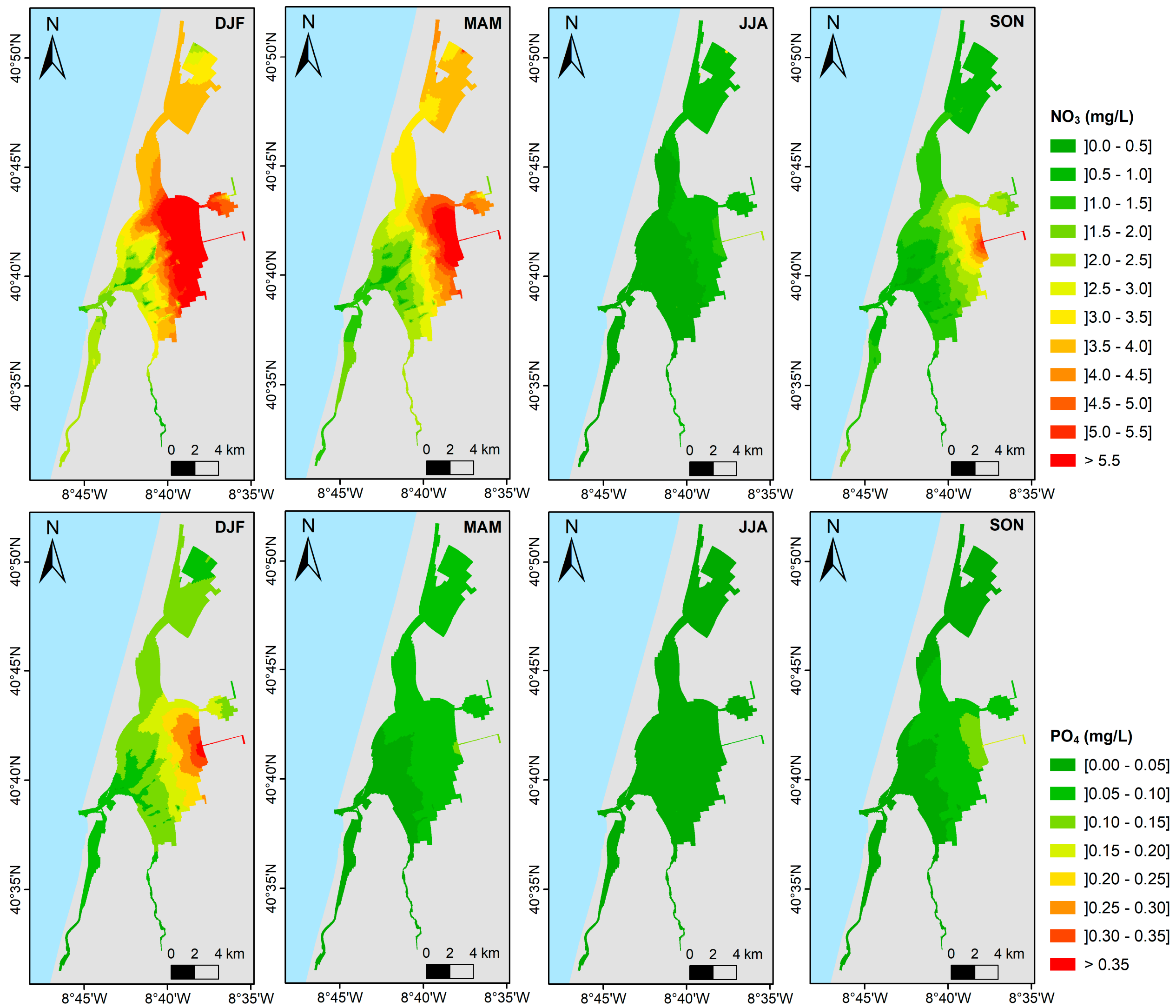

Figure 7. Nitrate (mg/L) and phosphate (mg/L) concentration seasonal averages for the present scenario.

In spring, the DO levels decrease compared to winter, exhibiting a negative longitudinal gradient. The DO concentration during spring ranges from 8.5 mg/L at the lagoon's mouth, gradually decreasing upstream to 7.8 mg/L. Conversely, the Chl-*a* concentration increases to values between 1.2 and 1.6 μg/L in the central area and 5.5 μg/L in the head of the Espinheiro channel. This increase in the Chl-*a* concentration is linked with the uptake of nutrients by phytoplankton, as evidenced by a decrease in the nutrient concentrations. For example, the nitrate concentration ranges from 0.8 mg/L at the lagoon's mouth to 7 mg/L in the head of the Espinheiro channel, while phosphate ranges between 0.03 and 0.09 mg/L. In the head of the Mira and Ílhavo channels, the Chl-*a* concentration decreases by 3.2 and 2.7 µg/L, respectively.

In summer and autumn, the combination of warmer water temperatures and reduced freshwater discharges may lead to decreased levels of DO. Additionally, warmer temperatures accelerate the metabolism of aquatic plants, while longer days provide ample sunlight for photosynthesis, leading to higher Chl-*a* concentrations in the water and consequently nutrient depletion. According to the model results, during summer, the DO concentration is approximately 8.2 mg/L at the lagoon's mouth, ranging from 8.0 to 7.5 mg/L in the central area of the lagoon, and decreasing to 6.5 mg/L at the head of the S. Jacinto, Mira, and Ílhavo channels.

During summer, the Chl-*a* concentration generally increases, ranging from 1.8 µg/L in the lagoon's mouth to 6 µg/L at the end of the Espinheiro channel. At the end of the Mira and Ílhavo channels, the Chl-*a* concentration is approximately 8.0 µg/L and 0.5 µg/L. Additionally, the nutrient concentration decreases significantly to values between 0.2 and 1.5 mg/L for nitrate and between 0.01 and 0.03 mg/L for phosphate. Finally, regarding the spatial variation in DO during autumn, an increase is observed relative to the summer, likely due to the decreasing water temperature. Specifically, the DO concentrations in autumn are around 8.2 mg/L at the lagoon's mouth, 8.0 mg/L in the central area, and 7.5 mg/L upstream. Additionally, a slight decrease in the Chl-*a* concentration occurs in the central region (1 µg/L at the lagoon mouth to 4 µg/L at the end of the Espinheiro channel). Upstream, the Chl-*a* concentration increases in the Mira and Ílhavo heads, probably due to the increase in the river contribution. Regarding the nutrient availability, an increase is observed relative to summer. Specifically, in the central region of the lagoon, concentrations vary between 0.5 and 5 mg/L for nitrate and 0.03 and 0.10 mg/L for phosphate.

For the future scenario, the water temperature presents a generalized increase between 2 and 4 °C throughout the lagoon (Figure 8), with a higher magnitude in station RA4 (near the Vouga River). This increase is primarily attributed to the rise in sea surface and air temperatures predicted by the SSP5-8.5 scenario (imposed at the ocean and surface boundaries—Table 1). Additionally, the expected reduction in freshwater input, which is typically cooler than oceanic waters, contributes to this warming. Concerning salinity, an increase between 0 and 4 is predicted at the lagoon mouth and central region for all seasons. Upstream, the salinity further increases, reaching a difference higher than 10 in winter and autumn. Due to the sea-level rise, a greater ocean water volume enters the lagoon at each tidal cycle, causing an upstream increase in salinity. This effect is particularly noticeable in seasons with a higher freshwater inflow, where typical salinity gradients become more pronounced.

Regarding the water quality variables (Chl-*a*, nitrate, phosphate, and DO), the difference between the future and present scenarios was computed and is presented in Figures 8 and 9 at stations RA1, RA4, RA8, RA11, and RA14. Generally, minimal deviations in water quality variables between future and present scenarios are observed at the lagoon mouth and in the S. Jacinto channel (RA1 and RA11, respectively—Figure 8) across all seasons. Conversely, variations are evident near the Vouga River mouth (RA4). Specifically, projections indicate a decline in the Chl-*a* concentration for spring, summer, and autumn, with minimal variations in winter. Also, the nitrate levels are expected to decrease in winter and late autumn, remaining stable during other seasons. The phosphate concentrations are anticipated to decrease in winter and late autumn but increase in spring and early summer. Additionally, the DO levels are projected to decrease in winter and increase in spring.

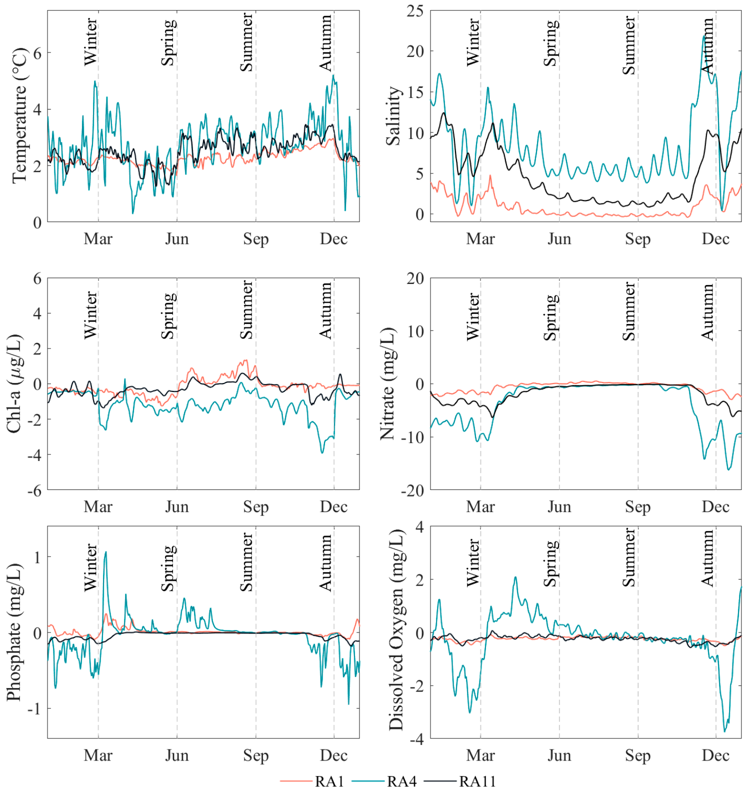

Figure 8. Difference between future and present water temperature, salinity, Chl-*a*, nitrate, phosphate, and DO concentrations, at stations RA1, RA4, and RA11.

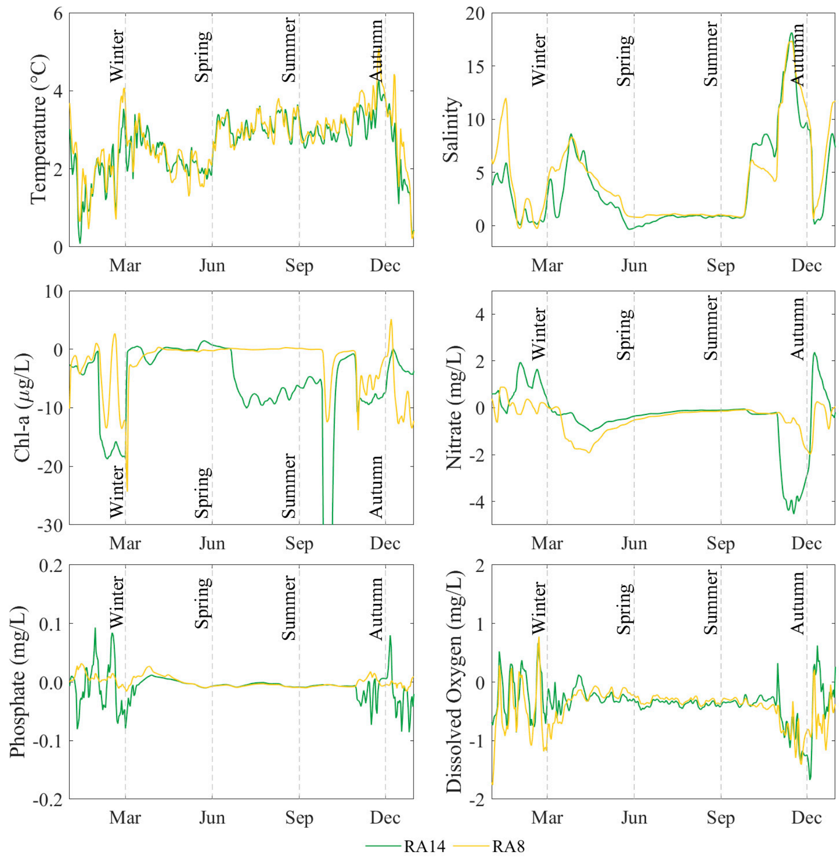

Figure 9. Difference between future and present Chl-*a*, nitrate, phosphate, and DO concentrations, at stations RA14 and RA8.

At stations located in the Mira and Ílhavo channels, RA14 and RA8, respectively, variations between the future and present are depicted in Figure 9. Generally, the water temperature is expected to increase by an average of 2 °C, with higher increases during summer and autumn. The Chl-*a* concentrations are predicted to decrease in winter and autumn in both the Mira and Ílhavo channels. At the same time, the nitrate levels are expected to increase in winter and decrease in spring and late autumn.

4.3. Seasonal Ecological Characterization

The ecological characterization of Ria de Aveiro was performed both under the present conditions and for the projected future scenario. As previously referred, a set of ecological indicators based on the predicted DO, Chl-*a*, and nutrient concentration (nitrate and phosphate) were used.

The results of the ecological indexes computed from the Chl-*a* concentration and DO are not provided as they show almost no spatial variation. Indeed, the DO results consistently indicate a Good status across the entire lagoon for all seasons. Considering future conditions, a decline in water quality is projected for the Vouga channel and a small area immediately downstream. Regarding the Chl-*a* concentration, the water quality in the majority of the lagoon is classified as Excellent all year round. However, this shifts during autumn and winter in the Mira channel: the downstream area remains Excellent, the middle channel changes to Good, and the channel end becomes Mediocre. Also, in the Ílhavo channel, the water quality is generally Excellent, deteriorating to Mediocre in autumn and winter. In the future, an improvement in the water quality is predicted, and the lagoon is classified as Excellent all year round.

Regarding the nitrate concentration (Figure 10), during the summer months (JJA), the ecological status of the entire lagoon is classified as Good. For winter (DJF), spring (MAM), and autumn (SON), the lagoon is classified as Good in the central region near the lagoon mouth and in the Mira and Ílhavo channels, except for the head of the Mira channel, which is classified as Fair. The lagoon's ecological status shifts to Fair from the middle of the central region towards the S. Jacinto and Espinheiro channels due to elevated nitrate concentrations resulting from higher freshwater input. In the future, due to the reduction in river discharges and nitrate carried by rivers, an improvement in the water quality status of Ria de Aveiro is expected. Specifically, for winter (DJF) and spring (MAM), the Fair water quality region observed in the present scenario is expected to be reduced and limited to the areas influenced by the Vouga and Antuã rivers. For summer and autumn, the water quality of the lagoon is projected to be Good.

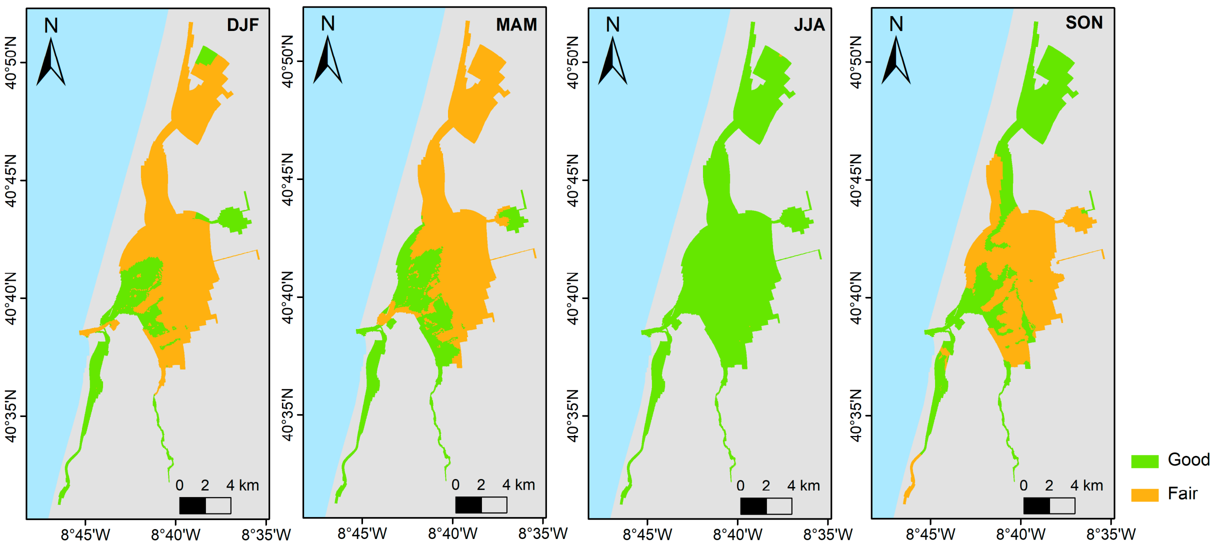

Figure 10. Seasonal ecological status of Ria de Aveiro from nitrate concentration for the present scenario.

Concerning phosphate, the results are not shown since only winter (DJF) exhibits spatial variability, with the region influenced by the Vouga River classified as Fair, while the remaining lagoon is classified as Good. Otherwise, for spring (MAM), summer (JJA), and autumn (SON), the water quality of Ria de Aveiro is consistently classified as Good. An improvement in water quality regarding the phosphate concentration is predicted for the future, with the entire lagoon presenting a Good status in all seasons, except for spring when a decline to a Fair classification is projected in the Vouga channel.

By aggregating the information of these four key variables (Chl-*a*, nitrate, phosphate, and DO) through the trophic index (*TRIX*), the water quality status of Ria de Aveiro shows spatial and seasonal variation for both the present and future scenarios (Figures 11 and 12).

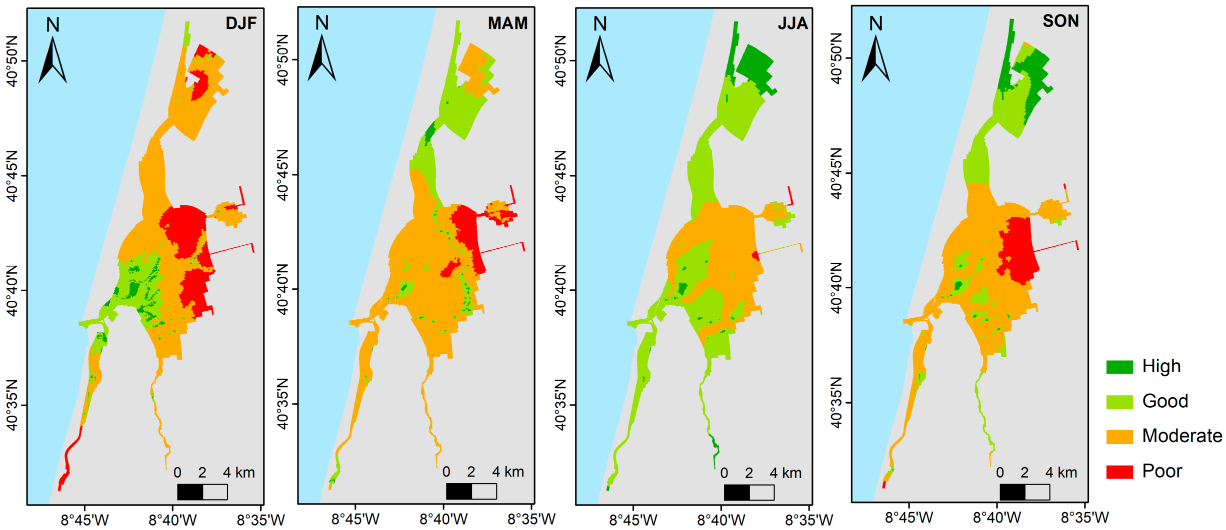

Figure 11. Seasonal TRIX of Ria de Aveiro for the present scenario.

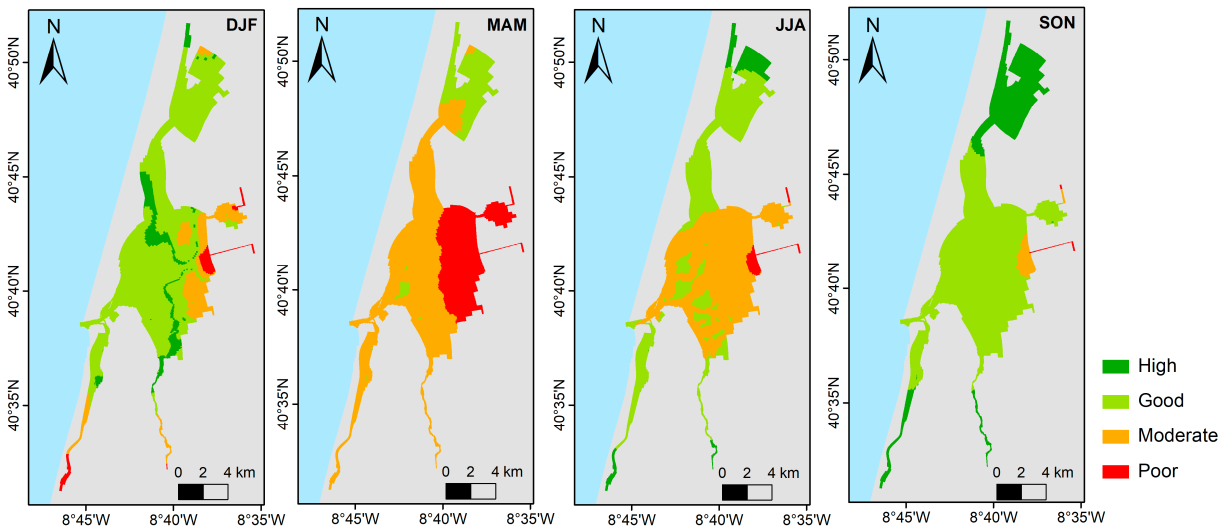

Figure 12. Seasonal *TRIX* for Ria de Aveiro for the future scenario.

Regarding the present scenario, in winter (DJF), the water quality in the central lagoon is classified as Good, shifting to Moderate immediately upstream, and deteriorating to Poor in the influence regions of Vouga, Antuã, and Ribeira do Moinhos. In the future, considering the changes imposed at the oceanic and landward boundaries, it is anticipated that the ecological status of the lagoon in winter will improve (Figure 12). Indeed, the ecological status of Ria de Aveiro is Good in the majority of the lagoon, shifting to Moderate at the end of the Mira and Ílhavo channels. Near the influence of the Vouga River, the lagoon presents a smaller area with a Poor classification compared to the present (Figure 12).

During summer (JJA), for the present scenario (Figure 11), the water quality is Good in the area around the mouth of the lagoon and in the S. Jacinto, Mira, and Ílhavo channels. In the central region of the lagoon, the ecological status of the lagoon considering the *TRIX* index is Moderate. For the future, a similar pattern is expected; however, the Moderate classification extends to the lagoon's mouth, and therefore a decline in the water quality is predicted.

During the transitional seasons (MAM and SON), the water quality in Ria de Aveiro is predominantly Moderate. Notable exceptions include the heads of the S. Jacinto and Ílhavo channels, which exhibit a Good status. In contrast, in the area influenced by the Vouga River, the ecological classification of the lagoon is considered Poor. Regarding future projections, an improvement in the ecological status of the lagoon is observed for autumn (SON), with water quality ranging from Good in the central region to High in the head of the Mira, Ílhavo, and S. Jacinto channels and Moderate in the head of the Espinheiro channel (Figure 12).

However, for spring (MAM), the extent of the Poor classification near the Vouga and Antuã rivers' influence zone is expected to increase in the future. These results are attributed to the heightened phosphate concentrations delivered by the Vouga and Antuã rivers predicted by the watershed model SWIM and used as the landward boundary condition.

5. Discussion

5.1. Model Validation

This work intends to assess the present and future ecological water quality of Ria de Aveiro through numerical modeling. For this purpose, the hydrodynamic and water quality model Delft3D was implemented and validated throughout the lagoon. Generally, the main difficulties and, consequently, source of possible errors identified are related to local bathymetric uncertainties, which are crucial for accurately representing hydrodynamic variables in all estuarine modeling studies [47], the absence of continuous measurements of river runoff and their properties, the scarcity of recent in situ data—particularly for water quality variables—and the potential presence of undocumented pollution sources [48]. Also, achieving accurate water quality predictions is difficult due to the interdependence of solutions and inherent complexity of associated processes.

Notwithstanding, the observed discrepancies are comparable to or smaller than those found in previous numerical applications in Ria de Aveiro [23] and other coastal lagoons and estuaries [5,14,34,49,50]. Therefore, it is considered that the model reproduces the observations with sufficient accuracy to describe the water quality parameters of Ria de Aveiro.

5.2. Seasonal Characterization of Ria de Aveiro: Present and Future

The seasonal abiotic characterization of Ria de Aveiro showcases dynamic variations in environmental factors such as the water temperature, salinity, DO, Chl-*a*, and nutrient concentrations over the year. These variations occur due to weather conditions, tidal dynamics, riverine inputs, oceanic influences, or changes in solar radiation. Typically, the lagoon experiences warmer temperatures and higher salinities in summer and autumn. Conversely, colder temperatures and lower salinities prevail in winter and spring, influenced by meteorological conditions and fluvial and tidal dynamics.

The DO levels are higher in winter and spring, inversely correlated with the Chl-*a* concentrations, which peak in summer and autumn. This seasonal dynamic is attributed to the enhanced environmental conditions favorable for primary production, leading to an increase in the Chl-*a* concentration and a decrease in the DO levels. Spatially, minimal Chl-*a* concentration occurs in the lagoon mouth (due to the greater marine influence), progressively increasing upstream (due to the river influence), which is consistent with previous studies [51,52].

The nutrient concentrations peak in winter near river mouths, primarily due to increased river runoff (e.g., agricultural drainage), which carries nutrients from the land into the aquatic environment. Previous studies [52,53] focusing on collected data at specific stations revealed a similar pattern, with nitrate concentrations higher in upstream stations compared to the lagoon mouth. Furthermore, both studies found that the nitrate concentration is higher in low tide, showing a strong inverse linear relationship with the salinity. This pattern indicates a conservative mixing between river waters with high nitrate concentrations and coastal waters with low nitrate concentrations [53].

Various studies have reported differing patterns regarding the phosphate concentration in Ria de Aveiro. Lopes et al. [53] found no clear seasonal variation and similar concentrations at high and low tides. However, Lopes et al. [52] reported that in one year, the mean phosphate concentrations were higher in winter, while in another year, higher concentrations were observed in summer. In contrast to these studies, the model developed in the present study predicts higher phosphate concentrations in winter near river mouths. This prediction aligns with the increased river runoff during this season, which carries more nutrients into the lagoon. Additionally, another study [51] found that the highest phosphate concentrations were recorded in autumn, further indicating variability in the observed seasonal patterns. These divergences could be attributed to differences in spatial coverage, temporal resolution, and the specific locations of the sampling stations. The studies with limited spatial coverage may not capture the full extent of the seasonal dynamics, particularly near river mouths where nutrient inputs can be more variable. Therefore, the model prediction of higher winter phosphate concentrations near river mouths provides a broader understanding that complements the localized observations from the other studies.

Regarding the response of the ecosystem to climate change, the projections indicate a water temperature increase between 2 and 3.5 °C, especially in summer and autumn, and an increase in salinity (1 at the lagoon mouth and up to 10 upstream) in winter and autumn. These changes are driven by global warming, reduced freshwater input, and sea-level rise.

Water quality variables showed minimal deviations from the present scenario at the lagoon mouth and S. Jacinto channel across all seasons. However, significant variations are observed near the Vouga River, indicating potential changes in nutrient dynamics and phytoplankton biomass. Indeed, a decrease in the Chl-*a* and nutrient concentration is projected in the upstream lagoon (near the freshwater sources), except phosphate, which is projected to increase in the Vouga River influence region during spring (MAM) and early summer (JJA). These results may have implications for the Ria de Aveiro ecosystem. For instance, the decrease in nitrate and the increase in phosphate concentrations in the Vouga region of influence might suggest an altered nutrient ratio, potentially leading to shifts in the dominant phytoplankton species towards those that thrive under higher phosphate conditions. This change is particularly significant because, according to several studies [52,53], phosphate is currently the limiting nutrient in Ria de Aveiro, with its limiting effect diminishing as the salinity increases. Therefore, an increase in phosphate could lead to more balanced nutrient conditions, altering phytoplankton dynamics in response to the varying salinity levels within the lagoon.

5.3. Ecological Status of Ria de Aveiro

Ria de Aveiro is characterized by its significant aquaculture industry and rich biodiversity, underscoring the critical importance of comprehensively assessing its ecological status both for the present and the future. Understanding and monitoring its environmental health is essential for sustainable management and conservation efforts.

Therefore, the ecological status of Ria de Aveiro was assessed through a set of indicators, based on the DO, Chl-*a*, and nutrient concentrations (nitrate and phosphate) individually and collectively (*TRIX*), for the present and future conditions.

The model results from the present work indicate that nutrients are the primary factor affecting water quality, rendering Ria de Aveiro the Fair classification in areas influenced by river inflows. Indeed, excessive nutrient inputs can result in eutrophication and algal blooms, leading to exceptionally high Chl-*a* levels and potential ecological imbalances.

When considering all the variables together, as measured by the *TRIX* index, the overall water quality shows seasonal variation. The central channels of the lagoon mostly hold a Good/Moderate status, while regions near river inflows tend to exhibit Moderate to Poor conditions. Indeed, since the S. Jacinto outfall implementation, which discharges treated effluent into the Atlantic Ocean from wastewater treatment plants and more than 10 municipalities, the nutrient loads from specific sources into Ria de Aveiro have effectively reduced [52], and the nutrient inputs in the basin of the River Vouga have been associated with diffuse pollution from rural activities as they tend to increase in winter due to the leaching from agricultural fields [26,53]. However, during specific tidal and wind conditions, such as flood tides and northwesterly winds, the sewer plume can interact with and exchange water with the coastal lagoon [28].

In the past, an assessment was conducted to identify sensitive and vulnerable areas within Portuguese transitional and coastal systems. The report [54] concluded that Ria de Aveiro exhibits a moderate degree of eutrophication and low human pressure compared to other estuarine systems. Also, since the nutrient loads were not predicted to increase, Ria de Aveiro was not identified as a vulnerable zone [54].

The water quality evaluation in this study considers the oxygen, nutrient, and Chl-*a* concentrations according to salinity classes. Higher salinity areas are more sensitive to changes in the concentrations due to lower reference values. Therefore, the salinity increase predicted in response to future changes in the main lagoon drivers (sea-level rise and reduced river flow) could lead to a potential decline in water quality assessments. However, for the nitrate, phosphate, and Chl-*a* indexes, an overall improvement in water quality occurs. Similar outcomes were obtained for the Tagus estuary [17], where the decrease in the river runoff and the increase in the mean sea level resulted in a higher water salinity and lower nutrient and Chl-*a* concentrations in the middle and upper estuary.

Regarding the *TRIX* index for the future, water quality is expected to improve in winter and autumn due to reductions in river-borne pollutants (due to the projected decrease in river flow and nitrate concentration), leading to a more consistent Good status across the lagoon. Despite these positive trends, certain regions, particularly those influenced by major rivers, may continue to face challenges with higher nutrient levels during specific seasons. For spring and summer, a decline in water quality is projected mainly due to the increase in phosphate concentrations in the lagoon.

While the model forecasts an overall improvement in water quality, uncertainties remain regarding the projected reductions in river nitrate levels. The river flow and nutrient concentrations imposed at the boundaries are derived from the SWIM watershed model, which inherently carries some degree of uncertainty. In scenarios where river flows decrease, nutrient concentrations could potentially rise, leading to higher nitrate levels than predicted. This, coupled with the projected increase in phosphate, could further impact the ecological status of Ria de Aveiro and the *TRIX* index, potentially exacerbating eutrophication risks. To refine these predictions, future research should focus on exploring how changes in river flow and nutrient loading may influence nutrient dynamics and water quality.

Even though total precipitation is projected to decrease, extreme flood events due to intense precipitation over short periods are anticipated to increase during the winter [55]. If land use and current water management do not change, these flood events could exacerbate nutrient loading into Ria de Aveiro, increasing eutrophication risk and impacting the lagoon's water quality. Future research should focus on extreme events, such as intense flood episodes, to understand their impact on water quality and ecosystem health, since Ria de Aveiro is quite sensitive to floods [22].

6. Conclusions

The present study successfully implemented and validated the Delft3D hydrodynamic and water quality modules to Ria de Aveiro to evaluate the present and projected ecological lagoon conditions. The modeling results demonstrated that, despite the inherent complexities and data limitations, the model accurately captures the seasonal variations in key parameters such as the water temperature, salinity, DO, Chl-*a*, and nutrient concentrations. Presently, Ria de Aveiro experiences significant seasonal fluctuations driven by meteorological, tidal, and riverine influences, with higher nutrient concentrations near river mouths due to agricultural runoff, particularly in winter. Projections under climate change scenarios indicate an increase in the water temperature and salinity, with potential reductions in the nutrient levels and Chl-*a* concentrations in upstream regions, though phosphate may increase near the Vouga River.

The model results highlighted that nutrient inputs significantly influence the water quality, with eutrophication risks predominantly in areas affected by riverine inputs. While future conditions may lead to improved water quality in some parts of the lagoon due to reduced river-borne pollutants, regions near major rivers might continue to face challenges, particularly with increased phosphate levels. Future research should focus on extreme weather events and their impacts on nutrient dynamics and water quality to better anticipate and manage the ecological responses of this sensitive coastal system.

The findings from this study are not limited to Ria de Aveiro; they could be applied to coastal environments facing similar pressures. The methodologies employed and the identified relationships between hydrodynamic factors, nutrient dynamics, and water quality can serve as a framework for managing and predicting ecological responses in comparable ecosystems globally.

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