



Thermal stratification and epilimnion water quality under climate and management scenarios: the Joumine reservoir (Tunisia)

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Abstract This study assesses epilimnion water quality in the Joumine Reservoir, Tunisia, by combining the PEGASE water quality model, the DEOLE-J thermal stratification model, and in situ measurements. Scenario analysis was developed to evaluate how future climate change and watershed management strategies may jointly influence water quality dynamics in semi-arid reservoirs. This multidisciplinary approach highlights the key drivers of nitrate, chlorophyll-a, dissolved oxygen, and water temperature, emphasizing the influence of thermocline variability on seasonal ecosystem dynamics. Among these variables, chlorophyll-a (Chl-a) shows the highest uncertainty, with noticeable under- and overestimation depending on the season, reflecting limitations

in simulating phytoplankton dynamics. PEGASE reliably simulates hydrological variability at both the catchment (river network) and reservoir scales, as well as nutrient inflows, while reservoir-specific dynamics linked to stratification and phytoplankton required other parameterization. Best Management Practices (BMPs), including agricultural measures such as cover crops, mulching, and reduced nitrogen and phosphorus inputs, were implemented in the scenarios. Scenario analysis revealed strong contrasts between management strategies. Without best management practices (BMPs) (SC1), wet-season nitrate rose by ~65% compared to reinforced management (SC3), with peaks above 22 mg/L and episodic eutrophication. Dissolved oxygen generally remained above thresholds but showed localized summer depletion. SC2, representing moderate climate change with partial adaptation (25% BMP adoption and partial

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wastewater treatment), produced intermediate nitrate and phytoplankton levels, showing partial mitigation and persistent oxygen stress. SC3, combining 75% BMP adoption with 90% advanced wastewater treatment, reduced nitrate loads by 63–66% and limited phytoplankton growth; however, oxygen stress persisted under extreme warming (+3.9 °C by 2100), with summer epilimnion temperatures rising ~2 °C and intensifying stratification. Climate change will likely worsen eutrophication and oxygen depletion without integrated measures. While BMPs and wastewater treatment reduce nutrient inputs, they cannot fully mitigate oxygen deficits caused by prolonged stratification. Overall, this study demonstrates the applicability of the coupled DEOLE-J and PEGASE models for simulating epilimnion water quality in semi-arid, data-limited contexts, and highlights the importance of implementing stricter nutrient regulations, enhancing wastewater treatment, and increasing monitoring frequency.

Keywords Joumine Basin · Water quality · PEGASE model · Joumine reservoir · Modeling · Stratification

Introduction

Thermal stratification is a key physical process regulating water quality in lakes and reservoirs worldwide, as it controls vertical mixing, oxygen renewal, and nutrient availability within the surface mixed layer (Duka et al., 2021; M. Liu et al., 2019). Under ongoing climate warming, intensified and prolonged stratification has been increasingly associated with eutrophication, harmful algal blooms, and oxygen depletion in reservoirs across diverse climatic regions (Jane et al., 2021; Woolway et al., 2022). These impacts are particularly pronounced in semi-arid and Mediterranean systems, where high summer temperatures, strong solar radiation, episodic inflows, and long water residence times amplify sensitivity to climate forcing (Giorgi & Lionello, 2008; Piccolroaz et al., 2024). As a result, understanding how stratification dynamics interact with biochemical processes has become central to predicting reservoir responses to climate change and to designing effective management strategies (Paerl & Paul, 2012; Woolway & Merchant, 2019).

The Mediterranean Basin, recognized as a major global biodiversity hotspot (Doga Derneği, 2010), is experiencing a marked decline in biological diversity, reflecting broader global trends (Newton et al., 2018). Although this region has high ecological value, supporting diverse species and essential ecosystem services, it faces increasing human pressures from irrigation-based agriculture (Harmanny & Malek, 2019), urban expansion (Ferreira et al., 2018; García-Nieto et al., 2018), and densely populated coasts.

Consequently, sustainable water resource management and risk mitigation are increasingly urgent (J. Liu et al., 2017). This challenge is exacerbated by non-balanced water distribution, worsening sub-regional water stress (Fader et al., 2020; Mekonnen & Hoekstra, 2016; UN-Water, 2017). Climate change significantly amplifies these vulnerabilities. The Mediterranean region is projected to warm approximately 20% faster than the global average and potentially experience a 12% decline in precipitation under a +3 °C warming scenario (IPCC, 2023). Northern Africa is expected to experience 10–20% less rainfall by 2050, accompanied by more erratic precipitation patterns and temperature increases of 1.5–3.6 °C (García-Nieto et al., 2018; Giorgi & Lionello, 2008; Iglesias et al., 2007). These changes threaten hydrological systems, compromise water quality, and pressure vulnerable ecosystems (Giannakopoulos et al., 2009; Lionello et al., 2014; Mariotti et al., 2015; Trambly et al., 2020). Combined with significant exposure and limited adaptive capacity, the region is especially at risk.

Within the Mediterranean, climate change intensifies precipitation extremes, leading to increased flood frequency and magnitude (Dottori et al., 2018; Fang et al., 2021; IPCC, 2023). To mitigate these impacts, dam operations are employed to reduce high flows and enhance low flows, thereby lowering flood risks and potential agricultural damage (Shrestha & Kawasaki, 2020; Van Oorschot et al., 2018).

However, these hydraulic structures significantly alter river hydrodynamics and geomorphology, impacting water quality and disrupting the ecosystem continuum (T. Wang et al., 2021). Dams disrupt sediment transport and thermal regimes, potentially altering ecological balances and leading to the occurrence of cyanobacterial blooms. Reservoirs act as both sinks and sources for persistent pollutants, despite

providing essential services like water supply and hydropower (Watkins et al., 2019; Xu et al., 2017).

These impacts arise from fundamental differences between lotic and lentic systems. Rivers transport pollutants rapidly downstream over large areas, while reservoirs allow slower dispersal but result in longer contaminant persistence, often affecting the entire water body (House et al., 1993). Impoundment reduces flow velocity and increases residence time, creating lentic conditions that favor the development of thermal stratification, which can be seasonal or diurnal (Long et al., 2019). This vertical density stratification restricts mixing, altering the distribution of nutrients, algae, and oxygen (Long et al., 2019). The water quality in the epilimnion is a particularly informative indicator of lake and reservoir health, as it is highly dynamic, altering nutrient concentrations and light availability, and represents the primary layer where phytoplankton, including cyanobacteria, are associated with environmental conditions. Epilimnion depth and mixing vary seasonally and diurnally, influencing temperature, constituent concentrations, and nutrient distribution (B. Wang et al., 2023; Wells & Troy, 2022). Accurate information of epilimnion depth is critical because it defines the vertical domain over which light, nutrients, and entrained deep water are mixed, thereby affecting productivity and bloom dynamics (Ghane & Boegman, 2025; Merino-Ibarra et al., 2021; Mesman et al., 2021). Since the epilimnion is the main phytoplankton habitat during stratification, monitoring and modeling its depth, temperature, turbidity, chlorophyll-a, and nutrient levels are key for understanding ecosystem responses, predicting blooms, and guiding management (Ghane & Boegman, 2025; Zhang et al., 2021). Reservoir operations also transform downstream hydrology, increasing dry-season flows, attenuating flood peaks, and modifying thermal regimes, specifically reducing fluctuations, lowering summer maxima, and delaying thermal cycles (Long et al., 2019).

The complexity of these ecosystem modifications necessitates sophisticated modeling approaches to assess reservoir effects and inform management decisions. Various studies highlight the importance of tailored models that can address specific management objectives while considering the intricate interactions within aquatic ecosystems (Jorde et al., 2007; Steel & Duncan, 1999). Extending beyond reservoirs, research in estuaries and coastal waters highlights

the importance of advanced modeling to capture the complex mixing and transport processes shaped by natural and anthropogenic influences (Dzwonkowski et al., 2023; Horner-Devine et al., 2015). However, persistent knowledge gaps, particularly concerning mixing dynamics in river plumes and inflow transition areas, underscore the need for more integrated and enhanced modeling approaches (Horner-Devine et al., 2015).

Despite these advances, important limitations remain in existing modeling approaches. Some simplified water quality models rely on vertically averaged conditions or fixed layer representations, which may not adequately capture the temporal variability of epilimnion dynamics during stratified periods. In contrast, vertically resolved hydrodynamic–ecological models (e.g., DYRESM-CAEDYM, CE-QUAL-W2) explicitly simulate stratification and biogeochemical processes but generally require detailed input data, vertical discretization, and calibration, which can limit their applicability in data-scarce semi-arid systems. Furthermore, standalone thermal models, such as DEOLE-J, provide detailed information on stratification dynamics but do not simulate biogeochemical processes.

In this study, the PEGASE model (Planification et Gestion de l'Assainissement des Eaux) was selected for simulating water quality in the study area. It is an integrated watershed–river model. Key reasons for its selection include its robustness, adaptability to data-scarce contexts, and ability to represent both classic nutrient dynamics and several phytoplankton dynamics (Deliège et al., 2009; Everbecq et al., 2019). Originally developed for the Walloon region of Belgium, PEGASE has been extensively applied in major European watersheds, including the Scheldt, Adour, Loire, Moselle, Garonne, and Meuse, as well as in North African basins, particularly in Tunisia, where it has demonstrated reliable performance despite data limitations (Deliège et al., 2010; Everbecq, 2001; Grard et al., 2014).

The model is deterministic and physics-based, featuring a detailed representation of hydrological and biogeochemical processes. It employs kinetic equations to simulate system dynamics, with most parameters grounded in physical, chemical, or biological properties and thus requiring minimal calibration (Boukari, 2019; Everbecq et al., 2019). PEGASE's spatial discretization allows accurate simulation at

both river and watershed scales (Grard et al., 2021), and its user-friendly interface facilitates adoption by operational authorities (Grard et al., 2014). Notably, to address challenges in data acquisition common in remote or under-monitored regions, the model integrates statistical techniques to reconstruct missing inputs (Deliège et al., 2009). This capability makes it particularly suitable for the current study site, where data availability is limited.

This model was previously applied by (Boukari et al., 2019) in the Joumine watershed to assess the potential impact of diffuse agricultural pollution in this semi-arid river basin in Tunisia. The thermal regime and stratification dynamics of the Joumine Reservoir were analyzed in a previous study using the DEOLE-J model (Madyouni et al., 2025). That work characterized the annual evolution of the thermocline depth, the thermal stability index, and the duration of the mixing, formative, and stable stratification phases. The results highlighted the impact of air temperature and wind speed on the timing and intensity of thermal stratification in the Joumine reservoir.

However, these previous studies were conducted independently and did not integrate thermal stratification dynamics with biochemical water quality processes.

Building upon these findings, the present study focuses on how stratification changes impact the epilimnion water quality under different climate change and management scenarios. Specifically, we examine the physical–biogeochemical linkages through the interactions among temperature, oxygen, nutrient availability, and phytoplankton dynamics. In this study, the DEOLE-Joumine model (Madyouni et al., 2025) will be used to determine the thermocline depth and epilimnion thickness of the Joumine reservoir. These outputs will serve as inputs to PEGASE, enabling water-quality simulations specifically in the epilimnion. This approach allows assessment of how thermocline variability, driven by climate change and upstream inflows, influences the epilimnion's physico-chemical and biological properties, including nutrients, dissolved oxygen, and phytoplankton dynamics.

More specifically, the coupling is implemented as a one-way dynamic linkage in which time-varying thermocline depth and epilimnion thickness derived from DEOLE-J are used to constrain the effective mixing volume in PEGASE. This enables simulations

to explicitly represent epilimnion-scale processes rather than relying on vertically averaged reservoir conditions.

Although the Joumine reservoir serves as a case study, the investigated processes and modeling approach have broader relevance for semi-arid and Mediterranean reservoirs facing similar challenges of intensified stratification, episodic nutrient loads, and limited monitoring. This study builds on prior applications of PEGASE in the Joumine watershed and DEOLE-J for thermal dynamics by coupling the two models. Specifically, seasonal average thermocline depth and epilimnion thickness derived from DEOLE-J are used to constrain mixing volumes and biogeochemical simulations within PEGASE. Key features of this integration include (i) dynamic definition of epilimnion mixing volumes based on thermocline depth; (ii) explicit simulation of nutrient, phytoplankton, and oxygen dynamics at the epilimnion scale rather than under vertically averaged conditions; and (iii) combined assessment of climate change and watershed management scenarios. The resulting framework offers a practical, process-based approach for evaluating climate-driven water quality responses in data-limited reservoirs, with potential applicability to comparable systems in North Africa, Southern Europe, and other semi-arid regions.

Methodology

Study area

The Joumine Dam watershed in the northwestern part of Tunisia is a critical rural agricultural basin and the country's primary water-producing region, contributing more than 80% of surface water and 60% of total resources. This sub-basin of Ichkeul covers 418 km², with altitudes ranging from 700 m in the upstream part to 45 m in the downstream part. It features a rough topography, with slopes ranging from 5 to 20%, reaching up to 40% in certain areas.

In the 1980s, the Ministry of Equipment constructed a water storage dam downstream as part of the Master Plan for using Northern Tunisia's water resources. Completed in 1984, this dam addresses flooding events in the Mateur Plain, storing about 76 Mm³ of water mainly for drinking and irrigation purposes. It contributes to the irrigation of 1500 ha and

protects the Mateur Plain from flooding. The reservoir has a mean depth of 40 m.

The watershed is characterized by its rural nature, with 57% of its area dedicated to agricultural land use. The dominant agricultural activity is wheat production, covering about 53% of cultivated land, while the remaining land is used for oats, legumes, fodder, and sunflowers. Approximately 10% of the basin consists of pastures and meadows for livestock. Most crops are rain-fed, so the timing of planting, fertilization, and the amounts of applied inputs depend on rainfall patterns.

Situated in a Mediterranean subhumid to semiarid climate region, the basin experiences large seasonal and annual precipitation variability, ranging from 550 to 850 mm per year (Slimani et al., 2007). The upstream hydrological regime is natural, with a mild wet season from September to April, during which maximum discharge occurs mainly from December to March, and a hot, dry season from May to August, when runoff is nonexistent, characterized by very low flows. The average daily discharge is about 2.5 m³/s, with maximum flow reaching 260 m³/s. The basin is drained by a dense hydrographic network, with the Joumine river being the main, almost permanent tributary.

The average annual rainfall in the basin is 757 mm, with a monthly distribution featuring a moderately rainy autumn period accounting for 27% of annual rainfall. Almost half of the total rainfall occurs in winter (December–February) as rainfall events of varying intensity. The spring period accounts for approximately 22% of the rainfall, followed by a dry summer period (around 5%), which extends from June to August (Boukari et al., 2019).

Data set

To assess the variation of water quality in the Joumine watershed, water samples were collected from the river network at different locations, including the main channel, tributaries, and the Joumine reservoir. Sampling was conducted from the surface to the deepest part of the reservoir at depths of 0, 5, 10, 15, and 20 m across eight sites over a year (May, June, August, and October 2021, and March and June 2022) (*MERGEFORMAT Fig. 1).

Two sets of samples were collected for chemical analysis and chlorophyll-a quantification. Water

temperature (WT), pH, salinity, and dissolved oxygen (DO) were measured directly using a multiparameter probe (WTW multi 340i). Nutrient analysis for nitrate (NO₃⁻) was performed using ionic chromatography (Limam, 2003).

For chlorophyll-a (Chl-a) determination, water samples were filtered through a glass microfiber filter (Whatman GF/C), and chlorophyll was extracted by immersing the filters in 10 ml of 90% acetone. The concentration of chlorophyll-a was measured spectrophotometrically using a 665 nm excitation filter and a 750-nm emission filter according to the method described by (Rodier et al., 2009).

Coupling and calibration of the PEGASE–DEOLE-J modeling framework

The PEGASE model requires several input datasets, including a digital elevation model (DEM), land use data, meteorological forcing, and information on anthropogenic pressures. In this study, a 30-m resolution DEM obtained from the USGS Earth Explorer platform was used to derive slope and delineate the hydrographic network. Land use data were based on the classification developed by (Boukari, 2019) from Landsat 8 imagery (May 2015, 30-m resolution), including agriculture, forest, urban areas, water bodies, pasture, and bare land. Meteorological data for the period 2020–2023 were provided by the National Meteorological Institute of Tunisia (INM) and included daily averages of air temperature and solar radiation. Anthropogenic inputs, such as water withdrawals, irrigation, pollutant discharges, and daily flow at the watershed outlet, were estimated using the water balance of the Joumine dam.

PEGASE is a physically based modeling framework that integrates hydrological, thermal, and ecological processes to simulate flow, nutrient transport, and phytoplankton dynamics at both basin and reservoir scales. PEGASE is a river water quality model based on longitudinal transport processes, with state variables integrated over the cross-section, and therefore does not explicitly resolve vertical stratification. The hydrographic network is discretized into interconnected segments with a typical spatial resolution of approximately 200 m, depending on the availability of hydrographic and topographic data. Each segment is defined by hydraulic characteristics such as discharge, velocity, and depth, and nodes enable

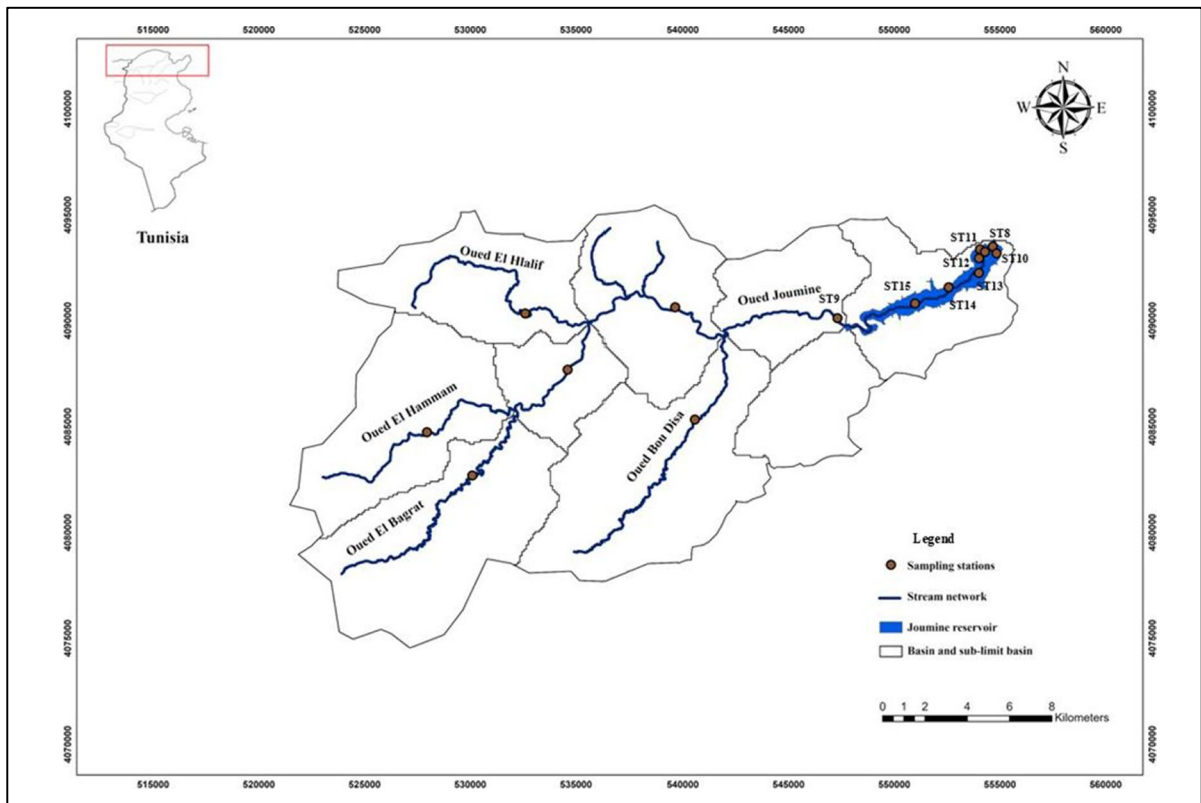


Fig. 1 Joumine basin and Joumine reservoir, including sampling stations and river network

mass exchange and extraction of simulation results. Water quality variables, including nutrients, chlorophyll-*a*, and dissolved oxygen, are simulated using an advection–reaction formulation that balances external inputs from tributaries and point sources with internal biochemical processes. In reservoir systems, PEGASE retains this longitudinal 1D structure, with adaptations to better represent water residence time, while the horizontal dimension is not explicitly resolved and concentrations are assumed laterally homogeneous within each segment. As a result, the computational grid remains strictly one dimensional.

Because PEGASE assumes a vertically homogeneous water column within each computational unit, it does not explicitly resolve thermal stratification. To account for this process, the model is coupled sequentially and in a one-way, offline manner with the DEOLE-J model (Madyouni et al., 2025), which provides a one-dimensional vertical representation of the reservoir. DEOLE-J simulates the temporal evolution of vertical water temperature profiles using

meteorological forcing and reservoir bathymetry, including hourly simulations and daily extraction of epilimnion temperature and thermocline depth, defined as the depth at which the vertical temperature gradient is maximum.

In the coupling procedure, the daily epilimnetic water temperature simulated by DEOLE-J is directly used as input to PEGASE to drive temperature-dependent biochemical processes. In contrast, the thermocline depth is represented by a seasonal average value derived from daily DEOLE-J outputs over stratified periods. This approach ensures a representative and stable characterization of the mixed-layer thickness, consistent with the conceptual structure of PEGASE.

The seasonal thermocline depth is used to define the vertical extent of the epilimnion, which represents the layer assumed to be vertically homogeneous within PEGASE. All biochemical processes, including nutrient cycling, phytoplankton dynamics, and dissolved oxygen evolution, are assumed

to occur within this vertically homogeneous layer. Variations in this thickness affect the definition of the active mixed layer and consequently the residence time and dilution of simulated constituents within this zone.

Short-term fluctuations in thermocline position (e.g., rapid deepening or shoaling events) are not explicitly represented. Instead, their effects are implicitly accounted for through the use of a representative seasonal mixed-layer depth. The hypolimnion is not explicitly simulated, and processes occurring below the thermocline, such as deep-water oxygen depletion or nutrient release, are therefore not resolved.

Model calibration focused on nitrate, dissolved oxygen, chlorophyll-a, and water temperature, with parameter adjustments including soil leaching coefficients, livestock nitrogen emissions, and phytoplankton kinetic rates adapted to Mediterranean conditions. Simulations were conducted over the period 2020–2023, during which water quality measurements were collected in the Joumine basin to evaluate model performance. Overall, this modeling framework combines a one-dimensional longitudinal representation of transport and water quality with an externally derived vertical thermal structure, corresponding to a vertically informed 1D (1.5D) approach. Calibration was performed using a step-wise, one-parameter-at-a-time approach, where each parameter was adjusted sequentially to minimize differences between simulated outputs and observed data while ensuring realistic parameter values.

To assess the model's ability to replicate key water quality parameters throughout the Joumine basin, a comparison between simulated and observed data was conducted using two complementary methods: spatial variation (comparing values across stations on a given date) and temporal variation (tracking values over time at a single station). The assessment focused on four primary variables: water temperature (TEMP), nitrate (NO_3^-), dissolved oxygen (DO), and chlorophyll-a (Chl-a), and used statistical tools including the coefficient of determination (R^2), which is calculated as the square of the Pearson coefficient, regression slope, and error metrics such as RMSE, Pbias, and MAE.

A detailed description of the PEGASE modules, parameter settings, and calibration procedures is provided in the Supplementary Material.

Scenario analysis

The simulation over the period 2020–2023, calibrated and validated against field observations, is considered as the baseline scenario (BL), representing current climate conditions and existing land use and management practices in the Joumine basin. All alternative scenarios were developed relative to this reference state. Following this baseline, three alternative scenarios were designed to represent contrasted and plausible future pathways combining climate change and watershed management responses.

Following the reference simulations from 2020 to 2023, we developed three alternative scenarios under the same hydraulic conditions for comparative analysis.

Scenario	Climate	Agri-cultural BMPs (% of area)	Urban improvements (% of network)
SC1 – “Climate stress” without management	Sum-mer: +1.9 °C (2050, RCP8.5), – 10% precipitation	0%	0%
SC2 – “Moderate climate” + partial BMPs + partial urban improvement	Sum-mer: +1.6 °C (2050, RCP4.5), – 6% precipitation	25% (cover crops, mulching, reduced N & P inputs)	40% (partial upgrading of waste-water treatment plants and connection of some villages)
SC3 – “Extreme climate” + enhanced BMPs + full urban improvement	Sum-mer: +3.9 °C (2100, RCP8.5), – 20% precipitation	75% (full adoption of sustainable agriculture for total P)	90% (advanced phosphorus treatment in nearly all plants and elimination of direct discharges)

BMPs Best Management Practices

The scenarios were constructed as integrated pathways in which climate forcing and management strategies evolve simultaneously. This approach was adopted to reflect realistic future conditions, where

adaptation measures such as Best Management Practices (BMPs) and improvements in wastewater treatment are implemented in response to increasing climate pressures.

Results

Assessment of model simulation

The model was calibrated over the year 2021 using available measurements of nitrate, chlorophyll-a, dissolved oxygen, and water temperature, focusing on the epilimnion of the Joumine Reservoir, the upper mixed layer critical for phytoplankton growth and nutrient dynamics. Both temporal and spatial trends across multiple stations were analyzed to assess the model's ability to reproduce observed seasonal dynamics within the epilimnion (Fig. 2).

Daily simulated concentrations were compared with observed values recorded during all monitoring campaigns for water temperature, dissolved oxygen, nitrate, and chlorophyll-a, specifically within the epilimnion. This comparison served to assess the model's performance in simulating the physico-chemical water quality dynamics of the river system and the epilimnion of the reservoir.

We assessed the fit between the simulated results and the field measurements obtained at station ST9, located in the lower reach of the Joumine River and representing the basin's outlet, as well as all stations within the reservoir, for the epilimnion layer.

At the reservoir inlet station (ST9), the simulation showed a moderate-to-high linear correlation with observations for nitrate ($R^2=0.95$, based on four measurements). However, as shown in Fig. 3, two predicted values deviated substantially from the measured values, resulting in a per cent bias (PBIAS) of +37%. Therefore, while the model captures the general seasonal trend (higher nitrate in winter, lower in summer), it may overestimate or underestimate absolute concentrations in some cases. The overall representation of nitrate dynamics is considered acceptable for scenario analysis, given the data limitations. For water temperature, the agreement was good ($R^2=0.96$), and for dissolved oxygen, the accuracy was reasonable ($R^2=0.59$). This confirms the model's ability to simulate key seasonal patterns in the epilimnion

at this critical inflow location (Fig. 3). This is particularly relevant, as ST9 reflects the influence of upstream catchments and strongly drives downstream biochemical dynamics in the epilimnion.

For nitrate (NO_3^-), model performance should be interpreted with caution due to the limited number of observations per station and date (generally $N \leq 6$). While moderate to high R^2 values were obtained (0.24–0.95), their statistical significance is constrained by the small sample size. Therefore, error metrics provide a more robust assessment. MAE values ranged from 0.19 to 1.72 mg/L, while PBIAS indicates that the model tends to overestimate concentrations on some dates, particularly when observed values are low. Despite these discrepancies, the model successfully reproduces the overall seasonal dynamics of nitrate, suggesting that the main nitrogen-related processes (mineralization, nitrification, and uptake) are reasonably represented in the epilimnion (Figure SM1 b and Figure SM2 f).

Water temperature simulations captured the temporal evolution of seasonal warming and cooling cycles, with MAE values between 1.0 and 3.5 °C. A moderate positive bias (PBIAS between +3.3% and +12.6%) indicates a tendency toward slight overestimation. The relatively low R^2 values (0.32–0.37) are partly explained by the narrow range of observed temperatures, which limits the relevance of correlation-based metrics. Spatial variability between stations appears less well represented, likely reflecting unresolved local heterogeneities (e.g., depth variations or localized heat exchanges), rather than model structural deficiencies.

For dissolved oxygen (DO), high R^2 values (up to 0.997) were obtained on some dates; however, these should be interpreted cautiously given the small number of observations and the limited variability in measured values. In such cases, correlation metrics may overestimate model performance. This is supported by PBIAS values (−4.7 to −11.6%) and the relatively narrow spread of simulated concentrations, suggesting that the model captures the general range of dissolved oxygen concentration but with limited sensitivity to spatial differences within the epilimnion. These discrepancies likely reflect unrepresented fine-scale processes such as localized mixing or biological activity, which are difficult to resolve at the current modelling scale exchanges (Figure SM1 a and Figure SM2 e).

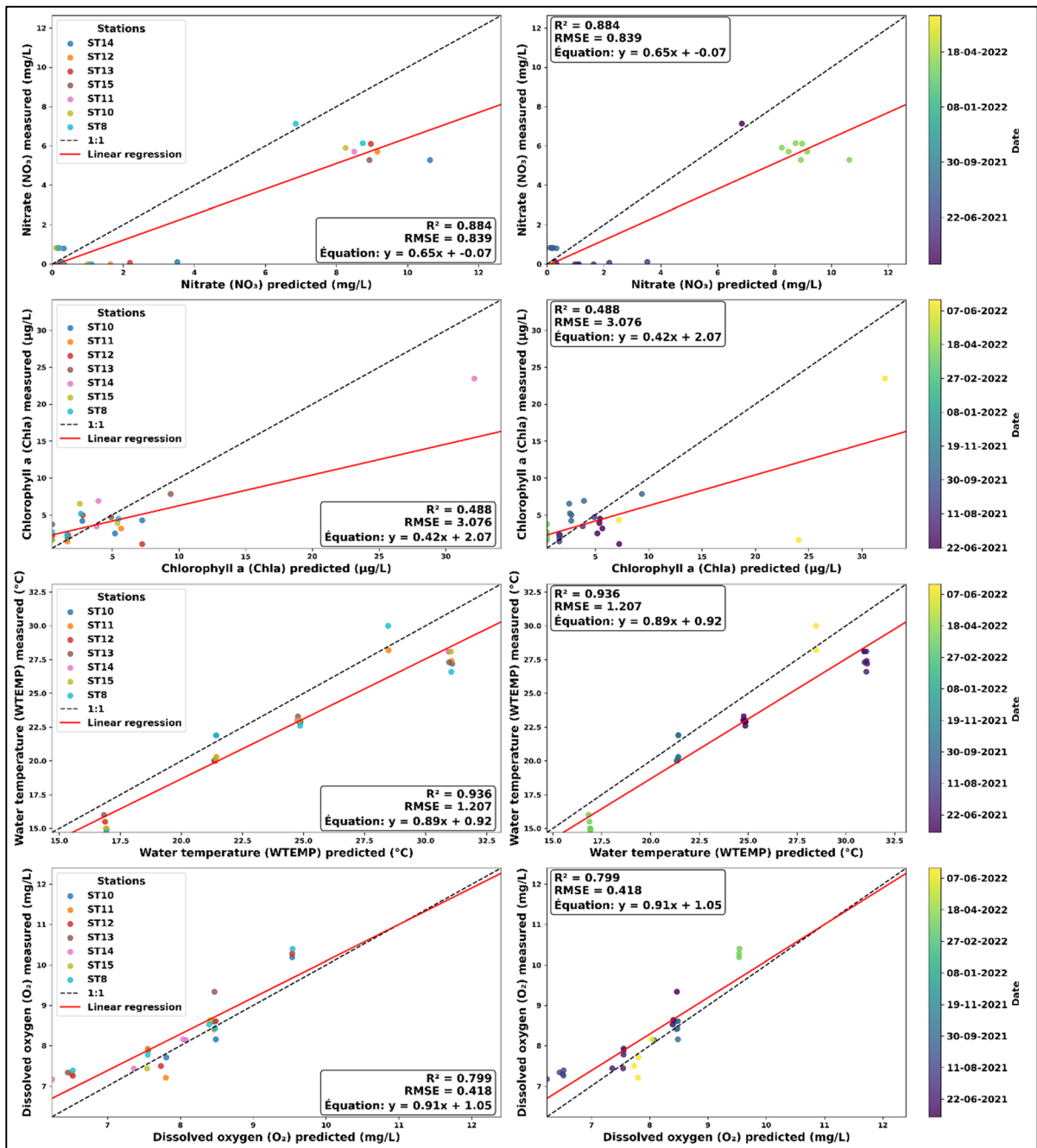


Fig. 2 Scatter plot comparison of simulated vs. measured values for water quality parameters (water temperature, dissolved oxygen, nitrate, and chlorophyll-a) in the reservoir at different measurement stations and dates

Chlorophyll-a simulations showed greater variability. Although high R^2 values were obtained at some stations, these are not fully reliable due to the low number of observations ($N=2-3$). More robust

indicators show moderate to high errors (MAE up to 3 µg/L and PBIAS ranging from -32 to $+92\%$), indicating both under- and overestimation depending on the period. Nevertheless, the model reproduces the

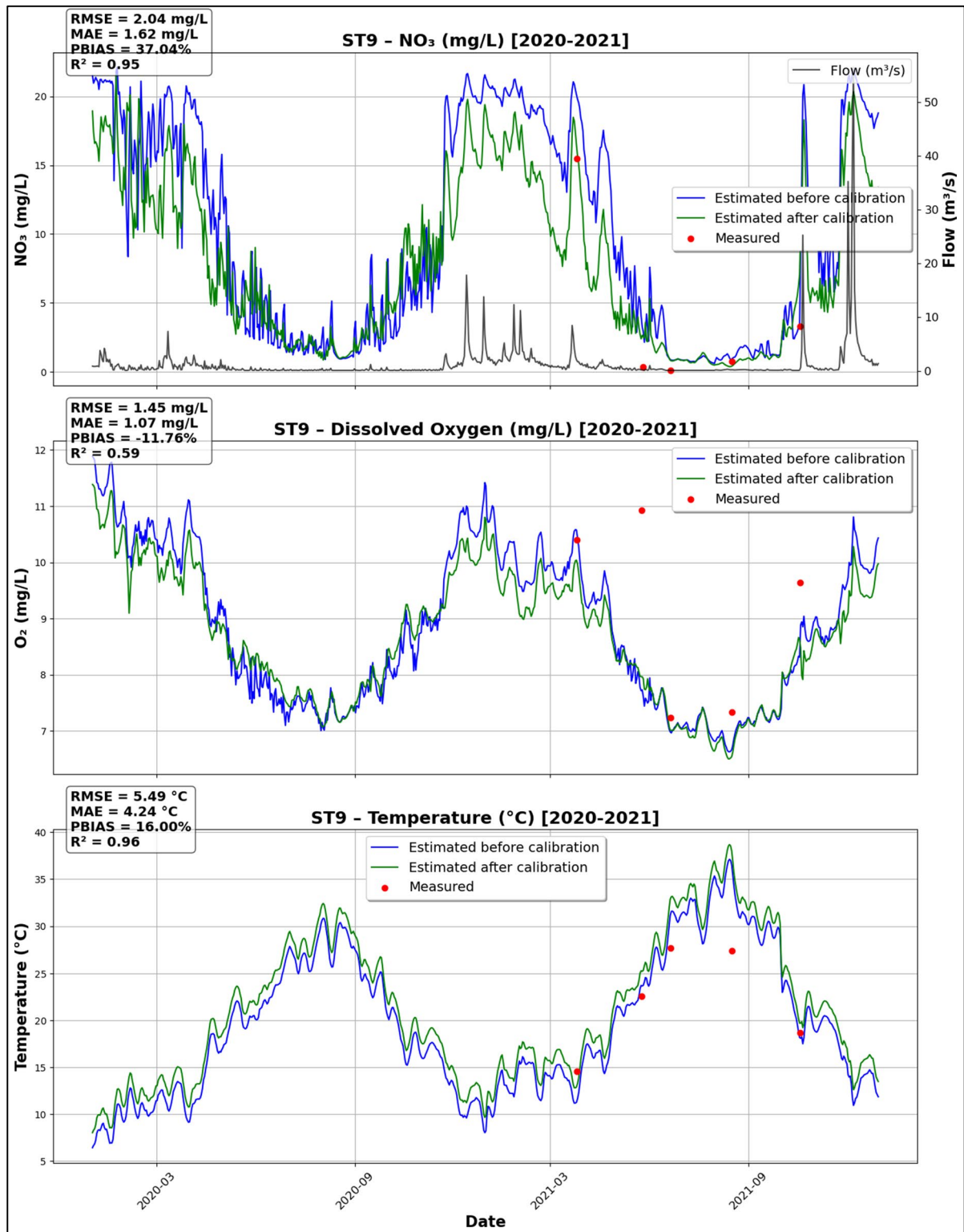


Fig. 3 Model performance at the reservoir inlet station (ST9): comparison of simulated and measured values for nitrate, dissolved oxygen, and water temperature (2020–2021)

general concentration range and seasonal tendencies of chlorophyll-a, suggesting that the main ecological dynamics are captured. At the same time, short-term variability remains more difficult to simulate (Figure SM1 d and Figure SM2 h).

Overall, the combined use of MAE and PBIAS provides a more reliable assessment than R^2 alone in this data-limited context. The model demonstrates a good ability to reproduce general seasonal patterns, particularly for nitrate and water temperature (Figure SM1 c and Figure SM2 g), which are primarily driven by catchment inputs and climatic forcing. In contrast, larger discrepancies in dissolved oxygen (Figure SM1 a and Figure SM2 e) and chlorophyll-a (Figure SM1 d and Figure SM1 h) highlight the influence of localized, short-term processes within the reservoir, which are inherently more complex to represent. These results therefore reflect both the strengths of the modelling framework and the limitations associated with data availability and spatial resolution.

Validation

Model validation for 2022 was carried out using a limited dataset with two measurement campaigns (March and June 2022) per station. Due to this limitation, statistical validation by station was not feasible. Instead, validation involved comparing model outputs to observations on specific dates, emphasizing spatial consistency across all stations for the epilimnion layer. Scatter plots and error metrics (e.g., RMSE, R^2) were calculated for each date, offering an indirect yet valuable assessment of model performance. Despite the low temporal resolution, the simulated patterns generally stayed within acceptable ranges, particularly for nitrate and chlorophyll-a concentrations in the epilimnion.

This validation method aligns with previous studies on the Joumine catchment, where statistical validation was not always possible due to limited data availability (e.g., Boukari et al., 2019). Here, the continuous simulation from 2020 to 2023, divided into eight periods based on thermal stratification dynamics, helped strengthen structural consistency across years and supported the plausibility of model outputs for the epilimnion.

To qualitatively assess the model's robustness beyond the calibration period, a comparison between simulated and observed values was performed at

station ST9 for the two 2022 measurement dates (29 March and 23 June) (Fig. 4). Although limited to a single measurement per parameter on each date, the validation shows that the model maintained good consistency with observed trends in the epilimnion. For nitrate, the simulated concentrations were in the same order of magnitude as observations, reflecting the continued influence of upstream inputs and confirming that catchment-driven nitrogen dynamics remained well represented 1 year after calibration. Water temperature predictions also matched observed values closely for both dates, suggesting that seasonal warming and cooling cycles were realistically captured. Dissolved oxygen showed larger discrepancies. Nevertheless, the general agreement between simulations and observations despite minimal data supports the model's ability to reproduce key biogeochemical patterns at the reservoir inlet, reinforcing trust in the model's performance under varying seasonal conditions.

Model validation was conducted using measurements from two sampling campaigns in 2022, providing an external assessment of model statistical performance under contrasting seasonal conditions. Importantly, the 2022 simulation was not independently initialized; it directly followed the calibrated 2021 simulation, which served as the initial condition. This sequential setup ensured dynamic continuity and provided an additional form of indirect validation, as the model's ability to reproduce 2022 patterns depends on its accuracy over the preceding year.

Simulated and observed values of dissolved oxygen (DO), water temperature, nitrate (NO_3^-) and chlorophyll-a (Chl-a) were compared for each date using regression analysis (Fig. 5).

Given the limited number of observations per date ($N=2-9$), correlation-based metrics such as R^2 are reported for descriptive purposes only, while their interpretation is limited by sample size and they are not used as primary indicators of model performance. Greater emphasis is therefore placed on error-based metrics (RMSE, MAE, PBIAS, and NRMSE), which provide a more appropriate assessment of predictive performance for limited datasets.

For dissolved oxygen, the model showed generally good agreement in terms of absolute errors, with RMSE values of 0.76 and 0.33 mg/L and low bias (PBIAS between -7.3 and $+2.6\%$). Although R^2 values were relatively high (0.93 and 0.69), their

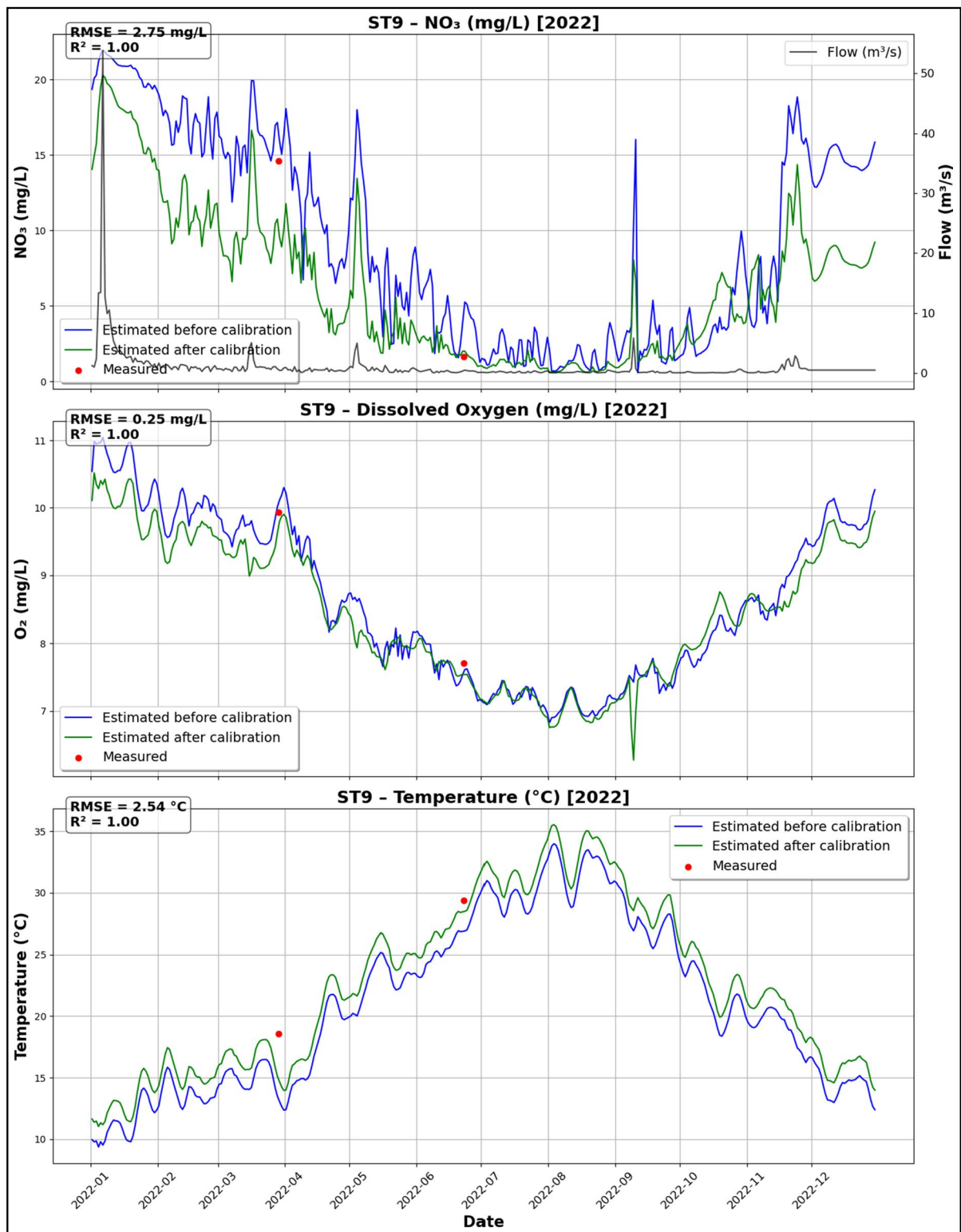


Fig. 4 Temporal variability of daily element concentrations (nitrate, dissolved oxygen and water temperature) located at the Joumine river inlet ST9 for 2022

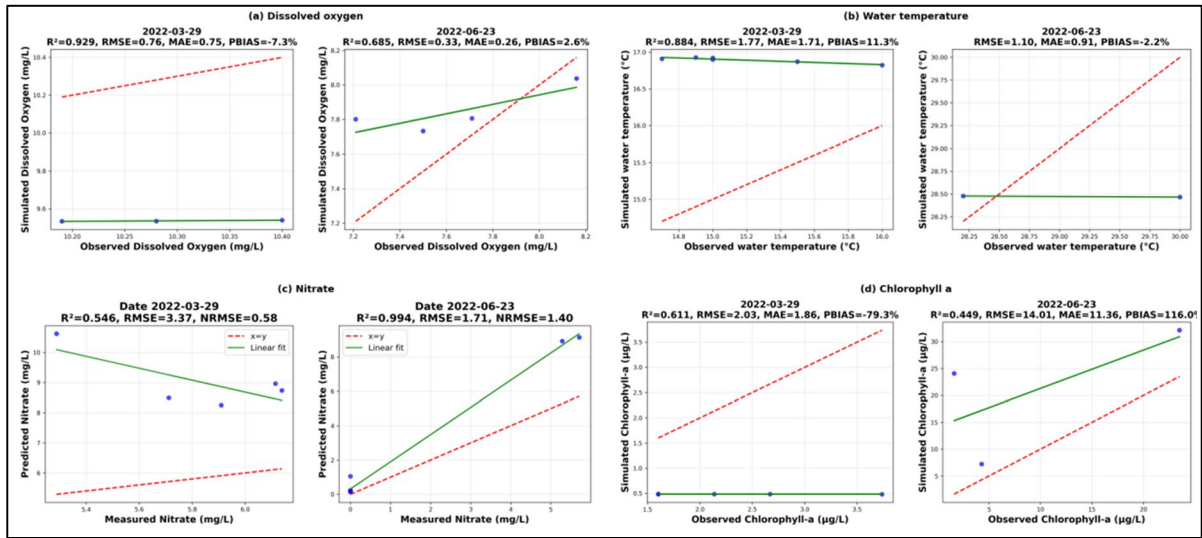


Fig. 5 Measured versus simulated concentration visualized by scatterplot diagrams of selected water quality parameters by date (**a** dissolved oxygen, **b** water temperature, **c** nitrate, and **d** chlorophyll-a) for 2022

interpretation is limited by the small sample sizes and they should be considered with caution rather than as definitive evidence of predictive skill. Overall, dissolved oxygen concentrations are reasonably well reproduced, although some spatial variability remains less accurately captured.

Water temperature simulations were consistently well reproduced across both sampling dates, with RMSE values of 1.77 °C and 1.10 °C and low to moderate bias (PBIAS = +11.3% and -2.2%). These results indicate a satisfactory representation of thermal conditions in the epilimnion, with relatively small absolute deviations. As with other variables, statistical inference remains limited for the June dataset ($N=2$) due to the very small sample size.

For nitrate, model performance differed between campaigns. On 29 March 2022, moderate agreement was observed (RMSE = 3.37 mg/L; MAE = 3.18 mg/L), with a positive bias (PBIAS = 54.6%), indicating systematic overestimation. Although the observed range (0–5 mg/L) represents ecologically relevant variability in nutrient concentrations within the epilimnion, prediction errors remain meaningful in relative terms. On 23 June 2022, the model reproduced spatial patterns more consistently, with lower absolute errors (RMSE = 1.71 mg/L; MAE = 1.03 mg/L), although a strong positive bias persisted (PBIAS = 84%). The

high NRMSE (1.4) indicates that errors remain large relative to observed variability. Overall, the model captures spatial trends but consistently overestimates nitrate concentrations, particularly under summer conditions.

Chlorophyll-a showed the largest discrepancies among all variables. On 29 March 2022, errors were moderate (RMSE = 2.03 µg/L; MAE = 1.86 µg/L), but a strong negative bias (PBIAS = -79.3%) indicates substantial underestimation. On 23 June 2022, model performance was substantially poorer, with high errors (RMSE = 14.01 µg/L; MAE = 11.36 µg/L) and strong overestimation (PBIAS = +116%). The high NRMSE values (0.86 and 1.43) confirm that chlorophyll-a variability is poorly reproduced, likely due to limitations in representing phytoplankton dynamics and associated biogeochemical processes such as grazing, light limitation, and sediment–water interactions.

Overall, the model reproduces general patterns of dissolved oxygen and temperature reasonably well, although predictive performance remains limited. Nitrate spatial trends are captured but with systematic overestimation, particularly under summer conditions. In contrast, chlorophyll-a remains poorly represented, highlighting clear limitations in the ecological parameterization of phytoplankton dynamics and reduced predictive skill. These results reflect both

data sparsity and the inherent difficulty of representing fine-scale spatial heterogeneity and short-term ecological variability in epilimnetic processes.

Scenario building

Figure SM 3, Figure SM 4, Figure SM 5, and Figure SM 6 show the simulation results for three contrasting scenarios that combine climate conditions and management practices in the Joumine reservoir catchment. These scenarios (see Scenario analysis) were created to assess how nitrate, chlorophyll-a, dissolved oxygen, and water temperature respond to future climate pressures, specifically in the epilimnion of the reservoir, from high climate stress without mitigation (SC1), moderate climate with partial adaptation strategies (SC2) to strengthened adaptation strategies (SC3).

Chlorophyll-a follows a similar spatio-temporal pattern: SC1 drives higher phytoplankton biomass due to nutrient enrichment, while SC3 results in substantially lower values, demonstrating the importance of nutrient input reduction in limiting eutrophication in the epilimnion.

For nitrate, SC1 produces the highest and most persistent concentrations, especially between December and April, when heavy rainfall and increased runoff drive diffuse nitrogen inputs. This pattern is most evident at in-reservoir epilimnion stations (e.g., ST14, ST11, ST13), where longer residence times enhance accumulation. SC2 shows intermediate behaviour, with reduced but still significant peaks, while SC3 displays both lower concentrations and reduced variability, highlighting the effectiveness of best management practices (BMPs) in controlling nutrient loads. At the reservoir inlet (station ST9), nitrate levels remain relatively lower and more stable across all scenarios, confirming that accumulation is mainly controlled by water residence time and slower circulation within the reservoir body. Under climate stress without management (SC1), average nitrate concentrations during the wet season (Dec–Apr) were up to ~65% higher compared to SC3 in the reservoir, with peaks exceeding 22 mg/L at mid-reservoir epilimnion stations (e.g., ST14). Implementation of reinforced BMPs and advanced wastewater treatment (SC3) reduced mean nitrate levels by ~63–65% compared to SC1 and by ~56–62% compared to SC2. The

upstream station (ST9) showed smaller reductions (~57% vs SC1, ~45% vs SC2).

For dissolved oxygen, all scenarios reproduce the typical seasonal pattern, with higher values in winter and lower values during summer, driven by temperature-dependent solubility. SC2 generally maintains the highest oxygen levels, followed by SC1 and SC3. This is largely attributable to the cooler climate under SC2, which limits stratification intensity and enhances oxygen availability in the epilimnion. However, this does not improve overall water quality: despite higher oxygen, SC2 still supports frequent phytoplankton blooms due to persistent nutrient inputs. Conversely, SC3 shows slightly reduced oxygen, particularly during warm periods, as higher temperatures (+3.9 °C relative to SC2) and microbial respiration offset the benefits of lower nutrient loads in the epilimnion. Station ST 14 occasionally records oxygen depletion under SC3, likely linked to stratification and localized consumption, whereas station ST9 remains more stable thanks to turbulent inflows and shorter residence times.

Water temperature shows a consistent summer increase across all stations. The ordering SC3 > SC1 > SC2 reflects the underlying climate forcing: SC3 corresponds to the most extreme horizon (2100 under RCP8.5), while SC1 and SC2 represent 2050 projections (RCP8.5 and RCP4.5, respectively). Quantitatively, summer temperatures increase by approximately 0.3–0.5 °C under SC1 compared with SC2, while SC3 shows a stronger rise of about 2–2.5 °C relative to SC2 and ~2 °C compared to SC1. The higher values under SC1 compared with SC2 arise from climate forcing, since management measures do not directly affect thermal conditions. These higher temperatures under SC3 are expected to strengthen thermal stratification, modulate phytoplankton dynamics, and potentially exacerbate oxygen stress within the epilimnion.

Overall, the results indicate that “extreme climate” conditions, unless mitigated by effective watershed management, lead to elevated nutrient concentrations, phytoplankton blooms, and potential oxygen depletion in the epilimnion. Reinforced BMPs, as in SC3, substantially mitigate these effects and promote more stable water quality, even under harsher climatic pressures.

Dissolved oxygen remained above the ecological threshold of 2 mg/L at all stations in summer,

with no hypoxic days observed in the reservoir and an ~0% reduction upstream under SC3 in the epilimnion. Chlorophyll-*a* responses were heterogeneous, with summer maxima under SC3 reduced by ~6% at mid-reservoir epilimnion stations (e.g., ST14), while upstream concentrations remained negligible. Water temperature, by contrast, increased consistently across scenarios, with SC3 producing ~2 °C higher summer means compared to SC1, strengthening stratification intensity and affecting epilimnion dynamics.

It is important to note that the scenario design combines both climate change and management interventions, which does not allow for a strict isolation of their individual effects. Therefore, the results should be interpreted as the combined response of the system to co-evolving drivers rather than as the attribution to a single factor. While this represents a limitation for process-level attribution, it provides a more realistic representation of future conditions in which climate change and management responses are intrinsically linked.

Discussion

This study contributes to current reservoir modeling approaches by explicitly linking thermal stratification dynamics to epilimnion-scale water quality responses, allowing direct assessment of climate-driven stratification effects under contrasting management scenarios.

This study enhances the understanding of climate–reservoir interactions by externally coupling the DEOLE-J thermal stratification model with the PEGASE water quality model, feeding PEGASE with DEOLE-J outputs. This approach allows the assessment of how thermocline variability, modulated by climate change and tributary inflows, affects key water quality parameters within the epilimnion in the Joumine reservoir (Tunisia). The epilimnion represents the primary layer where phytoplankton respond to light and nutrient availability, making it a relevant indicator of reservoir functioning (Ghane & Boegman, 2025; Wells & Troy, 2022). In stratified systems like Joumine, epilimnetic water quality has a strong influence on surface productivity and ecological exposure to eutrophication. Monitoring and modeling this layer thus provides a robust proxy for ecosystem status, integrating responses to both catchment-driven

nutrient inputs and in-reservoir processes. The seasonal stratification patterns described by Madyouni et al. (2025) provide the physical basis for interpreting variations in water quality in the epilimnion. During the stable stratification period (June–September), the strong thermal gradient limits vertical mixing and oxygen renewal, while promoting the retention of nutrients in the upper layer. Such conditions create a favorable environment for buoyant and thermophilic phytoplankton, particularly cyanobacteria, which dominate under warm, nutrient-rich, and low-oxygen conditions. Conversely, during the mixing period (January–February), vertical homogenization of the water column enhances oxygen renewal and nutrient redistribution, favoring diatoms and chlorophytes. DEOLE-J simulations (Madyouni et al., 2025) captured these seasonal dynamics, showing the strong summer stratification and shallower winter mixing depth. Overall, the coupling between DEOLE-J and PEGASE highlights how stratification dynamics directly control nutrient availability and phytoplankton composition in the Joumine Reservoir.

The coupled modeling framework enabled the assessment of seasonal stratification, hydrological variability, and anthropogenic pressures under three contrasting climate-management scenarios (SC1, SC2, and SC3), with a focus on nitrate, chlorophyll-*a*, dissolved oxygen, and temperature dynamics in the epilimnion. Performance evaluation highlights that the model reliably captures riverine processes at station ST9, located upstream of the reservoir and representing upstream dam conditions. At this site, nitrate concentrations and water temperature were reproduced with high temporal correlation (R^2 up to 0.95 for nitrate; $R^2 = 0.96$ for water temperature), confirming that catchment-driven loading and hydrological variability are well-represented (Kraemer et al., 2015; Šarović & Klaić, 2023). ST9 strongly drives downstream biogeochemical dynamics and serves as a benchmark for model calibration and scenario testing.

Simulating reservoir-specific processes introduced additional complexity. While the model successfully captured the overall seasonal dynamics of surface water temperature and nitrate in the epilimnion, performance for dissolved oxygen (DO) and chlorophyll-*a* (Chl-*a*) was more variable, with consistent temporal trends but greater discrepancies in spatial distribution and short-term variability, as also reflected by higher errors and bias, highlighting the influence

of localized processes that are not fully resolved by the model. Temporal dynamics were generally well reproduced, but consistent with observations from other Mediterranean reservoirs, spatial heterogeneity was less accurately represented, where localized variations in mixing, hypolimnetic oxygen depletion, and episodic nutrient pulses exceed the resolution of 1D models (L. Wang et al., 2024). The model shows both underestimation and overestimation of summer Chl-a depending on the period and station, reflecting limitations in representing short-term phytoplankton dynamics. These discrepancies highlight opportunities for improvement, particularly through refined phytoplankton parameterization. In the applied PEGASE configuration, phytoplankton are represented through multiple functional groups, although results are evaluated in terms of total chlorophyll-a. Given the ecological dominance of cyanobacteria during summer stratification in the Joumine reservoir, parameter sensitivity is strongly influenced by cyanobacterial growth processes. Further improvements could include enhanced representation of grazing, photoinhibition, and sedimentation processes, which are especially influential in shallow, well-lit epilimnetic layers.

Processes such as cyanobacterial dominance under stratified conditions, internal phosphorus release, and hypolimnetic oxygen depletion are well documented in stratified reservoirs and provide a conceptual framework for interpreting the simulated patterns. However, it is important to emphasize that these mechanisms are not explicitly represented in the current modeling framework, nor directly supported by the available dataset. Their inclusion here serves to contextualize the results within established limnological understanding rather than to demonstrate their occurrence in the Joumine reservoir.

Among all simulated variables, chlorophyll-a (Chl-a) shows the highest uncertainty, with strong under- and overestimation depending on season and station, reflecting limitations in representing phytoplankton dynamics (Arif et al., 2023). Similar patterns have been reported in Chinese and Mediterranean reservoirs, highlighting the common challenge of representing short-term algal dynamics in systems with rapid ecological transitions (Paerl et al., 2016). Episodic vertical mixing and entrainment events control nutrient fluxes from deeper layers into the epilimnion, which directly influence surface

nutrient availability and bloom dynamics (Ghane & Boegman, 2025; Merino-Ibarra et al., 2021). Modeling studies coupling epilimnion and hypolimnion processes indicate that phytoplankton competition and bloom formation are strongly dependent on physical and nutrient conditions within the mixed surface layer (Zhang et al., 2021).

The study faced several data-related constraints. Phosphorus measurements were unavailable, limiting the simulation of nutrient-limited algal dynamics and cyanobacterial bloom potential, a limitation frequently reported in Mediterranean reservoirs (Arif et al., 2023; Paerl et al., 2016).

As a result, phosphorus dynamics were not calibrated or validated in the model. Consequently, the model cannot robustly assess phosphorus limitation, N:P interactions, or the specific role of phosphorus in controlling phytoplankton dynamics and eutrophication processes.

Therefore, eutrophication dynamics are only partially captured, and interpretations based on nitrogen and chlorophyll-a should be considered with caution. In stratified reservoirs, internal phosphorus release from sediments and N:P interactions play a key role in regulating phytoplankton growth, particularly during summer stratification. These processes are not represented in the current modelling framework and may partly explain discrepancies in chlorophyll-a simulations.

Additionally, low temporal sampling frequency (monthly or bimonthly) reduced the capacity to capture short-term fluctuations driven by storm inflows or internal mixing events (Lewis et al., 2024). These limitations required pragmatic modeling choices, including the use of mean seasonal thermocline depth from DEOLE-J to drive PEGASE. While this approach provides a useful first-order representation of vertical structure, it may smooth high-frequency variability and limit the representation of transient exchanges between layers (Berger & Wells, 2008; L. Wang et al., 2024). Nevertheless, the continuous simulation from 2020 to 2023, where each year's outputs were used as initial conditions for the next, provides indirect evidence of model robustness and its ability to capture seasonal consistency despite limited high-frequency data, consistent with the concept of a unique steady annual cycle observed in marine ecosystem models (Pfeil & Slawig, 2021).

Despite these constraints, the Simulation provides robust insights for management applications.

It is important to note that management scenarios involving nutrient reduction (SC2 and SC3) represent combined nitrogen and phosphorus mitigation strategies, but only nitrogen dynamics are directly constrained by observations.

Therefore, the effects of phosphorus-related measures (e.g., reduced P inputs or advanced phosphorus treatment) should be interpreted qualitatively rather than as quantitatively validated outcomes. Scenario simulations (SC1, SC2, and SC3) indicate that climate change may exacerbate eutrophication and oxygen depletion in Mediterranean reservoirs, aligning with regional assessments (Piccolroaz et al., 2024; Woolway et al., 2022).

The epilimnion, as the primary layer for phytoplankton growth, is especially sensitive to stratification changes, affecting both bloom potential and ecological exposure to poor water quality (Mesman et al., 2021; Wells & Troy, 2022). Best Management Practices (BMPs), such as upstream nutrient loads reductions, were effective in controlling nitrate concentrations and algal biomass in the epilimnion but could not fully prevent oxygen stress driven by prolonged summer stratification. For example, studies in northern lakes show that climate warming prolongs summer stratification, increasing aerobic respiration and oxygen depletion; nutrient reductions control algal blooms but do not mitigate thermal-driven oxygen loss (Jansen et al., 2024). Similarly, BMPs in agricultural watersheds, including vegetative buffers and conservative agriculture, improve water quality, but hypoxia may still develop during summer months (Lizotte et al., 2021).

Scenario analysis shows that strengthened BMPs (SC3) reduced winter nitrate peaks by 63–66% in deep reservoir stations, whereas the upstream station (ST9) experienced smaller reductions (~32%). Summer Chl-a responses in the epilimnion were heterogeneous, with some stations showing modest reductions and others slight increases, indicating that nutrient management alone is insufficient to consistently lower algal concentrations. However, their influence on dissolved oxygen dynamics remains limited under warming conditions. Dissolved oxygen decreased slightly (3–5%) in the epilimnion, with no hypoxic events at deep sites, whereas ST9 showed a larger reduction (~8%) due to different hydrodynamic

conditions. These results suggest that thermal stratification exerts a dominant control on oxygen availability, through reduced mixing and increased temperature-dependent respiration.

These findings underline the importance of integrated watershed management (see Scenario analysis), through the implementation of Best Management Practices (BMPs), and climate adaptation strategies for sustaining water quality in Mediterranean reservoirs under future climate scenarios.

Although the scenario design does not allow a strict separation of climate and management effects, some qualitative insights can still be inferred. Variations in water temperature are primarily driven by climate forcing, whereas changes in nitrate and chlorophyll-a concentrations are mainly associated with management practices. However, these interpretations remain indicative and should be confirmed using a more systematic factorial scenario design in future work. Calibration was further constrained by parameter availability and temporal frequency. Low-frequency sampling limits the capture of episodic events, short-term algal blooms, and rapid biogeochemical responses (Zhu et al., 2024). Averaged inflow data underestimate high-magnitude pulses on epilimnetic chemistry and stratification (Lewis et al., 2024; Zhang et al., 2021). Using mean thermocline depth from DEOLE-J offers a pragmatic vertical mixing representation, potentially overlooking short-term nutrient redistribution events (Šarović & Klaić, 2023; Zhang et al., 2021). Although hydrological variability is represented through inflow boundary conditions, explicit analysis of water quantity dynamics (e.g., drought frequency, storage evolution, residence time changes) was not conducted. This represents an important limitation given the strong sensitivity of Mediterranean reservoirs to climate-driven hydrological deficits (Almeida et al., 2021; Woolway et al., 2022). Future work should explicitly couple reservoir hydrodynamics with water balance modeling to better capture drought–stratification feedbacks. Phytoplankton representation in PEGASE is based on functional groups derived from European temperate freshwater systems, which may not fully capture Mediterranean-specific community structure and metabolic responses (Paerl et al., 2016).

Despite these limitations, the DEOLE-J/PEGASE coupling provides a robust framework for assessing climate change impacts on epilimnetic

water quality. Our study reinforces the importance of integrated management strategies that combine watershed BMPs with in-reservoir adaptations to maintain ecological health in Mediterranean reservoirs under warming conditions.

Thermal stratification and oxygen dynamics in Mediterranean and North African reservoirs differ markedly from temperate systems, making them particularly vulnerable to climate change and eutrophication. Warm and/or dry summers combined with episodic rainfall and high evaporation promote prolonged stratification, isolating a warm, illuminated epilimnion from an oxygen-depleted hypolimnion (Fadel et al., 2015; Zouabi-Aloui et al., 2015). Internal phosphorus release from sediments is commonly reported to sustain eutrophication in such systems (Bormans et al., 2016), although this process is not explicitly simulated nor constrained by observations in the present study. Such feedbacks are widely observed in Mediterranean and semi-arid reservoirs, where stratification can persist for months (May–August) and hypoxic conditions recur annually (Fadel et al., 2015; Sánchez-España et al., 2017).

These processes are further reinforced by regional hydrological variability. In semi-arid catchments, nutrient inflows are highly episodic, with flash flood pulses alternating with prolonged droughts, producing sharp contrasts in epilimnetic nutrient dynamics (Fadel et al., 2015). Reservoir operation and water-level fluctuations (e.g., irrigation withdrawals, selective outlet depths) also strongly influence oxygen and nutrient regimes (Zouabi-Aloui et al., 2015). Mediterranean reservoirs often provide primary freshwater supplies for drinking and irrigation, making water quality degradation a major socio-economic concern. However, long-term monitoring data remain scarce, increasing reliance on models coupling climate, watershed, and reservoir processes to anticipate risks (Almeida et al., 2021).

By applying the DEOLE-J/PEGASE framework to the Joumine reservoir, this study contributes to address this knowledge gap. It provides one of the few modeling-based assessments of epilimnion dynamics under combined climate and management scenarios in North Africa, highlighting that Mediterranean reservoirs require region-specific strategies integrating both watershed nutrient controls and in-reservoir interventions.

Despite these insights, several limitations should be acknowledged. Field observations in the Joumine reservoir were temporally limited, reflecting typical monitoring constraints in semi-arid Mediterranean basins. However, the objective of this study was not short-term prediction but process-based assessment of epilimnion responses to climate change and management scenarios. Continuous simulations over multiple years (2020–2023), combined with independent thermal stratification outputs from the DEOLE-J model, allow the exploration of seasonal dynamics and scenario sensitivity beyond the discrete sampling dates. While higher-frequency observations would improve calibration and validation, the modeling framework provides robust first-order insights into stratification-driven nutrient, phytoplankton, and oxygen dynamics under data-limited conditions.

Despite the robustness of the coupled DEOLE-J/PEGASE framework in reproducing seasonal dynamics of the Joumine Reservoir, several limitations should be acknowledged. The study is constrained by limited field data, both in temporal resolution and completeness, with water quality measurements available only at monthly to bimonthly intervals and no phosphorus data, which restricts the ability to fully assess nutrient limitation, internal loading, and short-term ecological responses such as bloom events or storm-driven nutrient pulses.

This limitation particularly affects the interpretation of eutrophication processes and the evaluation of phosphorus-specific management strategies, which cannot be fully assessed within the current modeling framework. In addition, the use of a one-dimensional modeling approach limits the representation of spatial heterogeneity, including lateral gradients and localized mixing processes that can strongly influence oxygen and phytoplankton dynamics in stratified reservoirs. The external coupling between DEOLE-J and PEGASE also simplifies thermocline variability, relying on averaged representations that do not fully capture high-frequency stratification changes or feedbacks between biogeochemical processes and thermal structure, thereby smoothing short-term variability. Furthermore, phytoplankton are represented through aggregated functional groups and evaluated using total chlorophyll-a, which limits the explicit simulation of species-specific dynamics, particularly cyanobacterial dominance, while key ecological processes such as grazing, photoinhibition, and sediment

interactions remain simplified. Finally, the absence of explicit water balance and reservoir operation dynamics, including storage fluctuations, residence time variations, and drought impacts, limits the ability to fully capture long-term hydrological controls on water quality. Overall, these limitations imply that while the model is well-suited for seasonal-scale analysis and scenario-based assessment of epilimnetic water quality, it is less capable of resolving high-frequency events, fine-scale spatial variability, and fully coupled hydrology–ecology feedbacks.

Conclusion

In conclusion, the coupling of the PEGASE water quality model with the DEOLE-J thermal stratification model and in situ field measurements provided a consistent representation of the temporal and spatial dynamics of epilimnion water quality in the Joumine Reservoir (Tunisia). This integrated modeling–monitoring framework helped identify the key drivers of nitrate, chlorophyll-*a*, dissolved oxygen, and temperature within the epilimnion, while highlighting the strong influence of thermocline variability on seasonal ecosystem functioning.

Among the simulated variables, chlorophyll-*a* (Chl-*a*) exhibits the highest uncertainty, with pronounced under- and overestimation depending on the season. This reflects limitations in representing phytoplankton dynamics and associated ecological processes. In contrast, PEGASE adequately reproduces inflow-driven variability through river discharge forcing and associated nutrient inputs, providing first-order insights into epilimnetic water quality. Further refinement of epilimnetic process parameterization and integration of horizontal hydrodynamics would improve model performance for Mediterranean reservoirs.

Scenario analysis highlighted strong contrasts between management strategies. Without intervention (SC1), nitrate concentrations in the epilimnion increased by ~65% during the wet season compared to reinforced management (SC3), with peaks exceeding 22 mg/L and episodic eutrophication at mid-reservoir stations. SC2, representing moderate climate conditions with partial adaptation strategies, showed intermediate nitrate levels and phytoplankton biomass, indicating partial effectiveness of mitigation

measures. Dissolved oxygen generally remained above ecological thresholds but exhibited localized summer depletion. In SC3, combined Best Management Practices (BMPs) and advanced wastewater treatment reduced nitrate loads by 63–66% and limited phytoplankton development; however, oxygen stress persisted under strong warming (+3.9 °C by 2100), associated with an approximate +2 °C increase in summer epilimnetic temperature and enhanced stratification.

Overall, these results suggest that future climate change will likely exacerbate eutrophication and oxygen depletion in the epilimnion of the Joumine reservoir unless integrated management strategies are implemented. The scenario framework captures inflow-driven variability and its influence on nutrient dynamics and epilimnetic water quality, highlighting the sensitivity of the system to climatic and management conditions. While BMPs and advanced wastewater treatment effectively reduce nutrient inputs and tend to limit phytoplankton biomass, they are insufficient to fully mitigate oxygen deficits under prolonged stratification conditions. Sustainable reservoir management therefore requires combined watershed-scale measures (nutrient load reduction, improved wastewater treatment, and sustainable agriculture) and in-reservoir adaptations targeting stratified systems.

The DEOLE-J/PEGASE coupling proved particularly useful for simulating epilimnion water quality in semi-arid and data-limited contexts, providing insights into current and future vulnerabilities. These findings highlight the need for stricter nutrient regulations, enhanced wastewater treatment, and high-frequency monitoring of key epilimnetic variables.

Future research should focus on improving data resolution through high-frequency monitoring of key parameters, including phosphorus fractions and biological indicators, to better capture short-term variability and ecological dynamics. In parallel, incorporating species-specific phytoplankton dynamics and improving the representation of vertical exchange processes would enhance the realism of biogeochemical simulations. A more systematic scenario framework should also be adopted, based on a factorial design that combines multiple climate and management scenarios, allowing the disentanglement of their respective contributions and interaction effects on reservoir water quality. Finally, coupling with higher-dimensional (2D or 3D) hydrodynamic–biogeochemical

models would improve the representation of spatial heterogeneity and transport processes. Together, these developments would strengthen predictive capacity and support more effective adaptive management strategies to sustain epilimnion water quality under climate change.

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Data availability The datasets generated and analyzed in this study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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