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Ph.D. Thesis

Use of integrated lake-watershed models to unravel the synergistic impacts of climate change and pollution on a moderately deep temperate lake: the case study of Lake Pusiano and of its recent trophic evolution

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Abstract

Lakes are fragile ecosystems susceptible to multiple pressures. A major one is climate change, which heats water, altering chemical and biological equilibria, and modifies the mixing regime, preventing nutrients and dissolved oxygen from being distributed along the water column. Climate change manifests itself not only as a steady increase of temperatures, but also through extreme events such as droughts and heatwaves. These events can lead to intense lake stratification and water stagnation, lasting over prolonged periods, promoting the release of phosphorus from sediments under anoxic conditions. This condition worsens the lake trophic state, hampering restoration actions on lake watersheds aimed at reducing nutrient loads. Mild winters, as increasingly brought by climate warming, further create the conditions necessary for algal blooms to persist throughout the year.

A further critical anthropogenic impact on lake ecosystems is represented by combined-sewer overflows (CSOs). These act as point sources of untreated sewage to lakes and their tributaries during rainfall events, and during dry periods as well in case of failures in the sewer system.

Moderately deep lakes are more susceptible than shallow and deep ones to droughts and heatwaves. In fact, on one hand their depth is large enough to allow stratification, but on the other it is small enough to have the whole water volume influenced by climate change without appreciable lags. Therefore, processes such as hypolimnetic anoxia can rapidly develop, the ensuing potential release of internal load then playing a relevant role due to the moderate value of the ratio between lake volume and bottom surface.

In Europe, regional authorities have developed water protection plans for lakes that set quality standards, as an answer to the European Water Framework Directive (WFD). In Italy, these standards are also expressed as function of total phosphorus (*TP*) concentrations at spring mixing. However, targets set in previous decades, following success of early re-oligotrophication measures, must be updated to consider the combined detrimental effects of residual anthropogenic pressures and climate change.

Process-based numerical models of lakes and their watersheds are a valuable tool for supporting management strategies. In fact, they enable considering variable physical, chemical and ecological arrangements, while also incorporating meteorological and climatic conditions, which are now essential for environmental simulations.

The aim of this thesis was to produce such evolutive estimations of water quality status through hydrodynamic and ecological models for selected subalpine lakes in the Lombardy Region of Northern Italy, with a particular focus on Lake Pusiano as a case study. Specifically, near-future evolution of *TP* concentrations at spring mixing and both internal and external nutrient load series in response to changes in external factors were quantified. Attention was paid to the interplaying effects of anthropogenic pressures in the lake catchment and climate change, including the steady temperature increase and extreme events. Reduction scenarios of external nutrient loads were further considered. This work used multiple complementary numerical models: 1) the one-dimensional WET model for long-term ecological-hydrodynamic simulations of the lake physical, chemical and basic biological dynamics; 2) the SWAT+ eco-hydrological model to dynamically reproduce the processes

leading to external nutrient load from the catchment; 3) the Delft3D D-Flow three-dimensional hydrodynamic model of lake hydrodynamics, aimed at analysing circulations and water renewal under heavily stratified summer drought conditions.

The development of this research timely followed the observed relevant trophic decline of Lake Pusiano following the extended 2021-2023 drought, being directed towards explaining the cause-effects chain which led to such unexpected conditions.

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1.Overall Introduction

1.1 Background and motivation

Lakes as ecosystems are peculiarly vulnerable to the effects of climate change (Jiménez-Navarro et al., 2023). The most direct effect is water temperature warming, altering the equilibria of chemical reactions and the habitats of living species (Catalan et al., 2024). Another main issue related to warming waters is the alteration of the mixing regime, both for deep and shallow lakes. Due to rising temperatures, dimictic lakes would become monomictic. Meanwhile, subalpine lakes which used to mix completely once per year, may shift toward oligomictic or even meromictic regimes (Fenocchi et al., 2018). These changes are driven by the increased vertical temperature gradient (Livingstone, 2003) between the epilimnion and the hypolimnion, which leads to a prolonged stratification period, extending into late autumn. This condition favours prolonged hypolimnetic anoxia in moderately deep productive basins, resulting in the release of substances such as phosphorus, ammonium, and hydrogen sulphide from sediments, the last two compounds being harmful to fish fauna (Beauchamp et al., 1984, Randall and Tsui, 2002).

As a result, climate change impacts water quality not only through the direct effect of temperature warming, but also due to indirect effects due to lake mixing modifications. The European Union (EU) Water Framework Directive (WFD; 2000/60/EC; European Commission, 2000) establishes the quality standards that must be achieved in water bodies of member states. In Italy, these standards are ultimately defined at the regional level through Water Protection and Use Plans (PTUA), which for lakes set key threshold values for total phosphorus (*TP*) at spring mixing, phosphorus generally being the limiting nutrient. These thresholds will then be linked to the biological quality elements (i.e., phytoplankton, macrophytes, macroinvertebrates and fish), which define the ecological status of the lake (e.g. Copetti and Erba, 2024).

An emerging critical issue is that in some cases these target *TP* concentrations cannot still be met, despite the reduction efforts mainly implemented in the 1980s and 1990s, aiming at sewage collection and wastewater treatment plants (WWTP) implementation (Dezuanni et al., 2025). As a result, the nutrient loads from the catchments remain too high. The main problem in this regard is that present nutrient loads delivered from the watershed to lakes are largely unknown. Current regulations, in fact, require direct discrete monitoring of nutrient concentrations in streams at a typical quarterly resolution (2000/60/EC; European Commission, 2000), with the aim of calculating chemical and biological quality indices, but not for assessing nutrient loads (Fenocchi et al., 2023). A proper assessment of external load series would need a much higher sampling frequency and the constant availability of discharge measurements, which is usually guaranteed only for some closing section of river watersheds, allowing to understand load variability (Dezuanni et al., 2025). Such lack of information can lead to a misperception of the actual state of water quality, potentially giving the false impression that no further improvements are needed, even though problems may persist. Therefore, continuous updates to regulations are essential to address the challenges posed by climate change, along with the design of targeted interventions to reduce nutrient inputs.

The first main source of residual pollution to lakes and their watersheds is determined by diffuse loads, which can be tackled only by reducing the disposal at the source. Nature-based solution (NBS) approaches such as the installation of vegetated buffer zones next to riverbanks are available and can mitigate the problem, but for heavily anthropised conditions they may be insufficient (Duan et al., 2021). In the presence of combined-sewer systems, combined-sewer overflows (CSOs) release large quantities of untreated sewage into receiving water bodies during wet periods. However, due to ageing sewer system, the activation threshold is often lower than originally designed, CSOs being active also during dry periods in extreme cases. Therefore, the contribution of CSOs to nutrient loading can be hardly determined, case-by-case field monitoring being needed (e.g., Viviano et al., 2014; Salerno et al., 2018; Spill et al., 2025).

Nutrient pulses occurring after heavy rainfall events lead to excess nutrient concentrations in lakes, which trigger phytoplankton blooms (Morabito et al., 2018). Intense rainfall events in fact significantly increase surface runoff, facilitating the transport of nutrients from agricultural soils in which they were stocked and from urban areas, through the activation of CSOs, towards water bodies. In recent years, a shift has been observed in the seasonality of such blooms, which now occur not only in summer but also in winter, water temperatures compliant with algal growth being now attained through climate change also during such period, especially in case of episodic warm days (Wejnerowski et al., 2024). On the other hand, during drought periods, reduced precipitation and inflow discharge result in lower nutrient inputs to lakes, ordinarily leading to reduced algal production (Athukoralalage et al. 2024).

Climate change increases the frequency, intensity and duration of extreme weather events (IPCC, 2023). Shallower lakes are more exposed than deeper ones to such events, as the whole water volume can be promptly affected. For example, reduced inflow occurring with droughts would impair water circulations and increase water residence times (Pinardi et al., 2015; Fenocchi and Sibilla, 2016). In some cases, the proximity of inlets and outlets in the lake basin can further trigger "short-circuit" phenomena (Råman Vinnå et al., 2017), where most of new water from the tributary leaves the lake without really entering the basin. In such conditions, if a lake is deep enough to develop stratification, rapid deoxygenation of deeper layers is obtained due to lack of water renewal, especially in case of combined drought-heatwave phenomena (Woolway et al., 2025). This would trigger internal loading through sediment release, with greater nutrient release under prolonged and heavier stratification and anoxia. Such internal loading would increase lake productivity, something which tends to persist after extreme conditions have passed through nutrient recycling, in turn leading to hypolimnetic oxygen consumption through degradation of settling organic matter.

In this case, internal loading could become more important than external loading during dry periods and continue to play a significant role thereafter. This has been proved in this work to be one of the causes of the water quality decline of Lake Pusiano (Northern Italy), a moderately deep and sized temperate lake that, following the prolonged drought of 2021–2023, has shown a marked worsening of its trophic state, with intense algal blooms occurring throughout the year.

In the effort to analyse the evolutionary behaviour of lakes, with a focus on Lake Pusiano as case study, this work leverages on process-based numerical modelling. Numerical models are a fundamental tool for understanding, simulating, and predicting the behaviour of lakes and their watersheds in response to both anthropogenic pressures and climate change (Senent-Aparicio et al., 2021). Process-based models allow representing environmental dynamics with a good degree of flexibility from parameterization, allowing the evaluation of different management strategies and future climate change scenarios (Dresti et al., 2021). These models can simulate the physical, chemical, and biological dynamics of lakes and their catchments in detail, providing a valuable tool for environmental planning by stakeholders. Moreover, they enable integrating meteorological and climatic conditions, which are now essential due to the growing impact of climate change on the water balance, nutrient loads, and internal processes of lakes.

This Ph.D. thesis is motivated by the need to address key gaps in the understanding and management of lake systems through an integrated process-based catchment–lake modelling approach.

First, it aims to overcome the limited knowledge of nutrient loads originating from the watershed, which are often poorly quantified due to the scarcity of continuous monitoring data, by assessing whether eco-hydrological modelling tools can provide reliable estimates of their temporal dynamics, functional for lake modelling and especially catchment management activities.

A further gap concerns the quantification of internal nutrient loading through coupled ecological-hydrodynamic lake modelling. Internal loading is typically estimated using simplified analytical approaches, with potential large uncertainties. In this regard, the interactions between external and internal loading processes are also addressed, especially under conditions of climatic variability and extreme events such as intense rainfall and prolonged droughts, which are of increasing relevance with ongoing climate change.

The thesis also addresses the lack of integrated tools capable of supporting lake management, by evaluating whether frameworks made up by multiple complementary models can assist in assessing compliance with water quality requirements and in identifying effective mitigation strategies, such as BMPs and NBS.

1.2 Research objectives

This work is rooted inside an institutional collaboration agreement between Regione Lombardia, CNR-IRSA, and the University of Pavia – Department of Civil Engineering and Architecture, on the hydrodynamic and ecological modelling of major lakes in Lombardy, and especially focuses on Lake Pusiano. This lake effectively proved to be an ideal case study to understand how these mid-sized, moderately deep lakes can be affected by climate change and the ensuing meteorological extremes.

The original aim of the collaboration was to develop models to assess whether the analysed lakes can achieve the target *TP* concentrations at spring mixing by 2027, as required by the regional Piano di Tutela e Uso delle Acque (PTUA), allowing the evaluation of more realistic thresholds than the previously assumed ones. Once this primary goal was achieved, the research of this Ph.D. thesis turned to the Lake Pusiano case study, determining the external nutrient load series from the catchment by means of eco-hydrological modelling, to understand the actual variability with annual rainfall and discuss possible long-time changes. The internal phosphorus load of the lake was determined through coupled ecological-hydrodynamic limnological modelling, and its relationship with annual precipitation and external nutrient input was analysed. Scenarios were also developed to evaluate the possible reduction of external nutrient loads from the catchment through the implementation of Best Management Practices (BMPs), to assess their likely effectiveness on the basin and impact on the lake. Last, the study timely investigated the reasons of the recent observed trophic decline of Lake Pusiano, linking it to the extended drought which affected the region between 2021 and 2023, as well as to the hot summer 2022. The impact of the drought on external and internal loading was evaluated by means of modelling activities, which included an analysis by means of a three-dimensional hydrodynamic model of the circulation dynamics and of the influence of the tributary entrance with different discharges under strong stratification conditions, such as those of the hot summer 2022.

The thesis is structured around two levels of objectives, distinguishing between general and specific themes. The primary objectives are broader and more general in scope, addressing the main scientific and methodological challenges of the study, with a focus on the development and application of an integrated modelling framework to analyse external and internal nutrient loading dynamics and support lake management. The secondary objectives are more specific, targeting specific processes and case-study applications, and providing additional insights into physical mechanisms, management strategies, and the recent evolution of the lake under changing environmental conditions.

Primary Objectives

- Develop models to assess whether major lakes in Lombardy can achieve the target total phosphorus (*TP*) concentrations during spring mixing by 2027, and to define realistic threshold values keeping into account the specific dynamics of each lake.
- Develop an integrated catchment–lake modelling approach to better explain and support this assessment for the Lake Pusiano case study, deepening the knowledge on external load variability with annual rainfall.
- Evaluate whether the modelling framework can estimate both external and internal nutrient loads as a function of annual precipitation, and investigate potential long-term changes.
- Develop and analyse lake and watershed management scenarios.

- Investigate the effects of climate change, with particular focus on the impact of drought and heatwave conditions.

Secondary Objectives

- Define updated and more realistic *TP* threshold values for lakes.
- Analyse circulation dynamics for the Lake Pusiano case study under strong stratification conditions.
- Evaluate the effectiveness of nutrient reduction measures (e.g., BMPs) and their impact on lake water quality.
- Investigate the causes behind the recent trophic decline of Lake Pusiano.

To reach these goals, this work employed several complementary models, which in the end together allowed explaining what has happened to Lake Pusiano in the last years:

- **WET** (Water Ecosystems Tool; Nielsen et al., 2017, 2021; Schnedler-Meyer et al., 2021), a one-dimensional (1D) coupled ecological-hydrodynamic model used to reproduce the evolution in time of lake physical, chemical and biological processes in the water column.
- **SWAT** (Soil & Water Assessment Tool; Bieger et al., 2017), an eco-hydrological model used to estimate time series of surface and sub-surface runoff and nutrient loads released to the lake from the catchment.
- **Delft3D D-Flow (**Lesser et al., 2004**)**, a three dimensional (3D) hydrodynamic model used to analyse lake circulations and the influence of the main tributary on mixing dynamics and nutrient transport, particularly in relation to the extreme drought and heatwave conditions of summer 2022.

1.3 Layout of the thesis

This thesis presents methodologies and results mostly included into three scientific papers submitted to international peer-reviewed journals. Two papers have already been published, the last one being under review at the moment. These articles form the core content of the thesis. These contents are reported in Chapters 3-5, Chapter 1 being the present Introduction, while Chapter 2 is dedicated to the presentation of the Lake Pusiano case study. As regards Chapters 3-5, their content is as follows:

3. **Fenocchi, A., Pella, N., Copetti, D., Buzzi, F., Magni, D., Salmaso, N., & Dresti, C. (2025). Use of process-based coupled ecological-hydrodynamic models to support lake water ecosystem service protection planning at the regional scale. *Journal of Contaminant Hydrology*, 268, 104469. https://doi.org/10.1016/j.jconhyd.2024.104469**

This paper reports the work performed during the first year of the Ph.D., focused on developing a coupled ecological-hydrodynamic model for each major lake in Lombardy using the WET tool, with the aim of determining the near-future evolution of total phosphorus (*TP*) concentrations in response to different external loading scenarios. Nine lakes were studied, simulations being performed under the assumption of a constant mean annual nutrient load. These evaluations contributed to the update of the PTUA for these lakes in Lombardy.

4. Pella, N., Fenocchi, A., Copetti, D., Dresti, C., Rogora, M., Dezuanni, P., Buzzi, F., Valsecchi, L., López-Ballesteros, A., & Senent-Aparicio, J. (2026). Assessment of external and internal nutrient load to Lake Pusiano (Northern Italy) using watershed eco-hydrological modelling and lake ecological-hydrodynamic simulations. *Modeling Earth Systems and Environment*, 12, 156. https://doi.org/10.1007/s40808-026-02805-9

This paper adopts an integrated catchment-lake approach to analyse the behaviour of Lake Pusiano in the last 20 years. The main achievement is the assessment of annual external nutrient load variability with rainfall, obtained through the eco-hydrological SWAT+ model of the catchment. These estimated external nutrient loads were used as input for the lake model developed with WET, through which internal loading was determined as well. The paper also assesses the effectiveness of mitigation measures aimed at reducing nutrient inputs through the implementation of a Nature-Based Solution (NBS) and analyses its impact on lake *TP* concentrations at spring mixing, in relation to the thresholds established by the regional PTUA plan.

5. Pella, N., Copetti, D., Dresti, C., Rogora, M., Dezuanni, P., Valsecchi, L., Buzzi, F., & Fenocchi, A. (under review) The recent trophic decline of Lake Pusiano (Northern Italy) assessed by integrated lake-catchment modelling. Under review on *Aquatic Sciences*.

This paper, developed during the final phase of the Ph.D., includes a set of complementary models that reproduced the behaviour of Lake Pusiano and its catchment during and after the 2021-2023 drought period, which significantly degraded its water quality. To this end, the SWAT+ and WET models were used together to simulate the external and internal loading and the lake trophic behaviour. An ensuing hydrodynamic analysis of lake circulations and mixing under heavily stratified drought conditions was also performed by means of the Delft3D D-Flow model, which also allowed evaluating the effect of different discharges entering the lake. The main objective was to investigate the causes of this deterioration, leading to the intense cyanobacterial blooms observed between 2022 and 2024.

Chapter 6 then reports the results of the monitoring activities performed on the field, on Lake Pusiano and its catchment, not included in the aforementioned papers, dealing with both hydraulic and environmental parameters. This section describes the sampling campaigns and the hydraulic measurements performed on the lake water column and on the main lake tributaries. Some of the produced datasets were already used in the papers in Chapters 3-5, while others could serve for future research works. Nutrient loads based on experimental discrete data from the two main tributaries were also calculated and compared with those estimated through the SWAT+ model.

Chapter 7 last conveys the final discussion and Conclusions to the work, reporting the present limitations and illustrating future research prospects to overcome them.

2. Case study: Lake Pusiano

2.1 Site description and environmental setting

Lake Pusiano is a peri-alpine lake of glacial origin located in the Lombardy region of Northern Italy, its surface and watershed being shared between the provinces of Como and Lecco (Figure 2.1). Lake Pusiano is part of the so-called lake system “*Laghi Briantei”* or “*Laghi della Brianza”*, which also includes Lake Alserio and Lake Montorfano to the East, Lake Annone (which is actually made up by two almost independent basins) to the West, and Lake Segrino to the North. The latter is part of the Pusiano watershed. Lake Pusiano has a small island, called “*Isola dei Cipressi*”, with a surface area of 2.2 ha.

Lake Pusiano is classified as a warm monomictic lake, with a maximum depth of 25 meters and a surface area of 5.2 km^2. Basic morphometric and hydraulic parameters are reported in Table 2.1. The lake watershed covers a total area of 93.2 km^2, including the lake surface. The northern part of the basin is mainly mountainous, ranging from the highest elevation of 1435 m a.s.l. (Figure 2.2) of Mount Palanzone to the lake surface of 257 m a.s.l., with an average catchment elevation of 654 m a.s.l.. The lowest areas of the watershed correspond to the plains near the city of Erba and Lake Segrino, whose surface lies at 378 m a.s.l..

Global warming has significantly affected the lake water temperature T_w at spring mixing, as shown in Figure 2.3 for the 1972-2024 period. A clear trend is revealed therein: although interannual variations occur depending on colder or warmer years, the general pattern shows an increase in water temperature from $T_w \approx 5$ °C in the 1970s to $T_w \approx 7$ °C in recent years.

Phytoplankton population in Lake Pusiano was dominated by cryptophytes and chlorophytes from the early 1970s to the late 1980s (Copetti et al., 2017).. Between 2001 and 2019, recurrent algal bloom events were recorded, mainly due to cyanobacteria, particularly of *Planktothrix rubescens* (Legnani et al., 2005; ARPA Lombardia, 2020). In recent years, autumn blooms of cyanobacteria *Woronichinia naegeliana* have also become increasingly frequent (ARPA Lombardia, 2020).

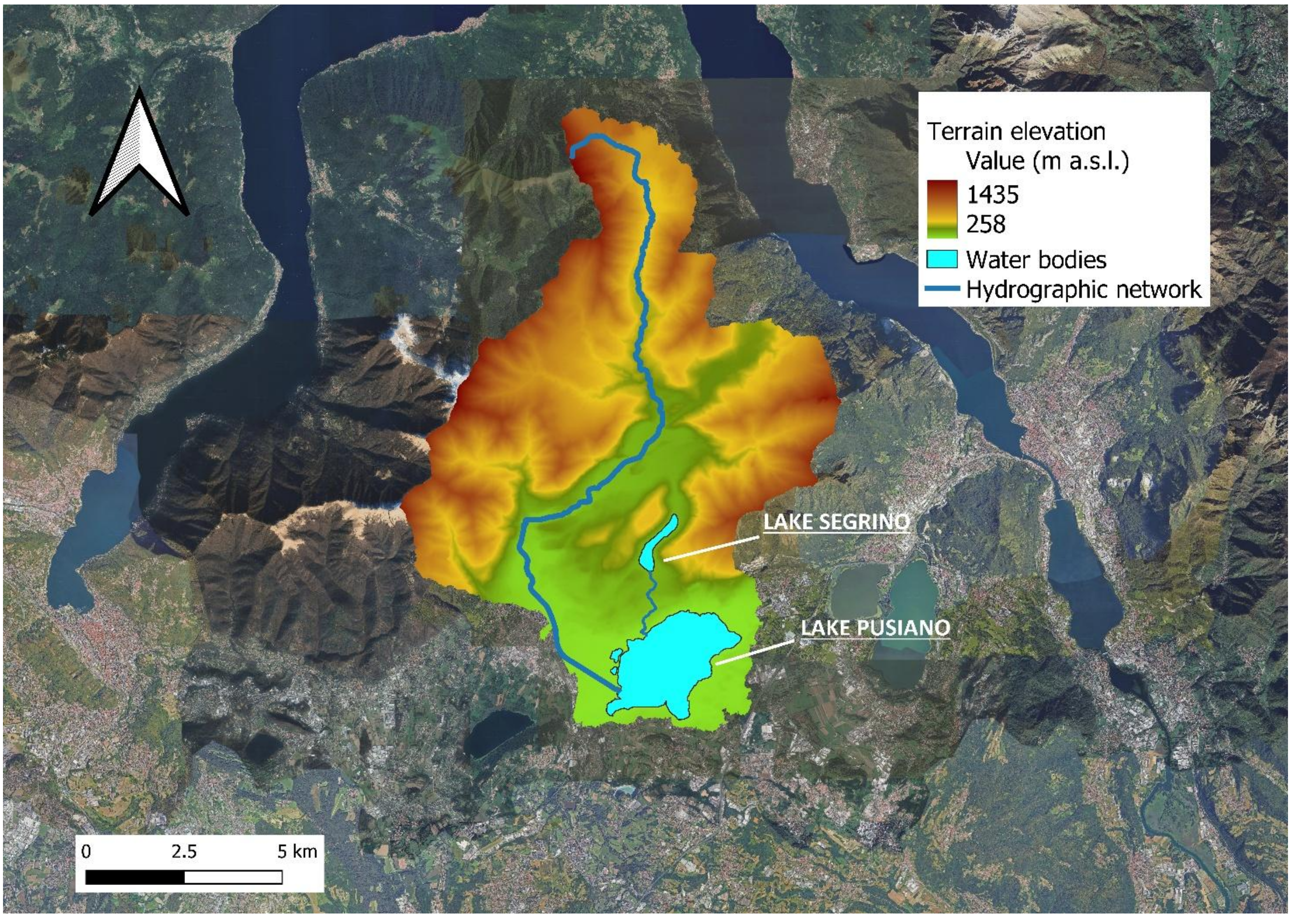

Figure 2.1. Location of the study area (orthophoto courtesy of Google Satellite).

Perimeter	*10.7 km*
Mean depth	*14.1 m*
Max depth	*25 m*
Surface area	*5.2 km*^{2}
Volume	69.2 *10^{6} m^{3}
Mean outflowing discharge	3.1 m^{3}/s
Residence time	*0.7 years*

Table 2.1. Basic morphometrical parameters of Lake Pusiano (OLL, 2005).

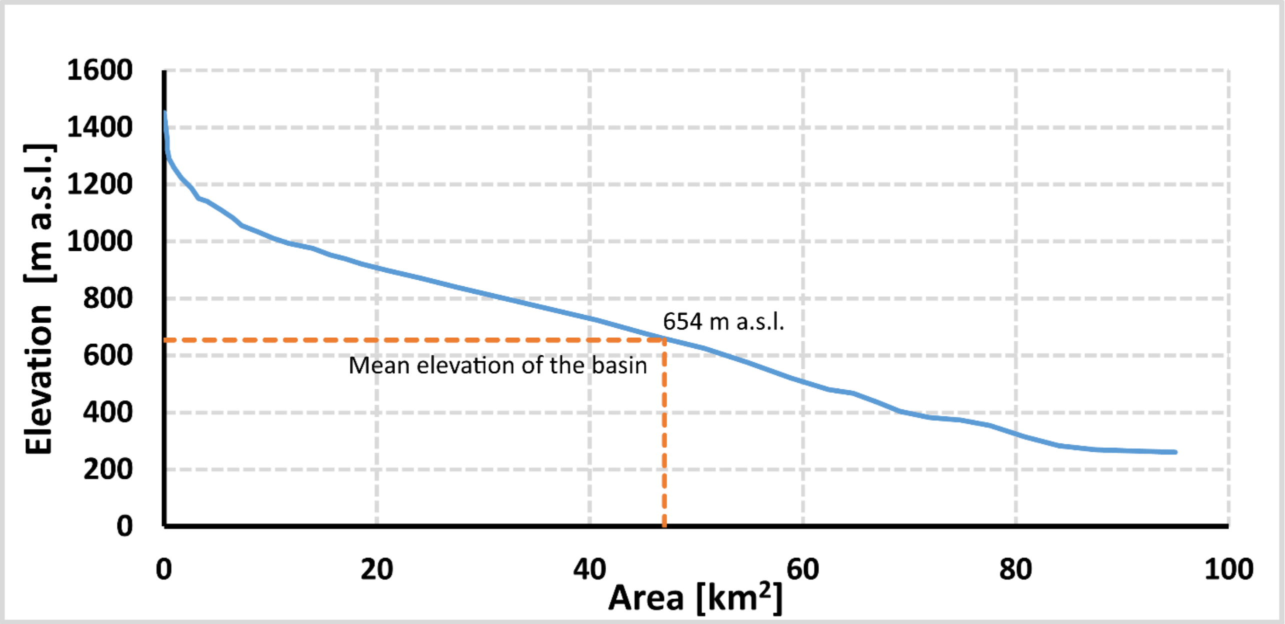

Figure 2,2. Hypsographic curve of the Lake Pusiano watershed (from the DTM with 5 m resolution of Regione Lombardia, 2015).

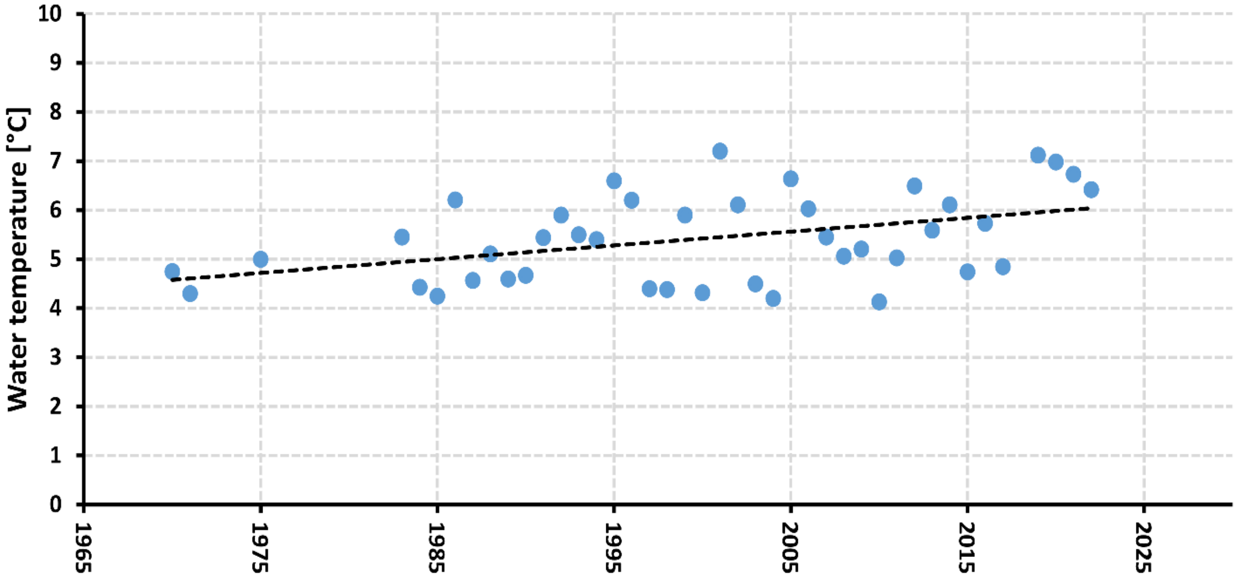

Figure 2.3. Trend of the water temperature at spring mixing in Lake Pusiano from 1972 to 2024 (CNR-IRSA Brugherio, unpublished data).

2.2 Hydrographic network and hydrological features

The main watercourse of the watershed is the Lambro River, which originates in the northern part of the catchment on Mount San Primo and flows into Lake Pusiano, taking the name "*Lambro Supralacuale*". In the upstream mountainous area, the river has torrential features, with a coarse gravel bed and steep slope, while its banks are vegetated. Upon reaching the plains near the city of Erba, at an altitude of about 300–350 m a.s.l., the river becomes more regular and features a channelized final stretch, called *Lambrone*, before entering Lake Pusiano. This artificial straightened segment was created in the early 19th century, when the Lambro River was deviated into Lake Pusiano to solve flooding and swamping problems in the area between Lake Pusiano and Lake Alserio (Figure 2.4). Here, the slope decreases, the cross section is prismatic and trapezoidal and drops in bed elevation by means of man-made bed jumps occur near bridge crossings. The Lambrone flows into Lake Pusiano with an average annual discharge $Q \approx 1.4$ m³/s at the mouth (Carraro et al., 2012). The tributaries of the *Lambro Supralacuale* include the Lambretto, Piott, Foce, Torrente della Valle di Rezzago, Ravella and Bova streams.

Water outflow from the lake occurs through two channels: the main one is an artificial canal leading to the Cavo Diotti dam, built for flood volume storage and downstream flood protection for the Monza area, whereas the secondary one is the original natural outflow, which rejoins the Lambro downstream of the Cavo Diotti dam, after merging with the outflow of Lake Alserio.

Figure 2.4. Historical hydraulic setup of the Lambro River near Lake Pusiano in the 18th century, prior to the building of Lambrone and Cavo Diotti (from: www.parcovallelambro.it).

The *Lambro Supralacuale* basin drains about 80% of the watershed, covering an area of 71.1 km². Several other watercourses and their respective catchments drain the remaining part of the Lake Pusiano watershed.

These include:

- The *Roggia Molinara* basin, covering 5.5 km² and draining urban areas of Ponte Lambro and Erba.

- The *Lake Segrino* basin, with its outflow running into Lake Pusiano, draining 5.12 km².
- The *Roggia Gallarana* basin, covering 1.47 km², which runs along the western shore of the lake.

The remaining areas of the Pusiano watershed correspond to the southern areas (Rogeno and Bosisio Parini municipalities) and the northeastern zone (Pusiano municipality), where no significant streams are present.

Lake Pusiano and its watershed lie within the Lombard pre-alpine belt. Precipitation is influenced by orography, with rainfall increasing with land elevation from South to North. According to the PTUA map (Figure 2.5; Regione Lombardia, 2004), average annual precipitation ranges from about 1500 – 1600 mm in the lowland lake area to ~1900 mm in the mountainous areas to the North. This map was produced by integrating the information collected by Ceriani & Carelli (2000) for the period 1891–1990 with precipitation data collected up to 2005 (Inneguale, 2007).

During the summer, the Pusiano basin is affected by intense thunderstorms, mainly caused by humid air masses from the Po Valley to the South meeting cold air masses descending from the mountains to the North. These contrasts can give rise to heavy downpours.

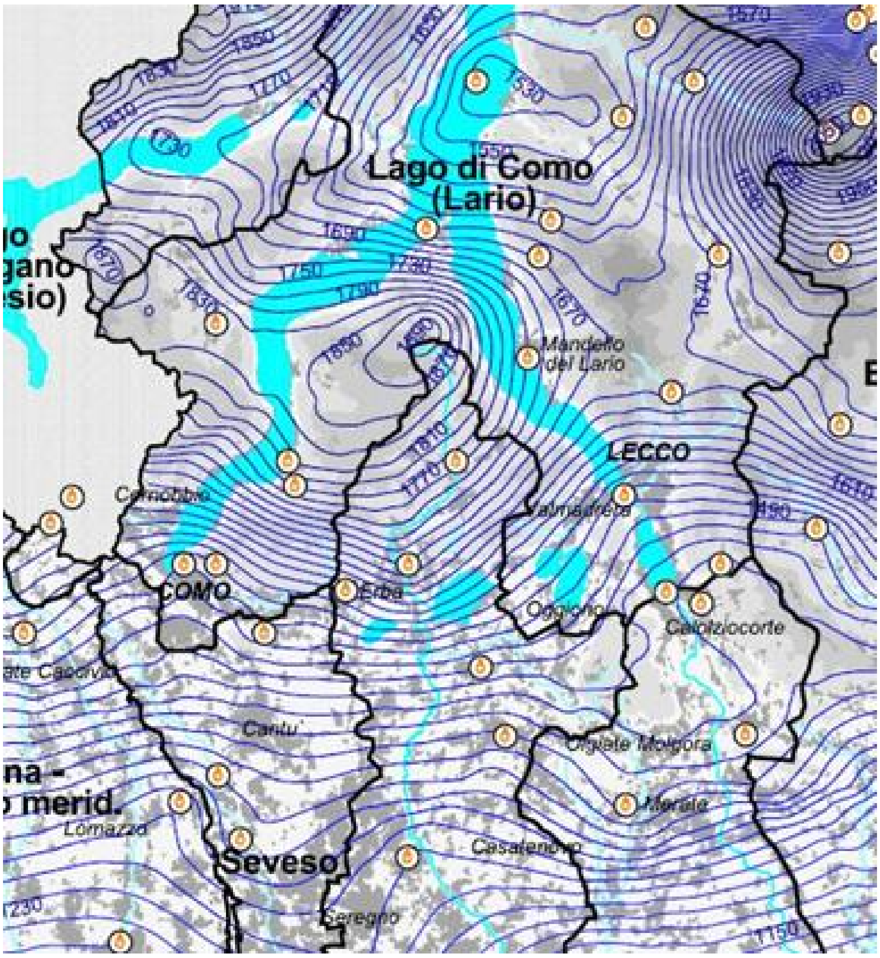

Figure 2.5. Mean annual precipitation map for the Pusiano watershed, made by Regione Lombardia (Regione Lombardia, 2004).

2.3 Nutrient pollution

The Lake Pusiano watershed is located in the Po Valley, one of the most densely populated and human-impacted areas in Europe. Land use in the Pusiano catchment is distributed as follows (CORINE Land Cover, 2018): 77% forested areas, mainly in the northern part; 13.6% urban areas; and 9.4% agricultural land and pastures. In the past, agriculture was much more widespread in this basin, but over the years it has been almost completely abandoned. The city of Erba, with ~ 16000 inhabitants, represents the main urban center within the watershed.

Although forests are the dominant land cover, the main source of environmental pressure, being practically represented by nutrient pollution, comes from the presence of Combined Sewer Overflows (CSOs), which are widespread throughout the urban areas of the basin. Due to the age and deterioration of the sewer network, some of these CSOs can be activated not only during rainfall events, but in case of failures they may also operate under dry-weather conditions, or at least for less intense storms than originally designed (Progetto PIROGA, 2012; Salerno et al., 2014; Viviano et al., 2014). According to studies made by Viviano et al. (2014), within the *Lambro Supralacuale* basin there are about 60 active CSOs up to the Caslino d'Erba monitoring station (which is about 6 km upstream of the lake), as shown in Figure 2.6.

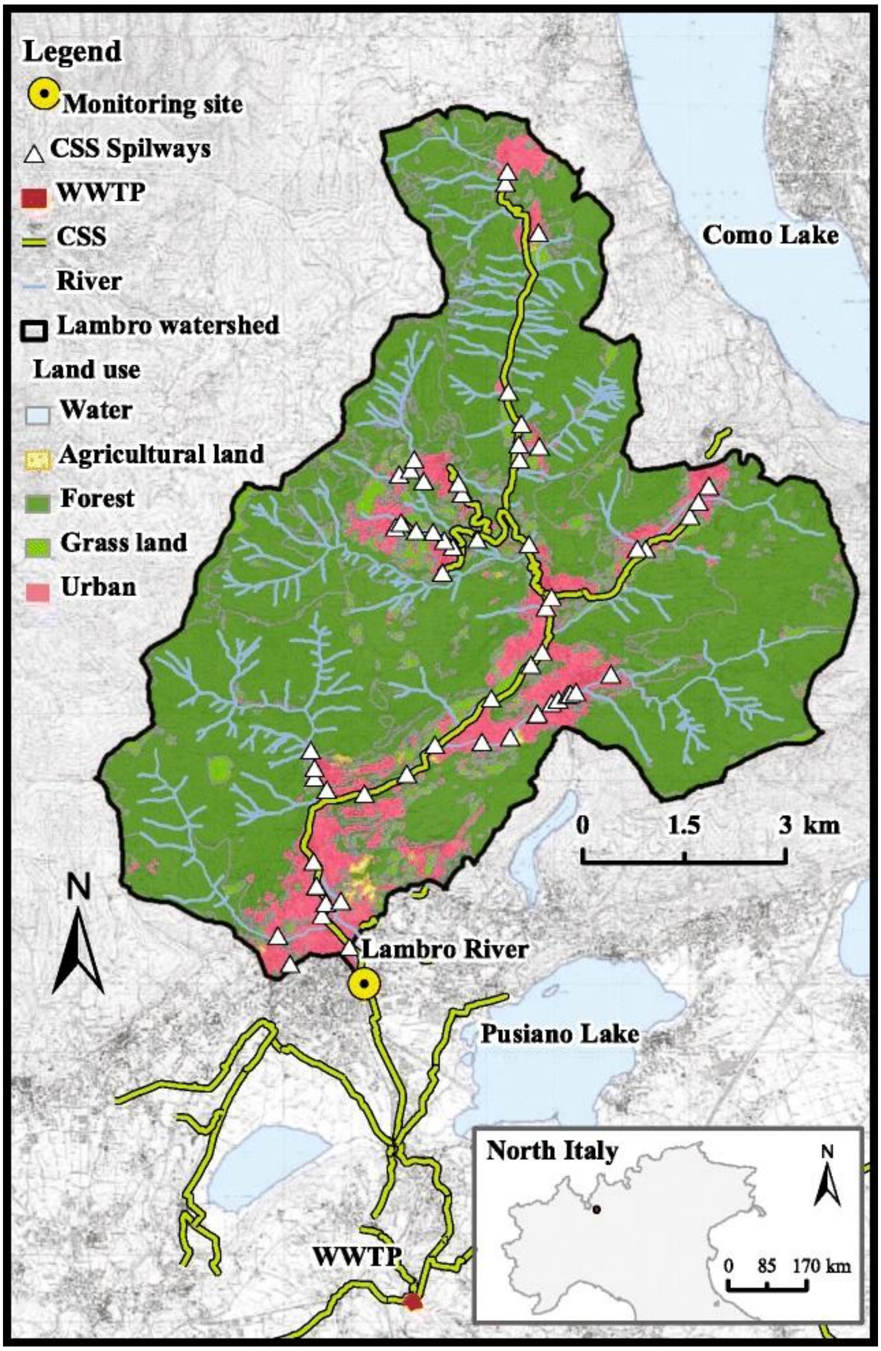

Figure 2.6. Map of the Pusiano Basin with land use and Combined Sewer Overflows (CSOs) up to the Caslino d'Erba monitoring station, adapted from Viviano et al. (2014).

Historically, the lake suffered from severe eutrophication caused by insufficient sewage collection and by the lack of wastewater treatment plants (WWTPs), with many domestic discharges flowing directly into the tributaries and the lake, peaking between the 1970s and the 1980s. Remediation measures, including the construction of the O-ring diversion system and the Merone WWTP, have significantly reduced the external total phosphorus (*TP*) load to the lake from ~21 t/a in the 1980s to ~6 t/a in 2014 (Figure 2.7), as well as the internal *TP* load from ~3.6 t/a to ~1.0 t/a by 2010 (Copetti et al., 2017). A relevant contribution to reaching these values by increasing the efficiency of the sewer network was given by the actions of the PIROGA project in the years 2008-2011, which were mainly directed towards fixing excess activation of CSOs. Following these interventions and the consequent improvement in water quality, the lake was up to recent years solidly classified as mesotrophic.

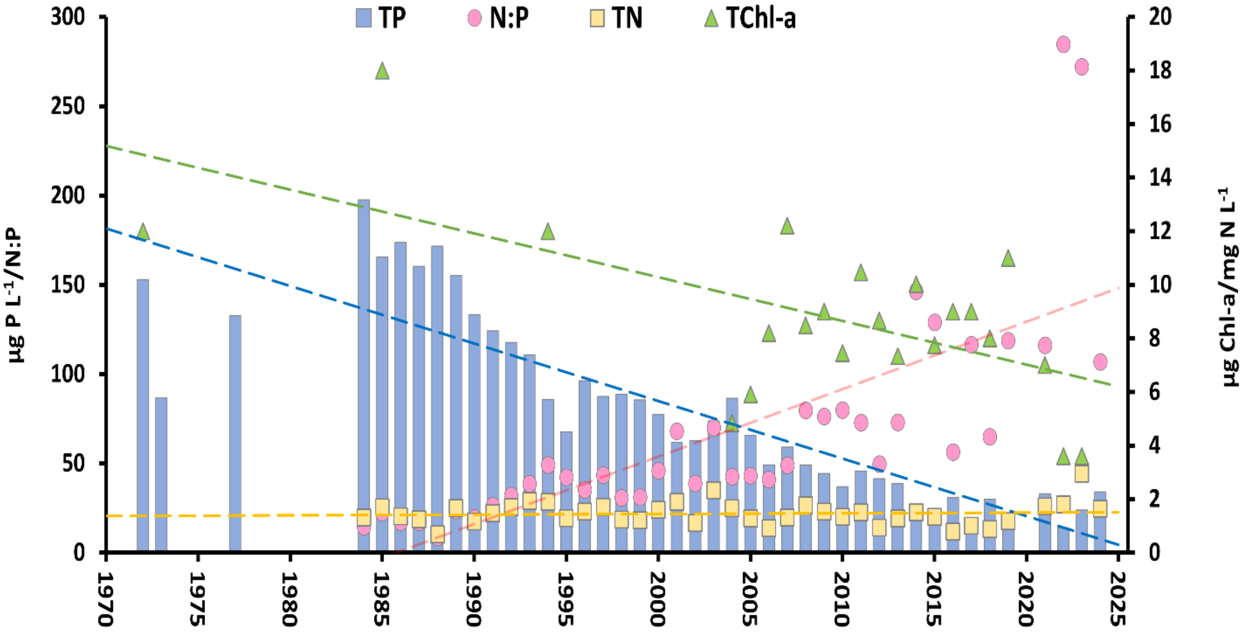

Figure 2.7 Trend of lake concentrations of TP, TN, and N:P ratio at spring mixing and of Chl-a concentration at annual peak from 1972 to 2024 for Lake Pusiano, together with their linear trends (dashed lines) (data obtained from Copetti, personal communication, only partially published in Copetti et al., 2017).

Long-term data of Lake Pusiano (Figure 2.7) show indeed a decrease in *TP*, and Chlorophyll-a (*Chl-a*) concentrations over time. Total nitrogen (*TN*) concentrations showed a much flatter trend between 1984 and 2015 , thus leading to an increase in the *TN:TP* molar ratio at winter overturn. This was close to the 16:1 Redfield ratio during the maximum eutrophication period (1984-1989), indicating a possible co-limitation by the two nutrients to primary production. Subsequently , the *TN:TP* ratio has increased up to current values >100:1, indicating a marked *P* limitation (Copetti et al., 2017).*TP* concentrations at spring mixing dropped from 200 µg/L in 1984 to 34 µg/L in 2024, which clearly represents an improvement in the lake trophic status. *Chl-a* concentrations have also declined over the years, with current annual average values below 10 µg/L.

In recent years, however, the 2021–2023 extended drought that affected Northern Italy is speculated to have triggered relevant internal *P* release processes (see Chapter 5), leading to the lake current transition from mesotrophic back to eutrophic conditions. $P\text{-}PO_4$ releases from sediments have up to now peaked in 2024, with concentrations of 442 µg/L having been reached in the deep hypolimnion. This exceptional release coincided with increased cyanobacterial blooms, which occurred not only in summer but also throughout the winter (Figure 2.8), supported by warmer temperatures than mean seasonal ones caused by climate warming.

Today, Lake Pusiano holds economic and social importance, particularly due to the presence of recreational fishing activities carried out in its waters. Its assets of ecosystem services is however endangered by climate change effects and possibly still too high pollution from its catchment relative to the climatic pressures.

Figure 2.8. Intense cyanobacterial algal bloom on Lake Pusiano on 6th February 2024, as seen from the pier of the Lake Pusiano tourist navigation service in the Pusiano municipality.

3. Scientific Paper 1

3.1 Introduction

This chapter reports the first journal paper resuting from the Ph.D., entitled *"Use of process-based coupled ecological-hydrodynamic models to support lake water ecosystem service protection planning at the regional scale"*, and published in the *Journal of Contaminant Hydrology*.

This chapter presents the work carried out during the first year of the Ph.D., which aimed at obtaining near-future *TP* concentrations at spring overturn for lakes in Lombardy, to update the PTUA of Regione Lombardia with proper values compatible with the actual evolution of those lakes. The research agreement made by Regione Lombardia with CNR-IRSA and the University of Pavia required the development of physical-chemical-biological numerical models for the lakes, with the goal of evaluating whether the prescribed environmental quality objectives could be reached or maintained.

The objective agreed with Regione Lombardia was to create models simulating the behavior of the lake using constant nutrient input loads, i.e. the ones given in the previous 2016 edition of the PTUA. This choice was done because, especially for the smaller lakes, detailed nutrient load series at a daily or even monthly scale are not available, measured concentrations on main tributaries from the WFD monitoring of ARPA Lombardia being generally obtained at quarterly resolution. This work involved setting up and calibrating the lake models with the available observations provided by ARPA Lombardia, and then running the model from the present times to the near-future to estimate the evolution. The paper first discusses the calibration of the model using a constant load, and then derives *TP* concentrations at mixing both for the calibration and forecast. The potential effects of nutrient reduction on *TP* concentrations at spring mixing were also considered.

I especially contributed to the modeling of Lake Pusiano and Lake Alserio. At the time the modeling began, no precise updated load estimations were available for both lakes. For Lake Pusiano, the most downstream ARPA monitoring station on *Lambro Supralacuale* (the only monitored inflow) is in Caslino d'Erba, located halfway through the catchment, about 6 km from the lake. This station only provided four samples per year, which was insufficient to determine a realistic nutrient load series. Another issue is the presence of the Erba urban area, located downstream of the monitoring station, which would certainly influence the nutrient load. In the model of Lake Pusiano, after evaluations involving the last estimations provided by OLL (2005) (*"Osservatorio dei Laghi Lombardi"*) and by Copetti et al. (2017), it was decided to consider a current external load of 4.5 t/a for *TP* and 262.5 t/year for TN. For Lake Alserio, lack of nutrient load estimations after the study of Rogora et al. (2002) which referred to data taken in the 1990s, in which nutrient loading was undoubtedly higher than present levels led to considering a loading proportional to that of Lake Pusiano, scaled down by the ratio between the watershed areas: 1.0 t/a for *TP* and 38.0 t/a for *TN*. The tuning of the mean annual loads for both Lake Pusiano and Lake Alserio to the values given here was obtained also through preliminary simulations made with the lake models.

Considering a constant external load, practically implemented in the models as constant input concentrations by dividing the mean annual loads by the mean annual discharges, mainly implies not accounting for precipitation variability. This is clearly a strong limitation if the aim were an accurate reproduction of lake intra-annual and inter-annual behaviour, but it could be accepted and was successful for the purposes of determining basic lake management directions of the research agreement. Specifically, it could lead to realistic estimations of the mean evolution of *TP* concentrations at spring mixing, which is the parameter of highest interest for management purposes. Moreover, as already stated, it was the only possible approach for many modelled lakes.

In any case, the model results are clearly influenced by the use of a constant inflow load. Also, the fact that the calibration was done during a period of improvement affects future projections. The only variability which is included in model results is the one due to air temperatures, whereas differences due to external loading between dry and rainy years are not represented. This leads in some cases to inconsistency between model results and observations for specific years, especially for the rainiest ones.

IIn case more precise results are needed at monthly or seasonal resolution for different aims than the current ones, it would be necessary to use a variable external load, distinguishing the lake behaviour during dry and wet years and properly reproducing the timing of the lake physical-chemical-biological dynamics, which would depend on differential load delivery up to the daily scale. In fact, the lake chemical and biological response strongly depends on both the amount of nutrients entering the lake and the timing of their input.

3.2 Paper - Use of process-based coupled ecological-hydrodynamic models to support lake water ecosystem service protection planning at the regional scale

Use of process-based coupled ecological-hydrodynamic models to support lake water ecosystem service protection planning at the regional scale

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Abstract

Protection plans of lake waters are based on ecological and/or chemical targets, often simplified in terms of total phosphorus (*TP*) concentrations, customarily the depth-averaged ones at spring mixing for temperate environments. These target lake *TP* concentrations are then commonly employed to determine target external loading through reverse use of Vollenweider-OECD-type steady-state empirical models. Such models are also adopted in their direct form to estimate lake *TP* concentrations following hypothetical external load reductions. However, such approaches suffer from extreme parameterisation and often give inaccurate results. Process-based coupled ecological-hydrodynamic models offer a much wider flexibility and produce an extensive set of information, solving many of the issues of Vollenweider-OECD-type models. However, their application has been up to now restricted to single lakes due to calibration effort and data availability burdens. To overcome these obstacles, in this study we developed a simplified application of the process-based coupled model QWET over 9 lakes in Northern Italy, making use of the ParSAC automatic calibration tool and feeding the models only with general data available from public monitoring. QWET models were calibrated over past observations, simulating nutrient reduction scenarios for the near-future decades. The advantages over traditionally employed models for lake water protection planning at the regional scale were hence identified through a practical application, determining the strengths and limits of the herein-adopted simplified process-based approach over lakes with different features. Obtained results were also analysed considering the specific case study.

Keywords: QWET; subalpine lake; watershed nutrient load; lake water quality; eutrophication recovery; WFD monitoring.

1. Introduction

Protection plans of lake waters worldwide are based on ecological and/or chemical targets (EU WFD, 2000; Poikane et al., 2019a, 2019b). Often, concentrations of limiting total phosphorus (*TP*) are then used as condensed reference parameters for simplicity (Stow et al., 2014; Poikane et al., 2019a, 2019b), depth-averaged *TP* concentrations at spring mixing being generally considered for holomictic lakes in temperate zones (Dresti et al., 2023a). The rationale is that the main cause of water quality problems in lakes is eutrophication due to excessive nutrient loads (Hutchinson, 1973; Schindler et al., 2016). Depth-averaged lake *TP* concentrations at spring mixing are in fact a proxy of both lake annual productivity and watershed loading, as given by Vollenweider-OECD (Vollenweider, 1968; Vollenweider and Kerekes, 1982) and similar (Bryhn and Håkanson, 2007) models. These empirical models have been commonly used in water protection plans both in their reverse form, to estimate target *TP* external loads from target lake *TP* concentrations at spring mixing, and in their direct form, to forecast lake *TP* concentrations in response to external load reduction scenarios (Trolle et al., 2011). Vollenweider-OECD-type models are also often used in their reverse form to assess present and past *TP* external loads from the watershed, their estimation being usually problematic. Incoming loads are in fact either theoretically estimated as constant values based on land use and occupation (Rast and Lee, 1983; Behrendt, 1996), regardless of their considerable dependence on annual rainfall (Moatar et al., 2017; Fenocchi et al., 2023), or experimentally evaluated, yet mostly through time-limited campaigns encompassing only major point inflows (Knapp et al., 2020; Fenocchi et al., 2023).

Despite Vollenweider-OECD-type empirical models having generally served as effective conceptual and practical tools for the development of restoration strategies (Steward and Lowe, 2009), they have multiple limitations. In fact, their response is steady-state, they neglect stratification and internal loading, and their model parameters were derived from regressions over groups of sample lakes (Vollenweider and Kerekes, 1982), so that the specific features of single basins cannot be considered (Håkanson, 1999). This has sometimes led to strongly incorrect results, such as repeated overestimations of the efficiency of re-oligotrophication measures (Bryhn and Håkanson, 2007; Lepori et al., 2022). Among the causes of these misestimations are enduring internal load, due to the slow release from sediments of phosphorus collected with the past pollution (Søndergaard et al., 2003; Jensen et al., 2006), and hypolimnetic nutrient accumulation (Rogora et al., 2018, 2021; Fenocchi et al., 2020), caused by weakened mixing in deep lakes with climate warming (Livingstone, 2003; Fenocchi et al., 2018). Parametric descriptions of lake *TP* concentration response times to external load reductions to enhance the information given by Vollenweider-OECD-type steady-state models have been proposed (Rossi, 1975; Rossi et al., 1986), yet their accuracy has always been questionable. Furthermore, sometimes target lake *TP* concentrations at spring mixing in water protection plans are defined in relation to hypothetical pristine concentrations from natural external loading, obtained through regressive approaches such as the Morpho-Edaphic Index (*MEI*), calculated as ratio between lake alkalinity and mean depth (Vighi and Chiaudani, 1985; Salerno et al., 2014). This application of multiple parametric approaches may result in significant errors, so that, in some instances, actual lake *TP* concentrations lower than the estimated pristine ones have been observed after external and/or internal load reduction interventions.

Many problems of Vollenweider-OECD-type models can be solved by process-based models. In fact, these numerical models allow interpreting a far higher external factor variability than empirical models due to their mechanistic and dynamic reproduction of processes, thus leading to more reliable forecasts (Bryhn and Håkanson, 2007; Bhagowati and Ahamad, 2019). Process-based models of lake ecological dynamics can be divided into pure ecological models, adopting a dynamic approach for the biogeochemical components and fixing lake physics to single or multiple pre-determined completely mixed layers, and coupled ecological-hydrodynamic models, which also dynamically model the physical processes (Bhagowati and Ahamad, 2019; Dresti et al., 2021). As such, the latter models are more flexible and accurate, especially when considering climate warming, which affects lake water temperatures and stratification and mixing evolution (Dresti et al., 2021). Coupled ecological-hydrodynamic models reproduce daily values at all depths for multiple variables, thus allowing a far more complete evaluation of lake water quality evolution than considering depth-averaged *TP* concentrations at spring mixing alone. Among them, one-dimensional (1D) models over the water column have been proven to be computationally affordable and to suitably reproduce lake stratification and mixing dynamics (Perroud et al., 2009; Dresti et al., 2021), in addition to lake chemistry and primary production (Rinke et al., 2009, 2010; Fenocchi et al., 2019).

Coupled ecological-hydrodynamic models have been so far applied to single basins. Over the regional scale required by water protection plans, it is usually concluded that their mass application is precluded by: (1) lake heterogeneity, preventing the use of a uniform modelling framework; (2) different data availability across basins (Ferreira et al., 2007; Valerio et al., 2022); (3) unsustainable efforts needed to serially calibrate coupled models through user-sensitive manual calibration (Fenocchi et al., 2019; Dresti et al., 2021). Because of these issues, many protection plans still rely on Vollenweider-OECD-type steady-state interpretations (Bhagowati and Ahamad, 2019). Nevertheless, as regards (1), process-based models have a broader applicability range than empirical ones, being much less parametrical. Addressing (2), regulations such as the Water Framework Directive 2000/60/EC of the European Union (EU WFD, 2000) institutionalised lake monitoring, enabling the creation of a minimum common water quality database for all relevant lakes. Last, referring to (3), the coupled ecological-hydrodynamic 1D model QWET (Nielsen et al., 2017, 2021;

Schnedler-Meyer et al., 2022) includes the ParSAC (Parallel Sensitivity Analysis and Calibration) multi-objective optimisation tool (Bruggeman and Bolding, 2020), allowing automatic calibration for the many parameters of coupled ecological-hydrodynamic models (Fenocchi et al., 2019; Dresti et al., 2021).

In this work, we hence tested a standardised simplified application of QWET at the regional scale over 9 lakes in Northern Italy with heterogeneous morphometrical and ecological properties. We relied for model setup and calibration only on data of common availability gathered within public monitoring activities. As time series of external loads are rarely available, we employed constant mean annual estimations, obtained from previous studies. Automatic calibration was systematically applied. Through this work, we wanted to: (1) quantify the benefits of simplified process-based modelling over empirical approaches for lake water ecosystem service protection planning at the regional scale; (2) check if general data from public monitoring activities allow implementing solid coupled ecological-hydrodynamic models; (3) discover the limits of employing constant external loads over different types of lakes; (4) verify if consistent results could be obtained through automatic calibration of models.

2. Data and methods

2.1. Case studies

Nine lakes in the prealpine range of Northern Italy, south of the European Alps, are the object of this modelling study (Fig. 1; Table 1). These include three large deep lakes (Lake Como, Lake Garda, Lake Iseo), one mid-sized deep lake (Lake Idro), one small, shallow alpine lake (Lake Endine) and four neighbouring small to mid-sized, shallow to moderately deep moraine lakes (Lake Alserio, Lake Annone East, Lake Annone West, Lake Pusiano). All these lakes experienced a common eutrophication process which started in the 1960s and peaked in the early 1980s (Salmaso and Mosello, 2010). National regulations then demanded the establishment of wastewater treatment plants and the reduction of phosphorus in detergents (Copetti et al., 2019), triggering a recovery process, with different velocities among lakes according to past pollution levels, basin morphometry and intervention efficiency (Salmaso et al., 2020).

The considered deep lakes are all experiencing a reduction in convective mixing frequency due to climate warming (Ambrosetti and Barbanti, 1999; Fenocchi et al., 2018), transitioning towards meromixis, supplemented by a decrease of deep intrusions by tributaries (Dresti et al., 2023b). These effects are exacerbated for Lake Iseo (Ambrosetti and Barbanti, 2005) and especially Lake Idro (Viaroli et al., 2018; Tartari et al., 2021), two meromictic basins that show increasing chemical stability due to intense calcite ($CaCO_3$) precipitation. Water warming, together with mixing weakening, has already caused ecosystem shifting for all considered lakes (Salmaso et al., 2014), hampering re-oligotrophication efforts through cyanobacterial blooms (Morabito et al., 2018) and bottom nutrient accumulation for deep basins (Rogora et al. 2018, 2021).

Water quality targets established by the EU through the WFD prescribe that all lakes should achieve by 2027 the "good" ecological status (EU WFD, 2000). This ecological target is defined in terms of phytoplankton, macrophytes, fish and macrobenthos indicators (EU WFD, 2000; Copetti and Erba, 2024). As nutrient concentrations are key chemical parameters in determining the ecological conditions through the trophic state, depth-averaged *TP* concentrations at spring mixing are often selected as a relevant indicator of the ecological state by EU member states (Poikane et al., 2019a). In fact, for the lakes considered in this paper, lake-specific target *TP* concentrations at spring mixing have been identified by the managing authority Regione Lombardia in past water protection plans by increasing the hypothetical pristine concentrations calculated through the *MEI* index by 25%. These *TP* concentrations have already been reached for some studied lakes, whereas for others uncertainties on present external nutrient loading do not allow determining if missing compliance is due to either too high external loads or to the slow inertial lake response. The present process-based models shed light on this issue.

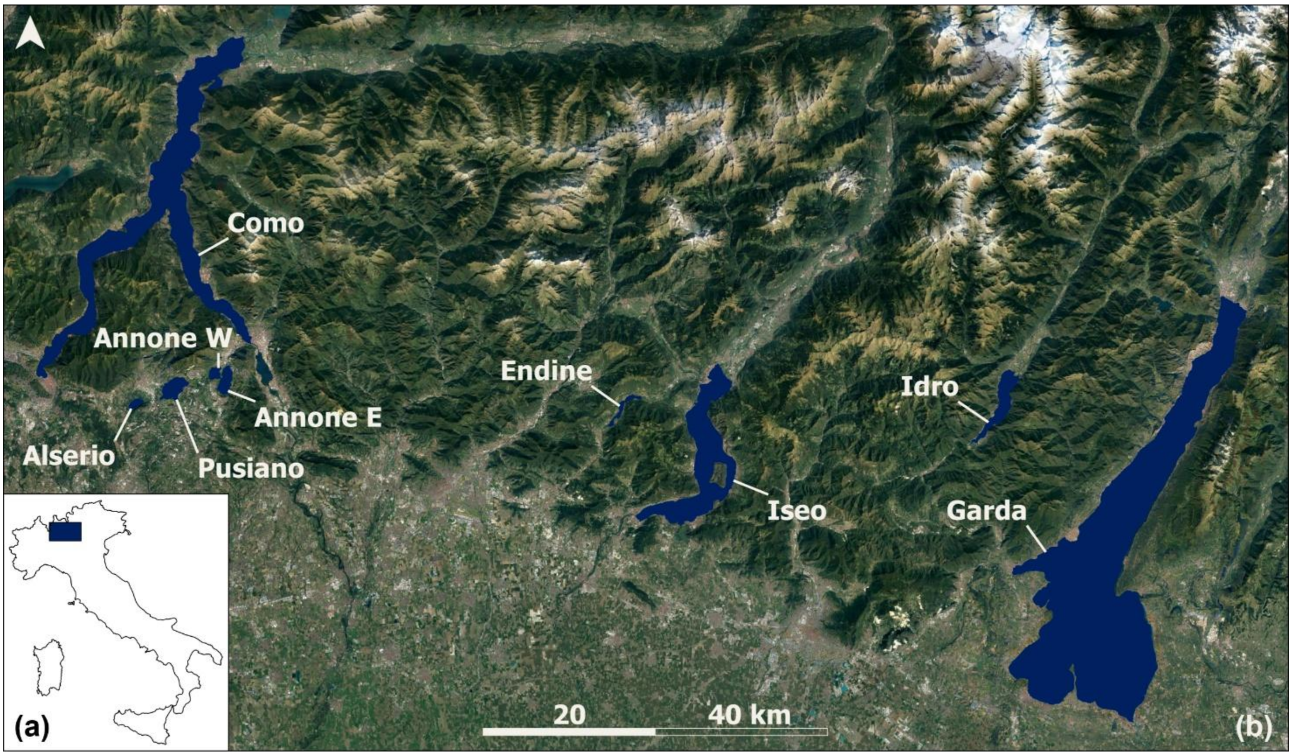

Fig. 1. Position within Italy (a) and map (b) of the lakes considered in the study (orthophoto courtesy of Google).

Table 1. Morphometrical and hydrological properties of the lakes considered in the study (morphometrical information was obtained from available bathymetrical data; * = Regione Lombardia, *unpublished data*; † = Fenocchi et al., 2023; ‡ = Hinegk et al., 2022).

Lake	Surface [km^2]	Volume [10^6 m^3]	Maximum depth [m]	Mean outflowing discharge [m^3 s^{-1}]	Renewal time [a]	Watershed area [km^2]
Alserio	1.3	7.0	8	1.0*	0.2	20.0*
Annone East	3.9	25.8	11	0.6*	1.4	27.3*
Annone West	1.7	6.8	10	0.4*	0.5	12.5*
Como	143.8	25979.4	426	174.0†	4.7	4547.5*
Endine	2.3	12.0	9	1.4*	0.3	36.5*
Garda	368.0	49183.7	350	53.0‡	29.4	2216.0*
Idro	11.3	834.1	124	30.4*	0.9	620.3*
Iseo	61.2	7973.8	252	53.6*	4.7	1800.2*
Pusiano	5.2	70.0	25	3.6*	0.6	93.5*

2.2. Modelling framework

The QWET (QGIS Water Ecosystem Tool) 1D coupled ecological-hydrodynamic model (Nielsen et al., 2017, 2021; Schnedler-Meyer et al., 2022) was employed in this study. QWET combines the 1D hydrodynamic model GOTM (General Ocean Turbulence Model; Burchard and Bolding, 2001) with the zero-dimensional (0D) biogeochemical model PCLake (Janse and van Liere, 1995), through the coupling library FABM (Framework for Aquatic Biogeochemical Models; Bruggeman and Bolding, 2014). The model is distributed as an open-source QGIS (QGIS, 2024) plugin and can be coupled to the ecohydrological model SWAT (Soil & Water Assessment Tool; SWAT, 2024) for integrated lake-watershed assessments on hydrological and nutrient balance. GOTM simulates stratification and mixing phenomena across a user-defined number of layers in which the water column is discretised, employing various user-selectable k-ε formulations for turbulence closure. This differs from the energy budget approach employed by the 1D hydrodynamic models DYRESM (Imberger et al., 1978; Imberger and Patterson, 1981) and GLM (Hipsey et al., 2019). PCLake is instead a process-based 0D biogeochemical model, reproducing ecological cycles and interactions throughout the food web across lake water and sediments. Through PCLake, QWET can potentially reproduce internal loading evolution following nutrient loss from bottom sediments, as it solves the nutrient mass budget inside the sediment layer. This is not completely simulated (Dresti et al., 2023a) by the 1D coupled models DYRESM-CAEDYM (Hamilton and Schladow, 1997) and GLM-AED2 (Hipsey et al., 2013), which parameterise orthophosphate ($P\text{-}PO_4$) release by sediments as function of a calibrated maximum flux under reference conditions and of water temperature (T_w) and dissolved oxygen (DO) concentration.

The herein-adopted hydrodynamic setup implements lake hydrological balance through the default basic QWET approach. A fixed flow rate, equal to the mean outflowing discharge (Table 1), enters and leaves the lake at the surface. Evaporation is nevertheless included to properly close the heat balance at the surface, the lake elevation being kept constant at the prescribed elevation through a residual input. The present biogeochemical setup follows a minimal NPD (Nutrients – Phytoplankton – Detritus) scheme and includes oxygen, carbon, nitrogen and phosphorus cycles, with a single generic phytoplankton group. In this scheme, phytoplankton is fed on inorganic dissolved nutrients, the organic detritus resulting from phytoplankton mortality being recycled into inorganic nutrients by parameterised mineralisation processes. The grazing effects of the higher trophic levels (Zhang et al., 2022, 2023) on phytoplankton are lumped into phytoplankton mortality, closing the food chain with the minimum model complexity and calibration effort. Constant nutrient concentrations are fed to the model with the main inflow, obtained as ratios between the available mean annual load estimations (Table 2) and the aforementioned discharges (Table 1). This simplified modelling framework, applied identically to all considered lakes, was constrained by data availability across them.

Constant nutrient loads were adopted since: (1) characterisations of total external input load series are missing, except for Lake Como (Fenocchi et al., 2023), Lake Iseo (Valerio et al., 2022) and Lake Pusiano (Copetti et al., 2017), single mean annual values from theoretical estimates or limited experimental campaigns being available for the other basins; (2) this assumption is of interest for the managing authority Regione Lombardia, whose task is determining threshold external load values to meet *TP* concentration targets; (3) when performing future extrapolations in a climate change context, determining reliable discharge and concentration series, including seasonal distribution and interannual rainfall variability, would be problematic and arbitrary (Dresti et al., 2023a). Through the constant-load approximation, the only interannual variations reproduced in model results are hence due to meteorology, thus revealing their impact on biogeochemical phenomena in the simulation results.

For Lake Idro and Lake Iseo, chemical stratification was implemented into the models to properly reproduce the vertical hydrodynamics and the cascading biogeochemical processes. Salinity data were obtained from regressions between sporadic total dissolved ion characterisations and regularly available conductivity data in water samples. Time-invariant vertical salinity distributions averaged over the calibration period were entered into GOTM for these lakes, as simulating their seasonal and interannual variations would have required characterising: (1) salinity, discharge and insertion depth time series of lake inflows; (2) $CaCO_3$ precipitation, which to the knowledge of the Authors has been only recently included for the first time into a process-based coupled ecological-hydrodynamic model by Many et al. (2024), however still neglecting its feedback on salinity; (3) for Lake Idro, the salinity input of the bottom thermal springs of calcium sulphate ($CaSO_4$) (Viaroli et al., 2018; Tartari et al., 2021). The geothermal heat associated to the bottom springs of Lake Idro was nevertheless implemented into its model, fixing in GOTM a constant bottom T_w = 7.0 °C. This is necessary to reproduce the peculiar thermal structure of this lake, in which the bottom spring input, combined with chemical stability, results in higher water temperatures at the bottom than in the overlying monimolimnion (Tartari et al., 2021). Last, the hypolimnetic withdrawal active since 2008 on Lake Annone East was implemented in the model of this lake at the actual withdrawal depth, entering the daily withdrawn discharge series obtained from the plant manager.

Model calibration was performed with ParSAC (Bruggeman and Bolding, 2020), following the bottom-up approach in Andersen et al. (2020, 2022) and Chou et al. (2021). In this strategy, parameters with increasing mutual dependence are incrementally added to the calibration, to reduce the risk of converging to sub-optimal solutions. The physical, oxygen and carbon, nitrogen, phosphorus and phytoplankton parameters were hence sequentially calibrated. The list of calibration parameters in the water column and in the sediment layer was taken from Regev et al. (2023), leading to 23 physical parameters and 89 biogeochemical parameters. Feedback of phytoplankton-induced turbidity on light extinction was not activated as it was found not to significantly improve GOTM results, so that physical parameters (i.e. meteorological series adjustment, light transmission and turbulence model parameters) were frozen after the relative calibration phase, as opposed to the biogeochemical parameters. Two to five ParSAC optimisation runs with 5000 realisations each were performed for each calibration phase to iteratively identify the optimal range of each parameter manually, hence making the overall calibration procedure actually semi-automatic and to some degree still dependent on expert judgement.

Table 2. Assumed mean annual nutrient loads and time periods of the simulations for the lakes considered in the study ([*] = Regione Lombardia, *unpublished data*; [†] = Fenocchi et al., 2023; [¶] = estimated through preliminary considerations and simulations; [§] = Decet and Salmaso (1997); [‖] = Viaroli et al., 2018; [#] = Scibona et al., 2022).

Lake	**Mean annual load [t a^{-1}]**					**Calibration period**	**Extension period**
	TP	**P-PO$_4$**	**TN**	**N-NO$_3$**	**N-NH$_4$**		
Alserio	1.0[*]	0.8[¶]	38.0[¶]	26.6[¶]	7.6[¶]	2007-2021	2022-2051
Annone East	0.7[*]	0.6[¶]	21.0[¶]	14.7[¶]	4.2[¶]	2007-2021	2022-2051
Annone West	1.5[*]	1.2[¶]	17.4[¶]	12.2[¶]	3.5[¶]	2007-2021	2022-2051
Como	265.0[*]	143.0[†]	7871.0[*]	4922.0[†]	576.0[†]	2004-2018	2019-2048
Endine	1.7[*]	1.4[¶]	50.0[¶]	35.0[¶]	10.0[¶]	2009-2021	2022-2047
Garda	97.0[*]	44.0[§]	3880.0[¶]	3395.0[§]	136.0[§]	2010-2022	2023-2048
Idro	15.0[‖]	7.5[¶]	850.0[‖]	595.0[¶]	42.5[¶]	2009-2021	2022-2047
Iseo	126.0[#]	28.0[#]	2117.0[#]	1510.0[#]	104.0[#]	2009-2021	2022-2047
Pusiano	4.5[¶]	3.6[¶]	262.5[¶]	183.8[¶]	52.5[¶]	2007(2013)-2021	2022-2051

2.3. Employed data

The herein-adopted QWET setup needs as input data: (1) the lake hypsometric curves expressing the depth-area relationship, to compute the volume of each model layer, obtained from available bathymetrical data; (2) the meteorological data series of air temperature, wind velocity, cloud cover, relative humidity and atmospheric pressure, to compute heat fluxes at the lake surface; (3) the inflowing discharges and concentrations of nitrates ($N\text{-}NO_3$), ammonium ($N\text{-}NH_4$), organic nitrogen (*ON*), orthophosphate ($P\text{-}PO_4$) and organic phosphorus (*OP*), which make up external loading; (4) the lake surveyed vertical profiles of T_w and *DO*, aforementioned nutrient and Chlorophyll-*a* (Chl-*a*; used as proxy of total phytoplankton biomass) concentrations, employed as initial conditions and as observations for model calibration.

Regarding meteorological data, publicly available daily series from the regional environmental protection agencies ARPA Lombardia and ARPA Veneto (for Lake Garda only) were employed. Cloud cover series were computed from measured shortwave radiation data as in Fenocchi et al. (2017). The series of observed meteorological variables were tuned during the physical parameter calibration phase through linear regression models. This allowed obtaining robust model results for T_w even employing weather stations located in the major urban centres close to the lakes, for which longer and more complete series are available, instead of coastal stations. Through meteorological series tuning, in fact, phenomena such as the higher windiness of lake valleys or the air temperature mitigation by lake water masses can be mimicked. Furthermore, the same meteorological data series could be employed for neighbouring basins, adopting different lake-specific tunings.

Constant inflow discharges and nutrient concentrations (computed as ratios between loads and discharges) were obtained from the sources referenced in Tables 1 and 2. For smaller lakes, only TP loads are generally available, so that missing $P\text{-}PO_4$ and nitrogen loads were determined applying nutrient load partition proportions from similar basins for which these data are available, sometimes correcting the estimations by means of the lake concentrations obtained in preliminary simulations. Organic nutrient fractions were obtained from sampled total and dissolved inorganic ones as: $ON = TN - N\text{-}NO_3 - N\text{-}NH_4$ and $OP = TP - P\text{-}PO_4$.

Lake surveyed vertical profiles were obtained from ARPA Lombardia, which performs monitoring campaigns in application of the WFD, with monthly frequency for larger lakes and bimonthly to quarterly frequency for smaller ones, and for Lake Garda from the Fondazione Edmund Mach di San Michele all'Adige (FEM), which has been performing monthly campaigns synergistically with ARPA Veneto since 1990. For Chl-*a*, integrated samples of the photic layer are available for all lakes at each sampling date.

2.4. Performed simulations

Lake models were calibrated against the whole available series of vertical profiles (for Lake Garda, the calibration period constraint was given by the adopted meteorological series starting in 2010), leading to calibration periods spanning 13 – 15 years (Table 2). For Lake Pusiano, the calibration period had to be eventually reduced to the last 9 years (see Paragraph 3.1). Simulations were then extended to the mid-XXI century (Table 2), to evaluate the near-future evolution of the studied lakes. This was done by repeating twice the meteorological series observed in the calibration period, hence not considering climate-change effects, which are nevertheless mostly appreciable over longer time scales. Three input-load configurations were considered: (1) constant present phosphorus and nitrogen loads (reference scenario); (2) constant present loads up to 2023, -15% linear variation in the 2024-2034 period, constant reduced loads afterwards; (3) same as (2), yet with a -30% linear variation in the 2024-2034 period.

Annual volume-weighted TP concentrations at spring mixing were extracted from the simulations to further evaluate model results against observations and assess near-future trends for this parameter of large interest for lake management. The considered observations were those from the field samplings closest to annual spring-mixing conditions, as inferred from T_w and DO profiles. In the simulations, the concentrations on the annual day of spring mixing were considered, this being evaluated as: (1) for holomictic basins (Lake Alserio, Lake Annone East, Lake Annone West, Lake

Endine, Lake Pusiano), as the day in which maximum bottom *DO* concentrations are reached before the decrease due to direct stratification; (2) for oligomictic (Lake Como, Lake Garda) and meromictic (Lake Idro, Lake Iseo) basins, as the day in which maximum *DO* concentrations are obtained at a depth which is always reached with some margin by annual spring mixing (60 m for Lake Como, 100 m for Lake Garda, 20 m for Lake Idro, 40 m for Lake Iseo). Exact spring-mixing days were considered for model results rather than the closest sampling days to avoid inconsistencies with the near-future extension period. Volume-weighting of *TP* concentrations was performed for the observations considering the available samples at their sampling depths, whereas in the simulations volume integration was performed across all model layers. This was the only viable choice to avoid inconsistencies with the near-future extension period, since for many lakes monitored by ARPA Lombardia samples are not systematically taken at the same depths at each sampling date. For meromictic Lake Idro and Lake Iseo, *TP* concentrations at spring mixing were also evaluated in the mixolimnion (0 – 30 m for Lake Idro, 0 – 60 m for Lake Iseo), to separate the already impacted monimolimnion when evaluating near-future *TP* concentrations.

Among the nine modelled lakes, results will be displayed here for Lake Annone East, Lake Como and Lake Iseo. These pilot basins were chosen as they are deeply meaningful to the evaluation of the adopted modelling approach, being respectively: (1) a small shallow eutrophic lake, in which furthermore hypolimnetic withdrawal is active and was implemented into the model; (2) a very deep oligomictic mesotrophic lake with a multi-basin morphometry, which challenges the 1D schematisation (Guyennon et al., 2014; Copetti et al., 2020); (3) a deep, potentially hypertrophic lake with permanent chemical stratification.

3. Results and discussion

3.1. Reproduction of observations in the calibration period

The observed and modelled series of volume-weighted T_w, *DO* and *TP* in the epilimnion and hypolimnion and of Chl-*a* in the photic layer are shown for the pilot lakes in Figs. 2 – 4.

While the accuracy of the hydrodynamic model GOTM in reproducing epilimnetic temperatures (Figs. 2a, 3a and 4a) is comparable to that of the DYRESM and GLM 1D models, it results for all lakes in much more precise hypolimnetic T_w predictions than those generally obtainable with such models (Fenocchi et al., 2017; Bruce et al., 2018; Dresti et al., 2023a), both for shallow (Fig. 2b) and deep (Figs. 3b and 4b) basins. This also holds within the calibration period for chemically stratified Lake Idro and Lake Iseo, even though the assumed constant salinity profiles would affect long-term projections, given the expected increase in the salinity gradient. The first reason for the accurate hypolimnetic T_w reproduction obtained here is that, through the ParSAC calibration, a large set of physical parameters can be considered, tuning each of them much more precisely than possible through manual calibration. Furthermore, the k-ε turbulence closure employed by GOTM gives a more precise representation of hypolimnetic mixing than the energy budget approach of DYRESM and GLM, especially for the extremely low-turbulence environments of deep lakes (Figs. 3b and 4b).

The robust simulation of mixing leads to a solid overall reproduction of the seasonal hypolimnetic *DO* dynamics for shallow lakes (Figs 2d), including summer anoxia and winter reoxygenation, and of the deep-hypolimnion dynamics of *DO* and nutrients for deep lakes (Figs. 3d, 3f, 4d and 4f). The latter are therefore proven to mainly depend on the implemented meteorological variability, which leads to a properly simulated interannual variation of mixing dynamics, and on long-term biochemical processes, such as nitrification, denitrification and mineralisation, whose parameters are calibrated for each lake. The overlooked yearly variable deep insertions of nutrients and oxygen by lake tributaries hence appear to have a significantly smaller influence on hypolimnetic dynamics, likely also due to the decreased intensity and frequency of such phenomena in the last 20 years due to climate change (Dresti et al., 2023b). For Lake Como, this also occurs as the lake deepest point near Argegno where samples are taken lies in a branch in which the hypolimnion is disconnected from the rest of the lake by an underwater ridge, hence separating it from the intrusions of the main inflows River Adda and River Mera (Copetti et al., 2020).

The constant load assumption reveals its weakness for nutrient variables in most of the water volume for shallow lakes (Figs. 2e and 2f) and in the epilimnion for deep lakes (Figs. 3e and 4e). For these layers, an averaged behaviour is in fact reproduced by the models, which does not represent the full observed variability. This is also due to the horizontal patchiness of nutrient concentrations over the mixed layer, so that the observations represent the local result at the sampling point, while the 1D model returns a horizontally averaged result (Gal et al., 2009; Fenocchi et al., 2019). The worst agreement with observations is obtained for all lakes for Chl-*a* in the photic layer (Figs. 2g, 3g and 4g). For Chl-*a*, a first additional error source compared to nutrients is the higher parameterisation level of biological variables compared to chemical ones in coupled models (Gal et al., 2009). Furthermore, the use of a single phytoplankton group is a radical approximation in the ecological chain, as the higher trophic levels and the constituent algal groups at finer taxonomic ranks, which are indeed characterised by specific ecological features and seasonality (Reynolds, 2006), are not considered. Nonetheless, the main aim of the implemented generic phytoplankton group in the present simplified model schematisation is to close the NPD cycle over an annual basis, these errors not being crucial for the evaluation of *TP* concentrations at spring mixing. Flaws in nutrient and especially phytoplankton biomass reproduction contribute to the errors in *DO* prediction in the epilimnion, for which a more smoothed behaviour than the observed one is reproduced, more evident for large lakes (Figs. 3c and 4c) than for small ones (Fig. 2c), likely due to the greater extent of horizontal patchiness over wider areas.

The constant load assumption cannot be employed when definite variations in input loads occur during the simulated period, exceeding the interannual oscillations due to rainfall variability. Among the modelled basins, this happened for Lake Pusiano, in which external loads from the watershed were significantly reduced from 2007 to 2012 circa as part of the PIROGA cooperative restoration project (Copetti et al., 2017). For this lake, the model allowed determining through preliminary simulations that an external mean annual *TP* load of 4.5 t a^{-1} (Table 2) best reproduces presently observed lake concentrations, lower than the available literature estimations obtained prior to the interventions on the watershed.

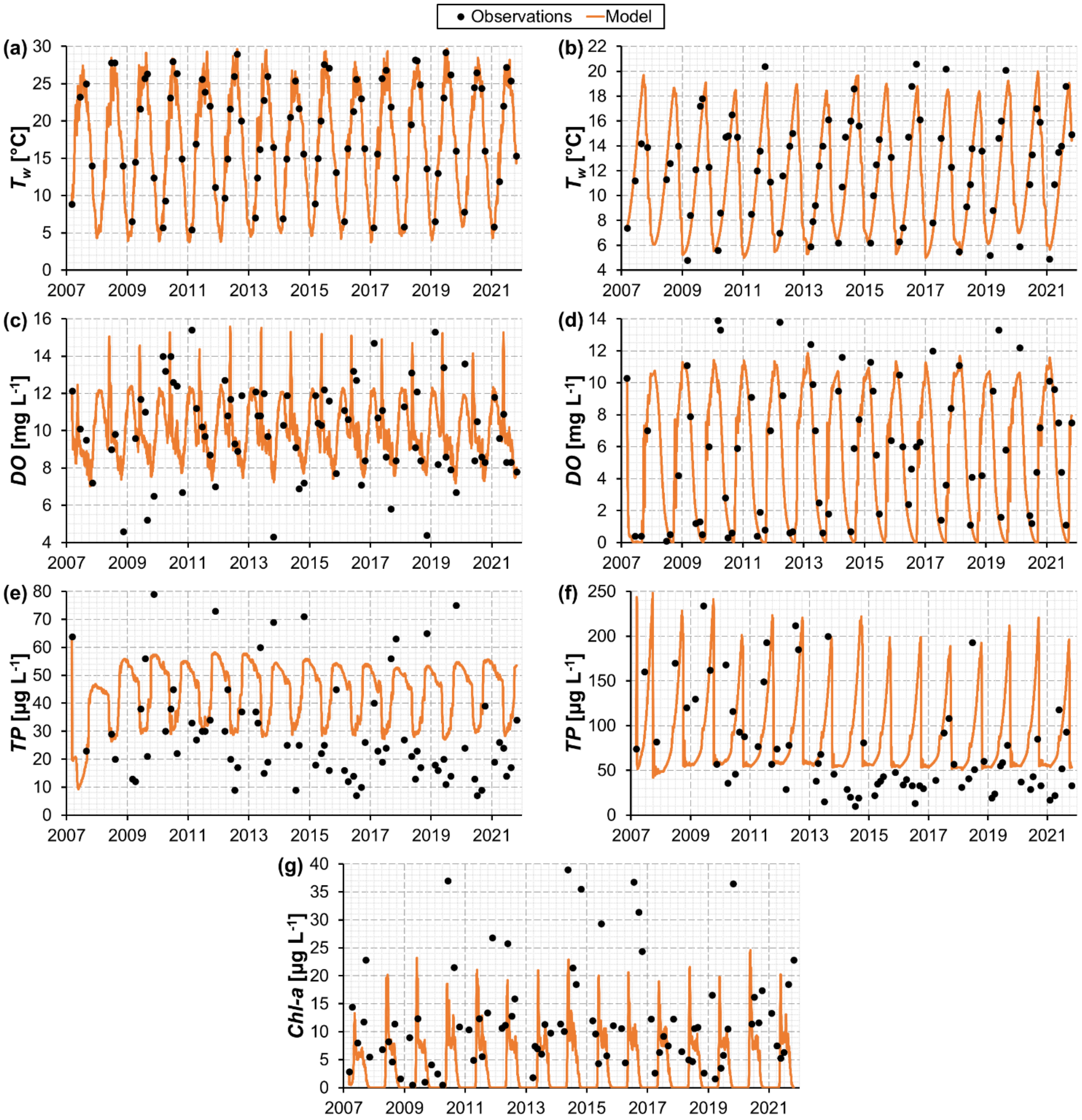

Fig. 2. Observed and modelled volume-weighted water temperatures (T_w), dissolved oxygen (*DO*) and total phosphorus (*TP*) concentrations in the 0 – 1 m epilimnion (a, c, e, respectively) and in the 8 – 11 m hypolimnion (b, d, f, respectively) and Chlorophyll-*a* (Chl-*a*) concentrations in the 0 – 6 m photic layer (g) for Lake Annone East.

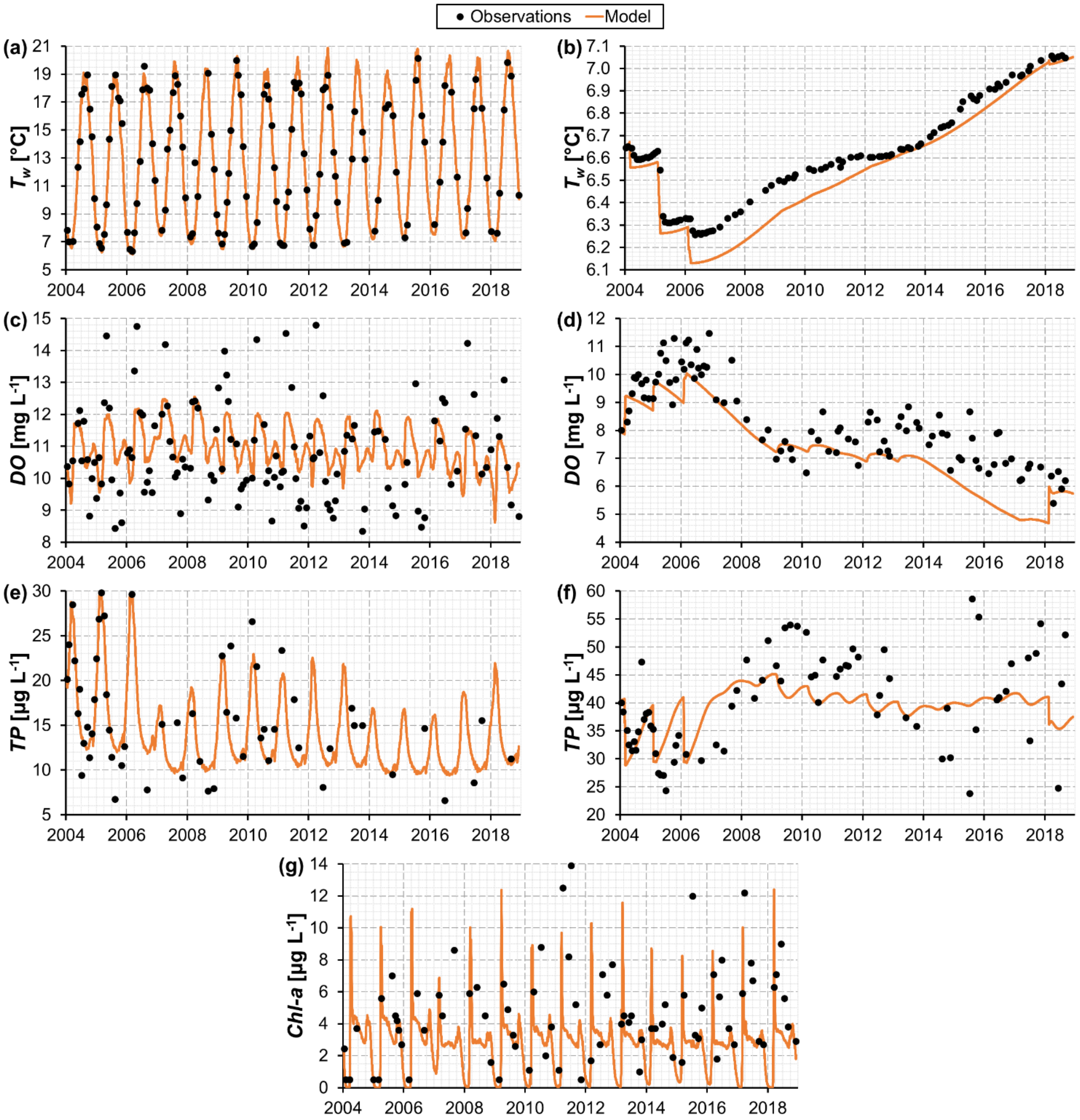

Fig. 3. Observed and modelled volume-weighted water temperatures (T_w), dissolved oxygen (*DO*) and total phosphorus (*TP*) concentrations in the 0 – 25 m epilimnion (a, c, e, respectively) and in the 200 – 426 m deep hypolimnion (b, d, f, respectively) and Chlorophyll-*a* (Chl-*a*) concentrations in the 0 – 20 m photic layer (g) for Lake Como.

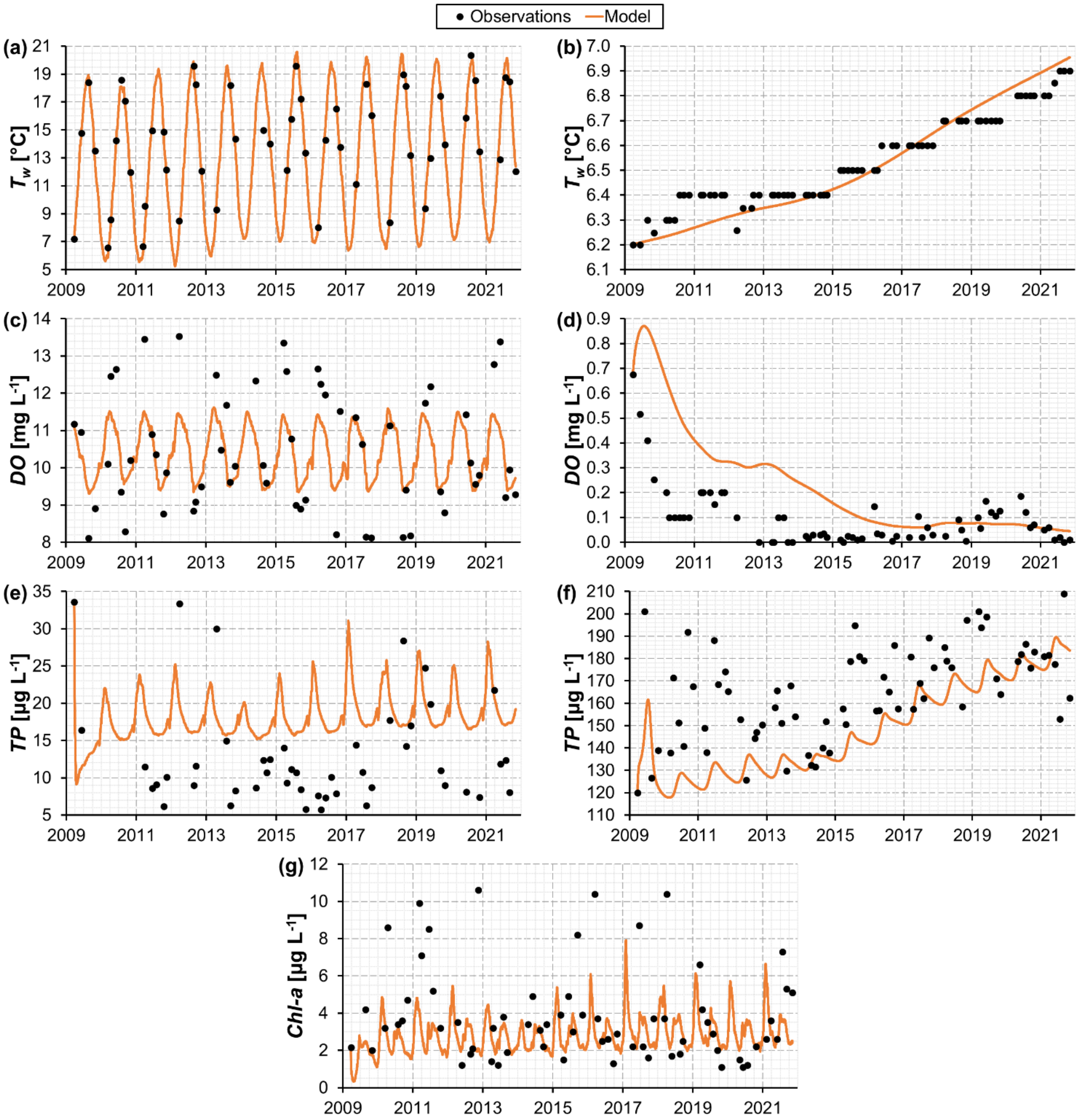

Fig. 4. Observed and modelled volume-weighted water temperatures (T_w; observations have 0.1 °C resolution), dissolved oxygen (*DO*) and total phosphorus (*TP*) concentrations in the 0 – 25 m epilimnion (a, c, e, respectively) and in the 200 – 252 m deep hypolimnion (b, d, f, respectively) and Chlorophyll-*a* (Chl-*a*) concentrations in the 0 – 20 m photic layer (g) for Lake Iseo.

3.2. Simulation of volume-weighted *TP* concentrations at spring mixing

The observed and modelled series of annual volume-weighted *TP* concentrations at spring mixing in the calibration period and in the following near-future extension are shown in Fig. 5 for the pilot lakes, over the entire water column and in the 0 – 60 m mixolimnion for Lake Iseo.

The implemented simplified modelling schematisation effectively reproduced the observed general trend of this derived variable for all the studied lakes. However, observed values display a higher interannual variability than simulated ones. This is due to: (1) the constant-load approximation; (2) the differences in the time of sampling from the annual day of spring mixing identified in the simulations; (3) the availability for many considered basins, including the displayed Lake Annone East (Fig. 5a) and Lake Iseo (Figs. 5c and 5d), of data not systematically sampled at the same depths, which influences the volume-weighted value calculations for the observations. For lakes in which there is a significant ongoing contribution by internal load (Lake Alserio, Lake Idro, Lake Iseo, Lake Pusiano), variations in the external input *TP* in the near-future extension period affect the volume-weighted concentrations at spring mixing less than linearly, due to the internal nutrient release from the sediments. For meromictic Lake Idro and Lake Iseo, the agreement between modelled and observed volume-weighted *TP* concentrations at spring mixing over the mixolimnion alone (Fig. 5d) is worse than over the entire water column (Fig. 5c). This is due to model calibration minimising the global error across all depths, so that a bias may be present over a portion of them, hence also explaining the better agreement of the *TP* concentrations averaged over the whole depth in Figs. 5a – 5c compared to those over partial layers (Figs. 2e, 2f, 3e, 3f, 4e and 4f). Furthermore, the influence of interannual load variability and of horizontal patchiness is far more prominent in the mixolimnion than in deep separated waters.

Focusing on pilot Lake Annone East (Fig. 5a), the simulation reproduces a decrease in volume-weighted *TP* concentrations at spring mixing in the calibration period, even though at a slower rate than in the observations. Such decrease is due to the hypolimnetic withdrawal, active since 2008 and implemented into the model. The model correctly reproduces that, through the withdrawal, the high *TP* concentration of the first simulated year 2007 is never reached again. The lower simulated decrease rate than the observed one may be due to both interventions to reduce external loads having been performed and to the imperfect modelling of nutrient loss from bottom sediments, an accurate calibration of such phenomenon requiring periodic data of nutrient content in the sediments. This would be also proven by the higher-than-observed reproduced sediment release in the latter half of the calibration period (Fig. 2f). For Lake Annone East, both the simulated and the observed volume-weighted *TP* concentrations at spring mixing stabilise by the end of the calibration period, a prompt adaptation to external load reductions occurring in the relative near-future scenarios, given the low inertia reproduced for all considered small shallow lakes.

As regards displayed Lake Como (Fig. 5b), the model well reproduces the slow decrease in volume-weighted *TP* concentrations at spring mixing observed in the calibration period. External nutrient loading to Lake Como has been pretty much stable overall in the last 20 years due to the absence of interventions on the watershed (Fenocchi et al. 2023), the oscillations around the reduction trend in the observations revealing the interannual load variability due to rainfalls. This gradual decrease in *TP* concentrations is therefore to be ascribed to the significant reduction of external loading performed to oppose eutrophication in the 1980s and 1990s, its effects on Lake Como being prolonged by the inertia due to the large lake volume. In the reference near-future scenario with constant loads, stabilisation of *TP* concentrations is obtained by 2030. Instead, in the scenarios with external load reduction the decreasing trend extends after loading stabilisation in 2034, approaching equilibrium by the end of the simulated period. This further proves the relevant inertia of this large lake. Similar results were obtained for Lake Garda, which shares watershed intervention history and morphometrical traits with Lake Como.

Considering the whole water column of pilot Lake Iseo (Fig. 5c), the model properly simulates the observed rapid increase in volume-weighted *TP* concentrations at spring mixing in the calibration period. This upsurge is due to a hypolimnetic accumulation process triggered by the increase of both thermal and chemical stabilities with global warming, leading to hypolimnetic anoxia and meromixis (Ambrosetti and Barbanti, 2005; Rogora et al., 2018), supplemented by the still high external loading and the increasing internal loading (Scibona et al., 2022; Valerio et al., 2022). This trend in *TP* concentrations carries on unaltered up to the end of the simulated period in the reference near-future scenario, milder increase rates being reproduced in the external load reduction ones. The increase process would nevertheless be further intensified by future climate warming, not considered in the present simulations, causing an additional growth of water-column stability. The relevance of hypolimnetic accumulation and internal loading phenomena on the increase of volume-weighted *TP* concentrations at spring mixing is confirmed by considering the mixolimnion alone (Fig. 5d). Within such layer, in fact, the -30% nutrient variation is reproduced to eventually stabilise *TP* concentrations, whereas an enduring rise occurs in the monimolimnion.

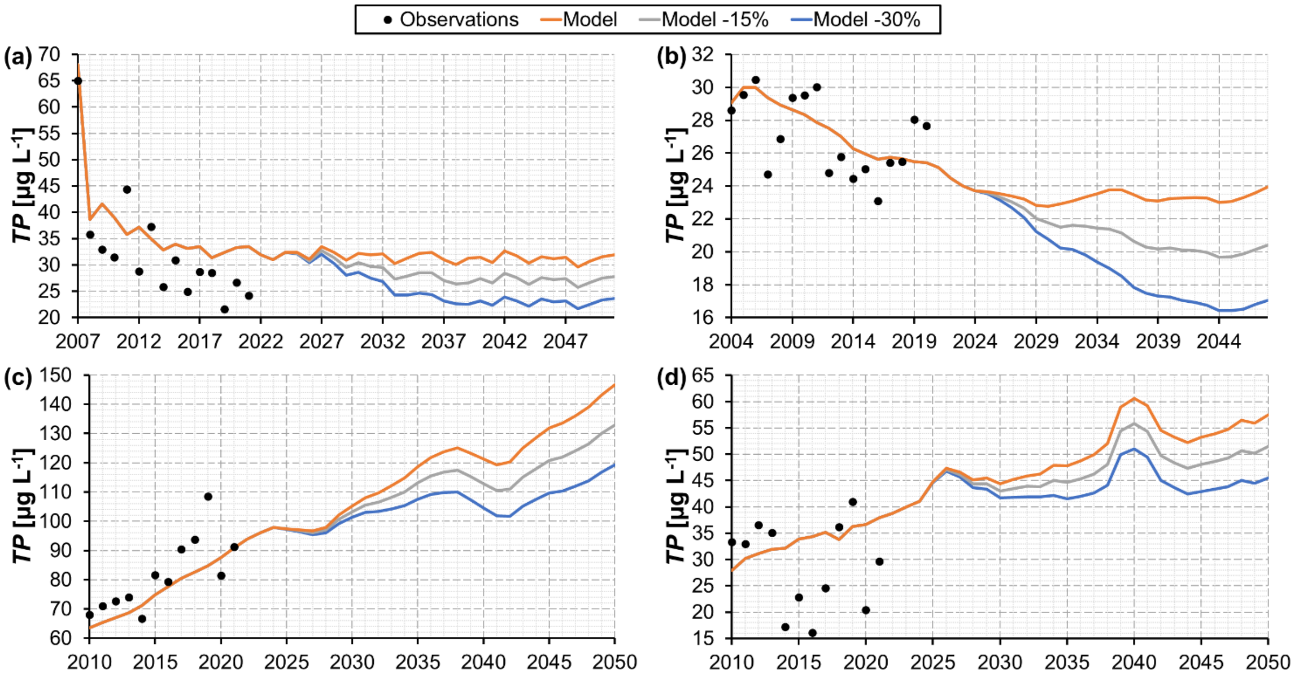

Fig. 5. Observed and modelled (constant nutrient loads and -15% and -30% external loading variations) volume-weighted total phosphorus (*TP*) concentrations at spring mixing over the water column for Lake Annone (a), Lake Como (b), Lake Iseo (c) and in the 0 – 60 m mixolimnion for Lake Iseo (d).

4. Conclusions

The adopted simplified process-based coupled ecological-hydrodynamic modelling approach, employing data from public monitoring and automatic calibration, allowed a deeper understanding of the present and near-future conditions of the studied lakes than allowable through Vollenweider-OECD-type approaches, offering more solid mechanistic bases and an insight into aspects other than volume-weighted total phosphorus (*TP*) concentrations at spring mixing. For such relevant variable, in any case, process-based coupled models allow computing the evolution in time with a much less parametrical approach than traditional steady-state models. All of this translates into valuable information for lake water ecosystem service protection planning. Further enhancement of the lake models implemented in this study would first require more precise quantifications of external loads from the watersheds, including their variability in time.

For an additional water quality improvement of the lakes considered in this study, supplementary external load reduction from their watersheds is central. In fact, except for the very large Lake Como and Lake Garda, for which residual effects of past major interventions against eutrophication are still ongoing due to their relevant inertia, the other lakes have reached a virtual equilibrium, which could yet be compromised by climate warming, not included in the present simulations, causing phenomena such as unexpected phytoplankton blooms and increased nutrient release from sediments. The effects of climate change are already critical for Lake Iseo, for which extensive external load reduction is compelling. Shallow lakes have largely disposed their internal load due to past widespread nutrient pollution, so that they seem to now react faster than in the past. Again, accurate quantification of present external loading levels is crucial, being the first step towards the identification of the further nutrient abatement potential in the watershed. This would lead to a more informed planning of interventions aimed at lake ecosystem service protection, being directed to either reducing nutrient release through policies on human activities or to decreasing the fraction which is delivered to lakes through sewage collection and treatment improvements.

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Data statement

The datasets analysed and generated in this study are available from the Corresponding Author upon reasonable request.

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3.3 Focus on Lake Pusiano

In the published paper, the model results for Lake Pusiano were not shown, preference having been given to large deep lakes. In Figure 9, the graph of the model-derived evolution of *TP* concentrations at spring mixing is presented, covering both the calibration period and future scenarios, under both present *P* and *N* loading and under -15% and -30% reduction scenarios of both.

The observed concentrations displayed as comparison belong to two different datasets. The first is the dataset from ARPA Lombardia, collected as part of the WFD monitoring program. The second dataset comes from the CNR IRSA in Brugherio, which has been taking at least one sampling of Lake Pusiano per year since 1972, at spring mixing.

Figure 9 shows an initial decreasing trend in concentrations from 2007 to 2012, made evident by the black lines obtained by quadratic polynomial regressions of the two datasets. This decreasing trend is due to nutrient pollution reduction measures implemented over those years, thanks to the actions of the PIROGA project, together with a reduction of internal loading (Copetti et al., 2017). The model clearly cannot reproduce this decrease, as constant external nutrient loading was set up to the levels of the calibration period 2013-2021, in which relatively stable *TP* concentrations at spring mixing were obtained, with a slight apparent increase. The model reproduces this increase, which protracts in the near-future projection period for the baseline scenario with constant loads, and is to be ascribed to non-equilibrium conditions of external loading related to lake nutrient metabolism, i.e. to still too high external loading. As a matter of fact, stabilization of *TP* concentrations is attained in the -30% reduction scenario. The unexpected 2021-2023 heavy drought made such increase much more dramatic in recent years due to the upsurge of internal loading, as will be explained in the next chapters of this thesis.

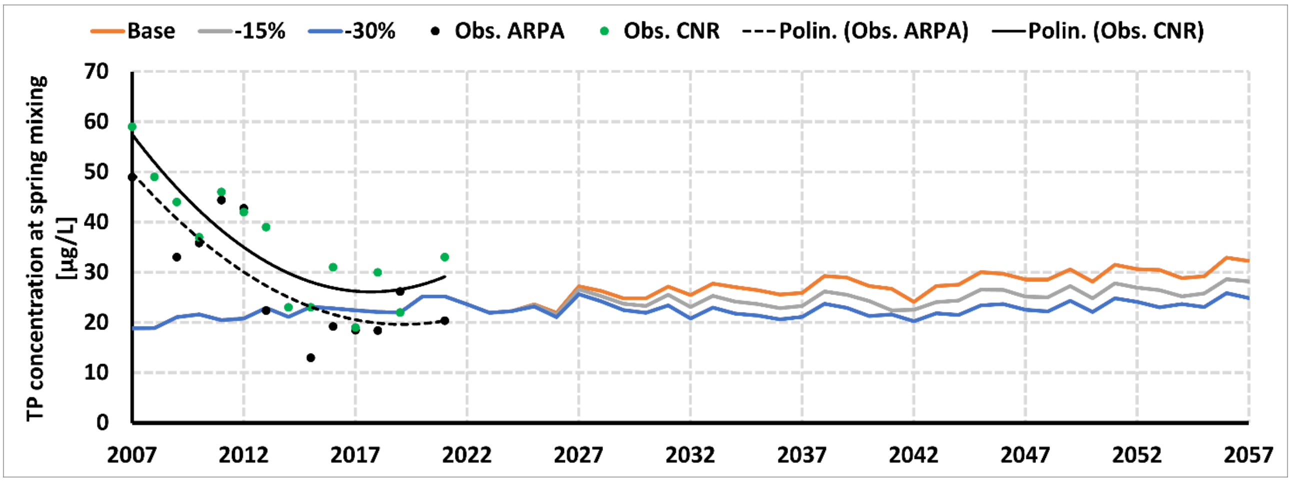

Figure 9. Modeled (baseline scenario with constant loads and -15% and -30% reductions) and observed volume-weighted TP concentrations at spring mixing for Lake Pusiano.

4. Scientific Paper 2

4.1 Introduction

This chapter addresses the second journal paper work of the Ph.D. thesis, entitled *"Assessment of external and internal nutrient load to Lake Pusiano (Northern Italy) using watershed eco-hydrological modeling and lake ecological-hydrodynamic simulations"*, currently under review in the journal *Modeling Earth Systems and Environment*.

The aim of this paper was to develop a better representation of the external nutrient load to Lake Pusiano, in order to get both an estimation of its interannual variability with precipitations and to ultimately lead to a more accurate lake model. At the end of the first paper, it became evident that using a constant nutrient load made it impossible to accurately model the lake internal dynamics.

Moreover, during this period, alongside the modeling work, a field monitoring campaign was performed on the lake, which started to reveal a clear deterioration in the trophic status, with significant cyanobacterial algal blooms. As a result, directing research towards the estimation of nutrient loads, both external and internal, became a priority, to determine the role of the two in determining the observed worsening water quality.

To solve this problem, a new approach was chosen, moving away from the traditional use of interpolation or regression relationships alone to reconstruct the load from discrete observations. Since nutrient loading in this basin is strongly affected by rainfall variability and by the presence and activation of CSOs in urban areas, such classic methods were unsuitable, mainly due to limited sample data. It was therefore necessary to find an approach that could integrate point-source nutrient loads, even in a simplified way, into the diffuse load modeling. Anyway, having a detailed representation of point sources is practically unviable, due to CSO activation being unpredictable in some cases.

The SWAT+ (Soil & Water Assessment Tool, Bieger et al., 2017) eco-hydrological model was chosen for the task in this work. SWAT+ is a physically based, semi-distributed eco-hydrological model that simulates the quantity and quality of surface and groundwater (at a simplified level for the latter, unless SWAT+ is integrated with dedicated groundwater models), and assesses the environmental impact of land use, land management practices, and climate change (*SWAT website, https://swat.tamu.edu/*). As such, it considers point loads as if they were diffused from urban areas, but it includes an approximate treatment of the nutrient releases from CSOs according to the USGS regressive equations of Driver & Tasker (1988). Additionally, SWAT+ allows for the estimation of nitrogen loads from atmospheric deposition, which has a relevant contribution for the mainly forested basin of Lake Pusiano.

Using the SWAT+ eco-hydrological model further made it possible to model the entire catchment, not just the one of *Lambro Supralacuale* for which monitoring data were available, getting an approximate modelling of the behaviour of the remnant ~20% of the basin. This holds not only for nutrient loads, but also for discharges, the only permanent station for flow rate monitoring being the one in Caslino d'Erba for *Lambro Supralacuale*, which is not even representative of the full Lambro inflow to Lake Pusiano.

Most of the work on the SWAT+ model was carried out during a three-month research stay in Spain under the supervision of the team at Universidad Católica de Murcia, who specialize in SWAT modelling. The majority of the work there focused on the calibration of the model, both for the hydrological and the ecological part, which was performed with the SWATplus-CUP v3.0 tool (Abbaspour, 2022).

The nutrient load time series used for model calibration, which was done at the monthly scale , were generated using the LOADEST (Load Estimator) software by the USGS (https://water.usgs.gov/software/loadest/), which allows using a multitude of regression approaches between available discrete nutrient concentration samples and daily discharge series to build continuous series of nutrient loads (Dezuanni et al., 2025). Though this may seem a contradiction with what was stated before about the flaws of interpolation approaches, it was the only possibility to run a calibration of the SWAT+ model, which required mean monthly concentrations of some sort and could not be completed with only four instantaneous concentration data per year. Moreover, while calibration was performed at the monthly scale, using monthly averaged data, the SWAT+ model was run at the daily scale, so that the model was still free to reveal the variability of nutrient load resulting from climate data, fed daily, according to the differential equations which make up the model.

Once the external nutrient load series were obtained for the period 2009-2023, they were used as input for the lake model implemented through the WET (Water Ecosystems Tool, Nielsen et al., 2017, 2021; Schnedler-Meyer et al., 2022) software, which provided important insights into internal nutrient loading, supplementing those given on the external one by SWAT+. A nutrient reduction scenario was then created through the application of Best Management Practices (BMPs) into the SWAT+ land uses module to study their impact on the lake through the WET model. This scenario was compared with the modeled *TP* concentrations at spring overturn in the baseline scenario to evaluate the effectiveness of the reduction.

4.2 Paper - Assessment of external and internal nutrient loads to Lake Pusiano (Northern Italy) using watershed eco-hydrological modelling and lake ecological-hydrodynamic simulations

Abstract

Eutrophication is still a serious issue for many lakes in the subalpine lake district of Northern Italy. Significant improvements have been achieved thanks to interventions carried out on their watersheds, whereas the Water Framework Directive of the European Union (EU WFD) has established ecological and chemical water quality targets. Unfortunately, climate change and remaining pollution inputs by human activities play a synergistic role in hampering remediation efforts. In fact, water warming strengthens stratification, leading in shallower holomictic basins to prolonged periods of hypolimnetic anoxia, boosting phosphorus (*P*) release from sediments and promoting phytoplankton blooms in some cases. This study focuses on Lake Pusiano, a 25 m-deep mesotrophic lake with a 5.2 km^2 area in Northern Italy. Lake Pusiano, after recovering from eutrophication in the last two decades, has experienced a recent deterioration in water quality, suggesting that nutrient loads are still excessive. The initial aims and final results of this study were an estimation of the current external nutrient loads from the watershed, assessing their variability in relation to annual rainfall, and evaluating the present internal load from lake sediments. To achieve these targets, an eco-hydrological model of the lake watershed was developed using SWAT+ (Soil & Water Assessment Tool). The obtained external nutrient loads from the basin were then fed into an ecological-hydrodynamic one-dimensional (1D) GOTM-WET (General Ocean Turbulence Model – Water Ecosystems Tool) model of Lake Pusiano, reproducing in-lake dynamics. Additionally, a nutrient loading reduction scenario was developed through the implementation of Nature-Based Solutions (NBS) on the watershed, with the aim of estimating the effect of realistic nutrient load reduction interventions on the lake status, which were deemed insufficient for safeguarding current spring-mixing total phosphorus (*TP*) concentration limits under the present climate-change pressures.

Keywords

process-based modelling; SWAT+; GOTM-WET; water resources management; NBS; EU WFD

1. INTRODUCTION

Water-quality deterioration issues for lakes at the foothills of the European Alps are still mainly related to eutrophication. Anthropogenic pollution from point and diffuse sources is still the main source of nutrient enrichment (Bhagowati et al., 2019). Nutrient loads entering the lakes are in fact in some cases still too high due to inefficiency of the sewer system, incomplete collection of sewage and insufficient capacity of the network and/or of the wastewater treatment plants (WWTPs), leading to frequent activation of combined-sewer overflows (CSOs) in combined-sewer systems. Since the 1980s, the quality status of many subalpine lakes has improved significantly after a series of interventions in their catchments. However, in some cases the re-oligotrophication efforts dealing with pollution input reduction measures have not given the desired results, due to either still excessive external loading, possibly from hardly addressable and assessable sources such as diffuse ones (Gonsiorczyk et al., 2024) or due to inefficient sewage collection and depuration, or from enduring internal loading from polluted sediments (Søndergaard et al., 2003; Jensen et al., 2006).

The role of meteo-climatic factors in this still problematic situation for eutrophication is generally detrimental, yet in some cases some positive effects may result from short-term random meteorological alterations or long-term climate change (Doubek et al., 2021; Woolway et al., 2022; Dresti et al., 2023). Climate change is known to play a synergistic role with nutrient pollution (Battarbee et al., 2012), global warming affecting lakes by increasing water temperatures. This leads to accelerated and extended biochemical activity and primary production, notably triggering more frequent and earlier phytoplankton blooms (Peeters et al. 2007; Navarro et al. 2023). Climate warming also enhances the duration and intensity of lake stratification, due to the differential increase of temperature along the water column (Livingstone, 2003; Woolway et al., 2021), which fosters internal-load release from sediments due to extended and enhanced bottom anoxia in basins suffering from hypolimnetic dissolved oxygen deficiency (Jansen et al., 2024). Climate change also has a significant impact on the hydrological cycle of lake catchments, especially on precipitation patterns. Extreme weather events, notably leading to extended periods of floods and droughts, are widely known to be exacerbated, altering nutrient delivery to lakes (Yang et al., 2019; Catalan et al., 2024).

In the European Union, the Water Framework Directive (EU WFD) requires local environmental agencies to carry out monitoring activities on the relevant tributaries of lakes, to assess the ecological status of the streams themselves (EU WFD, 2000). However, it does not demand the estimation of nutrient loads delivered to lakes. In fact, analysis of nutrient concentrations in water samples from tributaries is not mandatory and, even when performed, monitoring frequencies are generally too low to produce a reliable reconstruction of external nutrient loading evolution. Thus, the only available external load estimates are often constant mean annual values estimated from either land use and occupation (Rast and Lee, 1983) or from very limited and possibly outdated field observations (Fenocchi et al., 2023). Actually, accurate and updated assessments of external load series, including information on their variability with rainfall, are central to organising any intervention on the watershed aimed at nutrient pollution mitigation.

Addressing the EU WFD, regional authorities have issued plans aimed at reaching the required "good" ecological target for lakes. To this aim, target nutrient concentrations have been set by institutions, often on limiting total phosphorus (*TP*) (Poikane et al., 2019a, 2019b). In the case of Italy, the national law prescribes 15 µg/L and 20 µg/L depth-averaged *TP* concentrations at spring mixing for large and medium-to-small lakes, respectively. Regional authorities can then set individual limits on single lakes, basing on specific evaluations. As an example, in the Lombardy region of Northern Italy, limit depth-averaged *TP* concentrations at spring mixing have been established as 1.25 times the hypothetical pristine concentrations obtained from the Morpho-Edaphic Index (MEI), calculated as ratio between lake alkalinity and mean depth (Vighi and Chiaudani, 1985). These static limits, in addition to being determined through arbitrary or deeply uncertain criteria, do not consider the modifications in ecosystem dynamics with climate change, which have become increasingly relevant in recent years, especially for lake management purposes (Free et al., 2024).

Within this context, knowledge on the present external nutrient loading and of its variability with annual rainfall would allow defining a base level to be used for: (1) studies on long-term variation of nutrient loads evaluating the efficiency of past actions against nutrient pollution; (2) studies evaluating the effects of future climate change and/or of new remediation measures. These studies may be developed leveraging on numerical modelling, combining an eco-hydrological model of the watershed, reproducing external nutrient loads, with a coupled ecological-hydrodynamic model of the lake, evaluating its response to nutrient load alterations and climate change. In case estimations of past nutrient load series are available, eco-hydrological modelling could be restricted to future forecasts. However, due to the usual unavailability of nutrient load series, especially for minor tributaries and diffuse inputs, which can play a relevant role in many lakes (Janssen et al., 2019; Fenocchi et al., 2023), use of eco-hydrological modelling should be extended to the estimation of present and past loads, sometimes including flow rates themselves.

In this work, these modelling methodologies have been applied to Lake Pusiano, in the Lombardy region of Northern Italy. Eutrophication peaked in this lake in the mid-1980s, after which nutrient pollution countermeasures in the catchment were implemented, stabilising the lake to mesotrophic conditions and significantly reducing internal load by the early-2010s (Copetti et al., 2017). Starting from 2022, however, an increase of *P* concentrations in the hypolimnion has been observed. In addition, there has been a significant increase in algal production and especially in cyanobacterial blooms, occurring even during the winter (ARPA Lombardia, *pers. comm.*).

A model-chain approach was hence adopted in this study, using the SWAT+ (Soil & Water Assessment Tool; Bieger et al., 2017) eco-hydrological model and the GOTM-WET (General Ocean Turbulence Model; Burchard and Bolding, 2001 – Water Ecosystems Tool; Nielsen et al., 2017, 2021; Schnedler-Meyer et al., 2022) one-dimensional (1D) coupled ecological-hydrodynamic lake model. Eco-hydrological modelling was required because discharges and discrete *P* and nitrogen (*N*) concentration samples are available only at a single station on the main tributary Lambro River, 6 km upstream of Lake Pusiano. Therefore, to determine the total external nutrient load series delivered to the lake, there was the need both to transform such discrete data into continuous daily ones and to estimate discharges and nutrient load series from streams other than the main tributary, for which values at the mouth are furthermore needed for lake modelling. The eco-hydrological model notably enabled reproducing the interannual variability with rainfall of external loads from the catchment, which was previously undisclosed. GOTM-WET was then used to reproduce lake thermal dynamics, nutrient biogeochemical cycles and primary production. Process-based lake modelling was especially directed in this study at estimating internal load series from sediment release, complementing the external loads predicted with SWAT+. A nutrient pollution reduction scenario was also simulated with SWAT+, using realistic Nature-Based Solutions (NBS) on the watershed based on the actual land use distribution and mechanistically modelling their operations. Resulting reduced loads were then entered as input into GOTM-WET, simulating the effect of the NBS countermeasures on Lake Pusiano and evaluating their efficiency in relation to the target *TP* concentration defined for the basin.

The aims of this work are thus: (1) to estimate the recent external and internal nutrient loading history to Lake Pusiano by means of process-based modelling of both the lake and its watershed; (2) to evaluate the influence of nutrient loading on the lake trophic status by disentangling the role that climate change may have had in the recent evolution of the lake; (3) to discuss which remediation measures may be put in place, critically evaluating their effectiveness.

2. METHODS

2.1. Case Study

Lake Pusiano is a medium-sized lake of glacial origin in the Lombardy region of Northern Italy (Figure 1), one the most urbanised and industrialised areas of Europe. The lake has a surface of 5.2

km^2 and a volume of 70×10^6 m^3, maximum and mean depth being respectively equal to 25.0 m and 13.5 m for the mean lake surface elevation of 259 m a.s.l. (Fenocchi et al., 2025). Lake Pusiano is currently classified in terms of mixing regime and trophic status as warm monomictic and mesotrophic, respectively (Copetti et al., 2017). The water level of the lake is regulated by the Cavo Diotti Dam (Figure 1a), whose purpose is to reduce flooding downstream of the lake in the Lambro River, which is the Lake Pusiano only outflow and main inflow (Figure 1a). The Lambro River flowing into the lake has a mean annual discharge of 1.4 m^3/s (Carraro et al., 2012) and drains about 80% of the Pusiano watershed, collecting contributions from smaller streams flowing in secondary valleys.

The watershed of Lake Pusiano (Figure 1) lies between the two southern arms of Lake Como and covers an area of 93.2 km^2, including the lake itself, with slopes decreasing in the southward direction, becoming a flatland from the main town of Erba downstream. The maximum elevation of the watershed is 1450 m a.s.l., its bottom end being represented by the lake surface, the mean elevation being 760 m a.s.l. (Boguniewicz et al., 2006). The mean annual rainfall height in the watershed varies significantly with terrain elevation, ranging from around 1500 mm/a in the lake area to around 2000 mm/a in the highest part of the watershed (Viviano et al., 2014). Excluding Lake Pusiano and Lake Segrino, a 0.35 km^2-wide natural lake flowing into the main basin through a connecting stream (Figure 1), land in the Pusiano watershed is predominantly forested, 76% according to the CORINE Land Cover (CLC) 2018 map from the EU Copernicus service. The remaining soil is split between urban and agricultural uses, 13% and 9% from CLC 2018, respectively. Residual 2% is occupied by pastures. There has been no significant change in land use over the years, as testified by the comparison with CLC 1990.

The main source of nutrient pollution for Lake Pusiano are the CSOs of the urban sewer networks (Viviano et al., 2014). Lake Pusiano, as several other subalpine lakes in Northern Italy, underwent severe eutrophication in the 1960s and 1970s (Salmaso et al., 2007), the volume-weighted TP concentration at spring mixing reaching 153 µg/L in 1977 and about 200 µg/L in 1984 (Copetti et al., 2017). In the second half of the 1980s, a series of interventions in the watershed consisting in sewer network implementation and the activation of the Merone WWTP serving the catchment triggered a significant reduction in nutrient loads. The estimated annual external load of TP, which was around 21 t/a in the early 1980s, is now much lower, estimated as 6 t/a for 2014 (Copetti et al., 2017). However, due to the wide extent of anthropic pressures in the watershed and the presence of manifold CSOs, some of them activating also for much lower discharges than the original design ones due to sewer network aging (Viviano et al., 2014), a further, much-needed, reduction of external loads has not been attained yet. Following external load decrease, the internal load has also dropped significantly. From the mid-1980s, when it was estimated to be around 3.6 t/a, it decreased to about 1.0 t/a for 2010 (Copetti et al., 2017). In the same year, the observed *TP* concentration at spring mixing was 37 μg/L (Copetti et al., 2017). However, observations from the lake WFD monitoring activities performed by the Regional Environmental Protection Agency of the Lombardy Region (ARPA Lombardia) show that *TP* concentrations in the lake have started increasing again since 2015, notably those at the bottom during the stratified season. This behaviour exacerbated significantly during the extended 2021-2023 drought which affected Northern Italy, such meteorological extreme event being possibly linked to climate-change outcomes. As all Italian subalpine lakes (Rogora et al., 2018), Lake Pusiano is indeed experiencing the effects of climate warming, the temperature at spring mixing over the water column having increased from ~5 °C in the 1970s to ~7 °C in recent years.

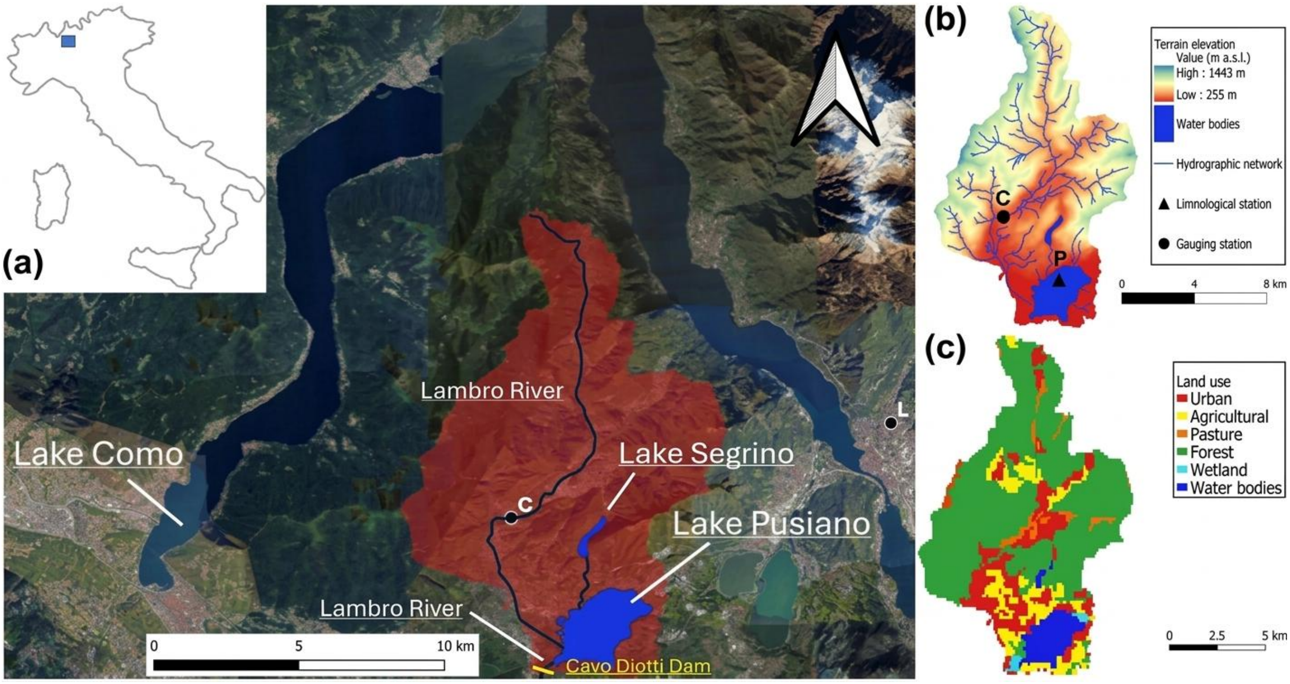

Figure 1. (a) Location of the Pusiano catchment in Italy and in the Lake Como area (orthophoto courtesy of Google Satellite); (b) elevation map of the Lake Pusiano catchment from the DTM by the Lombardy Region; (c) land use map in the Lake Pusiano catchment according to the Corine Land Cover (CLC) 2018 map (Caslino d'Erba meteorological, hydrological and water sampling station: C; Lecco Via Sora meteorological station: L; Lake Pusiano limnological sampling station: P).

2.2. Adopted data

The data used as model input and as observations for the calibration and validation of the SWAT+ and GOTM-WET models were obtained from the monitoring activities of ARPA Lombardia unless when differently specified.

The 2004-2023 daily meteorological data series at the ARPA Lombardia Caslino d'Erba and Lecco Via Sora stations (Figure 1a) were considered for setting up the watershed (SWAT+) and lake (GOTM-WET) models, respectively. Air temperature, shortwave radiation, relative humidity and wind speed data series were used as inputs for both models, the rainfall series being also needed by SWAT+. The SWAT+ model also included as input the mean 1999-2021 annual N deposition coefficient per unit rainfall depth. As no direct measurement of N deposition is available for the Lake Pusiano area, we used data from the Verbania atmospheric deposition sampling station managed by the Water Research Institute of the National Research Council of Italy (CNR-IRSA), located about 60 km west of the Pusiano basin. This station is still in the pre-alpine range of North-Western Italy, its annual rainfall amount and regime are consistent with those of the Pusiano area and it is subject to the same air pollution conditions. The use of a single average annual deposition coefficient value instead of variable ones is due to a limitation in the employed version of SWAT+.

The 2004-2023 daily discharge series at the ARPA Lombardia Caslino d'Erba station on the inflowing Lambro River (Figure 1) was employed for the calibration and validation of the hydrological component of SWAT+. For the calibration and validation of the ecological module of SWAT+, i.e. nutrient load estimations, the 2009-2023 quarterly data from water quality monitoring at the same Caslino d'Erba location were employed, integrated with additional samples collected and analysed by CNR-IRSA for 2023. Orthophosphate ($P\text{-}PO_4$) and nitrate ($N\text{-}NO_3$) concentration data series were considered.

Lake limnological data profiles sampled at the point of maximum depth (Figure 1b) were employed for GOTM-WET model calibration and validation. Water temperature (T_w) and dissolved oxygen concentration (DO) were measured along the water column with a multi-parameter probe (Idronaut Ocean Seven 316 Plus; Idronaut, Italy). Samples for the determination of $P\text{-}PO_4$, TP, $N\text{-}NO_3$, ammonium ($N\text{-}NH_4$) and total nitrogen (TN) concentrations were taken at discrete depths. Lake monitoring data series of these variables with quarterly frequency were available for 2009-2023, integrated with supplementary data from CNR-IRSA for 2023.

Laboratory analyses of water samples were performed by ARPA Lombardia and CNR-IRSA laboratories according to standard methods for freshwater analysis (APAT-IRSA, 2003; APHA AWWA WEF, 2012).

2.3. SWAT+ eco-hydrological catchment model

The SWAT+ (Soil & Water Assessment Tool; Bieger et al., 2017) model v2.3.3 was employed to implement the eco-hydrological model of the Lake Pusiano catchment for the 2004-2023 period. The surface morphology was defined through the 2015 Digital Terrain Model (DTM) with 5 m resolution provided by the Lombardy Region. Land use was defined according to the CLC 2018 map with 100 m resolution. The DSOLmap (López-Ballesteros et al., 2023) was used to define soil pedology in the model with 250 m resolution. Three slope classes (0% – 8%, 8% – 30%, > 30%) were used for the delineation of the Hydrological Response Units (HRUs), selecting the filtering based on area option in SWAT+, with a 100 ha threshold. The nutrient loading from urban areas was modelled in SWAT+ using the regressive equations obtained on experimental basins by the US Geological Survey (USGS; Tasker and Driver, 1988), which mimic the functioning of an average drainage network with CSOs activating during wet periods.

To calibrate and validate the ecological part of SWAT+, instrumental daily series of $P\text{-}PO_4$ and $N\text{-}NO_3$ loads for the Lambro River at Caslino d'Erba (Figure 1) were obtained from available discrete quarterly sampled concentrations and daily discharges using the LOADEST (LOAD ESTimator; Runkel et. al., 2004) software by the United States Geological Survey (USGS), as in Navarro et al. (2023) and Dezuanni et al. (2025). LOADEST performs regressions of available concentration data keeping into account their dependence on flow rate and seasonal and long-term trend factors, using the obtained regression laws to compute daily load series from the observed daily discharges. The other nutrient substances (NH_4, TN and TP) were not explicitly calibrated in SWAT+ due to reduced sample size.

The SWAT+ model was calibrated through a semi-automatic calibration approach using the SWATplus-CUP v3.0 software (Abbaspour, 2022). The SPE (SWAT Parameter Estimator) algorithm was employed for calibration, which is a new version of the Sequential Uncertainty Fitting Version 2 (SUFI-2) algorithm of previous SWAT-CUP versions. The model parameters included in the calibration process were determined through preliminary sensitivity analyses (Abbaspour, 2012), whereas optimal calibration ranges for them were obtained from literature and preliminary, iterative, calibration runs. The streamflow model was calibrated first, nutrient loads being calibrated afterwards over the daily series estimated through LOADEST, with the hydrological parameters obtained in the previous step. Five hundred model runs were performed for each parameter optimisation phase, repeating each of them multiple times till the final calibration ranges were identified for each parameter. For streamflow, the model was calibrated over 2004-2013 and validated over 2014-2023. For nutrient loads, the model was calibrated over 2014-2023 and validated over 2009-2013. Reversed calibration and validation periods were selected after preliminary tests to reduce model bias in nutrient load estimation, as will be explained in Paragraph 3.1. In both calibration procedures, optimisation was performed over aggregated mean monthly values to obtain better and more physically meaningful results in terms of water and nutrient budget. The reference metric in the parameter optimisation process was the Kling-Gupta Efficiency (*KGE*), the Percent Bias (*PBIAS*) and the Pearson correlation coefficient (*r*) being also evaluated. The *KGE* is an index of the ability of the model ability to reproduce peaks (Yin et al., 2021), thus being particularly meaningful in this context. For this metric, the ranges in Kouchi et al. (2017) were used as comparison, whereas for *PBIAS* and *r* the ranges given by Moriasi et al. (2015) were used as guide. The selected calibration parameters are reported with their final values and calibration ranges in Table 1.

Table 1. Selected SWAT+ calibration parameters from the sensitivity analyses with their final calibrated values and calibration ranges.

Parameter	Description	Change	Calibration range	Calibrated value
cn2.hru	Condition II Curve Number	Relative	-20% – +20%	-19.80%
epco.hru	Plant uptake compensation factor	Absolute	0 – 1.0	0.405
perco.hru	Percolation coefficient	Absolute	0.05 – 1.0	0.805
cn3_swf.hru	Soil water factor for CN3	Absolute	0 – 1.0	0.855
revap_min.aqu	Threshold depth from surface to water table for revap to occur	Absolute	0 – 10	8.95
bd.sol	Moist bulk density of the soil layer	Relative	-30% – +30%	9.30%

lat_orgp.hru	Organic phosphorus concentration in lateral flow	Absolute	0 – 200	31.0
surlag.hru	Surface runoff lag coefficient	Absolute	0 – 5	4.275
psp.bsn	Phosphorus availability index	Absolute	0.01 – 0.7	0.496

2.4. GOTM-WET ecological-hydrodynamic lake model

The Lake Pusiano model was implemented with the QGIS plugin version of the GOTM-WET (General Ocean Turbulence Model – Water Ecosystems Tool) model, QWET v3.4.1. GOTM-WET is a one-dimensional (1D) lake coupled ecological-hydrodynamic model (Nielsen et al., 2017, 2021; Schnedler-Meyer et al., 2022), which bridges the hydrodynamic model GOTM and the ecological model WET, in turn built over the PCLake ecological model platform (Janse and van Liere, 1995), through the FABM library (Framework for Aquatic Biogeochemical Models; Bruggeman and Bolding, 2014). The model was run over the 2009-2023 period for which limnological data were available, being initialised with the observations from the vertical profile acquired on 9th March 2009.

The hypsometric curve needed as model input was obtained from a sounding-line bathymetry of the lake taken by CNR-IRSA in 2004 with an approximately 50 m resolution. Daily cloud cover data, needed as input to the model together with the other recorded meteorological variable data series, were computed from measured shortwave radiation as in Fenocchi et al. (2017). A 0.25 m resolution was adopted for the vertical layers in GOTM-WET, resulting in 100 layers for the 25 m-deep Lake Pusiano water column. In addition to meteorological forcing, the model was driven by the overall 2009-2023 daily discharges and nutrient loads delivered to the lake from its entire watershed obtained from SWAT+. Due to the multiple input sources and the shallow depth of Lake Pusiano in the Lambro River mouth area, external discharge and nutrient load inputs were set at the surface, as they plausibly occur in the mixed layer under most conditions in the real world. A fixed lake level was assumed, with daily outflowing discharge equal to the inflowing one, plus an additional contribution automatically computed by GOTM-WET to balance evaporation (Fenocchi et al., 2025).

TP and *TN* loads were calculated in GOTM-WET assuming a fixed ratio of $P\text{-}PO_4$ and $N\text{-}NO_3$ to *TP* and *TN* respectively, based on an own analysis of observed data series on the inflowing Lambro River. The $P\text{-}PO_4$ load modelled with SWAT+ was assumed as 70% of the overall *TP* load, the remnant part being organic phosphorus (*OP*). *TN* was partitioned as 70% of modelled $N\text{-}NO_3$, 5% of $N\text{-}NH_4$ and 25% of organic nitrogen (*ON*). An NPD (Nutrients – Phytoplankton – Detritus) scheme was adopted for the WET biogeochemical module, including *DO*, carbon (*C*), *N* and *P* cycles, with a single phytoplankton group.

GOTM-WET calibration was performed with the built-in ParSAC (Parallel Sensitivity Analysis and Calibration; Bruggeman and Bolding, 2020) v0.5.7 automatic calibration package, which maximises the log-likelihood of the variable set using a Differential Evolution (DE) method (Olsson et al., 2024). A bottom-up sequential calibration of the physical, *DO* and *C*, *N*, *P* and phytoplankton parameters was performed, taking the list of calibration parameters for the water column and sediment layer from

Regev et al. (2023). Multiple ParSAC optimisation runs with 5000 realisations each were performed for each calibration step to identify the optimal range of each parameter. Observations from the whole simulated 2009-2023 period were employed for GOTM-WET model calibration, as this lake model was not addressed at prognostic use, but simply at describing the past study period. The obtained r and Mean Absolute Error (MAE) metrics are here reported for the model variables. The GOTM-WET input files of the final calibrated Lake Pusiano model, including parameter values, are included as Supplementary Information together with the final ParSAC input files, including selected calibration ranges for each parameter.

Internal loading across the reproduced 2009-2023 period was evaluated with the calibrated GOTM-WET model. This methodology has the potential to be more robust than previous indirect methods based on fixed, pre-determined anoxic volumes, stratification periods and release rates (Nürnberg, 2009). As an example, these indirect methods do not consider the minimal release which occurs even during the winter period under oxic conditions and cannot consider the continuous evolution of stratification and oxygenation conditions across different years. To compute internal loading through GOTM-WET, the released daily $P\text{-}PO_4$ mass fluxes per unit sediment area simulated for each vertical layer were multiplied by the lake bottom area for the depth interval specific of each layer, obtained from the hypsometric curve. Individual mass fluxes were then added up to compute the total daily internal loads, which were then aggregated on an annual basis and compared with the corresponding $P\text{-}PO_4$ external loads given by SWAT+.

2.5. External nutrient-load reduction scenario

An external nutrient-load reduction scenario for both P (TP) and N (TN) was developed and run with both SWAT+ and GOTM-WET calibrated models. To obtain external nutrient load reductions consistent with the Lake Pusiano watershed environment and its land uses, filter strip NBS were applied to urban and agricultural areas in the SWAT+ model of the catchment. A value of 5 was adopted for the DAFS (Drainage Area Filter Strip) ratio parameter (White et al., 2009; Bai et al., 2016), having been determined to yield best nutrient removal efficiencies through preliminary simulations. This allowed evaluating the effect of this NBS on the P and N external loads reproduced by the eco-hydrological model. The scenario was run over the same 2004-2023 period used for SWAT+ calibration and validation. The resulting reduced load series were then fed into the GOTM-WET lake model, evaluating the effects of this realistic external load reduction countermeasure on Lake Pusiano.

The Lombardy Region water protection plan currently prescribes for Lake Pusiano a volume-weighted TP concentration at spring mixing of 30 μg/L for the achievement of the “good” status according to the EU WFD. To assess the effectivity of the considered NBS for the lake, also in relation to the above-mentioned target, volume-weighted *TP* concentrations at spring mixing were computed from GOTM-WET model results for both the baseline and the external-reduction scenarios across the simulated period. Annual spring-mixing conditions in the model and in the observations were determined as in Fenocchi et al. (2025), whereas the relative *TP* concentrations were computed by volume weighting according to the lake hypsometric curve, considering all model layers for the simulations and the available discrete samples with their volume of pertinence for the observations.

3. RESULTS AND DISCUSSION

3.1. SWAT+ eco-hydrological catchment model

The calibration results show that both discharges and nutrient loads (Figure 2) have been satisfactorily reproduced at a monthly scale. For discharges, peculiarly high *KGE* values were obtained in both calibration and validation phases (Table 2) according to the evaluation thresholds given in Kouchi et al. (2017). The occurrence of multiple years with lower-than-average annual precipitation and especially the extended drought period 2021-2023 negatively affects indices such as *PBIAS* in the 2014-2023 validation phase, leading to a negative value implying an overestimation. This is ascribed mainly to the drought period, during which soil moisture and evapotranspiration conditions are likely to have changed compared to those described by the model parameters found through the calibration over 2004-2013. These different conditions led in the real world to a reduction in surface runoff for the same amount of precipitation, the predicted excess surface flow actually infiltrating into the soil or evaporating more extensively.

Good results according to Kouchi et al. (2017) were also obtained in terms of *KGE* for $N\text{-}NO_3$ and $P\text{-}PO_4$ nutrient loads (Table 2), proving that SWAT+ can modulate nutrient washout with rainfall and stocking into the soil during dry periods. The *PBIAS* for $P\text{-}PO_4$ is closer to zero during calibration (2014-2023) compared to validation (2009-2013). In the validation phase, the consistent positive values of PBIAS indicate an underestimation of nutrient loads, which can be related to the reduction of rainfall after 2014, peaking with the 2021-2023 drought, determining different nutrient release rates and relationships between nutrient loads and flowrate between the calibration and validation periods. Specifically, it is likely that the parameter set determined during the drier calibration period implied a more consistent nutrient pileup, while during the wetter validation period they were more easily washed out. By choosing reversed calibration and validation periods between the discharge and nutrient loads, we aimed at counterbalancing the major overestimation of external loads for *P*, which is the limiting nutrient for Lake Pusiano, that would have resulted in the later drier period from setting up model parameters for both discharges and nutrient loads over the earlier wetter one. This reduced the bias transferred from the catchment model to the ensuing lake one. For $N\text{-}NO_3$, we observe a *PBIAS* reversal between the calibration and validation phases, a negative value being attained in the 2014-2023 calibration and a positive one with a comparable absolute value in the 2009-2013 validation. As a matter of fact, $N\text{-}NO_3$ loads significantly depend on the atmospheric deposition process, which was included in this SWAT+ model, and hence echo the rainfall-runoff phenomena and their modelling flaws.

Overall, the nutrient loads obtained from SWAT+ reflect the runoff from the watershed and the different nutrient sources according to the soil uses. However, the modelled loads do not fully consider the complex dynamics of the CSOs present inside the basin (Salerno et al., 2014; Viviano et al., 2014), their contribution in terms of nutrient loads being parameterised in SWAT+ according to the averaged behaviour from Tasker and Driver (1988). Through the SWAT+ ordinary modelling approach, urban point loads are largely assumed as diffused loads on the soil, as the sewer network is not explicitly modelled. These simplifications in nutrient loading from urban areas, however, have their maximum impact over the time scales of a single rain event, i.e. some hours, and have a much smaller influence over the monthly to annual scales considered in nutrient budgeting. The influence of such representation is furthermore relevant at the local scale, differences being smoothed out at the overall watershed one.

Table 2. Performance at monthly scale of the SWAT+-simulated discharge Q and $N\text{-}NO_3$ and $P\text{-}PO_4$ loads at Caslino d'Erba during the calibration and validation periods.

Variable	***KGE***		***PBIAS***		***r***	
	Calibration	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**
Q	0.78	0.80	2.9%	-13.3%	0.85	0.86
$N\text{-}NO_3$ load	0.66	0.50	-21.0%	23.4%	0.74	0.69
$P\text{-}PO_4$ load	0.92	0.79	3.3%	17.3%	0.93	0.89

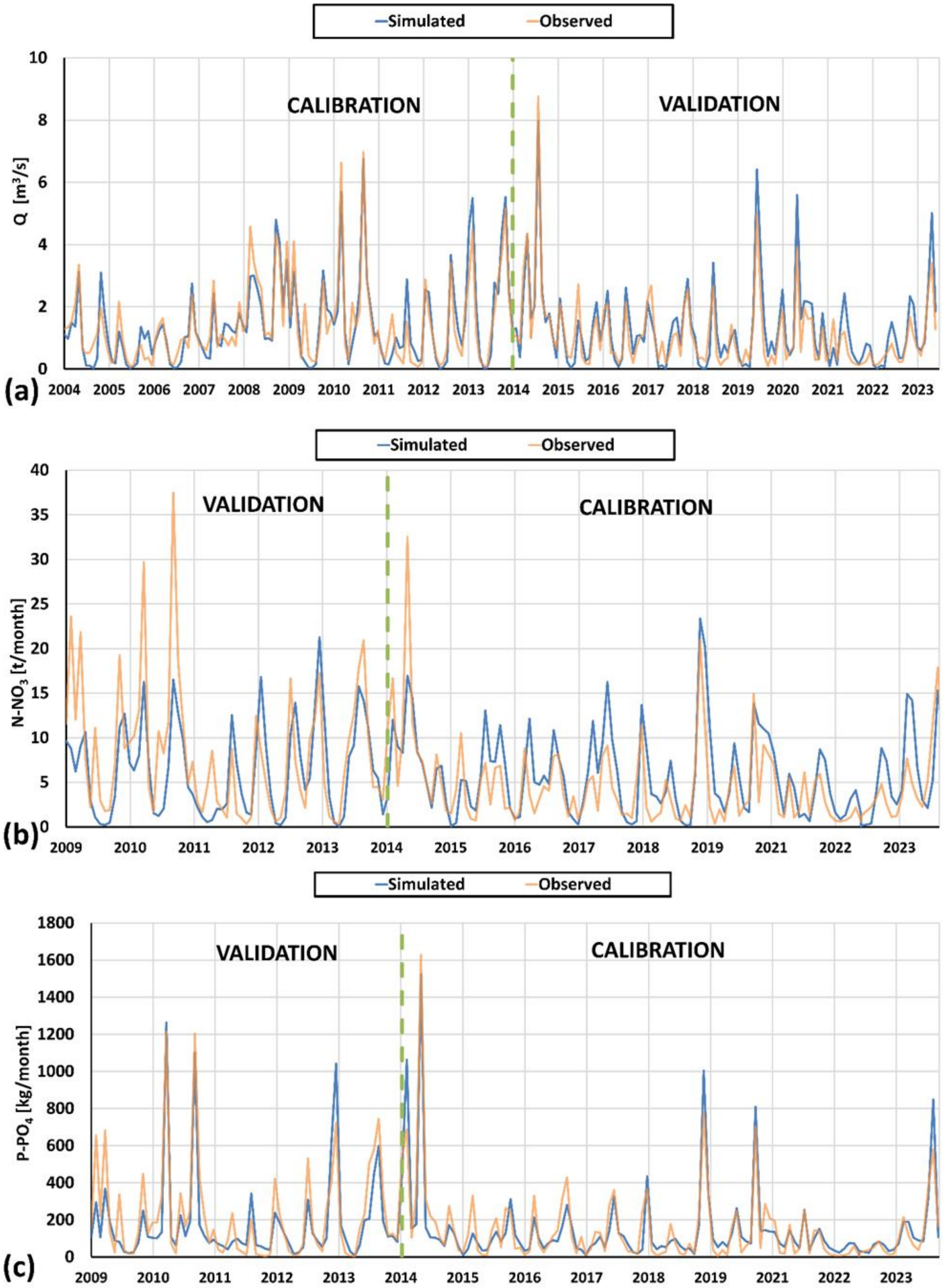
Simulated
Observed
Q [m³/s]
0
2
4
6
8
10
CALIBRATION
VALIDATION
(a)
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Simulated
Observed
N-NO3 [t/month]
0
5
10
15
20
25
30
35
40
VALIDATION
CALIBRATION
(b)
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2021
2022
2023
Simulated
Observed
P-PO4 [kg/month]
0
200
400
600
800
1000
1200
1400
1600
1800
VALIDATION
CALIBRATION
(c)
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2021
2022
2023

Figure 2. Observed and SWAT+-simulated series of mean monthly discharge *Q* (a) and of total monthly *N-NO₃* (b) and *P-PO₄* (c) loads at Caslino d'Erba (calibration and validation phases are separated by the vertical green dashed line).

3.2. GOTM-WET ecological-hydrodynamic lake model

Table 3 displays the results of the calibration of the GOTM-WET model of Lake Pusiano over the 2009-2023 simulated period. Model results are variously presented there over the 0-3 m epilimnion, in the 22-25 m deep hypolimnion and over the whole 0-25 m water column, according to the specific relevance of each variable in the framework of the study.

Table 3. Performance of the calibrated GOTM-WET model for T_w, *DO*, $N\text{-}NO_3$ and $P\text{-}PO_4$ concentrations in the 0-3 m epilimnion, in the 22-25 m deep hypolimnion and over the whole 0-25 m water column.

Variable	*r*	*MAE*
T_w (0-3 m)	0.99	0.93 °C
T_w (22-25 m)	0.65	0.62 °C
T_w (0-25 m)	0.99	0.85 °C
***DO* (22-25 m)**	0.53	2.81 mg/L
***DO* (0-25 m)**	0.74	2.76 mg/L
$N\text{-}NO_3$ (0-3 m)	0.13	0.31 mg/L
$N\text{-}NO_3$ (0-25 m)	0.40	0.26 mg/L
$P\text{-}PO_4$ (22-25 m)	0.38	0.03 mg/L

Figures 3 and 4 display volume-weighted selected results of relevance for the study aims in the 0-3 m epilimnion and in the 22-25 m deep hypolimnion, respectively.

Concerning T_w, very good results are obtained in the epilimnion (Figure 3a). In the hypolimnion (Figure 4a), the interannual trend associated with the succession of colder or milder winters and summers is reproduced, even though a more mediated behaviour than the observed one is simulated at the intra-annual scale, the 1D scheme likely revealing limitations in representing the cooling during the winter mixing period for Lake Pusiano. Considering the whole water column, an overall good reproduction with $r = 0.99$ and $MAE = 0.85$ °C is obtained (Table 3), this being due to both the accurate $k\text{-}\varepsilon$ turbulence closure employed by GOTM (Burchard and Bolding, 2001) and the use of consistent meteorological data, which are furthermore tuned in the GOTM physical module calibration to optimally describe the weather in the Lake Pusiano area (Fenocchi et al., 2025).

As regards *DO*, we can state that its modelling in the hypolimnion highly depends on the representation of water mixing through the T_w simulation (Fenocchi et al., 2025). In fact, the occurrence of anoxic conditions at the bottom during the stratification period (Figure 4b) has been caught in most simulated years, but the 1D model appears to over-estimate oxygen depletion, possibly due to the inability of the 1D schematisation to capture three-dimensional wind-driven mixing phenomena, already hampering hypolimnetic T_w predictions.

Simulated $N\text{-}NO_3$ concentrations in the epilimnion layer (Figure 3b) capture well the average observed intra-annual and interannual trends in the epilimnion, especially from 2016 onwards, which corresponds to the calibration phase of nutrient loads in the SWAT+ model. This occurs because $N\text{-}NO_3$ concentrations at the lake surface strongly depend on inputs from the tributaries, also due to *N* not being the limiting nutrient. Input $N\text{-}NO_3$ loads from the watershed have been specifically modelled in SWAT+, so that the GOTM-WET results reflect the proper load modulation of the eco-hydrological model. The satisfactory reproduction of seasonal patterns in surface $N\text{-}NO_3$ concentrations further hints at an adequate simulation of uptake and nitrification/denitrification processes. The decrease in $N\text{-}NO_3$ concentrations during the prolonged drought period from 2021 to 2023 due to significant input reduction, including depositions from rainfall, is also reproduced.

The calibrated GOTM-WET model shows a slow increase in $P\text{-}PO_4$ concentrations at the lake bottom (Figure 4c). Despite the inability to capture the variability of observations, the modelled behaviour corresponds with the overall observed trend up to 2020, reflecting a gradual rise in hypolimnetic $P\text{-}PO_4$ concentrations. The model is yet then unable to reproduce the observed sharp increase in bottom $P\text{-}PO_4$ concentrations occurring from 2021 onwards. Such observed increase is likely due to the occurrence of significantly boosted sediment release phenomena triggered by the 2021-2023 drought, possibly involving littoral zones as well. As recently shown for a German shallow lake by Gonsiorczyk et al. (2024), littoral processes and lateral *TP* transport from shallow-water zones may indeed contribute significantly to lake eutrophication. Those phenomena cannot be fully modelled in the 1D model schematisation and elude the parameter set for sediment release phenomena found calibrating over the whole 2009-2023 period, of which the 2021-2023 drought represents a minor portion.

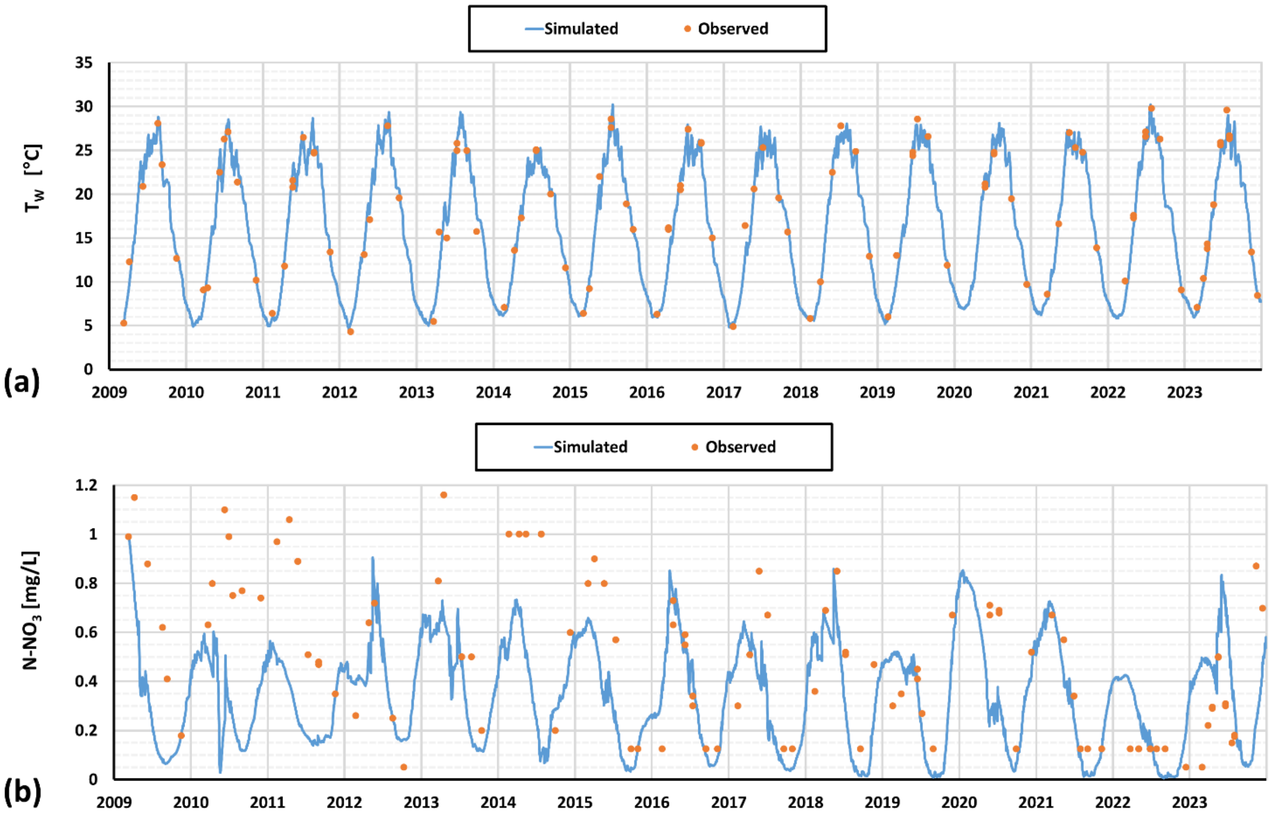

Figure 3. Observed and modelled volume-weighted T_w (a) and $N\text{-}NO_3$ concentrations (b) in the 0 – 3 m epilimnion.

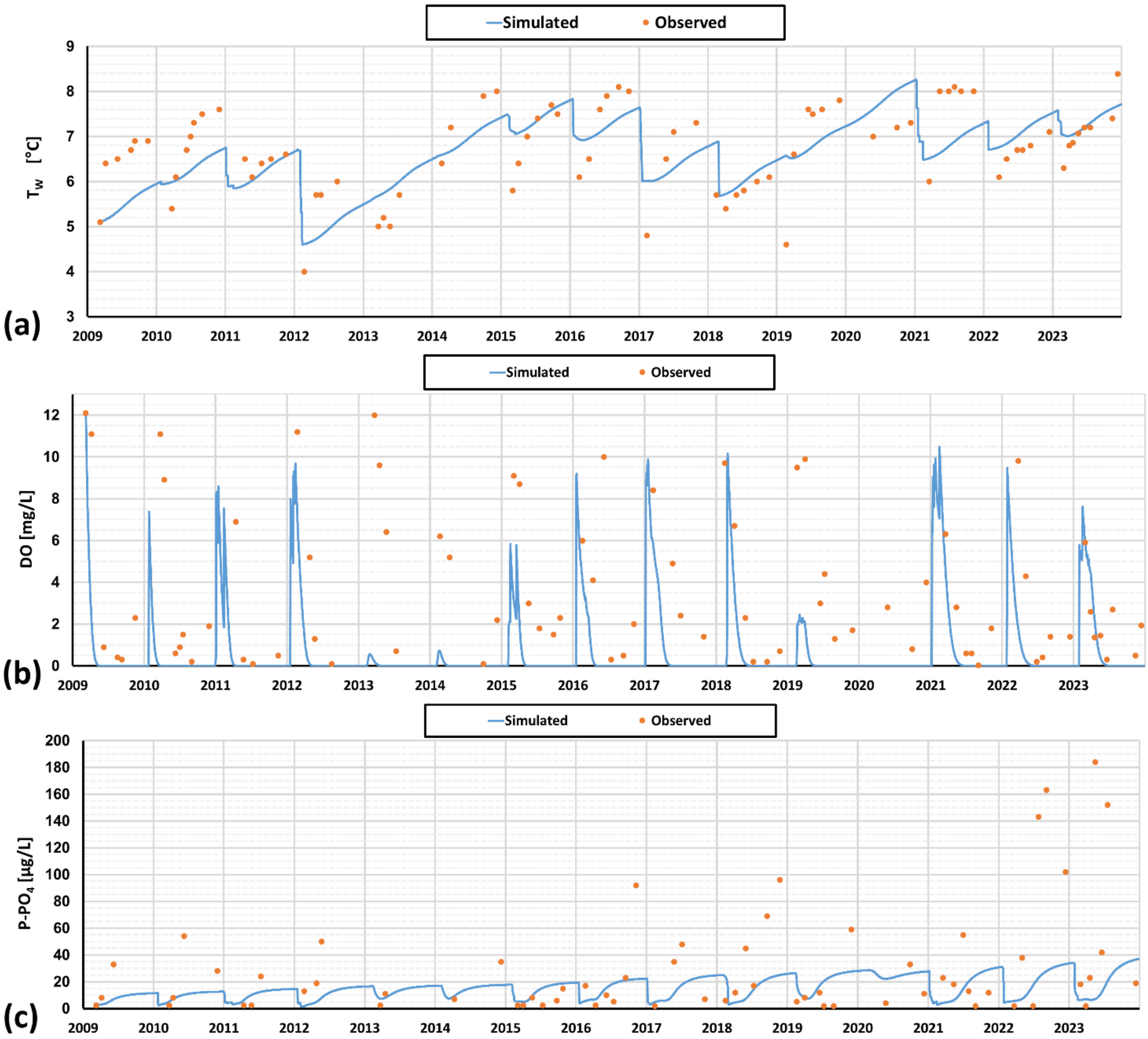

Figure 4. Observed and modelled volume-weighted *T_w* (a) and *DO* (b) and *$P\text{-}PO_4$* (c) concentrations in the 22-25 m deep hypolimnion.

3.3. Evaluation of external and internal loading

The SWAT+ model of the lake watershed estimates a relevant interannual variability of the *P* and *N* external loads (Figure 5), depending on implemented precipitation series and calibrated rainfall-runoff transformation (Figure 5a) and production and storage processes for nutrients in soils. *TP* and *TN* loads were evaluated from the $P\text{-}PO_4$ and $N\text{-}NO_3$ loads given in Figures 5b and 5c, respectively, according to the fixed ratios given in Paragraph 2.4. Average external loads of 4.47 t/a and 151.28 t/a result over the whole simulated 2004-2023 period for *TP* and *TN*, respectively. For *TP*, a maximum of 11.59 t/a was found for 2014 and a minimum of 1.56 t/a for 2022, thus revealing a variability of almost one order of magnitude with annual rainfall for the limiting nutrient between wet and dry years. For *TN*, a maximum of 256.01 t/a was found for 2008 and a minimum of 57.90 t/a for 2022, the former value being more than four times the latter one. Considering the 2009-2014 period, the simulated mean annual *TP* external load to Lake Pusiano is 6.21 t/a, which is congruent with the 6 t/a estimation given in Copetti et al. (2017) for such interval. Due to fixed parameters and soil uses, the calibrated eco-hydrological model cannot capture any improvement or worsening in nutrient pollution control, but only alterations in nutrient delivery due to rainfall variability, quantitative values being clearly subject to model process representation and calibration uncertainties. In this sense, the effect of the change in the overall rainfall regime after 2014 is well delineated, the mean annual external load of *TP* being 5.14 t/a over 2004-2014 and 3.65 t/a over 2015-2023.

As regards the 2009-2023 internal load evaluated through the GOTM-WET lake model, it must be first highlighted that: (1) lack of specific data on nutrient content in lake sediments prevented an accurate calibration of nutrient yield and release processes and a direct validation of results (Fenocchi et al., 2025); (2) the extended 2021-2023 drought triggered previously unpredictable behaviours in the last two years of the simulated period. Despite all uncertainties of the lake model, the produced estimations have the potential to be more robust than those obtainable through traditional indirect methods and furthermore, as for external loading, they allowed estimating a possible interannual variability of internal loading. The simulated internal load of $P\text{-}PO_4$ in the 2009-2014 period averages 1.38 t/a, consistent with the previous estimation around 1 t/a given in Copetti et al. (2017) for such interval through indirect measurements. Minimum and maximum values of 1.23 t/a and 1.86 t/a were reproduced for the years 2009 and 2020, respectively. The prospected dramatic rise in internal loading over 2021-2023 is not predicted by the presently calibrated GOTM-WET model, revealing that the triggering phenomena are not properly modelled therein.

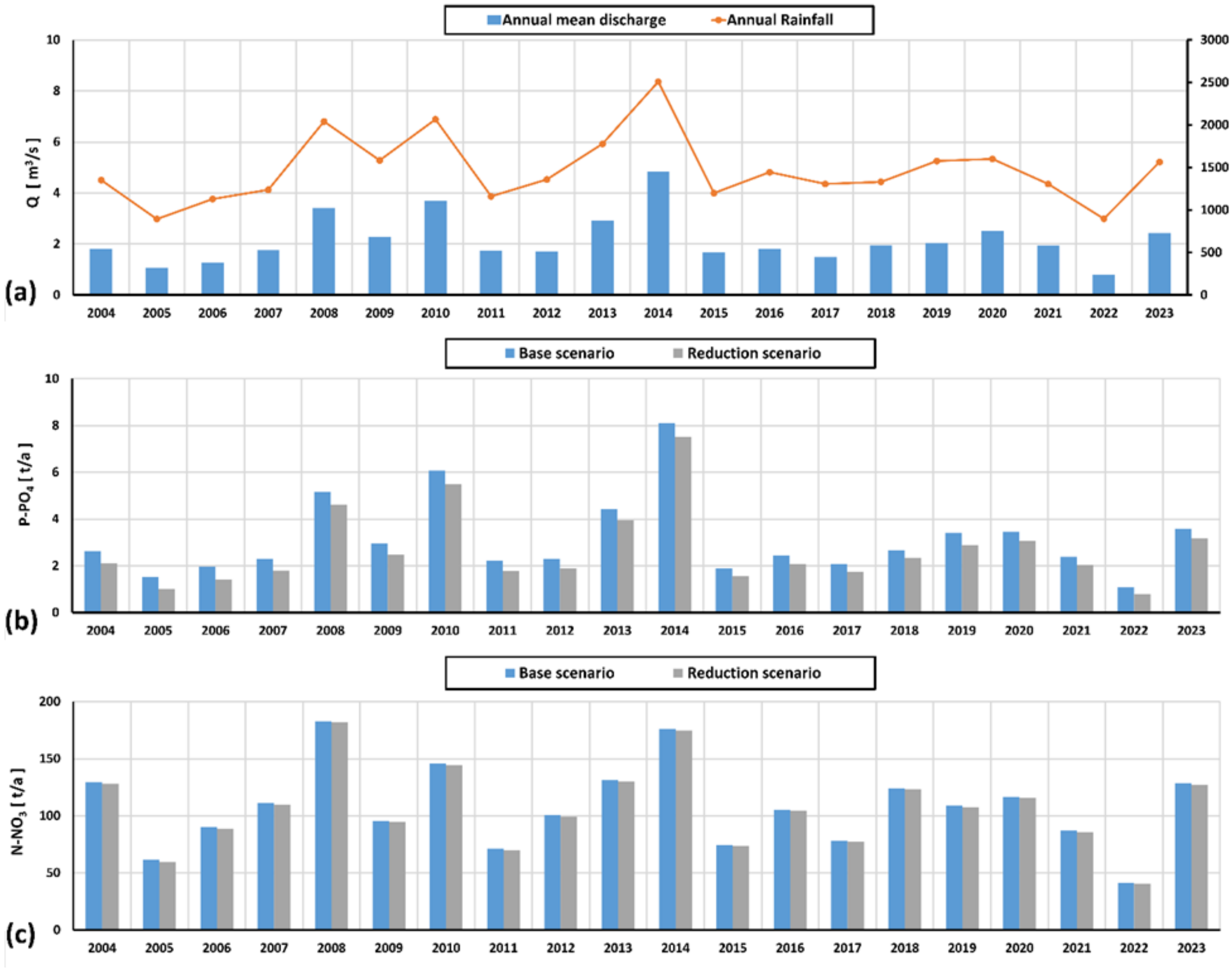

Figure 5. Results from the SWAT+ model of the Lake Pusiano catchment: (a) simulated total mean annual discharges and observed annual rainfall at Caslino d'Erba; (b) simulated total annual $P\text{-}PO_4$ loads for the actual base scenario and for the prospected nutrient reduction scenario; (c) simulated total annual $N\text{-}NO_3$ loads for the actual base scenario and for the prospected nutrient reduction scenario.

Comparing the trends of external and internal loads of $P\text{-}PO_4$ over the 2009-2023 period covered by both models (Table 4), it appears that simulated internal loading is much more stable than the external one over the years, having a coefficient of variation of 10% compared to the 54% of external loading. This is expected, considering that internal loading ordinarily evolves over longer time scales than the external one due to the long time required for the disposal of sedimented organic matter, whereas external loading largely depends on interannual rainfall variability (Viviano et al., 2014; Copetti et al., 2017; Chang et al., 2023). For internal load, simulated maximum values occur in the wettest years, when the external loading is also higher. The reason of this simulated phenomenon is likely that rainy spring periods trigger more intense primary production, which enriches sediments with nutrients through settling of organic matter. This is then mineralised and released as internal load in the same year once that anoxic conditions are established in the summer. On the opposite, during the 2021-2023 extended drought, an uprise of internal loading, though vastly inferior to the prospected one, is simulated despite very low external loads, caused by reproduced intense anoxic conditions. A significant peak of internal load is simulated in 2020, possibly due to the warm winter between 2019 and 2020, which prevented the lake from fully mixing and the hypolimnion from fully reoxygenating, as resulting from both observations and the GOTM-WET simulation (Figures 4a and 4b). The prolonged anoxic period at the bottom caused extended release from the sediments, leading to simulated higher annual cumulated internal loading.

On average, the reproduced internal load is around half of the external one in the analysed period (Table 4). There is yet a significant interannual variability of the ratio between internal and external loads, mainly depending on annual rainfall, ranging from a minimum of 19% for the wet year 2014 to a maximum of 130% for the dry year 2022. The latter value is however presumably underestimated, as further, unsimulated sediment release mechanisms would have been activated during that year. Given the reproduced peak of internal loading in 2020 and the unreproduced relevant uprise of 2021-2023, we can hypothesise that internal loading dynamics in Lake Pusiano may be affected not only by annual precipitation, but also by lake stratification dynamics, in turn influenced by air temperature. As such, they would be directly influenced by global warming in the long term.

Table 4. Comparison between the simulated internal and external *P-PO₄* annual cumulated loads in the 2009-2023 period.

Year	*Internal load [t/a]*	*External load [t/a]*	*Internal / External load ratio*
2009	1.23	2.96	41%
2010	1.36	6.06	22%
2011	1.48	2.22	67%
2012	1.29	2.30	56%
2013	1.39	4.43	31%
2014	1.55	8.11	19%
2015	1.43	1.88	76%
2016	1.44	2.44	59%
2017	1.38	2.07	67%
2018	1.24	2.67	46%
2019	1.48	3.41	43%
2020	1.86	3.46	54%
2021	1.29	2.38	54%
2022	1.44	1.09	132%
2023	1.41	3.57	39%
Minimum value	1.23 (2009)	1.09 (2022)	19% (2014)
Maximum value	1.86 (2020)	8.11 (2014)	132% (2022)
Mean value	1.42	3.27	54%
Standard deviation	0.15	1.73	26%
Coefficient of variation	10%	53%	49%

3.4. External load reduction scenario

The SWAT+ simulations implementing filter strips into the urban and agricultural areas of the catchment revealed a simulated average annual reduction of 16.0% in the external *P-PO₄* load entering the lake (Figure 5b). For *N-NO₃*, the reproduced average annual reduction is much smaller, around 1.3% (Figure 5c). The latter much lower decrease is because while the *P-PO₄* load mostly comes from urban sources and is thus sensitive to filter strip implementation in the model, the *N-NO₃* load mostly comes as an actual diffused load over the whole watershed, which is mostly forested, due to rainfall deposition.

Figure 6 then reports the volume-weighted *TP* concentrations at spring mixing for both the baseline and the external-load reduction scenarios in the 2009-2023 period from the GOTM-WET simulations. While in the first years of the simulated period the reproduced *TP* concentrations are lower than the target value of 30 µg/L under both scenarios, such threshold is always exceeded after 2013, even for the NBS scenario. Therefore, the external-load reduction attained through the simulated realistic implementation of NBS in the Pusiano watershed appears insufficient to trigger a sensible improvement of lake conditions. The simulated rise of *TP* concentrations at spring mixing follows that of bottom $P\text{-}PO_4$ concentrations (Figure 4c) and is supported by observations of years prior to the 2021-2023 drought, a rise being already evident from 2016 onwards. The reproduced volume-weighted *TP* concentrations at spring mixing are on average 10.5% lower in the nutrient reduction scenario than in the baseline one, highlighting a sublinear proportionality to nutrient load reduction. This mostly occurs because in the process schematisation present in coupled ecological-hydrodynamic models external load reduction does not directly impact *P* concentrations in lakes, but rather affects first phytoplankton biomass (Fenocchi et al., 2020; Dresti et al., 2023). In fact, the *P* concentrations which are most impacted by nutrient reduction in the simulation are those at spring mixing, primary production ordinarily being minimal during late winter. The presence of internal loading then adds up in determining such sublinear reduction in lake concentrations.

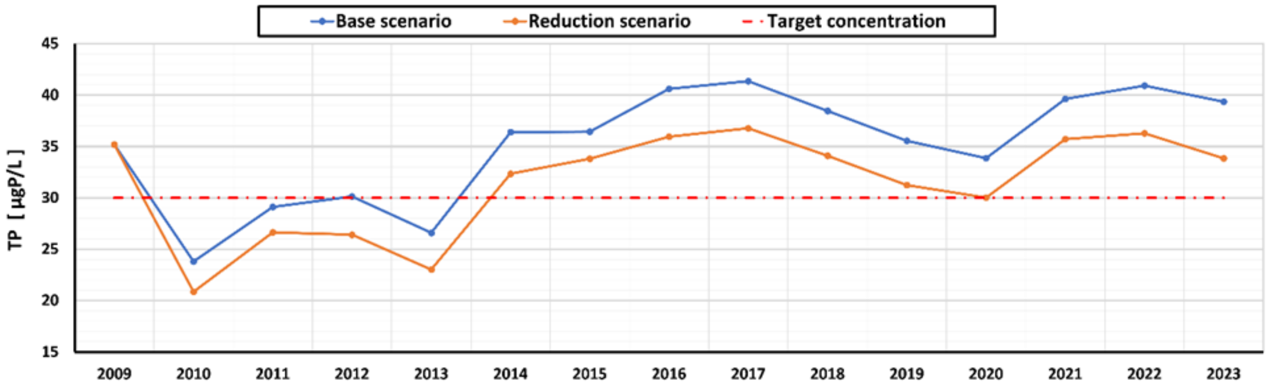

Figure 6. Comparison between baseline and external-load reduction scenarios for the simulated volume-weighted *TP* concentration at spring mixing. The target concentration of 30 µg/L given by the Lombardy Region is also displayed.

The considered NBS scenario was formulated to include a realistically implementable and economically sustainable intervention in the Pusiano catchment. This scenario results in simulated moderate reductions of *P* levels, as obtainable through such type of NBS in this watershed with minor agricultural development (Yu et al., 1993), not enough to reach and maintain the target concentration (Figure 6). Structural interventions on the sewer network would be needed to obtain a substantial improvement for the Pusiano basin, likely addressed towards improving CSO operation in urban areas

(Viviano et al. 2014). Such possibility was not explored in the present work as its process-based modelling would require a detailed reproduction of the sewer system at the catchment scale, which cannot be performed through the present model chain, as detailed in Paragraph 3.5.

A further reason behind the ineffectiveness of the implemented external load reduction scenario is that Lake Pusiano is suffering from the effects of global warming, which is strongly connected to the simulated and observed rise in *TP* concentrations at spring mixing. Lake bottom temperatures are indeed increasing, with strengthening and extending stratification. Simulations and field data have also proven that in some recent years complete oxygenation of the bottom layers has not occurred in spring due to incomplete mixing. These prolonged and more severe periods of anoxia would lead to an increased $P\text{-}PO_4$ release from the sediments. The GOTM-WET model reproduced that the depth below which hypoxic conditions with $DO < 4$ mg/l occur during the stratified season dropped from 16 m in 2009 to 10 m in 2023, thus favouring *P* release in the hypolimnion over a larger lake sediment area. The decrease in bottom *DO* concentrations is confirmed by observations (Figure 4b), which show a decline, especially in recent years.

Furthermore, the implemented reduction of external loading does not likely have a substantial impact on the internal load. In some years, a very low reduction of internal load is reproduced by the model, whereas in other years an increased load is observed. Within the simplified schematisation given by the model partial differential equations, this last occurrence could be due to the reduction in primary production having a negative impact on the overall lake oxygenation due to reduced photosynthesis. This could slightly increase internal loading for the moderate depths of Lake Pusiano. To achieve a consistent reduction in the internal *P* load, interventions aimed at reducing the external load should be carried out over longer time periods; decades being indeed ordinarily needed to successfully deplete the internal load of eutrophied lakes (Nürnberg, 2009).

3.5. Considerations on the present status of Lake Pusiano

The results of the SWAT+ – GOTM-WET model chain state that the external load to Lake Pusiano is likely still too high, especially considering the climate warming context, which has been demonstrated to mimic or intensify the effects of eutrophication (Scheffer et al., 2001; Peeters et al., 2007; Jöhnk et al., 2008). In the subalpine area of Northern Italy, where climate warming is significantly more intense than the global average (Dokulil et al., 2010), deep lakes have been proved to be remarkably affected by climate change, in some cases combined with still too high catchment loads (Lepori & Roberts, 2015; Rogora et al., 2021; Dresti et al., 2023).

The sewage collection measures carried out in the Lake Pusiano watershed over the years have certainly improved the situation, yet the main problem remains the presence of manifold CSOs, which are activated during rainfall but sometimes also under dry weather conditions due to imperfect functioning (Salerno et al., 2014; Viviano et al., 2014). The nutrient pollution from the CSOs is inherent to heavily urbanised watersheds such as the Pusiano catchment in its terminal lowland region around the lake, which receives on the other hand limited nutrient load from agriculture and livestock. According to the most recent estimates, the CSOs in the Pusiano watershed are around 60, i.e. 0.85 per km^2 (Viviano et al., 2014). Another issue is the presence of highly urbanised runoff areas in the immediate proximity of the lake, which can be the source of diffuse loads not intercepted by the sewer network.

Studying and assessing the impact of CSOs on external loads would require an extended sampling and analytical campaign at the sub-daily scale. For the eco-hydrological model, a sub-daily reproduction of loads would be needed, something which cannot be presently done through SWAT+, including detailed modelling of both the sewer and river networks. This could be achieved adding to the model chain further software such as the well-known EPA-SWMM (Environmental Protection Agency – Storm Water Management Model; Rossman, 2017) for the sewer network and HEC-RAS (Hydrologic Engineering Center – River Analysis System; Brunner, 2024) for the river network. This approach is however hardly viable, especially considering the required set of data. Nevertheless, through the implemented SWAT+ model, we have obtained a reliable assessment of the annual external load and of its variability, which was before undisclosed.

External nutrient load variability due to rainfall must be considered when making evaluations of lake water quality, as done in the present study. Variations in lake water quality and ecological status due to alternating wet and dry years are often misattributed, especially by institutions in charge of water resources management, to successes or failures in nutrient pollution control. As an example, during the hot 2022 summer within the 2021-2023 extended drought, clear water conditions were observed in some lakes in Northern Italy due to limited external loading, slightly reducing primary production (ARPA Lombardia, *pers. comm.*). This was however a transient condition, as heavy rainfall occurred in 2023 and especially 2024, delivering a huge amount of nutrients stocked in the soil, fostering primary production. In Lake Pusiano, the extended drought is speculated to have caused increased water residence times and thus to have strengthened anoxic conditions in littoral areas, contributing to boosted internal loading of $P\text{-}PO_4$, bottom $N\text{-}NH_4$ accumulation and lake productivity enhancement. So, what apparently looked like an improvement in lake water quality turned out eventually into an enduring worsening, high productivity being sustained by the ensuing intense rainfall events of 2023-2024, triggering significant external loading from the catchment. The extended 2021-2023 drought may be attributed to increased climate variability brought about by climate change (Golosov et al., 2012). Lakes of moderate depths such as Lake Pusiano are greatly affected by interannual meteorological variability, whose intensification with climate change may pose new, previously unpredictable, problems for lake nutrient load management.

4. CONCLUSIONS

The main aims of this work were to evaluate the present external and internal nutrient loads to Lake Pusiano and pre-eminently to estimate their interannual variability with rainfall. This set of information is necessary to assess the effectiveness of past interventions and to evaluate the combined impacts of climate change and pollution in relation to the targets set by protection plans.

To achieve this aim, a SWAT+ eco-hydrological model of the watershed was developed, indicating a variation of almost one order of magnitude for annual *TP* loads between wet and dry years. The obtained nutrient load series were then used as input for a coupled ecological-hydrodynamic 1D GOTM-WET model of Lake Pusiano. This model reproduced an increase in volume-weighted *TP* concentrations in the water column at spring mixing in the last decade, exceeding the value of 30 μg/L prescribed by the regional water protection plan. Amidst all modelling uncertainties, the model results match fairly well the observations up to recent years. The simulation of external load reduction through filter-strip NBS in urban and agricultural areas did not result in significant reductions of simulated lake *TP* concentrations, more extensive interventions being needed to obtain a sensible improvement, likely involving CSO operation improvement.

The recent sharp increase in *TP* concentrations, especially at the lake bottom, observed during and after the 2021-2023 drought was not reproduced by the present GOTM-WET model. Having proved that external loading is unlikely to have risen recently, this lake productivity increase could then be attributed to an upsurge in *P* release from sediments due to phenomena triggered by the extended drought, not properly reproduced by the lake model.

The herein-presented coupled catchment-lake approach could serve as inspiration for applications to other lakes and their watersheds, to estimate external and internal nutrient loads considering interannual precipitation variability. This study could also foster decision-makers to apply a more targeted management of water resources from a quantitative point of view. The potential of this methodology is that, in the end, it allowed providing a reliable value of the external loads to the lake from the catchment with the low-frequency data available for tributaries from ordinary institutional monitoring activities. The lake model has further allowed to estimate internal loading, that otherwise would have had to be evaluated through more approximated methods based on indirect experimental data.

Data Availability Statement

The datasets analysed and generated in this study are available from the Corresponding Author upon reasonable request.

Funding Declaration

The Authors declare they have no competing interests of any sort.

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4.3 Results of the SWAT-WET model

This paper enabled the acquisition of several useful insights, particularly regarding the lake changes in recent years. First, the modeling with a variable nutrient load through a watershed-lake revealed stronger correlations between modelled and observed in-lake nutrient concentrations, especially for those at the surface, which are best correlated with external loading. Additionally, when comparing the mean annual external loads estimated in this study with those assessed by Copetti et al., 2017, the SWAT+ model produced highly consistent results.

The SWAT+ model clearly highlighted the nutrient load variability between drought and rainy years, and confirmed that the external load could not have increased during the 2021-2023 extended drought, as was also proven by the concurrent field monitoring activities. Therefore, the lake water quality deterioration could not be attributed to external causes, but was rather due to internal loading. In the end, this approach proved highly effective, as the combined use of LOADEST and SWAT+ allowed for the estimation of nutrient loads from the catchment in a condition with severely limited data, while still maintaining a good level of accuracy. This methodology could be applied to other contexts where nutrient input data are scarce, yet reliable estimates are needed to direct lake management activities.

5. Scientific Paper

5.1 Introduction

This chapter reports the third journal paper work of this Ph.D. thesis, entitled *"The recent trophic decline of Lake Pusiano (Northern Italy) assessed by integrated lake-catchment modelling"*, currently under review in the journal *Aquatic Sciences*.

This work focuses on the investigation performed to understand the causes behind the deterioration of the trophic status of Lake Pusiano during 2022–2024, i.e. during and after the extended 2021-2023 drought that affected Northern Italy. Following the modeling with SWAT+, it became evident that the magnitude of the external nutrient load was consistent with the lake model results at the surface. However, a key issue emerged: during the drought, the model was unable to accurately simulate bottom-layer dynamics during the stratified period, in which the epilimnion and the hypolimnion are essentially separated. Considering that the lake model was mostly calibrated to reproduce the lake behaviour in the previous years, this was interpreted as a sign that a regime shift in the bottom dynamics of Lake Pusiano occurred during the 2021–2023 drought.

The first goal of this study was therefore to improve the lake model for the specific 2022-2024 period, to formulate coherent hypotheses on the cause-effect dynamics leading to this decline. The research integrated information from previous modeling efforts and from monitoring data, which by this point covered two full years of sampling and could be used in the WET model calibration. The modeling and monitoring activities on the catchment confirmed that the external load had not increased, indicating that the lake trophic deterioration could not be attributed to external inputs. A decrease in nutrient concentrations at the lake surface was observed during the drought period, corresponding to reduced precipitation. The focus then shifted to internal causes, with internal loading emerging as the main suspect. *TP* concentrations at the lake bottom, obtained by ARPA Lombardia and CNR-IRSA samples, showed a significant increase in the 2022–2024 period. In particular, late-summer *TP* concentrations reached 442 µg/L in october 2024.

From a modeling perspective, the focus shifted to simulating the 2022–2024 period, as the lake physical and chemical conditions during this time were well known. Moreover, the availability of a solid, estimated external loads allowed for better correlations between external load and in-lake concentrations of various nutrients. The models also captured the climatic conditions of the period effectively, with data on precipitation, temperature, and other meteorological variables integrated into SWAT+ and WET models. The idea was then to calibrate the lake model on the observations obtained in such period alone, leveraging on the fact that such calibration forces lake parameters to holistically reproduce the dynamics characterizing this period. From the obtained parameters and the collateral results they yield, such as internal-loading reproduction, one could then formulate hypotheses on the reasons behind the trophic decline of Lake Pusiano. Although not flawless, this approach is likely one of the best options in absence of continuous monitoring data to understand in retrospect what happened.

In addition to the previously discussed models, this article employed the Delft3D D-Flow (Lesser et al., 2004) three-dimensional (3D) hydrodynamic model to assess the fate of the Lambro inflow inside the lake under different flow rates. Lake Pusiano has a unique feature: its main inflow is located close to its outflow, which is regulated by the Diotti Dam. During low-flow conditions, such as those in the hot summer of 2022, a short-circuit phenomenon may have occurred, where the close-to-null inflow discharges may have water exited the lake immediately without circulating inside the lake main basin. In such conditions, the lake residence time may have increased by a huge amount, promoting nutrient recycling and oxygen depletion.

In summary, three different complementary models were employed to analyze all potential causes behind the trophic deterioration occurred in recent years in Lake Pusiano and understand the cause-effect chain, i.e. SWAT+, WET and Delft3D D-Flow, considering both hydrodynamic and biogeochemical aspects.

5.2 Paper -The recent trophic decline of Lake Pusiano (Northern Italy) assessed by integrated lake-catchment modelling

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CRediT authorship contribution statement

Conceptualisation: Nicolò Pella, Andrea Fenocchi; Methodology: Nicolò Pella; Andrea Fenocchi; Software: Nicolò Pella, Andrea Fenocchi; Validation: Diego Copetti, Michela Rogora, Fabio Buzzi; Formal analysis: Nicolò Pella; Investigation: Nicolò Pella, Andrea Fenocchi; Resources: Nicolò Pella, Diego Copetti, Paolo Dezuanni, Lucia Valsecchi, Fabio Buzzi; Data curation: Diego Copetti, Michela Rogora, Lucia Valsecchi; Fabio Buzzi; Writing – Original draft: Nicolò Pella, Andrea Fenocchi; Writing - review and editing: Nicolò Pella, Diego Copetti, Claudia Dresti, Michela Rogora, Paolo Dezuanni, Fabio Buzzi, Andrea Fenocchi; Visualisation: Nicolò Pella; Supervision: Andrea Fenocchi; Project administration: Claudia Dresti; Funding acquisition: Diego Copetti, Claudia Dresti, Andrea Fenocchi

Abstract

Climate change is altering the equilibrium of lake ecosystems, not only through steady water warming, but also with increasing occurrence, duration and intensity of droughts and heatwaves. These events, especially if concurrent, have relevant effects on shallow lakes, triggering severe stratification periods that lead to acute bottom anoxia. Such conditions trigger the release of phosphorus and toxic ammonium and hydrogen sulphide from sediments. Moreover, the anoxic volume in the hypolimnion can extend beyond the central basin towards littoral areas, increasing the bottom surface contributing to the release and hence internal nutrient loading. This promotes cyanobacterial blooms that persist throughout the year, sustained by warmer winters brought by climate warming. Such phenomena have been observed in Lake Pusiano (Northern Italy), where a prolonged drought between 2021 and 2023 led to a marked decline in water quality, increased phosphorus release from the sediments, and extensive cyanobacterial blooms. To better understand these dynamics, a modelling approach was applied using three complementary numerical models: (1) a SWAT+ eco-hydrological model of the lake watershed was employed to estimate external loading; (2) a one-dimensional coupled ecological-hydrodynamic WET model of the lake was used to quantify internal loading; (3) a three-dimensional Delft3D D-Flow lake hydrodynamic model was implemented to evaluate the role of the main tributary in mixing dynamics. Model results confirm that the prolonged drought and summer heatwave conditions experienced by Lake Pusiano during 2021-2023 are the ultimate cause of its recent trophic decline, having triggered an enduring regime-shift in lake productivity.

Keywords

Drought; Internal load; Climate change; SWAT+; QWET; Delft3D D-Flow

1. Introduction

Climate change impacts lakes on multiple levels. First, the increase in air temperatures directly affects lakes by altering their natural mixing regime (Woolway and Merchant, 2019). Shallow and deep dimictic lakes in colder regions would become monomictic (Ficker et al., 2017; Anderson et al., 2021), whereas shallow monomictic basins in warmer areas would transition to polymictic (Woolway et al., 2022; Robbins et al., 2025). For deep lakes in warmer areas in which mixing is already scarce, such as the Italian subalpine lakes (Ambrosetti and Barbanti, 1999; Salmaso et al., 2014; Rogora et al., 2018), the mixing regime would pass from oligomictic to meromictic, as climate warming increases the vertical temperature gradient between the epilimnion and hypolimnion (Livingstone, 2003; Fenocchi et al., 2018), with a steady decrease of the mixing depth (Fenocchi et al., 2018; Rogora et al., 2018).

Shallow basins, in addition to the long-term effects of climate warming, are much more susceptible than deep lakes to extreme weather events, such as heatwaves, droughts and storms, which are known to increase with climate change (IPCC, 2023). In fact, such episodes are likely to affect the whole water volume of shallow lakes, their low inertia further making them less resilient than deep basins to short-term events. Prolonged heatwaves during the summer season would significantly warm up the surface waters, readily determining intense stratification. The comparatively low hypolimnetic volume of shallow lakes would cause extensive depletion of dissolved oxygen (*DO*) under stratified conditions, leading to anoxic conditions bringing about significant phosphorus (*P*) release from sediments, i.e. internal loading. In case of extended stratification persisting until late autumn, as determined by climate warming (Woolway et al., 2021), combined with higher-than-usual water renewal times due to droughts, the anoxic volume could expand upwards, affecting not only the central, deepest lake areas, but also the littoral zones. This would cause a relevant increase in the bottom surface contributing to sediment release (Gonsiorczyk et al., 2024). Along with *P*, anoxic sediments would also trigger the accumulation of ammonium ($N\text{-}NH_4$) and the formation of hydrogen sulphide (H_2S), which are toxic to the biota, notably fish and benthic organisms (Beauchamp et al., 1984, Randall and Tsui, 2002). Part of these two substance masses would be released, another part remaining stocked in the sediment pores (Sakai et al., 2013), with possible mobilisation with storms in littoral areas (Luther et al., 2004).

Sampling of lake physical and biochemical parameters is traditionally carried out at the vertical of maximum depth, to gain information on the whole water column. In the European Union (EU), the Water Framework Directive (WFD, 2000/60/EC; European Commission, 2000) prescribes the deepest lake column as the sampling point for monitoring activities, due to its representativity. However, the effects of climate change force us to shift our focus to what is happening in the littoral zones as well, especially as regards lake sediments (Gonsiorczyk et al., 2024). The underlying assumption of sampling at the lake deepest point is that in lakes, the time scales of horizontal advection are substantially smaller than those of vertical transport (Perroud et al., 2009; Rinke et al., 2010; Dresti et al., 2021). This assumption is impaired when water stagnation prevents horizontal mixing, causing non-uniform nutrient concentration distributions, which can notably arise with sediment release from littoral areas. As a matter of fact, distance from the water surface, i.e. water depth, is usually assumed as the independent variable in determining the vertical profiles of lake chemical parameters. However, when processes at the sediment-water interface are involved, including *DO* and released substances, the key parameter would rather become the distance from the bottom.

As anticipated, prolonged drought periods, whose intensity and duration are expected to increase with climate change (IPCC, 2023), beside causing water scarcity problems for human activities, have devastating effects on freshwater ecosystems (Mosley, 2015; Woolway et al., 2025). As regards water quality, the halt of external nutrient load supply to lakes due to lack of rainfall could cause temporary improvements in the trophic state. For example, during the drought that affected Northern Italy between late 2021 and early 2023, an increase in lake transparency was observed in some lakes during the hot summer 2022 due to a considerable decrease in primary production (ARPA Lombardia, *personal communication*). Considering water quality parameters only, neglecting ecosystem stress conditions, the qualitative status of some lakes could even improve during drought periods, because lower external loads help meeting imposed total phosphorus (*TP*) concentrations limits at spring mixing set by authorities. This improvement, however, is only illusory, as the lake would return to the previous trophic condition once that external loading is restored. Pre-existing problems, such as the release of uncontrolled sewage discharges and the excessive activation of combined sewage overflows (CSOs) during rainfall or even dry periods due to the ageing drainage network, can be solved only through sewer-network restoration and improvement. Unfortunately, in fact, anthropogenic nutrient loads from urban areas are often still high compared to pre-industrial levels, which, combined with the effects of ongoing climate change, can lead to lakes becoming eutrophic again (Moss et al., 2011; Posch et al., 2012; Winder et al., 2012).

Furthermore, enduring droughts would trigger multiple other effects, which could potentially cause cascading processes leading to long-lasting trophic decline (Catalan et al., 2024). In this study, we deal with such issue for Lake Pusiano, a moderately deep, mid-sized lake in Northern Italy. Following major restoration measures in the basin from the mid-1980s onwards, which significantly reduced both external and internal loads (Copetti et al., 2017), the lake trophic state improved from eutrophic to mesotrophic. However, during and following the extended drought that affected the region between late 2021 and early 2023, its trophic state has started to decline. Since 2022, an exceptional increase in P concentrations in the hypolimnion has been observed, as monitored by the Regional Environmental Protection Agency of Lombardy (ARPA Lombardia) and the Water Research Institute of the National Research Council of Italy (CNR-IRSA). This led to prolonged and intense cyanobacterial blooms. Interestingly, primary production has been occurring not only in summer, but also throughout the winter months.

Another important element of extended droughts, especially for lakes with depths and size up to those of Lake Pusiano, is the associated lack of water renewal and mixing provided by tributary intrusions, leading to the increase of water residence times (Pinardi et al., 2015; Fenocchi and Sibilla, 2016). This would have happened in Lake Pusiano in 2021-2023, especially during the hot and dry summer of 2022. In this lake, the proximity of the main inflow to the outflow may, under specific flow conditions, further trigger the short-circuiting of the riverine through-flow (Råman Vinnå et al., 2017), preventing water renewal and oxygenation.

This work aims to disclose the role of all these phenomena in the recent trophic decline of Lake Pusiano. To such scope, it is necessary to: (1) quantify the external and internal nutrient loading during and after the drought period; (2) assess the influence of the lake main tributary on mixing and water renewal dynamics under different flow conditions. To achieve this, a process-based modelling approach was adopted, integrating different models considering both physical and ecological aspects. First, to study the lake water quality aspects and the evolution in time of external and internal nutrient loading, Lake Pusiano and its catchment were modelled for the study period 2022-2024 using the one-dimensional (1D) ecological-hydrodynamic lake model WET (Water Ecosystems Tool; Nielsen et al., 2017, 2021; Schnedler-Meyer et al., 2022) and the watershed eco-hydrological model SWAT+ (Soil & Water Assessment Tool; Bieger et al., 2017), respectively. Then, a three-dimensional (3D) hydrodynamic model of Lake Pusiano was implemented using Delft3D D-Flow (Lesser et al., 2004), to study water circulations and stratification conditions in summer 2022, in addition to assessing the effect of the inflow of the main tributary Lambrone stream on the mixing of Lake Pusiano. In addition to the specific case study, the results of this work shed light on cascading processes driven by climate change which can increasingly occur in similar environments, providing useful information for management authorities and stakeholders.

2. Case study

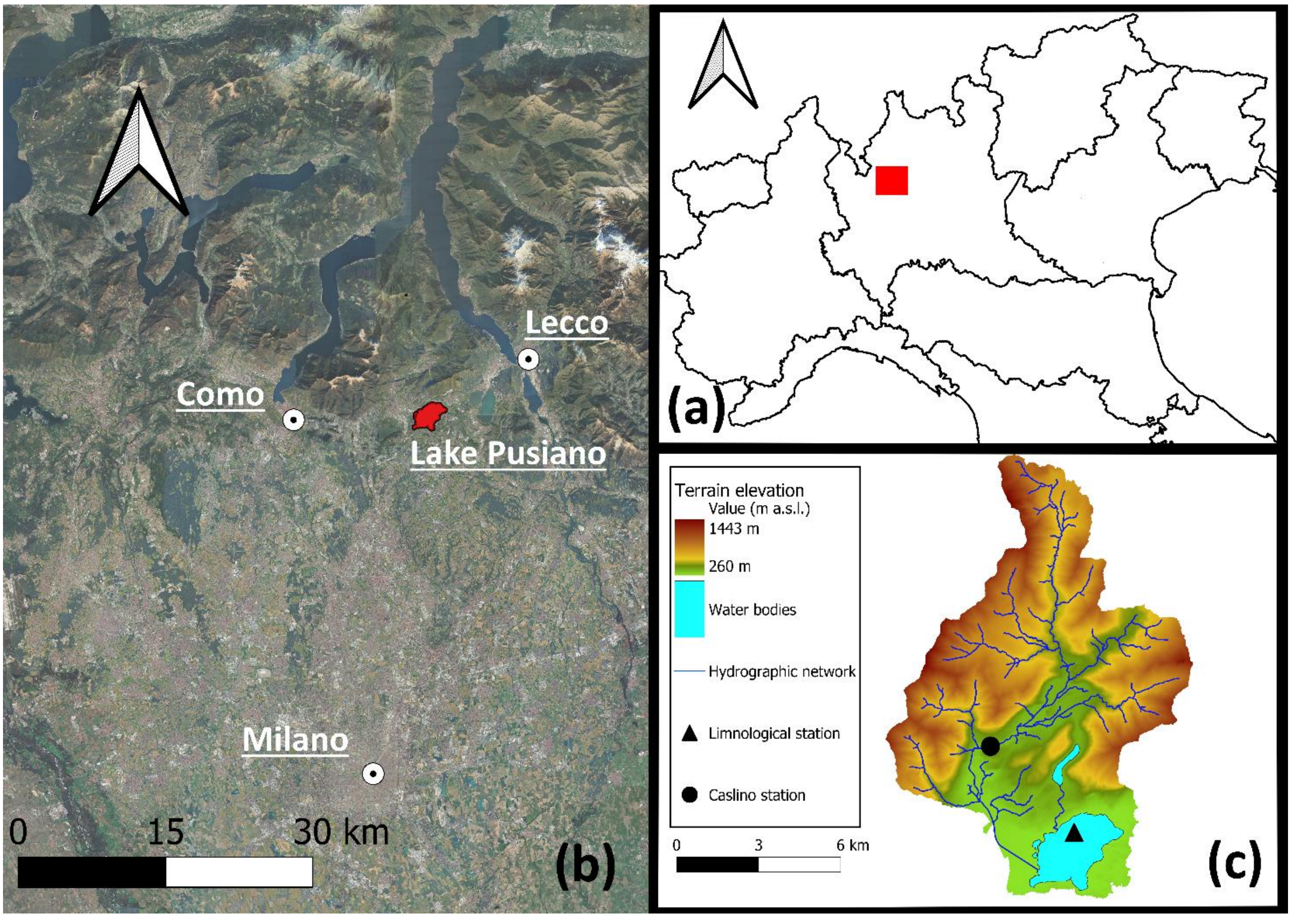

Figure 1. (a, b) Location of the study area (orthophoto courtesy of Google Satellite); (c) elevation map of the Lake Pusiano catchment and location of the Caslino d'Erba meteorological and eco-hydrological station and of the limnological sampling station.

Lake Pusiano is located in the Lombardy region, Northern Italy, between the cities of Como and Lecco and north of Milan (Figure 1). The lake is classified as warm monomictic, with a maximum depth of 25 m. The Lake Pusiano catchment (Figure 1c) covers an area of 93.2 km^2, including the 5.2 km^2 surface area of the lake. The watershed is mainly mountainous in its northern part, with a maximum elevation of 1443 m a.s.l. and flat in its southern part close to the lake, whose mean surface water elevation is 259 m a.s.l. Precipitation within the catchment varies from approximately 1500 mm/a near the lake to 2000 mm/a at highest elevations. The Pusiano catchment is mainly forested (77%), with residual urban (13.6%) and agricultural (9.4%) cover. The main source of pollution is represented by combined sewer overflows (CSOs), which are ubiquitous on the watershed (Viviano et al., 2014). Lake Pusiano has several tributaries, the most important being the Lambrone stream (Figure 2a), draining 80% of the Pusiano catchment, with an annual mean discharge of 1.43 m^3/s (Carraro et al., 2012). The lake is regulated by the Cavo Diotti Dam, which controls the outflow of the Lambro river (Figure 2a). Lake Pusiano hosts a 2.2 ha island called "Isola dei Cipressi" (Island of the Cypresses), located approximately 150 m away from the lake northern shore (Figure 2a).

Historically, Lake Pusiano experienced severe eutrophication in the 1960s – 1980s (Copetti et al., 2017). Then, interventions aiming at improving sewage collection significantly reduced *TP* loads, which was estimated to have decreased from 21 t/a in the 1980s to 6 t/a by 2014.These management actions were specifically targeted at reducing the amount of *P* in the lake, as this was identified as the primary limiting factor for its productivity (Vuillermoz et al. 2006). Internal *TP* loading was also estimated to have dropped from 3.6 t/a in 1985 to 1.0 t/a by 2010 (Copetti et al., 2017). As of today, Lake Pusiano is classified as mesotrophic, past interventions having allegedly led to stable water quality conditions. However, recent data have evidenced that *TP* concentrations have started to rise again since 2022, especially during the stratification period and during the whole 2021-2023 drought, likely due to boosted sediment release (Pella et al., *under review*). Bottom *TP* concentrations sampled at the end of the stratification period in November have increased from 30 µg/L in 2021 to 292 µg/L in 2024. Climate warming has further impacted the lake, with spring mixing temperatures rising from ~5 °C in the 1970s to ~7 °C in recent years, strengthening the warm monomictic behaviour. The rise in *TP* concentrations also led to an increase in algal blooms caused by cyanobacteria, which in recent years have not been limited to the summer period but have lasted throughout the entire year, leading to a trophic decline for Lake Pusiano. Mild winters, as a matter of fact, create favourable conditions for the occurrence of such phenomena in lakes (Wejnerowski et al., 2024), together with the cascading effects of droughts (Mosley, 2015; Woolway et al., 2025).

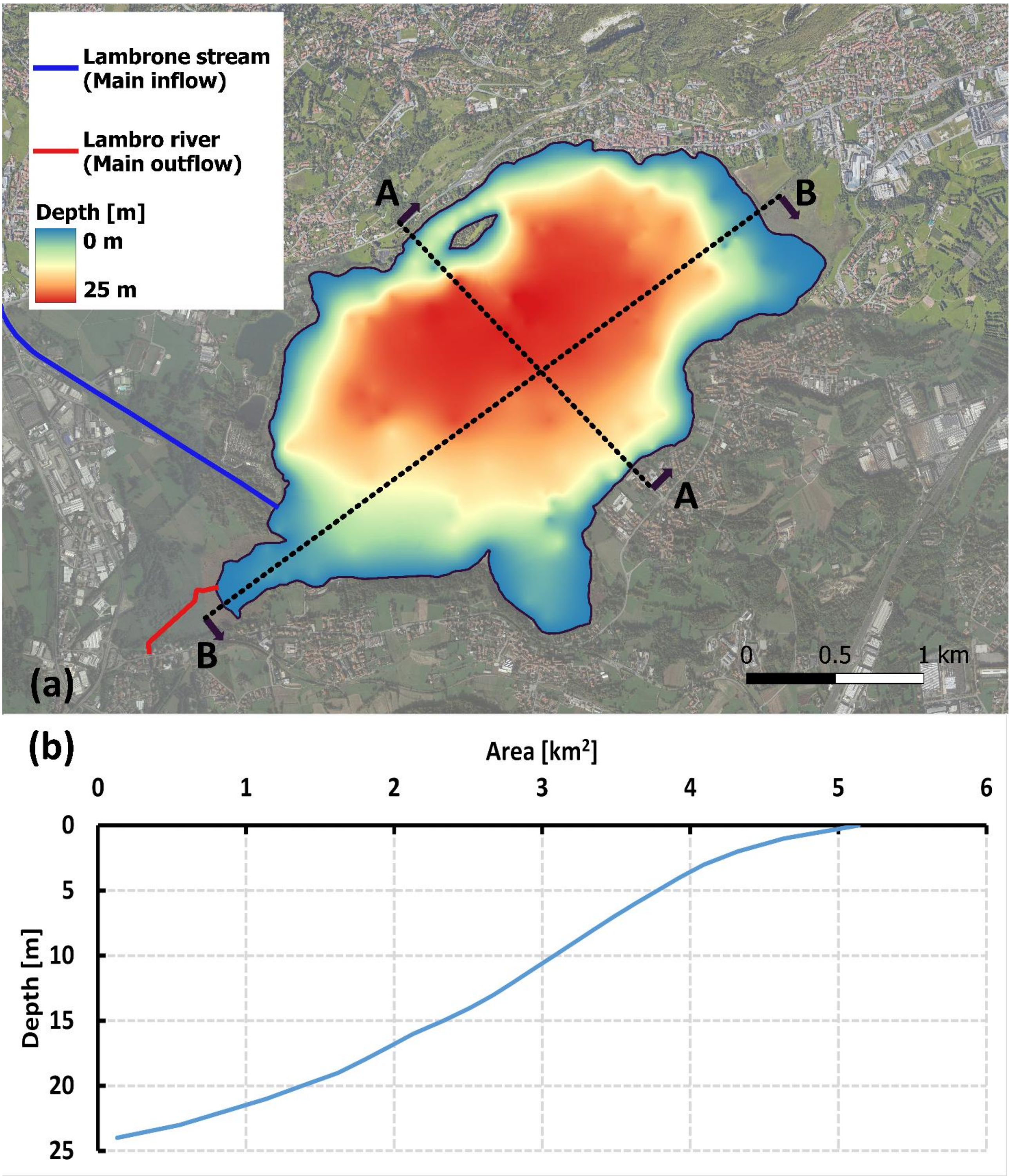

Figure 2. (a) Lake Pusiano bathymetrical map, also showcasing the main inflow (Lambrone stream), the main outflow (Lambro river) and the A and B vertical planes used for displaying the results of the 3D lake hydrodynamic model; (b) Area-Depth hypsometric curve of Lake Pusiano, obtained from the bathymetry.

3. Methods

3.1. Adopted data

The SWAT+ eco-hydrological model of the basin was fed with 2022-2024 daily meteorological data obtained from the Caslino d'Erba station run by ARPA Lombardia (Figure 1c). The model was previously calibrated and validated in Pella et al. (*under review*) using 2004-2023 daily discharges and 2009-2023 quarterly samples of $N\text{-}NO_3$ and $P\text{-}PO_4$ at Caslino d'Erba from ARPA Lombardia.

The meteorological data used as boundary conditions by the 1D WET and 3D Delft3D D-Flow models were obtained from the Lecco meteorological station (Figure 1b) run by ARPA Lombardia. The considered meteorological variables are air temperature, relative humidity, wind speed, shortwave radiation and atmospheric pressure. Cloud cover data, needed by the WET model (Fenocchi et al., 2025), were computed from measured shortwave radiation as in Fenocchi et al. (2017). The data series covers the 2022-2024 period considered in this study, without any significant gap. While mean daily data over the whole 3-year span were considered in the WET model, hourly data for the 7-day period 26th June - 3rd July 2022 week were employed for Delft3D D-Flow.

Two datasets of lake water column data were used for the calibration and validation of the WET model as well as initial conditions of the WET and Delft3D D-Flow models: 1) the one resulting from the WFD monitoring by ARPA Lombardia, which covers the 2022-2024 period with 6 samplings per year; 2) the one resulting from the monitoring activities by CNR-IRSA, with X samplings in 2023 and Y samplings in 2024. The considered limnological variables are water temperature (T_w) and concentrations of dissolved oxygen (*DO*), nitrates ($N\text{-}NO_3$), ammonium ($N\text{-}NH_4$), total nitrogen (*TN*), orthophosphate ($P\text{-}PO_4$), and total phosphorus (*TP*). T_w and *DO* profiles were obtained with a multiparameter probe (IDRONAUT Ocean Seven Plus). For nitrogen (*N*) and *P* compounds, water samples were collected at discrete depths and analysed at the ARPA Lombardia and CNR-IRSA laboratories according to standard methods for freshwater analysis (APAT-IRSA, 2003; APHA AWWA WEF, 2012).

The Lake Pusiano bathymetry implemented in the Delft3D D-Flow model (Figure 2a) and the derived hypsometric curve needed by the WET model (Figure 2b) were obtained from a sounding-line survey performed by CNR-IRSA in 2004, with an approximately 50 m resolution. For the present study, the original data was re-interpolated at 5 m resolution using the Kriging technique through GIS software.

3.2. SWAT+ model

The SWAT+ (Soil & Water Assessment Tool; Bieger et al., 2017) v2.3.3 process-based eco-hydrological model was applied to the Pusiano watershed. The herein-adopted SWAT+ implementation was introduced in Pella et al. (*under review*), having been calibrated and validated therein to reproduce inflows and external loads of *N* and *P* to Lake Pusiano over 2004-2023. The SWAT+ model was herein applied as-is, extending it over the 2024 year to cover the 2022-2024 study period of this research. As in the previous work, the SWAT+ results were used for discharge and external nutrient load assessments and for feeding the 1D WET model of Lake Pusiano, ensuring a variable input load to the lake model.

3.3. WET model

The 1D WET (Water Ecosystems Tool; Nielsen et al., 2017, 2021; Schnedler-Meyer et al., 2022) model was used to simulate the physical and biogeochemical behaviour of Lake Pusiano along the water column. The lake model was implemented using the QWET v3.4.1 QGIS plugin. The WET model couples hydrodynamic and ecological processes, using the GOTM (General Ocean Turbulence Model; Burchard and Bolding, 2001) model for the formers and the PCLake (Janse and van Liere, 1995) model for the latters. Mutual connections between the two is ensured by the FABM (Framework for Aquatic Biogeochemical Models; Bruggeman and Bolding, 2014) library.

The WET model was here applied to the 2022-2024 study period. Calibration was performed over 2022 and 2023, with 2024 serving as validation. The ecological model setup implemented in Pella et al. (*under review*) was retained, including an NPD (Nutrients – Phytoplankton – Detritus) schematisation, including the DO, carbon (C), N and P cycles, with a single phytoplankton group. The recalibration over a much shorter period with respect to the previous study was found necessary to specifically reproduce the geochemical features of the 2022-2024 period affected by the extended drought, which have led to a sharp increase in internal loading and an ensuing P accumulation in bottom waters.

The water column was divided into 100 horizontal layers, each with 0.25 m thickness. A fixed-level schematisation was assumed for the lake, with the outflowing discharge equalling the imposed inflowing one and an automatically computed residual inflow balancing evaporation (Fenocchi et al., 2025). Water and nutrient load inflows and outflows were set to occur at the lake surface. The daily external loads of $N\text{-}NH_4$, organic nitrogen (ON) and organic phosphorus (OP) were determined from the $N\text{-}NO_3$ and $P\text{-}PO_4$ ones modelled by SWAT+ using the same partitions as in Pella et al. (*under review*). The WET model was initialised with the vertical profile of the model variables measured by ARPA Lombardia on 23rd March 2022, which worked as initial day of the simulation.

WET model calibration was performed using the automated approach in the ParSAC (Parallel Sensitivity Analysis and Calibration; Bruggeman and Bolding, 2020) module of QWET, running 5000 realisations for each of the 4 sequential calibration phases. The first phase focused on hydrodynamic model parameters. This was followed by calibration of the DO cycle parameters, with two subsequent phases dedicated to N and P cycle parameters. Phytoplankton parameters were not calibrated in the present study, as this was found to have an overall detrimental effect on P and N cycle simulation which did not compensate the improvement in Chlorophyll-*a* (Chl-*a*) concentration reproduction. For the evaluation of the WET model performance over the calibration and validation periods, the Pearson correlation coefficient (r) and the Mean Absolute Error (MAE) metrics were evaluated in the 22-24 m hypolimnion layer, to specifically address bottom dynamics, and over the whole water column (0-24 m).

The assessment of lake internal loading is challenging, two approaches being possible: (1) analytical, fully parametrical methods that rely on indirect experimental measurements to quantify sediment release (Nürnberg, 2009); (2) application of coupled ecological-hydrodynamic models to directly reproduce the release phenomenon, though with a residual degree of parameterisation (Dresti et al., 2023a; Pella et al., *under review*). The second approach was followed in this study, comparing the internal $P\text{-}PO_4$ load assessed with WET with the external one determined with the SWAT+ catchment model.

3.4. Delft3D D-Flow model

In addition to the already highlighted possible short-circuiting due to the proximity of the lake main inlet and outlet, the side entrance of the Lambrone stream into Lake Pusiano, which is both located and oriented laterally (Figure 2a), does not allow a clear through-flow from the inlet to the outlet of the lake through the point of maximum depth. In the traditional theory of tributary intrusions in lakes (Fischer et al., 1979; Imberger and Patterson, 1981), leveraging on a 1D vertical schematisation, it is assumed that the intrusion of tributaries can occur at any depth depending on the density difference between the inflow and the lake water column, thus possibly helping lake mixing and water renewal throughout the water column (Dresti et al., 2023b). However, for this to hold, the lake bathymetry should straightly degrade from the tributary entrance to the point of maximum depth, so that the lake bottom does not constrain the intrusion, which is not the case of the Lambrone stream in Lake Pusiano, in which a 5 m-deep plateau is present in the inlet area (Figure 2a). A 3D hydrodynamic model is thus required to determine the fate of the tributary waters inside the lake (Råman Vinnå et al., 2017), as done in this study.

The 3D hydrodynamics of Lake Pusiano were simulated using the Delft3D D-Flow module of the Delft3D FM (Flexible Mesh) Suite 2023.02 (Lesser et al., 2004). Delft3D D-Flow solves the 3D RANS (Reynolds-Averaged Navier-Stokes) equations using the Boussinesq hydrostatic approximation. The FM version of Delft3D allows using an unstructured grid in the horizontal direction in addition to the curvilinear grid characterising the previous versions. A layer-based meshing approach is employed in the vertical direction, a *z-layer* scheme with step-like bottom and variable number of horizontal layers having been selected herein due to the strong depth heterogeneity across the lake and temperature stratification (Platzek et al., 2014). Turbulence modelling is achieved through parameterised eddy viscosity and diffusivity in the horizontal plane, a more accurate $k\text{-}\varepsilon$ closure having been here selected in the vertical direction in which modelling of stratification/mixing dynamics is critical.

The 3D hydrodynamic model of Lake Pusiano was aimed at reproducing the stratification and circulation dynamics during the dry, hot summer of 2022, gaining knowledge on the hydrodynamic conditions which likely initiated the trophic decline of Lake Pusiano. Additional understanding of the effects of different discharges of the main inflow Lambrone stream on the circulations of Lake Pusiano under strong stratification was also pursued.

The simulation reproduced a period of 7 days from 26th June 2022, when an observed vertical temperature profile taken by ARPA Lombardia was available for use as horizontally uniform initial condition, to 3rd July 2022. The observed initial profile (Figure 3) reveals an already strong stratification by mid-June, also due to the relevant positive air temperature anomaly of June 2022 (see Paragraph 4.1). In such days, the discharge of the Lambrone stream at Caslino d'Erba averaged 0.26 m^3/s, with no visible surface flow at the inlet into the lake due to stream penetration into the bottom gravel layer in the downstream reach of the tributary. However, a small hyporheic discharge would have nevertheless reached the lake, which could be estimated to be in the order of $Q_1 = 0.2$ m^3/s (Scenario S1). To further investigate the role of river-induced circulations and mixing in Lake Pusiano under strong stratification, the simulation was repeated with $Q_2 = 2$ m^3/s (Scenario S2), representative of ordinary low-flow conditions, and for $Q_3 = 10$ m^3/s (Scenario S3), hinting at high-flow conditions. For all scenarios, a temperature $T_w = 19$ °C was employed for the Lambrone stream, based on a measurement provided by ARPA Lombardia taken in the simulated days.

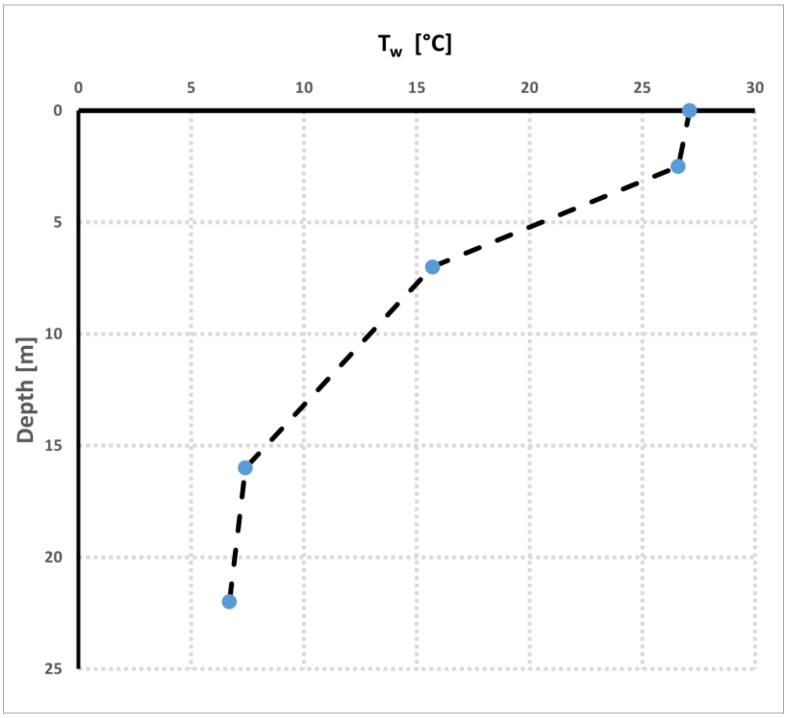

Figure 3. Observed water temperature profile obtained by ARPA Lombardia on 26th June 2022, used as initial condition in the 3D hydrodynamic model.

The hourly meteorological variable series at the Lecco station were assumed to be uniform over the lake surface grid cells, notably wind speed and direction. Figure 4 displays the hourly feather plot of winds in those days, starting from 21st June. Overall, the typical pattern observed in subalpine lakes with southbound winds during the night and northbound winds during the day is evident. A noticeable increase in wind speed occurred between June 28th and 29th, due to a night thunderstorm event, in which a maximum wind speed of 4.7 m/s was achieved.

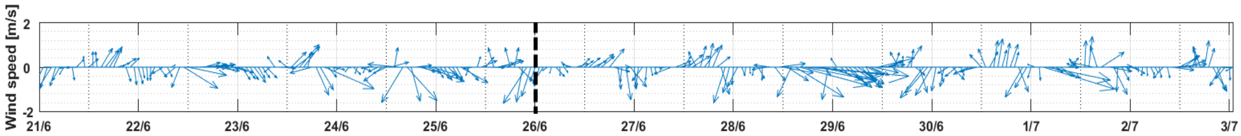

Figure 4. Feather plot of the wind speed and direction at the Lecco station used for the 3D hydrodynamic model simulation from 21th June to 3rd July 2022 (the simulation starts on 26th June).

The implemented 3D model of Lake Pusiano employs an unstructured grid with triangular elements having a resolution of 20 m, generated with the RGFGRID tool of the Delft3D suite, resulting in 31 958 vertical stacks of cells. Along the *z* axis, the water column was discretised into 100 uniform *z-layers*, each with a thickness of 0.25 m, resulting in 1 698 622 mesh elements overall.

The Lambrone stream discharges for each scenario were appended as boundary condition to the mesh elements in the Lambrone mouth area (Figure 2a). The same discharges with a negative sign were appended to the elements in the Lake Pusiano outlet area (Figure 2a). This way, an almost constant mean lake level was reproduced, evaporation being negligible over the 7-day simulated period. To improve simulation stability, inflow and outflow discharges were gradually increased from zero to the final steady values through a 24 h-long linear ramp.

A fixed horizontal eddy viscosity and diffusivity of 0.2 m^2/s was employed (Amadori et al., 2021), whereas a Chézy value $C = 45\ m^{1/2}/s$ was adopted for bottom friction (Smolders, 2022). The "Composite" heat flux model was used, which considers the complete heat balance at the lake surface (Gill, 1982; Lane, 1989). Stanton and Dalton numbers $St = 6.50 \times 10^{-4}$ and $Da = 1.3 \times 10^{-3}$ were considered, as in Amadori et al. (2021). A Secchi depth of $SD = 4.0$ m measured by ARPA Lombardia on 26th June 2022 was entered to properly reproduce light extinction. The wind-drag coefficient was modelled as function of wind speed according to Wüest and Lorke (2003). The default Courant number $CFL = 0.7$ and time step $\Delta t = 30$ s were adopted.

A numerical passive tracer was included in the simulations to determine the fate of water entering Lake Pusiano from the Lambrone stream and the water renewal induced by the inflow. A unit tracer concentration was assigned to water entering the lake at the Lambrone boundary condition, the initial lake water tracer concentration being set to zero. To properly reproduce the Lambrone flow path inside the lake, the release process was started on 29th June after a three-day spin-up, when realistic flow and internal-wave conditions for the lake (Carraro et al., 2012) are deemed to have established from the water-at-rest conditions employed as initial hydrodynamic configuration.

For simplicity, only the results at the end of the simulation are presented in this paper. For the same reason, colour maps of model variables are plotted only for vertical Plane A and Plane B in Figure 2a. Results in the horizontal plane are represented at 4 m depth, where the riverine intrusion tends to persist under the simulated conditions (see Paragraph 4.5).

4. Results and Discussion

4.1. Considerations on the 2022–2024 meteorological features

Starting from the second half of 2021 until the early months of 2023, significant drought affected Northern Italy. Rainfall records from the Caslino d'Erba meteorological station (Fig. 1c) show that in 2022 the annual rainfall was 897 mm, well below the 1494 mm annual average calculated over 2004–2024. Starting from spring 2023, the drought ended, and precipitation increased, adding up to 1565 mm in 2023 and notably to 2104 mm in rainy year 2024.

Figure 5 shows the trend of monthly cumulated precipitation and average air temperature from the Caslino d'Erba station for the years 2022 and 2024, as well as for the mean year 2004–2024. Starting from rainfalls, the monthly cumulated precipitation in 2022 was remarkably lower than the 2004–2024 average, except for September and, marginally, December. On the contrary, in 2024 rainfall was higher than average, especially in February, March, May and October, flood events having occurred in these last two months. As regards air temperatures, the year 2022 was systematically warmer than the 2004-2024 average year from April to December, the largest anomaly lasting from May till July, with a maximum of +2.83 °C in July. In the same month the monthly average even exceeded 25 °C in 2022. A remarkable extreme event, made up of superimposed drought and heatwave, thus occurred in summer 2022, these phenomena having been determined to cause ecological consequences larger than the sum of the individual events (Woolway et al., 2025). In 2024, winter was warmer than the historical average, with a maximum +0.74 °C anomaly in February. This condition surely contributed to the unusual cyanobacterial bloom observed in such month (see Supplementary Information). A drop in temperatures coincided with increased precipitation in spring 2024, followed by a slight rise in the second half of the year, with a maximum +0.43 °C positive anomaly in August.

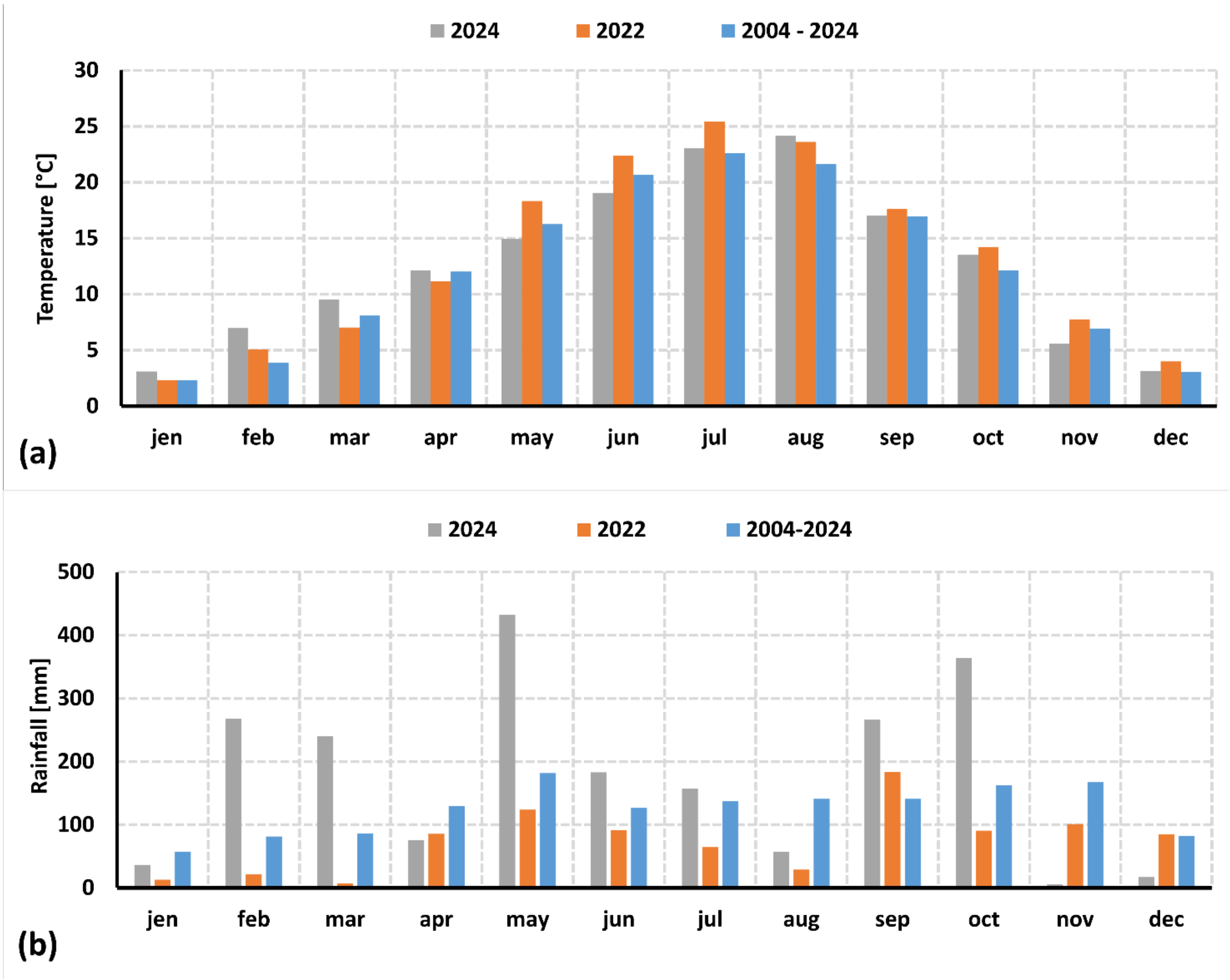

Figure 5. (a) Mean monthly air temperatures and (b) monthly cumulated precipitation for the years 2022, 2024 and for the mean year 2004-2024.

4.2. SWAT+ results

The SWAT+ model estimated a variable, realistic external nutrient load entering the lake, including the effects of both the drought period and the ensuing increase in precipitation. Figure 6a shows the cumulated monthly rainfall along with the average monthly streamflow entering the lake resulting from the 2022-2024 SWAT+ model simulations carried out in this study. Model results highlight the large variability of discharge with precipitation in the study period. From 2022 until mid-2023, a minimal streamflow is reproduced due to the extended drought, whereas from mid-2023 until the end of 2024, the increase in monthly precipitation drives a significant rise in streamflow. The increase in discharge leads to a parallel increase in simulated monthly nutrient loads from the dry to the wet period (Figure 6b). The nutrient load upsurge is due to the combination of: (1) washout of organic and inorganic nutrients accumulated in the soil during the drought period; (2) increased N wet depositions, included in the model (Pella et al., *under review*); (3) the parameterised simulation of the activation of CSOs in urban areas, done according to Driver and Tasker (1988) in the Pusiano watershed model (Pella et al., *under review*). The simulated external load to Lake Pusiano for $P\text{-}PO_4$ rises from less than 0.1 t/month in summer 2022 to peak values up to 1.5 t/month in 2024.

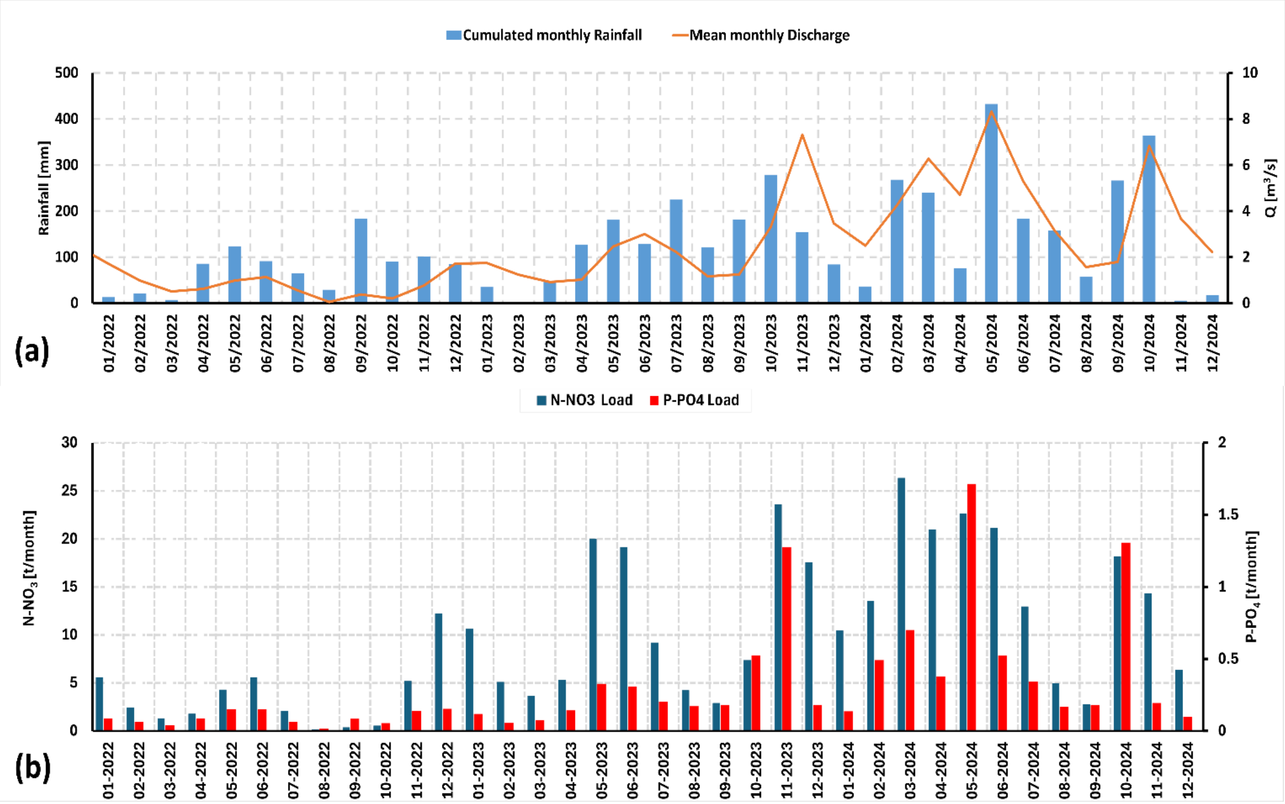

Figure 6. (a) Cumulated monthly observed rainfall in Caslino d'Erba and simulated total mean monthly discharges released to Lake Pusiano from SWAT+ in the 2022-2024 period; (b) total monthly $N\text{-}NO_3$ and $P\text{-}PO_4$ loads released to Lake Pusiano from SWAT+ in the 2022-2024 period.

4.3. WET results

Variable	**Calibration (2022-2023)**		**Validation (2024)**	
	MAE	***r***	***MAE***	***r***
T_w (22-24 m)	0.27 °C	0.85	1.06 °C	0.7
DO **(22-24 m)**	1.76 mg/L	0.7	1.72 mg/L	0.95
TP **(22-24 m)**	70 µg/L	0.5	100 µg/L	0.74
$P\text{-}PO_4$ (22-24 m)	60 µg/L	0.56	70 µg/L	0.61
TN **(22-24 m)**	0.65 mg/L	0.48	0.68 mg/L	0.48
T_w (0-24 m)	0.58 °C	1	0.81 °C	0.99
DO **(0-24 m)**	2.66 mg/L	0.63	1.75 mg/L	0.87
TP **(0-24 m)**	30 µg/L	0.71	60 µg/L	0.77
$P\text{-}PO_4$ (0-24 m)	20 µg/L	0.72	40 µg/L	0.65
TN **(0-24 m)**	0.55 mg/L	0.52	0.49 mg/L	0.27

Table 1. Performance of the WET model in the calibration and validation phases for T_w, *DO*, *TP*, *P-PO4* and *TN* concentrations in the bottom layer (22-24 m) and in the whole water column (0-24 m).

Table 1 displays the error metrics for relevant WET model variables in the calibration and validation phases, for the 22-24 m bottom layer and the 0-24 m water column. The model performance is very good overall for all statistical indicators according to the ranges given for water quality models by Moriasi et al. (2015). The statistics obtained in the bottom layer are also similar to those calculated for the water column, which are the object of the ParSAC calibration. For T_w, very good results were achieved at the bottom and especially for the whole water column. *DO* depletion in the stratified period and partial replenishment during the winter is properly reproduced at the bottom, the correct simulation of such process strongly depending on the accurate simulation of lake stratification and mixing (Fenocchi et al., 2025). The metrics for *TN* show acceptable values, still with comparable performance between the calibration and validation phases and considering either the whole water column or the bottom layer. Regarding *TP* and $P\text{-}PO_4$, good metrics are obtained, with superior agreement in the bottom layer.

As an example, Figure 7 shows the calibration and validation results for $P\text{-}PO_4$ in the 22-24 m deep hypolimnion. The model can reproduce the continual increase of $P\text{-}PO_4$ occurring in the stratified season through all three simulated years, being generally able to simulate the low concentrations observed during the winter. A much more smoothed behaviour is yet reproduced in the stratified season, mostly leading to lower concentrations than the observed ones. Furthermore, the model reproduces a gradual increase of *P-PO₄* concentrations under stratification conditions, as would result from internal loading due to anoxia. Such dynamic is not fully clear from the observations, showing for 2024 a peculiar trend with a decrease and then a rapid increase in autumn, the peak exceeding 400 µg/L. This discrepancy may be first ascribed to horizontal advection processes which are not simulated by the 1D model. A further reason is that sampling is not always performed in the exact same point, so that the distance from the bottom is not perfectly constant among samples, variations of lake level further adding to the issue. As relevant *P-PO₄* concentration gradients exist near the bottom of lakes with significant sediment release, taking samples at a constant distance from the bottom would be crucial for data consistency. Above all, model calibration optimises model performance throughout the entire water column, which implies that peaks at specific depths may be underestimated or overestimated.

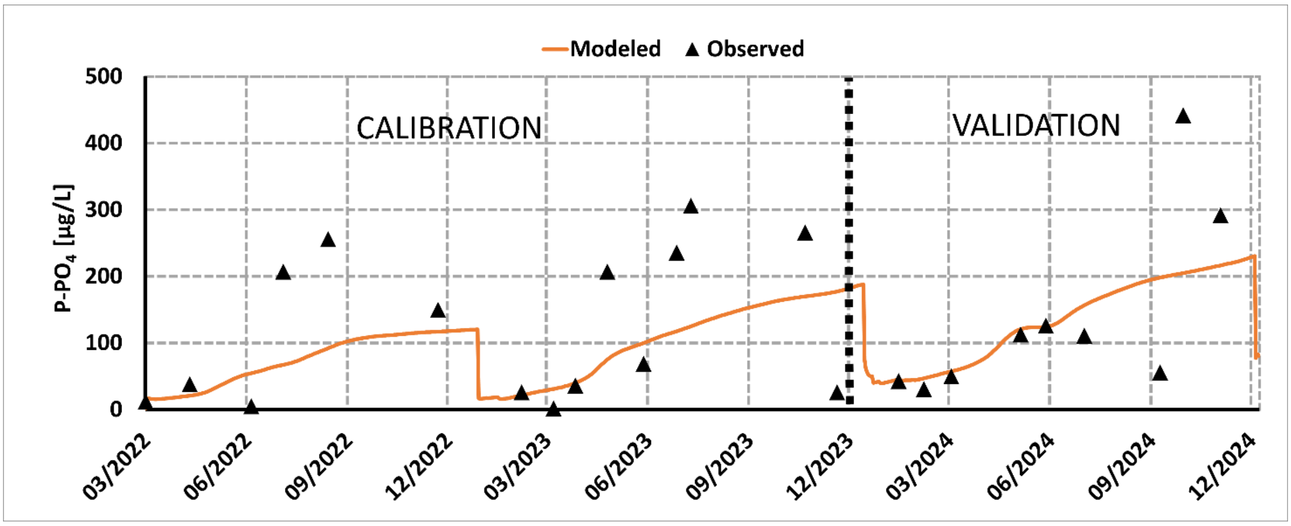

Figure 7. Observed and modelled volume-weighted *P-PO₄* concentrations in the 22-24 m bottom layer.

4.4. Considerations on integrated catchment-lake modelling

The abrupt trophic decline of Lake Pusiano observed in the study period could be conceptually due to either an increase of external loads from the catchment or a sudden increase in the internal load. The SWAT+ model confirmed that external load from the catchment could by no means increase during a drought, also considering that relevant failures in the sewer system or illegal sewage discharges to the lake did not happen. On the contrary, the SWAT+ model allowed estimating the extent of load reduction occurring during such period. Consequently, an increase in internal loading appears to be the most plausible explanation, likely triggered by the peculiar climatic conditions which occurred during the hot, dry summer 2022, which put Lake Pusiano under heavy environmental stress (Mosley, 2015). A rise in internal loading is caused by an increase of the *P* mass released by lake sediments. This *P* mass is made up by a mass flux per unit surface multiplied by the bottom area contributing to the release and by the duration of the release process. The unit mass flux, in turn, depends on *P* availability in sediments, the release process being further related directly to bottom T_w and inversely to bottom *DO* concentration. We investigated all these factors to analyse the likely causes of what has been observed in Lake Pusiano.

The year 2022 was marked by conditions that favoured the increase of *P* release, especially in the hot summer. Starting from lake physics, the water column stratified very early due to high temperatures and low rainfall, which determined low discharges in the Lambrone stream, minimising river-induced mixing (Mosley, 2015; see Paragraph 4.5). This is shown in Figure 8a, which displays the trend of the Schmidt stability index calculated from daily T_w simulated by the WET model in the study period, comparing them with discrete values from the T_w observed profiles. Figure 8b, which displays the Schmidt stability values from T_w observations over 2009–2024, shows a maximum value of 1211 J/m^2 obtained in July 2022, due to the exceptionally hot and dry conditions of such month.

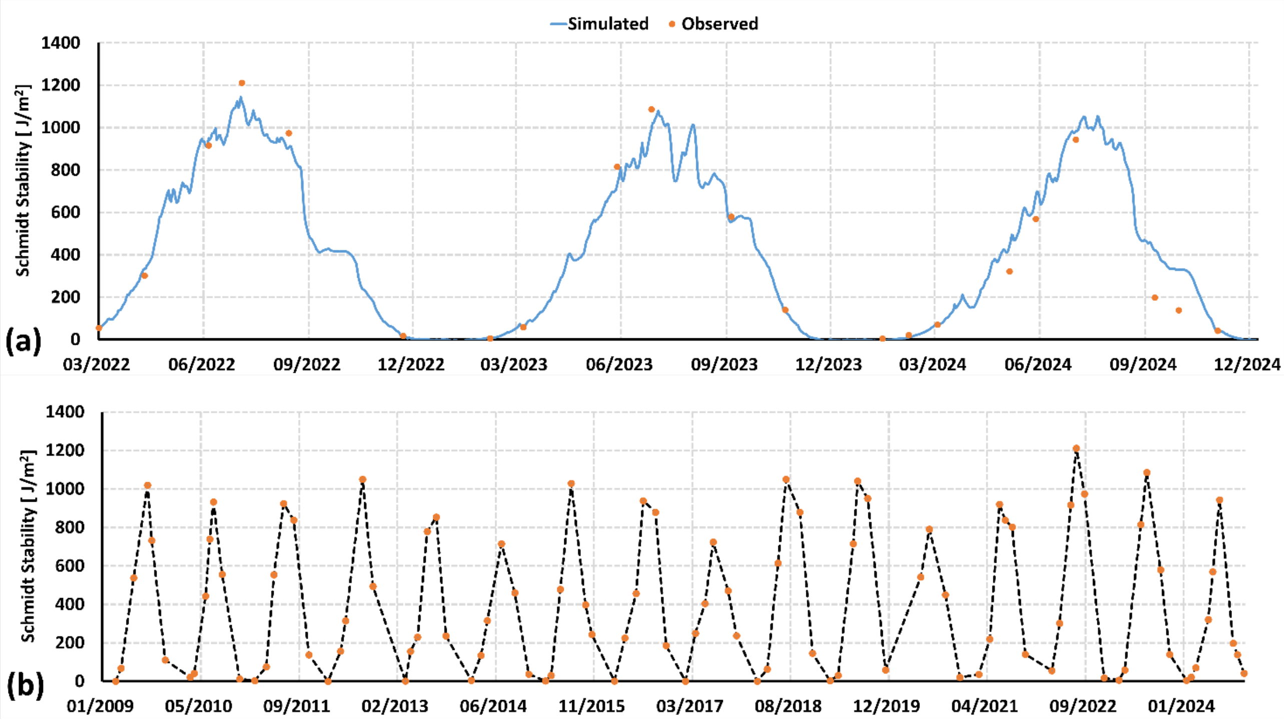

Figure 8. (a) Comparison between the daily values of Schmidt stability calculated from the WET model and the discrete values derived from observed temperature profiles over 2022-2024; (b) Schmidt stability values calculated from observed temperature profiles over 2009-2024.

The strong stratification observed during the hot, dry year 2022 acted detrimentally on all factors contributing to internal loading. In fact, enhanced hypolimnion isolation boosted *DO* depletion, whereas the duration of the sediment release process due to hypolimnetic anoxia was increased. The hot air temperatures also triggered higher-than-usual hypolimnetic T_w. However, we hypothesise that the main factor determining the upsurge of internal loading in 2022 is the increase in the anoxic volume, expanding towards shallower zones than in previous years due to water stratification and stagnation (Gonsiorczyk et al., 2024). Due to the morphometry of Lake Pusiano (Figure 2), thickening of the anoxic layer produces a more than linear increase in the anoxic bottom surface.

Figure 9 displays the heat maps of *DO* concentration throughout the water column and of *P-PO$_4$* mass flux per unit bottom area released from lake sediments at all depths, resulting from the three-year WET simulation. The year 2022 is confirmed to be the one in which release conditions protracted for the longest period. The simulation further reproduces a *P* release from sediments which increases from 2022 to 2024. This increase complies with observations and may be attributed to the feedback loop between rising *P* availability in sediments and primary production increase, the latter boosting the sedimentation and accumulation of organic matter at the bottom. The priming of this loop may lie in the exceptional release occurred in the hot, dry summer of 2022, such nutrient stock being made available for primary production only at the end of stratification. Furthermore, the increase in rainfall observed in 2023 and especially in the wet year 2024 would have helped sustain this regime shift through external loading. The increase in primary production in 2023 and 2024 and its low values in 2022 due to the drought are showcased by the *DO* concentrations in Figure 9a, in which peak values due to photosynthesis are obtained around June in the latter two years, the bloom being almost absent in the first one. This self-sustaining mechanism was simulated to lead to sensible *P-PO$_4$* releases occurring at depths as shallow as 10 m by 2024, involving a 2.51 km^2 bottom surface (Figure 2b).

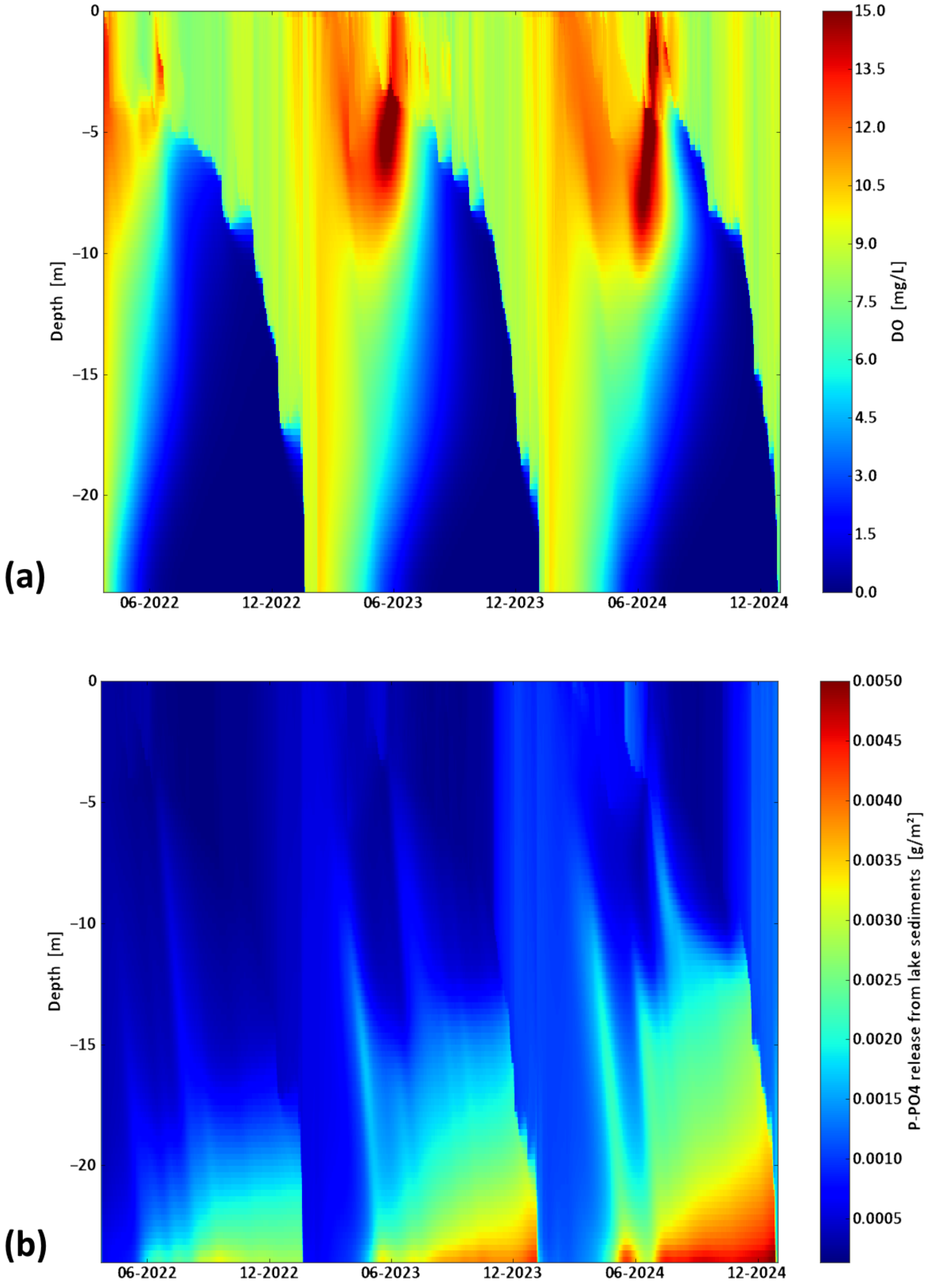

Figure 9. (a) Heat maps of (a) *DO* concentration over the water column and (b) *P-PO*$_4$ mass flux per unit area released from lake sediments at all depths obtained from the WET model results for 2022-2024.

Therefore, while it is commonly assumed that *P* release occurs only in the deepest region of a moderately deep lake, climate warming and stagnation conditions induced by droughts may extend internal loading to littoral zones as well (Gonsiorczyk et al., 2024). In addition, in heavily stratified conditions, significantly lower *DO* concentrations may be obtained for the same depth in littoral areas compared to pelagic ones, due to closeness to the bottom. To better understand to what extent littoral zones are affected by anoxia, targeted sampling in those zones would be needed, overcoming the limit of sampling being restricted to the lake deepest point in long-term and institutional monitoring programs. For Lake Pusiano, we do not know how much *P* is stored in littoral sediments. Given the lake long history of pollution and recovery, it is possible that sediments in littoral areas are rich in *P* due to past accumulation, so that once that these areas become involved in the release process, a large increase in internal loading is triggered.

As previously stated, internal load is partly influenced by the external load from the current year, as boosted productivity results in higher *P* availability in sediments (Søndergaard et al., 2003). Primary productivity further depends, in addition to external loading in the current year, on internal loading occurring in the previous year, which is made available to the photic layer as soon as stratification breaks down (Christensen et al. 2015). Therefore, the pool of *P* available at the beginning of the year is also a proxy of external loading in the previous year, through the mediation of internal loading, thus reflecting the meteorological conditions of the previous year (Kong et al., 2023; Catalan et al., 2024). The availability of *P*, together with the mild temperatures of the 2022-2023 and especially 2023-2024 winters, could explain the extended cyanobacterial blooms observed during those periods, which could represent an anticipation of the future increasingly warmer winters expected with climate change.

Considering the results of the SWAT+ model, the annual cumulated external load of $P\text{-}PO_4$ rises from 1.1 t in 2022, well below the 3.1 t/a average estimated for 2004-2023 in Pella et al. (*under review*), to 6.2 t in 2024 (Table 2). The internal load simulated by WET also increases from 1.2 t in 2022 to 3.1 t in 2024 (Table 2). Therefore, according to the model, an almost threefold increase in internal load has been obtained within a couple of years. Such high internal load values had only been recorded in the mid-1980s, before measures for the reduction of external loads were implemented (Copetti et al., 2017). As a result of the 2022 drought and subsequent 2024 floods, the ratio between internal and external load notably passed from 112% in 2022 to 50% in 2024, despite the evident increase of sediment release (Table 2).

Year	**Cumulated observed rainfall [mm]**	**External $P\text{-}PO_4$ load from SWAT+ [t]**	**Internal $P\text{-}PO_4$ load from WET [t]**	**Internal/external load ratio**
2022	897	1.1	1.2	112%
2023	1466	3.6	2.2	61%
2024	1906	6.2	3.1	50%

Table 2. Annual cumulated observed rainfall in Caslino d'Erba and modelled external (WET) and internal (SWAT+) $P\text{-}PO_4$ loads in the study period

The results of the WET model regarding the release of *P-PO_4* from the lake sediments is an outcome of model calibration, obtained feeding ParSAC with observations of nutrient concentrations throughout the water column. The external loads entering the lake determined with SWAT+ led in Pella et al. (*under review*) to very good WET model performances for chemical variables over 2009-2023 at the lake surface, where the influence of external loading is more direct. This suggests that the estimated order of magnitude and variability of external loads is consistent with reality. In addition, the present automatic WET calibration, done without fixing pre-determined constraints and starting from default values shows that the high, increasing observed 2022-2024 *P-PO_4* hypolimnetic concentrations (Figure 7) could originate only from an intensifying release from sediments.

In the WET simulation, algal blooms occurred in the study period not only during the usual productive seasons but also in winter months (Figure 9a), consistently with observations. The cause of the traditional spring bloom is warming air and water temperatures and is fed by hypolimnetic nutrients brought to the photic layer by mixing at the end of stratification (Wetzel, 2001). In moderately deep monomictic lakes, direct stratification does not cease at the end of winter, but rather at the end of autumn (Wetzel, 2001). Therefore, if some consecutive days of unusually high air temperatures occur in winter, as increasingly observed in the last years with climate warming, an early algal bloom is produced, fed by newly available nutrients, including those from internal loading. Due to strong stratification, ensuing blooms occurring in the summer and in early autumn are instead mainly driven by external loads, and as such may happen after significant impulse releases with flood events (Morabito et al., 2018).

4.5. Delft3D D-Flow results

The drought period, in addition to influencing nutrient inputs from the watershed, also affected circulation dynamics, contributing to water stratification and stagnation. In fact, the minimal flow rates observed in the Lambrone stream during the period increased water residence times and, together with strong stratification, prevented riverine water from supporting renewal in deeper layers where sediment release occurs.

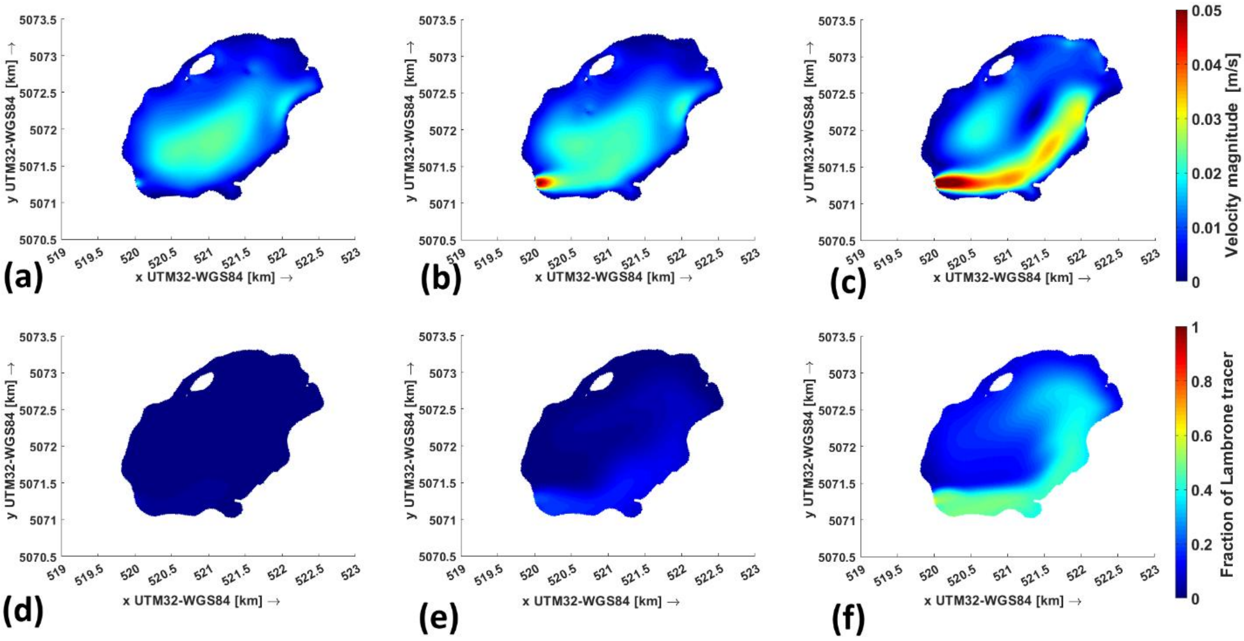

Figure 10. Velocity magnitudes (a, b, c) and Lambrone tracer concentrations (d, e, f) on the horizontal plane at 4 m depth in order from left to right for Scenarios S1, S2, S3 at the end of the 3D simulations.

Figure 10 depicts the velocity magnitudes and the Lambrone tracer concentrations on the horizontal plane at 4 m depth, where the intrusion occurs on average in the three scenarios, at the end of the simulation, allowing comparisons on the effects of different discharges on the horizontal extension reached by riverine waters in 4 days. Starting from the velocity magnitudes, we can see that in Scenario S1 (Figure 10a) we have a flow field shaped by wind only. The influence of the Lambrone inflow is already noticeable in Scenario S2 (Figure 10b) and becomes the main driving mechanism of water motion in Scenario S3 (Figure 10c). The horizontal extension of the tracer entering Lake Pusiano from the Lambrone stream clearly increases with the flow rate. Under Scenario S1 (Figure 10d), the tracer entering the lake does not reach the lake centre within 4 days due to the extremely low discharge of the tributary. Part of the inflowing volume, due to the low to null momentum which makes it more vulnerable to diffusion phenomena, remains in the Lambrone mouth area and leaves the lake through the outlet without entering the main basin. This behaviour, which represents the real conditions attained during the dry, hot summer of 2022, causes minimal water renewal, even at the intrusion depth. Scenario S2 (Figure 10e) shows that, under ordinary discharge conditions, the tracer manages to reach the main lake basin, with concentrations around 15% at 4 m depth. Once inside the lake, the tributary plume makes a counterclockwise turn, sticking to the shore and proceeding towards the North-East, making another counterclockwise turn before reaching the opposite edge of the lake and proceeding towards the deepest region of the basin. This flow pattern of the tributary, determined by the combination of riverine and wind-induced currents (Schimmelpfennig et al., 2012; Fenocchi and Sibilla, 2016), is even better defined for Scenario S3 (Figure 10f), in which the tracer reaches the lake centre, with Lambrone tracer concentrations around 50% and a much more widespread dispersion, determining a significant water renewal at the intrusion depth by 4 days. The described flow pattern of the tributary is determined by the interaction among the lake shore geometry, the bathymetry, and the orientation of the entrance of the Lambrone stream, which points towards the opposite shore, away from the lake outlet. Therefore, if the inflow has enough momentum, short-circuiting is avoided. For this counterclockwise path to occur, the geostrophic forces should not significantly overcome the inertial forces of the riverine and wind-induced currents, i.e. the Rossby ratio (Ro) should not be $\ll$ 1. This non-dimensional parameter is expressed as (Pedlosky, 1992):

$$Ro = \frac{U}{Lf}$$

where U is a representative velocity scale, which for the flow of the Lambrone stream into Lake Pusiano is $U \approx 5 \cdot 10^{-2}$ m/s, L is a representative length scale, which considering the lake average width is $L \approx 1.5$ km, and $f = 2\omega \sin\varphi$ is the Coriolis frequency, with $\omega = 7.3 \cdot 10^{-5}$ rad/s being the Earth rotation rate and $\varphi =$ 45.8° the latitude of Lake Pusiano. Employing these values, $Ro \approx 0.32$ is obtained, which means that geostrophic forces do not prevail enough on the inertial ones to prevent the counterclockwise gyre from developing.

By comparing the Lambrone tracer concentrations at the end of the simulations in vertical Planes A and B among the three scenarios (Figure 11), it can be seen that the Lambrone stream more precisely enters the lake at a depth centred around 3.5 m for Scenario S1 (Figure 11a and 11d), 4.0 m for Scenario S2 (Figure 11b and 11e) and 5.0 m for Scenario S3 (Figure 11c and 11f). The riverine plume sticking to the south-eastern shore can be well seen, in addition to the return flow for Scenarios S2 and S3. The increase of the intrusion depth with the Lambrone discharge is due to the higher discharge, which can overcome the warming of riverine water with entrainment by turbulent mixing. In this regard, for Scenarios S2 and S3, short-circuiting from the Lambrone stream to the lake outlet is limited to water escaping from the riverine intrusion towards the hydraulic right due to the mutual mixing of river and lake waters. This situation can occur only in the initial phase of the intrusion, as the depth in the bay where the lake outlet is placed does not exceed 1 m (Figure 2a), being for this reason object of extensive macrophyte colonisation recently. Such fraction reaching the outlet directly can be visualised in Figure 11e and 11f on the far right of vertical Plane B. For more relevant short-circuiting to occur, the Lambrone stream and Lake Pusiano surface water temperature should be close one another, so that intrusion would occur at the very surface. However, leveraging on available temperature measurements of both water bodies, this condition is unlikely to occur due to the alpine, steep nature of the tributary and the low altitude of the lake basin.

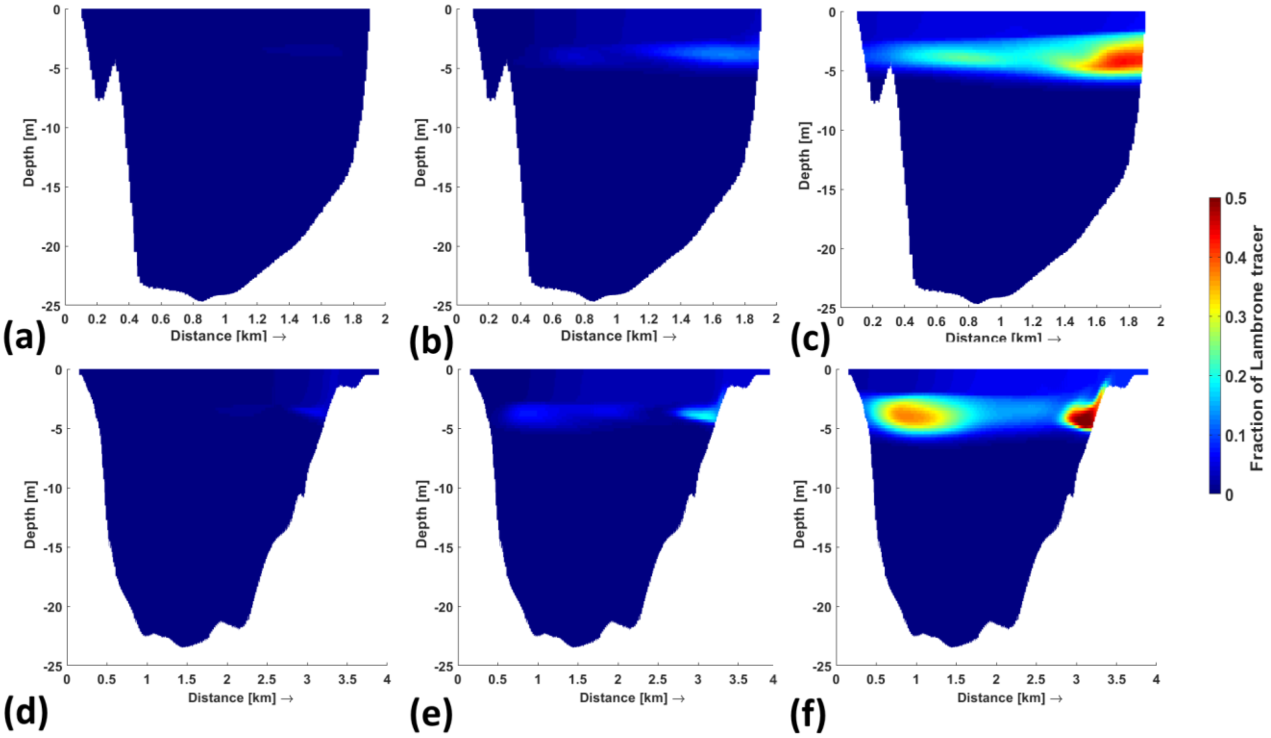

Figure 11. Fraction of Lambrone stream tracer concentrations at vertical Plane A (a, b, c) and Plane B (d, e, f) in order from left to right for Scenarios S1, S2, S3 at the end of the 3D simulations.

The influence of the intrusion of the Lambrone stream on lake stratification can be seen through the water temperature in Planes A and B (Figure 12). In Plane A (Figure 12a, 12b and 12c), increase in inflowing discharge brings about a thinning of the surface warmest layer near the southeastern shore. This is due to the insertion of riverine water, which locally distorts the vertical temperature profile, as also evident in Plane B under Scenario S3 (Figure 12f). Despite this deformation, even the highest tested flow rate is unable to mix the waters below 5 m due to strong stratification conditions as those of simulated summer 2022, combined with the morphology of the inflow area.

Even if not reaching the hypolimnion due to stratification, water renewal from the Lambrone stream is nevertheless relevant for water oxygenation, especially in the littoral area near the south-eastern shore, along which a significant riverine current has been shown to form. Such current is expected to convey large quantities of *DO*, rivers being usually close to saturation conditions due to the turbulence of lotic waters (Dresti et al., 2023b). In the absence of this current, such as during drought periods, such littoral area could be at risk of sediment hypoxia. In April 2024, after the end of the extended drought period, a massive fish death was observed in that very lake shore area, between the municipalities of Rogeno and Bosisio Parini. In those days, heavy winds blew in the area, with speeds around 15 m/s at the Lecco station. It is possible that the shear stress on the sediments induced by wind-induced current and waves triggered the release of H_2S and $N\text{-}NH_4$ (Reese et al., 2008; Tang et al., 2020; Centeno et al., 2025) accumulated during the drought, both compounds being toxic to fish (Beauchamp et al., 1984; Randall and Tsui, 2002). Similar events were observed by Luther et al. (2004) in a marine inland bay.

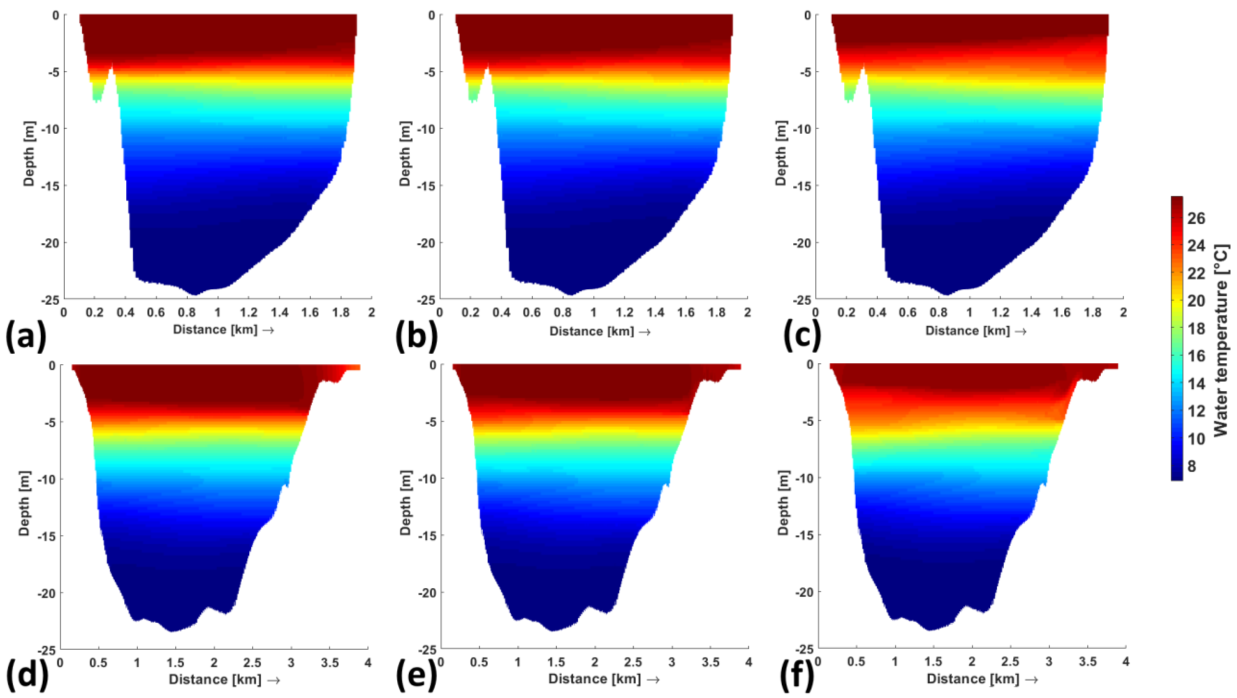

Figure 12. Water temperatures at vertical Plane A (a, b, c) and Plane B (d, e, f) in order from left to right for Scenarios S1, S2, S3 at the end of the 3D simulations.

Figure 13 displays the direction and magnitude of the horizontal and vertical velocities for vertical Plane A. The 3D flow field is overall strongly affected by stratification, forming four stacked recirculating cells in the vertical plane with a conveyor-belt layout, alternate upwelling and downwelling occurring at the shores. The interfaces between the circulation cells are determined by primary and secondary thermoclines in the water temperature vertical profile. This prevents vertical mixing, enhancing the residence time of hypolimnetic waters, boosting *DO* depletion and thus favouring sediment release of *P* and its accumulation at the bottom. The intrusion current of the Lambrone stream is also visible from Figure 13 for Scenario S3, determining a stronger current than the wind-induced one at the surface in Plane A (Figures 13c and 13f), as was also evident from Figure 10c. In the depicted frame at the end of the simulation, the riverine current strengthens a wind-induced structure, visible for Scenarios S1 and S2 (Figures 13a and 13b, 13d and 13e). Below the Lambrone intrusion, no substantial differences subsist between scenarios. A noticeable difference in the horizontal velocity magnitudes above the intrusion depth is yet visible in Plane A for Scenario S3 (Figure 13f), in which lower velocities are reproduced compared to Scenarios S1 and S2 (Figure 13d and 13e). This is because the flood inflow intrusion influences the layout of surface wind-induced currents to some extent. One last thing that can be noticed from Figure 13 is how the channel between the lake shore and the island is disconnected from the surface gyres in the main basin, making this littoral area vulnerable to nutrient accumulation and recycling (Pinardi et al., 2015). Extensive phytoplankton blooms have been observed in that area during the last years (see Supplementary Information). Actually, it seems that independent vertical cells form in that region for all scenarios, strengthening the isolation of the water volume.

A limitation of the presented 3D simulations is that they do not implement the presence of suspended sediments in inflowing tributary waters, which is typically prominent in flood events (Fink et al., 2016; Råman Vinnå et al., 2017 Dresti et al., 2023b). In fact, the presence of high concentrations of suspended sediments would raise the density of the inflowing water, allowing it to reach larger depths and thus mix a thicker layer. However, due to the morphometry of the lake and the layout of its entrance, it is possible that most suspended sediment would nevertheless settle in the plateau close to the mouth, prior to reaching the lake deepest region.

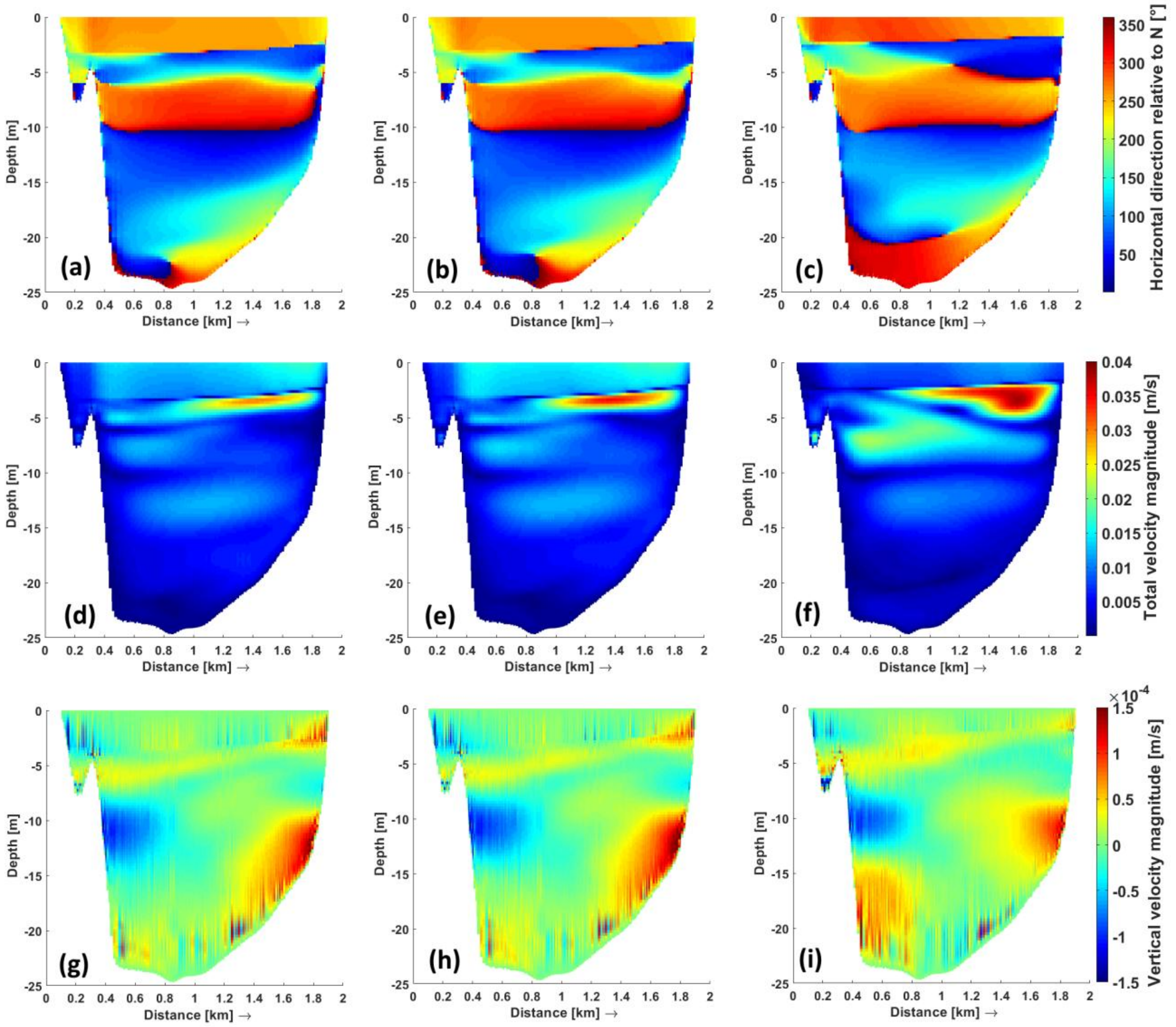

Figure 13. Horizontal velocity direction relative to the North (a, b, c) and magnitude (d, e, f), vertical velocity magnitude (g, h, i; positive and negative values indicate upwelling and downwelling, respectively) in order from left to right for Scenarios S1, S2, S3 at vertical Plane A at the end of the 3D simulations.

5. Conclusions

In light of the performed study, leveraging on multiple complementary process-based models of the lake and its watershed for the 2022-2024 study period, we can state that the ultimate cause of the notable internal load increase observed in Lake Pusiano in recent years is the combination between climate warming, unfavourable weather conditions, lake morphology and still excessive external loading. These factors altogether caused extensive water column stratification and hypolimnetic stagnation, leading to a regime shift in both lake primary productivity and sediment release regimes, the latter involving also littoral areas.

The reduction of external loads achieved through past interventions is likely insufficient for reaching a good ecological status, as prescribed by the EU regulations. Therefore, efforts should still focus on reducing external loading. In a study on the prospected future evolution of Lake Pusiano, currently under completion by the Authors, we proved that the observed increase in internal loading will halt when a new equilibrium will be achieved, limitation by external loading coming into play again.

Ecological targets should be set also considering the increasing role of internal loads, whose response to interventions is often delayed, as the nutrient surplus stocked in sediments must be depleted to make internal load ineffective. Engineering techniques to artificially accelerate this process, such as hypolimnetic withdrawal, or sediment removal or inertisation exist, but have high costs and applications have highlighted side effects, so that they are viable only in limited cases.

Overall, the use of an integrated lake-catchment process-based modelling approach, including the eco-hydrological watershed model SWAT+ and the 1D ecological-hydrodynamic lake model WET, supplemented by Delft3D D-Flow for additional 3D hydrodynamic insight, allowed an in-depth assessment of the cause-effect chains for a combined drought and heatwave extreme event in Lake Pusiano. This methodology proved itself valuable for water quality management and the prevention of future adverse ecological events for lake ecosystems under the threats of climate change.

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Data availability statement

The datasets analysed and generated in this study are available from the Corresponding Author upon reasonable request.

Funding Declaration

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Competing Interest declaration

The Authors declare they have no competing interests of any sort.

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6. Field work and monitoring activities

6.1 Introduction

During the Ph.D. period, field activities were also carried out , alongside the modeling work, consisting in the monitoring of Lake Pusiano and of its tributaries, namely the *Lambro Supralacuale* and the *Emissario del Segrino*, close to their outlet into the lake, but far enough to be independent from lake level. The purpose of the fieldwork was to observe the measured concentrations of nutrient loads in the lake and in the streams, for which discharges were also measured, formulating rating curves that can also be used in the future, and water level and temperature stations were set up.

For Lake Pusiano, only a limited amount of data was available throughout the year. The WFD monitoring activity carried out by ARPA Lombardia is performed in compliance with current regulations, through sampling of the lake at the deepest point and of its main tributary *Lambro Supralacuale* at various sections once per season (such as in Lasnigo), for a total of 4 samples per year for both the tributary and the lake. This represents a problem for numerical modelling development, as the low sampling frequency on the Lambro River did not allow for the direct use as a nutrient load to be used as input to the WET model. In addition, the sampling and discharge measurement station is located in Caslino d'Erba, about 6 km upstream from the mouth into the lake, and also upstream of the Erba urban area. The presence of the town could pose a problem, as using the concentration and discharge data collected at Caslino d'Erba to calculate the load would lead to underestimation. These considerations led to undertaking field monitoring activities with a watershed-lake approach, i.e., divided between the tributary streams of the lake and the lake itself.

The construction of rating curves aimed at establishing relationships between water level and discharge for the studied streams. These were prodromic to the installation of automatic level gauges at the same cross sections of *Lambro Supralacuale* and *Emissario del Segrino* where rating curves were determined. This allowed level monitoring to be automatically performed on a hourly basis, such measurements being converted into discharge ones. Finally, to obtain water quality data for these streams, water samples were collected on an almost monthly basis and analyzed in the laboratory to obtain concentration values that can be used in nutrient load calculations.

As for the choice of the watercourses selected for monitoring, the Lambrone stream is quite obvious, being by far the main inflow to Lake Pusiano, draining about 80% of its catchment. The other watercourse, the *Emissario del Segrino*, drains just above 5% of it. It is a small regulated natural stream connecting Lake Segrino to Lake Pusiano, crossing anthropised areas, including a farm with livestock and residential zones. This small stream was already closely monitored in the past (Progetto PIROGA, 2012), as it shows a poor qualitative state with high *TP* concentrations around 62 µg/L from evident sewage contamination, which is still present to this day and thus requires attention.

Lake monitoring instead focused on collecting data on the water column, providing more information on how the lake is evolving, notably increasing the sampling frequency compared to the quarterly monitoring of ARPA Lombardia, the own sampling days being arranged not to overlap with theirs. In the following sections of the thesis, these samples are used to both greatly improving the quality of model calibration and validation and as stand-alone observations to evaluate lake behaviour.

Analyses of stream and lake water samples was performed in the ARPA Lombardia and CNR-IRSA laboratories in Verbania Pallanza according to standard methods for freshwater analysis (APAT-IRSA, 2003; APHA AWWA WEF, 2012).

6.2 Activities performed on the lake

The sampling activity conducted on Lake Pusiano aimed at complementing the institutional WFD monitoring already performed by ARPA Lombardia. From April 2023 to May 2025, a total of 9 sampling campaigns were carried out: specifically, 4 in 2023, 3 in 2024, and 2 in 2025. Sampling was performed from a boat, collecting samples at the deepest point of the lake as done by ARPA Lombardia.

The monitoring activity involved sampling the water column at discrete depths and using CTD and fluorometer probes.

The CTD probe IDRONAUT (https://www.idronaut.it/) Ocean Seven Plus (Figure 10) allowed the measurement of vertical profiles of physical-chemical parameters such as dissolved oxygen (*DO*), *DO* saturation, water temperature (T_w), *pH*, and electrical conductivity. The bbe moldanke (https://www.bbe-moldaenke.de/en/) field fluorometer FluoroProbe was used to measure the concentration of total Chlorophyll-a (*Chl-a*) and likely phytoplankton group percentages according to their specific pigments along the water column, providing high resolution vertical profiles.

Own water samples were collected at discrete depths using a Niskin bottle, from the surface down to 1 m above the bottom. Deeper samples would have been too much influenced by *P* release, which determines a concentration gradient rising asymptotically at very close distances from the bottom sediment-water interface. Samples were always taken at the same depths to ensure continuity in the monitoring, specifically: 0.5 m, 5 m, 10 m, 15 m, 20 m, and 23 m. The collected samples were then analyzed in the laboratory of CNR-IRSA Verbania, mainly to obtain information on nutrient concentrations. An integrated layer sample was also collected and analyzed for *Chl-a* concentration in the laboratory. For this variable, the ISPRA *("Istituto Superiore per la Protezione e la Ricerca Ambientale")* protocol for the sampling of physical-chemical parameters supporting biological elements in lacustrine environments was followed. According to it, the depth of the integrated layer to be sampled was determined each time using the Secchi disk to identify the euphotic zone. Once the Secchi depth was measured, the value was multiplied by 2.5 to define the depth of the integrated layer. The integrated sample was composed of water sub-samples collected at regular intervals of 1 m down to such depth, which were then mixed.

The increased sampling frequency has certainly allowed a better understanding of the lake seasonal dynamics for the 2023-2025 years. For example, the data obtained from T_w and *DO* probes made it possible to assess the stratification state of the lake during different times of the year. Another important result was obtained from late-summer sampling, at the end of the stratification period, which provided information on maximum bottom *TP* concentrations.

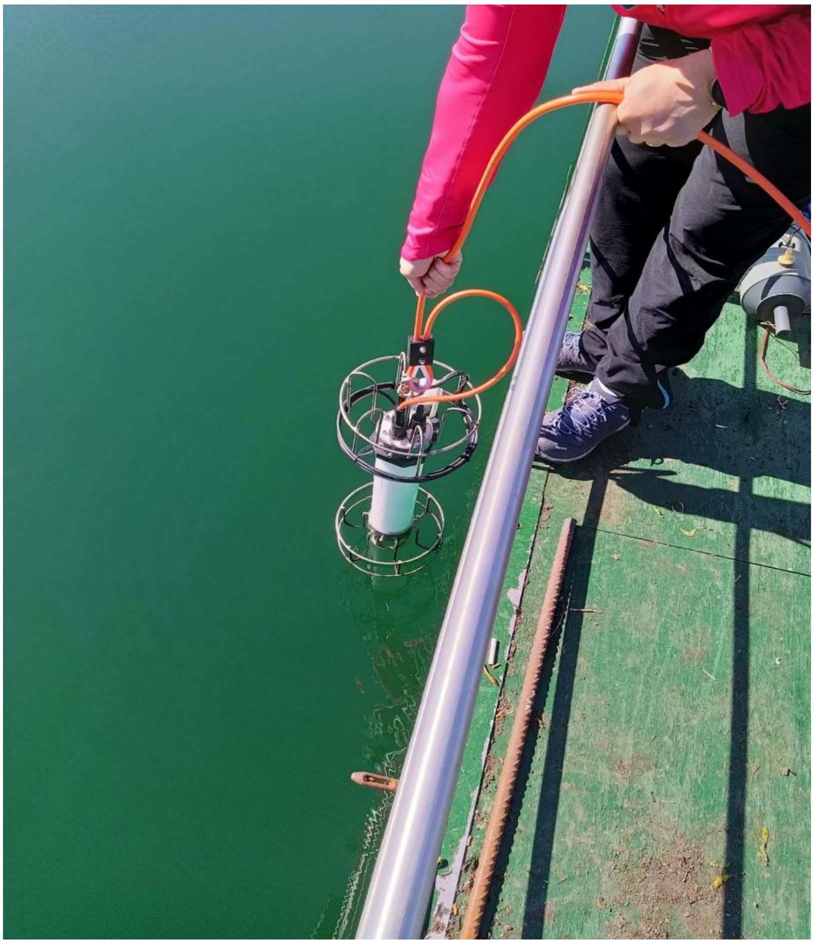

Figure 10. Use of the CTD probe IDRONAUT Ocean Seven Plus during the sampling activity carried out on the lake.

6.3 Activities performed on the catchment

The activities on the catchment initially started with water sampling from the streams but were later expanded to include discharge measurements and monitoring to address nutrient loads.

To such aim, specific cross-sections along the streams for flow rate measurement and monitoring had to be identified, which had to be close to the lake inlet to be representative of overall discharges and loads but still independent from lake level for rating curve assessments.

For the Lambrone stream, the chosen section was located near the SP639 bridge in the downtown of Erba, about 2 km upstream of the lake (Figure 11), while for the *Emissario del Segrino*, the section was placed about 200 m upstream of it, near the San Lorenzo church of the Eupilio municipality (Figure 12). Accessibility also played a part in the choice of both sections, extreme riverbed regularity also aiding measurements for the *Lambro Supralacuale* section.In this area shows good regularity. Finally, these same sections were used in studies made by CNR IRSA Brugherio about twenty years ago (Salerno, 2005), in which rating curves were determined and hydrometric staffs were installed, but had to be clearly redone due to stream morphological changes, yet they served as comparison with newly collected data. For Lambrone, the existing hydrometric staff was used to refer the hydrometric measurements of this work, In the case of the Lake Segrino outlet, the measuring section was moved a few meters upstream than the historical one to facilitate discharge measurements and the installation of the automatic level gauge. Therefore, the old hydrometric staff could not be used, so the variation in water depth was referenced to the intrados of the bridge leading to the church, from which hydraulic measurements were taken and the measuring device was installed.

Figure 13 shows the location of monitoring stations operated by ARPA Lombardia and CNR-IRSA along the rivers, as well as the lake monitoring station.


N
Gauging station on the Lambrone stream
Lambrone stream
0
250
500 m
(a)
(b)

Figure 11. Gauging section on the Lambrone stream, just upstream of the SP639 bridge in the downtown of Erba (a) and Satellite image showing the location of the Lambrone stream monitoring station (b) (Orthophoto courtesy of Google Satellite).

Figure 12. Gauging section on the Emissario del Segrino, near the bridge leading to the San Lorenzo church in the Eupilio municipality (a) and Satellite image showing the location of the Emissario Segrino monitoring station (b) (Orthophoto courtesy of Google Satellite).

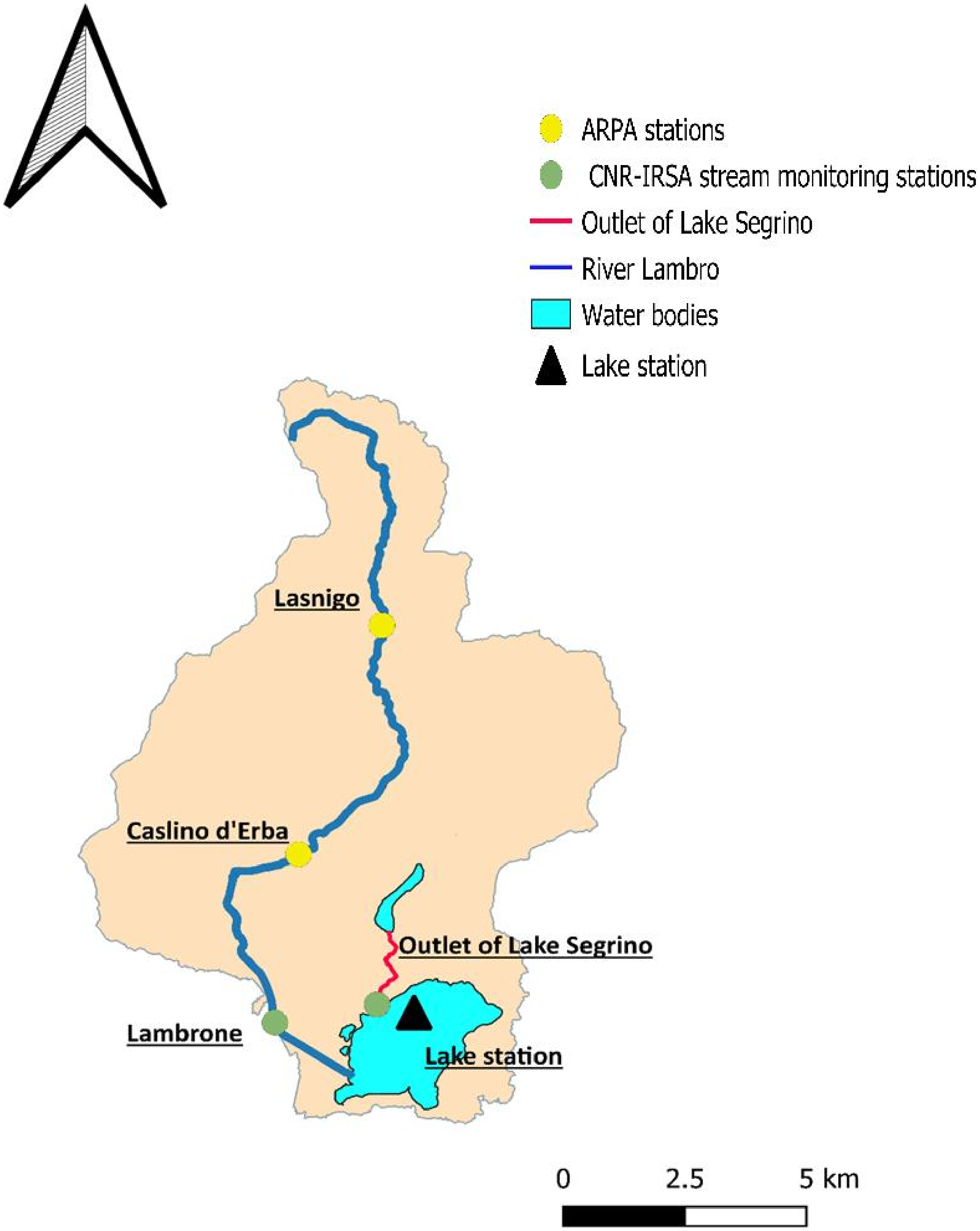

Figure 13. Map of the CNR-IRSA and ARPA Lombardia monitoring stations in the Pusiano watershed.

6.3.1 Discharge measurements

Discharge measurements were performed by determining flow velocities through a Valeport Model 002 mechanical current meter and later trough a Seba Hydrometrie FlowFlat electro-magnetic current meter and wetted areas through geometric surveys.

Measurements were performed according to the ISO 748:2021 regulations. The protocol begins with the measurement of the total width of the cross section (Figure 14), which is then divided into a suitable number of verticals where the water depth is recorded and velocity measurements are taken. In the case of the Lambrone stream, of approximate 1.0 m width, verticals were spaced 1 m apart, whereas in the Lake Segrino outlet they were spaced 30 cm apart. Since water depths in the sections never exceeded 50 cm, even under the highest flow conditions which were measured, the one-point method was employed, which prescribes one velocity measurement per vertical at 40% of the flow depth, measured from the bottom, where the mean value of the fully turbulent logarithmic profile is approximately located. Velocity was measured for a duration of one minute at each vertical (Figure 15), in order to obtain both an average value, smoothing out turbulent oscillations, and the standard deviation for each point. The mid-section method given in the ISO 748:2021 regulations was employed to compute discharges from field measurements. This method calculates total discharge Q as the sum of the partial discharges Q_i computed for each vertical:

$$Q = \sum_{i=1}^{n} Q_i$$

where n is the total number of verticals, and the generic partial discharge Q_i is given by:

$$Q_i = V_i h_i \frac{b_{i-1} + b_{i+1}}{2}$$

with:

- h_i : water depth at vertical i
- b_{i-1} : distance between verticals i and $i-1$

- b_{i+1} : distance between verticals i and $i+1$
- V_i : mean velocity at vertical i

The influence area of each vertical is hence defined as the depth at vertical *i* multiplied by half the distance between the preceding and following verticals *i-1* and *i+1*. For the residual half-distances in proximity of the riverbanks, discharge was assumed equal to zero if the bank was sloping down to null depth and vegetated. If, however, the bank consisted of a vertical wall, the velocity measured in the end vertical was extended up to the wall. This correction, which is not part of the original mid-section method, was applied to the hydraulic right bank of Lambrone section, where a concrete wall is present.

Tables 2 and 3 report the obtained discharge measurements, together with the corresponding hydrometric stage values read from the staff gauge for Lambrone and the distances from the bridge extrados for the Lake Segrino outlet stream. It is notable to observe that measurement days were selected to have the widest diverisity of stage and discharges within the practically measurable range, considering that surveys were done by means of wading on the Lambrone stream and from the church bridge through an extensible rod for the Lake Segrino outlet stream.

Date	**Level on the hydrometric staff**	**Discharge**
	[cm]	**[m^3/s]**
16/11/2023	*45*	*1.41*
12/12/2023	*40*	*0.78*
06/02/2024	*21*	*0.06*
21/05/2024	*68*	*6.08*
11/03/2025	*55*	*2.82*

Table 2. Stages and discharges from the measurements carried out on the Lambrone stream station

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Date	Distance from the intrados	Discharge
	[cm]	[l/s]
12/12/2023	*79*	*336*
21/05/2024	*69*	*706*
24/04/2024	*89*	*70*
09/04/2025	*94*	*56*

Table 3. Stages and discharges from the measurements carried out on the Lake Segrino outlet stream station.

Figure 14. Section survey and division into verticals at the Lambrone section.

Figure 15 . Measurement of velocity with the Valeport Model 002 current meter along the verticals at the Lambrone section.

6.3.2 Installation of water level and water temperature monitoring instruments

To calculate nutrient load series, discharge data on a daily basis at a station next to the river mouth are the first requirement. This principle led to the installation of the automatic level gauges on the final reaches of *Lambro Supralacuale* and *Emissario del Segrino*.

Two main categories of devices are available for water level monitoring:

1. **Non-contact devices** (e.g., ultrasonic or LIDAR sensors), typically installed on bridges. These work by sending a signal that is reflected by the water surface, the travel time being inversely related to the water level. They are widely used for large rivers, with the advantage of being unaffected by floods due to their placement high above water. However, they are bulky and difficult to install in constrained locations, especially in public areas.
2. **Submersible devices** (e.g., pressure transducers), which were adopted for this study. Pressure transducers measure the absolute pressure at a point. This pressure can be converted to a submerged depth if measurements of air pressure, needed to pass from absolute to relative water pressure, and of water temperature, needed to assess its density, are available. To do

this, the HOBO U20L-04 loggers were chosen, which also measure water temperature, which is a useful data for climate change studies and lake models. Furthermore, the temperature data is useful to identify the period in which the sensor is out of water due to lack of water in the stream. When this happens, in fact, the measured temperature shows much wider day-night oscillations, equalling the air temperatures measured by the third logger, which was placed near the Lake Segrino outlet stream sensor (Figure 16). As the altitude difference between the two stream sensors is negligible, this atmospheric sensor was used to transform the absolute pressures measured by both into relative ones.

To protect the HOBO loggers, they were placed inside perforated aluminum enclosures to allow water and air circulation (Figure 16), which were anchored to large boulders on the riverbed for stream sensors and attached (Figure 17) to a tree for the atmospheric sensor (Figure 18). The setup allowed easy data download by simply unscrewing the enclosure cap and connecting the device to the HOBO USB interface.

Figure 16. Metal enclosures of the automatic water level and temperature measuring devices installed on the Lambrone stream, on the outlet of Lake Segrino, plus the one used to measure reference atmospheric pressure in order to convert water pressure into level, in addition to air temperature.

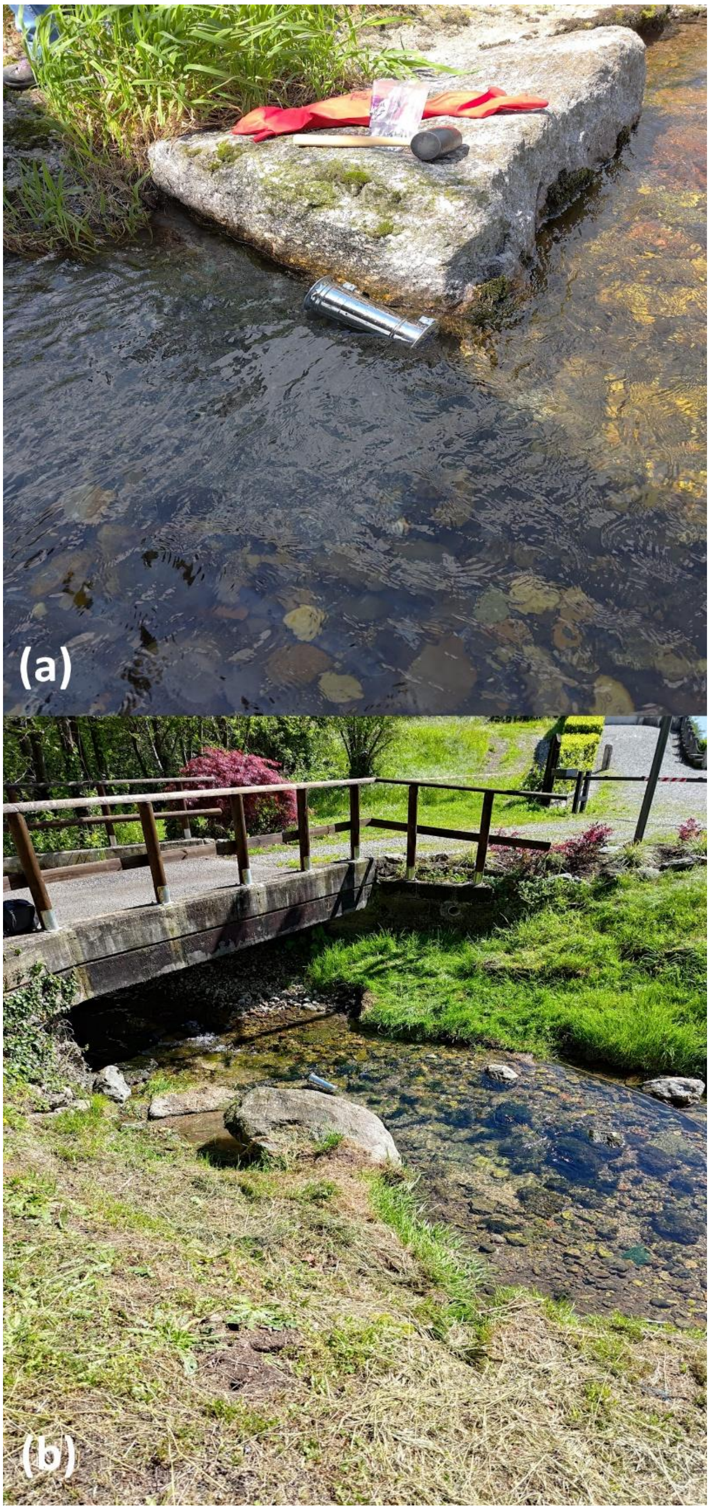

Figure 17. Installation of the HOBO monitoring device on the Lambrone stream (a) and on the outlet stream of Lake Segrino (b).

Figure 18. HOBO monitoring device installed next to the Lake Segrino outlet stream for measuring reference atmospheric pressure needed to convert the water pressures measured by the stream gauges into levels, in addition to air temperature.

6.3.3 Construction of rating curves

Rating curves were constructed from the series of stage and discharge measurements obtained from the surveys and the related post-processing activities.

For the Lambrone, the rating curve was developed with reference to the staff gauge (Figure 19), while for the Lake Segrino outlet stream(Figure 20), measurements were based on the distance between the bridge intrados and the water surface. For convenience, rating curves for both streams use as input the levels/distances expressed in [cm], the Lambrone stream one returning flow rates in [m^3/s] and the Lake Segrino outlet one in in [L/s]. Rating curves for both sections were derived using 2nd-degree polynomial regressions.

For the Lambrone stream (Figure 19), two different regressions were employed according to the stage, to obtain a better fit:

$$\boldsymbol{Q\ [m^3/s] = 0.0005h^2 - \ 0.00004h \text{ for } h < 0.4\ m}$$

$$\boldsymbol{Q\ [m^3/s] = 0.0042h^2 - 0.2620h + 4.5688 \text{ for } h \geq 0.4\ m}$$

where h [cm] is the stage, measured on the hydrometric staff. This subdivision of the rating curve is physically due to the change in the cross section, which is approximately rectangular up to $h \approx 0.4\ m$ and becomes thereafter trapezoidal, with a sharper increase in conveyance with stage due to widening. For the Lambrone section, the curve showed an excellent fit even at high discharges, with $R^2 = 0.9999$ for the first equation ($h < 40$ cm) and $R^2 = 0.9999$ for the second equation ($h > 40$ cm). These very high R^2 values are likely due to the artificial and extremely regular nature of the cross section. Moreover, the absence of vegetation on the bed, which is made by large cobbles, which are furthermore quite stable, , further contributes to the solidity of the rating curve.

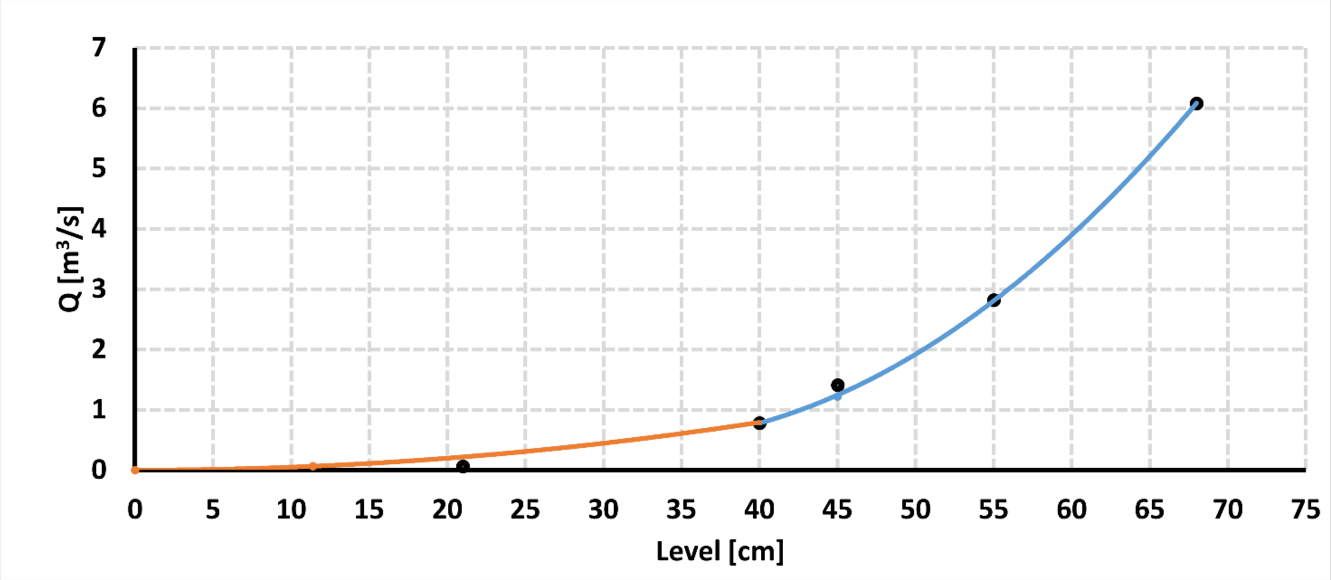

Figure 19. Rating curve of the Lambrone stream station (the two regressive equations are displayed through different colours), together with measurements.

The rating curve found for the Lake Segrino outlet stream is:

$$\boldsymbol{Q\ [L/s] = 0.8263h^2 - 161.4000h + 7913.4000}$$

where *h* [cm] is the distance from the bridge intrados.

In this case, an $R^2 = 0.9963$ is obtained, the lower value compared to the Lambrone station being due to the more irregular cross section, which is also partly vegetated and more prone to morphological changes.

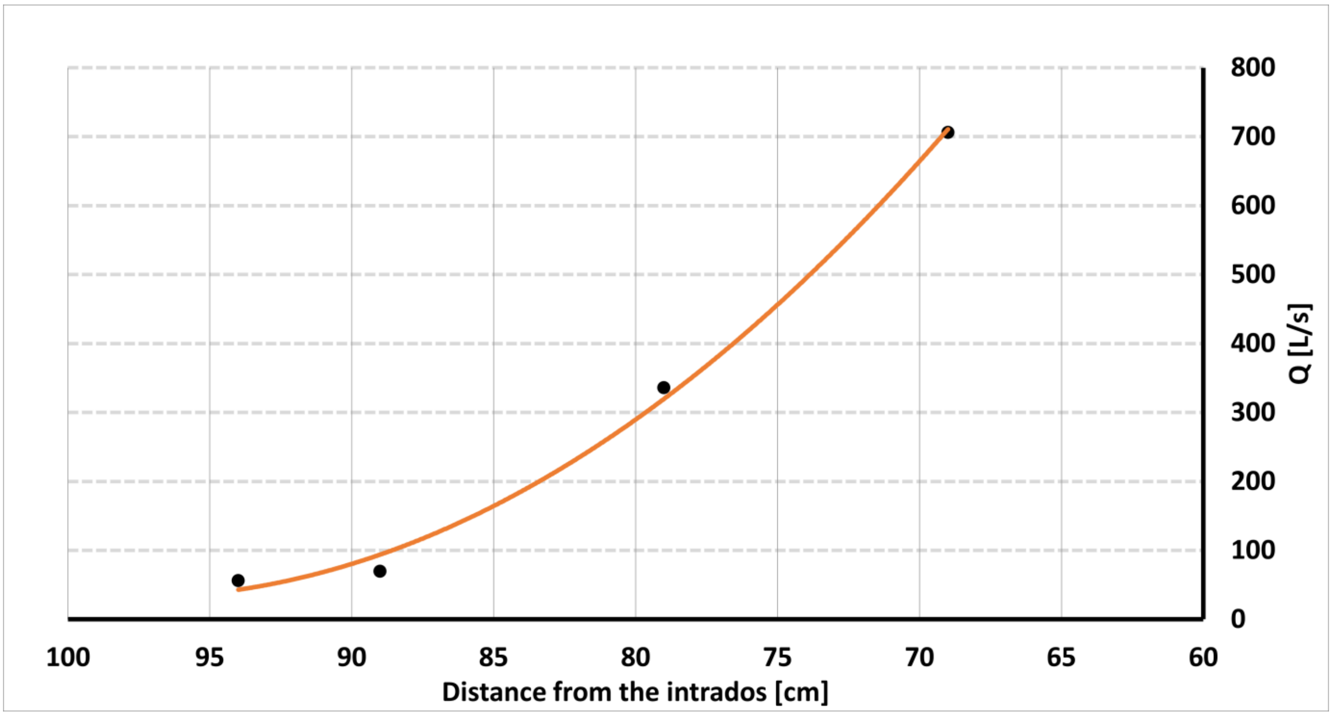

Figure 20. Rating curve of the Emissario Segrino outlet stream station, together with measurements.

6.3.4 Concentrations in the two streams

This section addresses the evaluation of nutrient concentrations obtained from the sampling campaigns performed on the tributaries of Lake Pusiano during the Ph.D. work. To compare the current situation with past conditions, present concentrations surveyed in 2024 at the Lambrone stream and at the Lake Segrino outlet stream were compared to those obtained from monthly samples collected by CNR-IRSA Brugherio in 2002. The year 2024 was chosen as a reference for the present period among those of the Ph.D. work because more data were available and the drought period had ended, to avoid considering too much peculiar conditions. The year 2002 was selected as reference for past conditions past conditions due to data availability, and to represent conditions before the interventions of the PIROGA project. The comparison focuses on *TP* and *TN* concentrations. It should be highlighted that sampling sections were practically coincident in the two years.

Figure 21 shows the graphs of *TP* and *TN* concentrations for the Lambrone stream. The monthly sampled *TP* concentrations in 2024 are consistently lower than those in 2002, especially in the last four months of the year, where *TP* concentrations in 2002 exceed 100 µg P/L in November due to a heavy flood event which occurred in late November 2002. The annual mean *TP* concentration in 2002 was 69 µgP/L, compared to 34 µg P/L in 2024. Regarding *TN*, concentrations were generally higher in 2002, except for April, a reduction in present times being evident. The mean annual concentration decreases from 3.40 mg N/L in 2002 to 3.00 mg N/L in 2024. Analyzing the *TP* and *TN* time series for 2024, it is noticeable that both peak in April, likely due to heavy spring rainfall, which likely caused a high nutrient load from runoff.

For the Lake Segrino outlet stream (Figure 22), *TP* concentrations show a slight increase from 2002 to 2024, with mean values rising from 49 µg P/L in 2002 to 68 µg P/L in 2024. *TP* peaked at 158 µg P/L in December 2024. *TN* shows a similar trend, with annual mean concentrations slightly increasing from 2.4 mg N/L in 2002 to 2.74 mg N/L in 2024.

Due to the comparability of annual rainfall between 2002 and 2024, the decrease in *TP* and *TN* concentrations observed on the Lambrone stream is a sign that an improvement in sewage collection efficiency has indeed been obtained through the years in the watershed, mainly through the actions of the PIROGA project. Concentrations obtained from sampling in 2023 and 2025 are consistent with those of 2024, proving this decrease in nutrient pollution. In contrast, the Lake Segrino outlet stream showed no reduction in nutrient load; the data even suggesting an increase. This is a sign that sewage contamination is still a reason of concern for this stream, which should be addressed. These high concentrations are primarily due to livestock-related and domestic discharges, which in case of contamination are active both during rain events and dry periods. This is also corroborated by the strong odor present in almost all conditions near the measurement section.

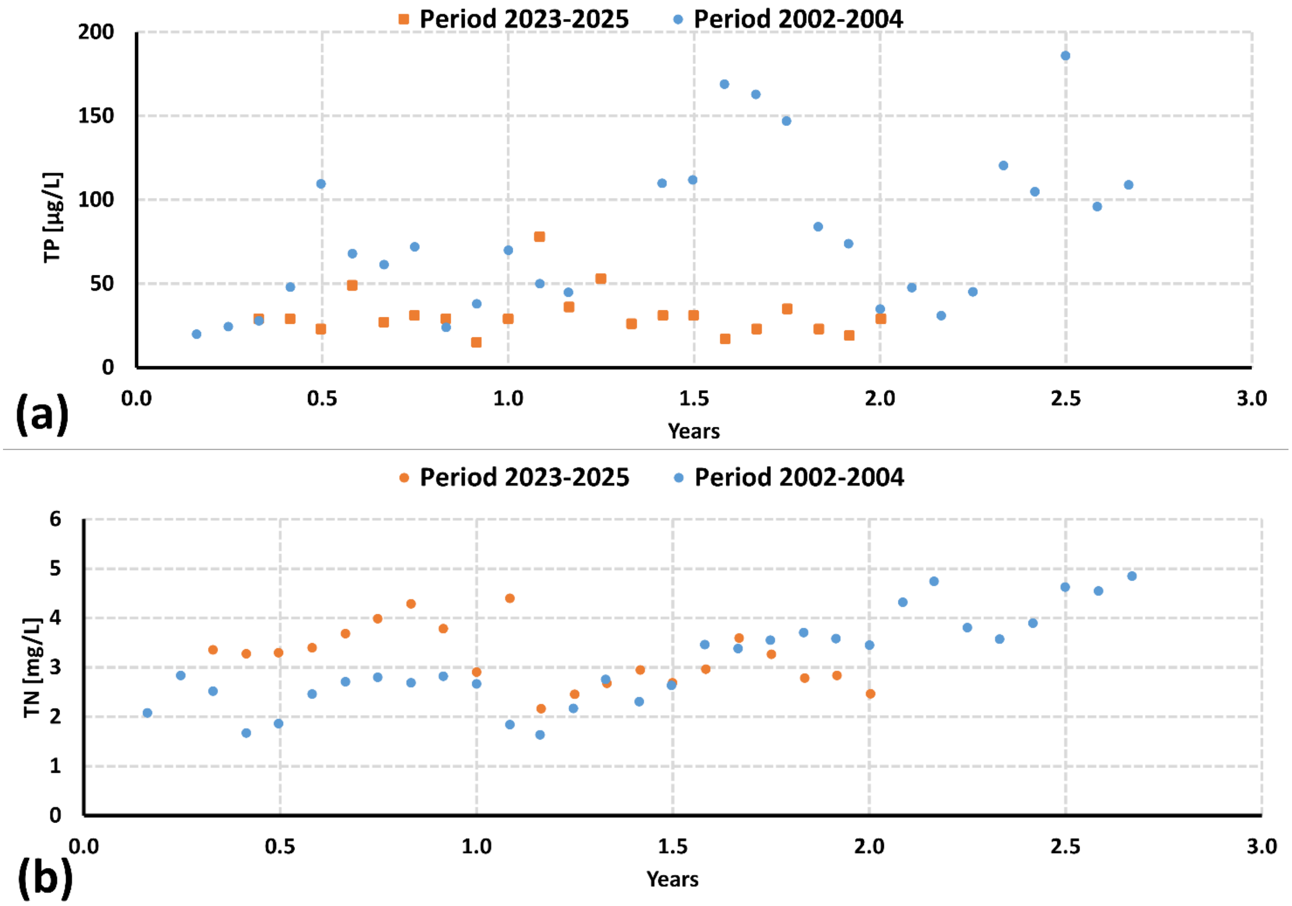

Figure 21 .Comparative analysis of TP (a) and TN (b) concentrations measured at the Lambrone station during the monitoring periods 2002–2004 and 2023–2025.

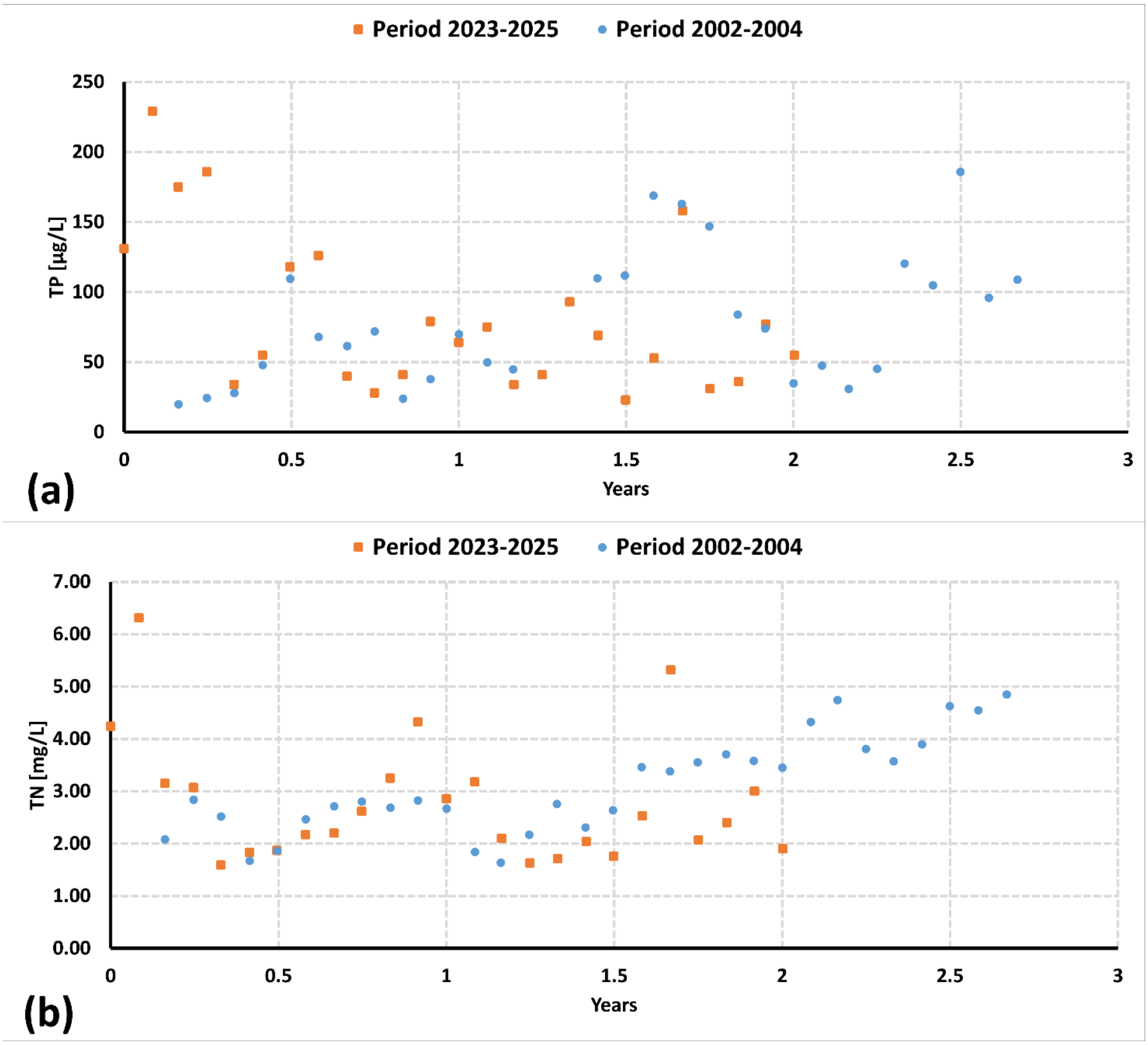

Figure 22. Comparative analysis of TP (a) and TN (b) concentrations measured at the Emissario Segrino station during the monitoring periods 2002–2004 and 2023–2025.

6.4 Estimation of nutrient loads at the Lambrone station from observations and comparison with SWAT+ numerical modelling

To compare the nutrient loads obtained from the SWAT+ model with those which can be estimated from field measurements at the Lambrone station, which is made possible with some approximation for 2023 and 2024 due to the pursued increased sampling frequency, it is first necessary to reconstruct the daily mean discharge series at such station. To such aim, the monitored discharge series at the Lambrone station starts from April 2024, so it is necessary to find a regression of the own discharge series with the upstream one in Caslino d'Erba by ARPA Lombardia, available since 2004, to estimate the previous data. Figure 23 shows the two series for the period of common availability 25th April 2024 – 9th April 2025, whereas Figure 24 displays the linear regression between them, which has the following equation:

$$Q_{Lambrone} = 1.5145Q_{Caslino} - 0.4626$$

where the flow rates are expressed in [m^3/s]. This regression yields $R^2 = 0.9866$. The two sections are ~4 km apart, and there are no additional ordinary inflows except for the Bova stream, which is the last right-bank tributary of the Lambro upstream of Lake Pusiano. This plays a part in the high R^2 value.

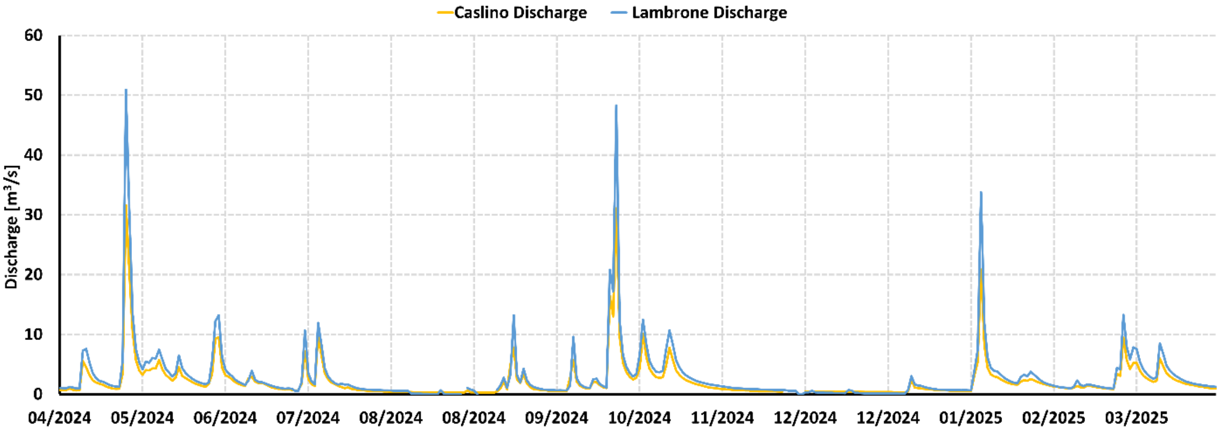

Figure 23. Comparison between the discharges at the Caslino (ARPA Lombardia) and Lambrone (own) stations from April 2024 to April 2025.

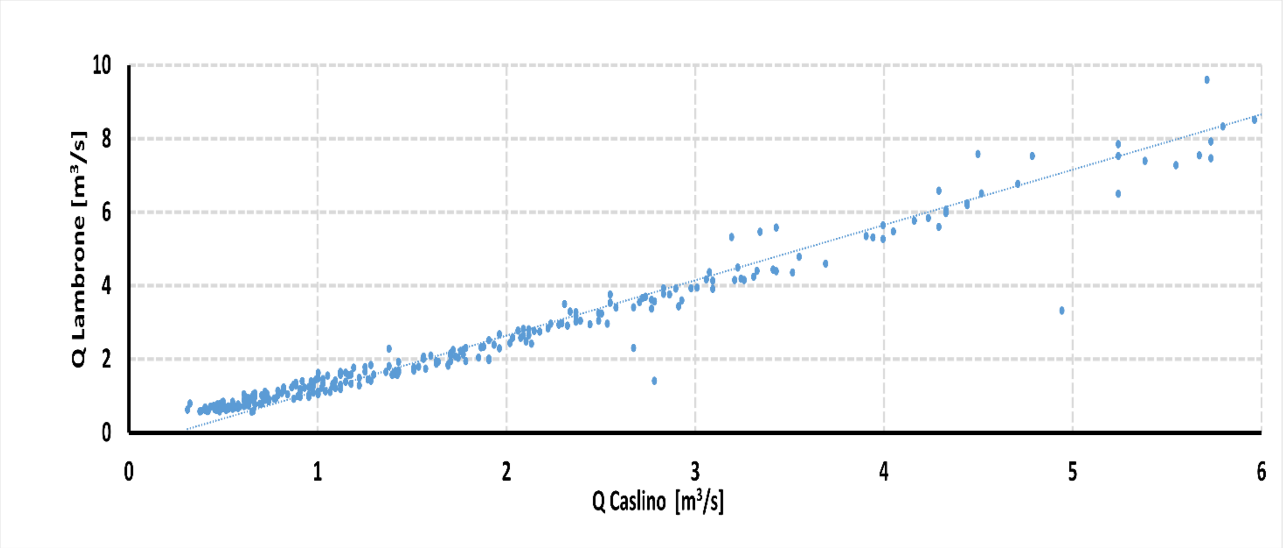

Figure 24. Linear regression between the April 2024 – April 2025 discharge series at the Caslino and Lambrone stations.

The regression linking the two discharges has a negative intercept. This term accounts for the physical phenomenon whereby, when discharge at Caslino is below ~0.46 m³/s, there is effectively no visible flow at the Lambrone section. This behavior is caused by groundwater subsidence due to the coarse granulometry of the riverbed, which allows part of the surface flow to infiltrate within the sediments as hyporheic flow. This observation is consistent with the measurements and field observations. The slope coefficient is instead > 1, returning higher discharges at the Lambrone station than at the Caslino one under ordinary and flood conditions, due to the larger drained area.

Once that mean daily discharges were determined for 2023-2024, the USGS LOADEST software (see Chapter 2) was applied to determine the load series, using as input such daily discharges and the available ~monthly samples.

The nutrient loads estimated for 2023-2024 through three different techniques are hereinafter compared, these being:

1. **SWAT+ eco-hydrological process-based modelling**;
2. **LOADEST software**, whose results derive from statistical regressions obtained directly from collected samples;
3. **the commonly adopted averaging method (**Moatar and Meybeck, 2005; Phillips et al., 1999; Verhoff et al., 1980; Walling and Webb, 1985), an interpolation-based approach that

considers the mean concentration and the mean discharge over all sampling days to compute a mean annual load L:

$$L = K\left(\frac{\sum_{i=1}^{n} c_i}{n}\right)\left(\frac{\sum_{i=1}^{n} Q_i}{n}\right)$$

where k is a conversion factor to account for the measurement units, n is the overall number of samples and c_i and Q_i are the generic sampled concentration and discharge, respectively.

Orthophosphate$P\text{-}PO_4$ is considered in this evaluation as: 1) P is the limiting nutrient still controlling lake trophic status; 2) this fraction of TP was explicitly calibrated in SWAT+ (see Chapter 2)

As shown in Figure 25, differences between the three methods are apparent for $P\text{-}PO_4$. For all three methods, the $P\text{-}PO_4$ load was much lower in 2023 than in 2024. This is primarily due to the low rainfall in the first part of 2023, with drought conditions persisting until April (1565 mm total annual precipitation at the Caslino d'Erba station). In contrast, 2024 was much wetter (2104 mm total annual precipitation at the Caslino d'Erba station), resulting in higher nutrient load. SWAT+ consistently produces the highest $P\text{-}PO_4$ loads in both 2023 and 2024. This is likely because the averaging method employs discharges and concentrations typically collected only during dry periods, water sampling being impossible during flood events, in which large nutrient loads are released. The same flaw affects the LOADEST estimation, leading to a biased regression. In this case, it is possible that considering biased daily regressed values leads to annual loads which are even lower than those of the averaging method. Even though the same sample data were used for SWAT+ model calibration, the model was free to reproduce nutrient wash-out dynamics during floods, leading to higher loads, which are deemed to be more realistic and prove the relevance of the eco-hydrological modelling effort undertaken in this thesis, other techniques likely leading to underestimations.

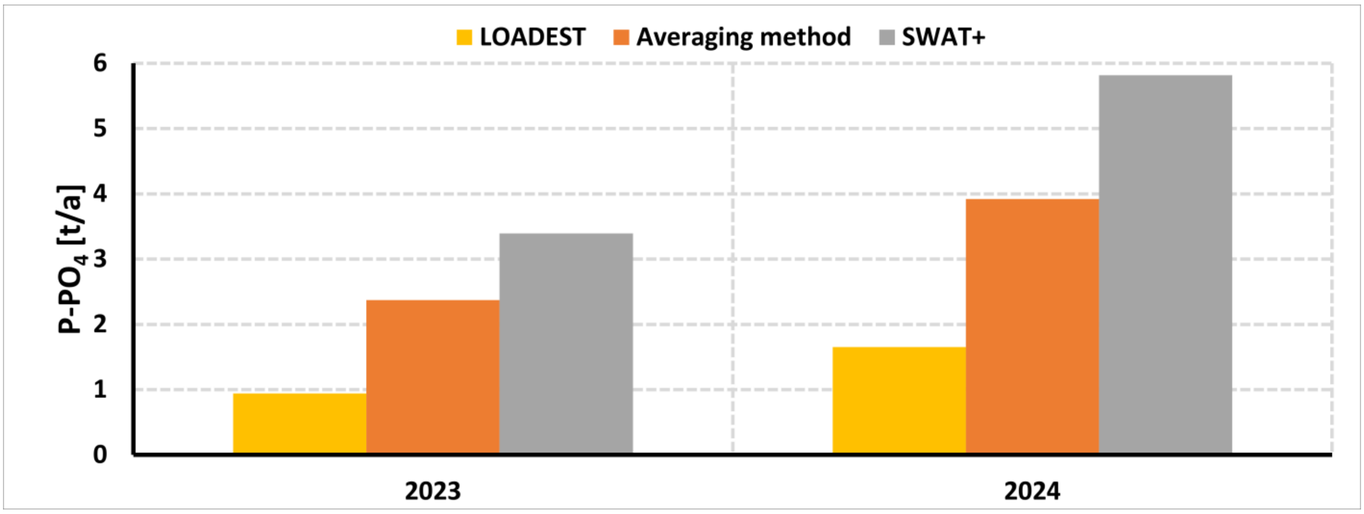

Figure 25. Comparison between the total annual P-PO$_4$ *loads evaluated with LOADEST, the averaging method and SWAT+ at the Lambrone station for the 2023-2024 years.*

7. Overall Conclusions

7.1 General Summary of the Outcomes

The performed analyses and the data collected throughout this Ph.D. thesis allow for the formulation of several relevant statements on the Lake Pusiano case study, which can give an insight on the likely evolution of similar basins exposed to climate change and nutrient pollution pressures.

The initial target of this work was to develop models to assess whether the lakes under study in Lombardy can achieve the "good" ecological status by 2027 in terms of total phosphorus (*TP*) concentration at spring overturn, as required by the regional Water Protection and Use Plan (PTUA). The implemented models made it possible to define more realistic target thresholds compared to previous ones. Subsequently, different models were developed to investigate the Lake Pusiano case study in much greater depth, leading to significant findings.

In the first chapter of the core of the thesis, based on the article *"Use of process-based coupled ecological-hydrodynamic models to support lake water ecosystem service protection planning at the regional scale"*, several 1D coupled ecological-hydrodynamic models were developed for lakes in the Lombardy region of Northern Italy. Starting to deal with the specific case study of the thesis, Lake Pusiano was therein modeled in the WET software, with constant nutrient loading as input. This model enabled an assessment of *TP* concentrations at spring mixing in relation to water quality goals. Observations highlighted a decreasing trend in *TP* concentrations for Lake Pusiano between 2007 and 2021. However, model results, consistently with recent data obtained after 2021, predict an increase in spring-mixing *TP* concentrations with the present assumed nutrient loading levels. This is to be attributed to these likely being not low enough for an equilibrium to be obtained under present and future climate change. Near-future simulation scenarios up to 2051, also involving 15% and 30% nutrient load reductions, showed that only in the latter case was a stabilization of spring-mixing *TP* levels observed, complying with the presently assumed *TP* target concentration of 30 µg/L, which was otherwise exceeded.

The second chapter of the core of the thesis, based on the article *"Assessment of external and internal nutrient loads to Lake Pusiano (Northern Italy) using watershed eco-hydrological modelling and lake ecological-hydrodynamic simulations"*, involved the coupled use of the WET and SWAT+ models. SWAT+ enabled the estimation of nutrient loads from the watershed, notably reproducing the interannual variability with rainfall, an extremely important insight which was previously unavailable for the Lake Pusiano case study. The mean annual loads obtained from the SWAT+ eco-hydrological model were found to be consistent with available mean estimates obtained from different methodologies reported in the literature. The produced nutrient load daily series were used as input for the WET lake model, improving its results for the variables which more directly depend on external-load variability. Additionally, the WET model was notably used for a direct, process-based estimation of internal phosphorus loading release from sediments. This is another element of novelty of this work, as indirect estimation techniques based on water phosphorus concentrations are commonly employed to such aim. The estimated internal loading was compared with the external loading computed by SWAT+. An external nutrient-load reduction scenario based on a realistic implementation of Best Management Practices (BMPs) on the watershed, namely filter strips on urban and agricultural areas, confirmed that the 12% phosphorus load reduction obtained from such low-impact intervention is insufficient to meet the target concentration of 30 µg/L in the near future. "Hard" interventions on the watershed, aiming at higher reductions, thus appear to be needed. As a matter of fact, in recent years, particularly over the past decade, observed *TP* concentrations on Lake Pusiano at spring mixing have frequently exceeded the PTUA threshold of 30 µg/L.

In the third chapter of the core of the thesis, derived from the article *"The recent trophic decline of Lake Pusiano (Northern Italy) assessed by integrated lake-catchment modelling"*, several models were used to investigate the causes of water quality deterioration in Lake Pusiano during an extended drought period. The SWAT+-WET model results suggested that during 2022–2024, and especially during the jointly hot and dry summer 2022, strong anoxic conditions developed, affecting even shallower-than-usual, littoral zones of the lake, leading to increased anoxic volumes and sediment area, boosting phosphorus release and consequently internal loading from sediments, originating not only at maximum depths but also in shallow zones. These conditions led to a relevant nutrient mass being made available for primary production, despite the low-to-null external loads of the drought period, which was recycled during later years and supported by external loading in the rainy 2024 year. This led to the intense observed cyanobacterial blooms, which occurred even during the winter in hotter-than-usual days. A 3D hydrodynamic model developed in Delft3D D-Flow further allowed for the analysis of the hydrodynamic impact of the entrance of the Lambrone stream during periods of strong summer stratification, under different discharge scenarios. Under all simulated Lambrone discharge conditions, the stream water does not penetrate beyond 5 meters depth due to the mouth being in a shallow peripheral area outside of the main deep lake basin, acting as a topographical constraint. Because of this, even under the highest simulated flood flow, the colder Lambrone inflow did not plunge deeper towards the depth of neutral buoyancy, also due to the strong stratification rapidly warming intruded water with turbulent entrainment. In the scenario with minimum discharge, representing the typical conditions of summer 2022, flow of the stream towards the main lake basin was extremely limited, part of the inflow short-circuiting towards the lake outlet nearby, further limiting water renewal. This surely contributed to triggering the biochemical processes discussed before. For the tested flood flow, instead, a definite riverine-like stream forms inside the lake, fostering rapid water renewal in the surface layer. Overall, this chapter addresses how extreme events related to climate change can significantly impact lake ecosystems, which are inherently fragile and vulnerable environments. This is especially true for temperate lakes in the depth range of Lake Pusiano, which are deep enough to seasonally stratify, furthermore with an anoxic hypolimnion, thus being exposed to internal loading problems, but at the same time are not deep enough to mitigate the impact of external load peaks with heavy rainfalls. In particular, it shows how the 2022 drought triggered a progressive deterioration in water quality, the effects of which are still evident today due to nutrient recycling.

Performed field activities for monitoring lake and tributary stream waters under the chemical, biological and hydrological point of views were described in the fourth chapter. Results of 2023-2025 water sampling were presented and compared with past ones from the period 2002-2004. The results showed that nutrient concentrations from the Lambrone stream and the Segrino lake outlet have not displayed a further decrease compared to those values, which were sampled after major interventions on the watershed had been completed. This confirms that, unless further actions to make the sewer network more efficient are performed, external nutrient loading will not change. The present sampling campaign began during a drought period, which may have influenced nutrient concentration values. Measured nutrient concentrations and flow rates for both streams were used to calculate loads, which were compared with SWAT+ results. The comparison showed that SWAT+-predicted loads were higher than those obtained via regression and interpolation of field values. This was mainly attributed to field sampling not covering rain events, in which non-linear increases of nutrient loading take place. Field measurements also provided essential data for model calibration and input.

7.2 Concluding Remarks

This Ph.D. thesis represents a relevant contribution, as Lake Pusiano and its watershed was modeled and analyzed under various conditions and perspectives. The models allowed for an insight on past changes, present conditions, and future trends, adding up to previous knowledge. A dual focus on hydrodynamics and biogeochemical processes was adopted throughout.

The coupling of SWAT+ and WET models accounted for climate, land use, hydrology, and water quality within the watershed and dynamically integrated them with the lake internal processes on the vertical, such as thermal stratification, oxygen dynamics, and the distribution nutrients. Modelling lake hydrodynamic processes together with biogeochemical ones is essential in the context of climate change, which strongly influences physical dynamics, in turn affecting lake chemistry and ecology.

The WET model made it possible to estimate internal phosphorus loading from sediment release, a task usually performed through complex and indirect methods based on hypolimnetic nutrient concentrations. The coupled SWAT+-WET approach applied herein is flexible enough to be extended to other lakes. The SWAT+ model, when driven by precipitation input, outputs nutrient loads to be used as input for WET, allowing for scenario development addressing nutrient delivery variations with rainfall regime modifications induced by climate change.

All in all, in a world increasingly affected by pollution and climate change pressures, process-based models are essential tools for environmental management and planning, allowing for the evaluation of manifold scenarios.

7.3 Present Limitations and Future Perspectives

Any environmental modeling effort involves uncertainty due to the complexity of the real systems and processes being represented and, in summary, simplified and somehow parameterized. Lakes are particularly challenging to model because of their highly dynamic internal conditions, in which physical, chemical and biological spheres are mutually interdependent.

The available lake and stream concentration data represented the best possible dataset and were instrumental for model calibrations. An inherent problem appears in the non-constant lake sampling depths adopted by ARPA Lombardia when used for scientific research. Use for long-term data-series monitoring and analysis is in fact hampered, constant depths being needed for such important task. Furthermore, under the sediment phosphorus release conditions of Lake Pusiano, it would be more effective to take the bottom sample at a given constant distance from the bottom rather than from the surface, to consider lake level variations and slight differences in the location of the sampling vertical among campaigns. This would prevent the sample position inside the steep concentration gradient at the bottom from overly affecting time series. About tributary stream sampling, general missing coverage of rain conditions remains an important limitation. As regards both sampling activities.

model accuracy is directly influenced by the quality of calibration, which depends on data availability. More frequent sampling (e.g., every 15 days) would greatly improve model performance, but it would also allow getting a deeper insight into lake processes, such as during the hot, dry summer 2022. In this sense, the installation of a limnological buoy would prove highly valuable, providing high-frequency data on parameters such as water temperature and dissolved oxygen and Chlorophyll-a concentrations over the water column, which are critical to identifying mixing events, stratification/anoxia periods and phytoplankton blooms. This type of high-frequency monitoring (HFM) is becoming the new ideal standard in lake monitoring due to the continuous, high-resolution data it provides.

Phytoplankton modeling in WET was done through a single group, using Chlorophyll-a as a calibration proxy. This is a clear limitation, even though a detailed reproduction of phytoplankton intra-annual succession dynamics was never an explicit target of this work. Furthermore, HFM data would be needed to really understand short-term phytoplankton dynamics, both for modeling and data analysis purposes. Last, differences in data collection methods between ARPA Lombardia (integrated samples) and CNR-IRSA (Fluoroprobe) could not ensure a perfect consistency of the available series.

As regards the modeling chain, errors in the SWAT+ ecohydrological model on the reconstruction of load series propagate to the lake model, impairing WET model performances. Additionally, the 1D hydrodynamic modeling in WET, while useful to make long-term limnological evaluations, provides only a horizontally averaged representation of lake conditions. Because of this, a perfect agreement of epilimnetic nutrient and especially Chlorophyll-a concentrations could never be obtained, these variables having heterogeneous values over the lake surface (horizontal patchiness). Some detailed insights were gained in this work from the 3D hydrodynamic model, but such models are computationally intensive and unsuitable for long-term simulations, especially if coupled with ecological modules. Combining high-resolution (space and time) qualitative outputs with long timescales remains difficult, also as regards obtaining the spatially distributed data needed for an optimal calibration and setup of 3D models. Presently implemented phytoplankton modeling could be improved by incorporating biomass and biovolume data for group of species, which are available for Lake Pusiano. These could help identifying the onset of algal blooms and reproducing group succession, at the cost of making the model more complicated and more difficult to calibrate.

As a further modeling work development, climate change scenarios could be applied to the SWAT+-WET chain, enabling realistic projections to be developed for Lake Pusiano.

In terms of fieldwork, monitoring could be expanded to include previously unmonitored streams, such as the small irrigation canals *Roggia Molinara* and *Roggia Gallarana* near their mouth into the lake, and the lake outlet stream. Measuring their flow rates and nutrient concentrations would improve the understanding of Lake Pusiano nutrient budget. Lake monitoring could also benefit from sediment sampling at multiple locations, including both the deepest area and shallower zones, to actually estimate the phosphorus pools at each point, determine the released fluxes, and refine WET model parameters related to sediment release. It would be interesting to validate SWAT+-WET model predictions regarding the hypothesis that anoxic volumes have recently extended to shallower nearshore areas, triggering exceptional phosphorus release. CTD profiles of dissolved oxygen concentration should be taken together with sediment analysis for such an assessment.

Another useful line of investigation would involve sampling benthic macroinvertebrates, which serve as bioindicators and could provide additional insights into water quality.

In conclusion, modeling enables the integration and interpretation of vast datasets, allowing for a level of understanding that was impossible just a few decades ago. Although models are still and always will be simplifications and cannot fully capture the complexity of reality, they are indispensable tools for limnological studies. To validate models and truly understand lake dynamics, modeling must be integrated with rigorous fieldwork. This thesis has aimed to show that models must be firmly grounded in observed reality. Field investigations were essential to understanding the lake behavior in recent years and contributed significantly to achieving more accurate and reliable results.

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