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Highlights

- Combined effect of septic systems and climate change are assessed on lake P.
- Lake quality is likely to shift from oligotrophic to meso-eutrophic in the future.
- Radiative forcing differences are small compared to human pressures.
- Larger household size and occupancy accelerate lake degradation.
- Septic system upgrades delay eutrophication under climate change.

Can Septic-System Management Practices Outweigh Climatic and Anthropogenic Drivers of Phosphorus-induced Lake Eutrophication?

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Abstract: Excess phosphorus loading is a major driver of lake eutrophication, with significant consequences for aquatic ecosystems and human health. The contribution of septic systems to lake phosphorus concentrations has recently become an increasing concern. However, the combined effects of evolving septic-system conditions and climate change remain poorly understood. Here, we assess lake phosphorus dynamics using an integrated septic system-lake phosphorus model that simulates septic contributions as a function of system age, operational performance, and soil characteristics. For future conditions, climate scenarios are based on an ensemble of climate projections under Shared Socioeconomic Pathways (SSPs) 2-4.5 and 5-8.5, while anthropogenic scenarios include variations in household population density, occupancy rates, and septic-system compliance. Results for a lake in Quebec, Canada, indicate that climate change alone increases the likelihood of a transition from oligotrophic toward meso-eutrophic conditions under status quo human activities. Anthropogenic pressures exert a stronger influence: increased population density, followed by higher occupancy rates and reduced septic-system performance, substantially accelerates lake degradation. The implementation of source-separation technology significantly improves water quality, although its impacts differ slightly between the two SSPs. Under current anthropogenic conditions, septic-system upgrades can maintain a healthy lake state, while under increased human pressure, they can delay the onset of eutrophic conditions. Proactive management of watershed development and septic-system performance is therefore essential to prevent long-term degradation of lake water quality under changing conditions.

Keywords:

Septic systems

Lake phosphorus

Climate change

CMIP6

Integrated Lake phosphorus model

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1 Introduction

Excess phosphorus inputs from agriculture, urban runoff, and decentralized wastewater systems are widely recognized as primary drivers of freshwater eutrophication (Correll, 1998; Raulino et al., 2021). Elevated phosphorus concentrations degrade lake ecosystems, impair recreational uses, and threaten drinking water supplies. Among these sources, septic systems, which are the most common form of decentralized domestic wastewater treatment, represent a potentially significant yet frequently underrepresented contributor of phosphorus (Withers et al., 2014). Septic systems are commonly used across most countries, particularly in rural and remote areas, with more than 1 billion people globally relying on them as their primary sanitation solution (Industry Research, 2025). In Canada, approximately 15 % of households depend on septic systems (Statistics Canada, 2011). Lakes located near such systems are therefore particularly vulnerable to water quality degradation (Wang et al., 2024), yet monitoring and regulatory oversight remain limited (Swann, 2001). Reported annual failure rates of 10 % to 20 % are associated with improper siting, inadequate maintenance, overloading, unsuitable soil conditions, and hydrogeological constraints (Sarac et al., 2001; Sprouse et al., 2024). Additional factors, including household size and water use patterns, can further compromise system performance, increasing phosphorus release to groundwater and surface waters (Ravi & Johnson, 2021).

Climate change is expected to intensify these pressures by altering hydrological regimes and thermal dynamics (Asif et al., 2023; Gedney et al., 2006). Increases in rainfall intensity and runoff enhance phosphorus transport (Tilahun et al., 2025), while rising air temperatures elevate water temperatures and modify stratification patterns, oxygen availability, and sediment-water interactions (Cheng et al., 2020; Harvey et al., 2011). Consequently, preserving lake water quality requires an improved understanding of the combined effects of climate change and septic system performance on phosphorus dynamics. Future climate conditions are commonly projected using Global Climate Models (GCMs), which provide physically based representations of the Earth's climate system (Salehie et al., 2023). Recent simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) offer projections under Shared Socioeconomic Pathways (SSPs), which describe alternative trajectories of population growth, land use, technological development, and greenhouse gas emissions (Eyring et al., 2016; Riahi et al., 2017; Tebaldi et al., 2021). Since raw GCM outputs are typically too coarse for regional analyses, downscaling techniques are applied to translate projections to relevant spatial and temporal resolutions (Gebrechorkos et al., 2023; Meenu et al., 2013). These downscaled climate data are then coupled with watershed models to estimate future phosphorus export (Tilahun et al., 2025;

van Puijenbroek et al., 2014) or with lake models to determine phosphorus concentrations under a changing climate (Terry & Lindenschmidt, 2023).

Despite these advances, important limitations remain. Most lake phosphorus impact assessment studies either neglect septic system contributions entirely (Robertson et al., 2016) or represent them using static export coefficients that fail to account for temporal dynamics in septic system performance, including aging, regulatory compliance rates, and maintenance practices (Roberts et al., 2009; van Puijenbroek et al., 2014). While combined impacts of climate change and population growth on lakes have been explored (Couture et al., 2014; Jin et al., 2015), the coupled effects of climate change and progressive septic system deterioration on future lake phosphorus concentrations remain poorly quantified. Moreover, the effectiveness of septic management strategies in mitigating climate and development-driven increases in phosphorus loading is still uncertain.

This study addresses these gaps by evaluating the combined impacts of climate change and septic system-related anthropogenic pressures on lake phosphorus concentrations using an integrated septic system-lake modeling framework. Septic system conformity (or compliance) is represented as a function of system age, operational performance (e.g., tank and drain field condition, distance from lake), and soil characteristics such as bulk density and phosphorus adsorption capacity. The model simulates phosphorus transport through both surface and underground pathways, accounting for attenuation processes and time lags in nutrient delivery to receiving lakes. The lake model dynamically simulates phosphorus concentration considering lake water volume and mass of phosphorus in the system. Downscaled climate projections under multiple SSP scenarios are incorporated, along with future anthropogenic scenarios that include increased wastewater generation (driven by population growth and occupancy patterns) and higher rates of septic system failure. Finally, management scenarios, including technological upgrades, are evaluated to assess their potential to offset projected increases in phosphorus loading under changing climatic and socio-environmental conditions. The framework is applied to the Lake en Coeur Basin in Quebec, Canada, a rural watershed containing more than 100 septic systems and no significant agricultural or urban phosphorus sources. Recent concerns regarding declining water quality and increasing phosphorus concentrations have been raised by local stakeholders. Since septic systems constitute the dominant anthropogenic phosphorus source in this basin, the watershed provides a relatively controlled setting to directly evaluate their impact on lake water quality under changing conditions. In addition, since septic systems represent the primary manageable source of nutrient inputs, the basin offers an opportunity to assess how improvements in septic system management may influence future lake phosphorus concentrations and eutrophication risk. The site is also representative of many rural lake watersheds in Canada (Chaffin et al., 2014; Scavia et al., 2014) and elsewhere, where dense lakeshore development relies on septic systems and where water quality concerns are increasingly reported (Oldfield et al., 2020). More details regarding the study area are presented below.

2 Case study

The Lake en Coeur watershed (1.70 km^2) is located in the municipality of St-Hippolyte in the Laurentian region of Quebec, Canada. It has an annual total precipitation of 1200 mm, and the annual temperature of 4.4 °C (Government of Canada, 2025). The watershed is centered around Lake en Coeur, with an area of 0.44 km^2, as shown in **Fig. 1**. The lake provides various services to the local community and harbours several fish species, such as brook trout and other salmonids, whose survival depends on the oxygen concentration. The watershed is a part of the Laurentian Biology Station, implemented for research and educational purposes, and benefits from a provisional status as a biodiversity reserve (Herischi et al., 2018). Land cover is predominantly forested; however, residential development is concentrated along the lake shoreline (**Fig. 1**). Out of the 108 houses, 100 are situated less than 100 meters from the lake (Herischi et al., 2018). These residences primarily rely on septic systems for wastewater treatment. As the population density around the lake relative to its surface area is considerable, concerns have been raised regarding septic systems' role in the alteration of the natural phosphorus concentration in the lake.

Indeed, concerns regarding water quality degradation emerged between 2003 and 2007, prompting investigation into the potential contribution of septic systems. As a result, a monitoring program between 2007 and 2016 was implemented and the inspection of 100 septic systems revealed that about 88 % of them comply with regional regulations (Herischi et al., 2018). Lake's phosphorus concentrations have been monitored since 2006 by the *Réseau de Surveillance Volontaire des Lacs* (RSVL); however, the dataset is not continuous and contains missing data. While currently the phosphorus concentration is below the oligotrophic threshold of 0.01 mg P/L set by the Government of Quebec (Berryman, 2006) to preserve lakes health, stakeholders have expressed concern regarding the future trajectory of phosphorus concentration under changing environmental and anthropogenic conditions. Since Lake en Coeur's main anthropogenic phosphorus export is attributed to septic systems, it is an ideal case study to evaluate their isolated impact on lake water quality.

3 Materials and methods

3.1 Lake phosphorus model

Lake phosphorus concentrations were simulated using the model developed in Oniga et al. (2026), see Section S1 of the Supplementary Materials for details. In brief, the model computes coupled annual water and phosphorus mass balances of the lake, with annual phosphorus concentration obtained by dividing total phosphorus mass by lake volume. The lake water balance is expressed as:

$$S_{lake}(t) = S_{lake}(t_0) + \int_{t_0}^{t} S_{sep,surf}(t) + S_{sep,gw}(t) + S_{runoff}(t) + S_{precip}(t) - S_{evap}(t) - S_{outflow}(t) - S_{seepage}\ dt \quad (1)$$

where, S_{lake} (m^3) is the lake water storage and $S_{lake}(t_0)$ is the lake initial volume, set to 1,347,000 m^3, based on bathymetric estimates reported by Herischi et al. (2018). Lake area (0.44 km^2) and catchment area (1.7 km^2) as well as their delineations were derived from GIS analysis (Rosas-Chavoya et al., 2022) and are consistent with values reported in the Lake en Coeur management plan (Herischi et al., 2018). $S_{\text{sep,surf}}$ and $S_{\text{sep,gw}}$ represent water inputs from septic systems via surface overflow and groundwater (subsurface) pathways, respectively (see Section S1.1 and **Table S1** in the Supplementary Materials). Surface contributions occur only under non-compliant system conditions, whereas subsurface contributions are continuous and range between 248 and 210 L/d per capita, becoming a non-negligible component of the water balance given the high number of septic systems in this area.

S_{runoff} denotes catchment runoff excluding septic contributions and is estimated using a Budyko-based water balance framework (Yao et al., 2017). It is computed from precipitation over the catchment (excluding the lake surface), reference evapotranspiration estimated using the Hargreaves equation (Berti et al., 2014) and soil water losses represented through infiltration (see Supplementary Materials for corresponding equations). The initial infiltration (groundwater recharge) rate was set to 208 mm/yr based on regional estimates for southern Quebec (Chemingui et al., 2015; Huet et al., 2016), and subsequently calibrated using a scaling factor of 0.53, yielding an effective recharge rate of 110 mm/yr in the model. S_{precip} is direct precipitation over the lake surface, calculated from precipitation rate and lake area. S_{evap} represents lake evaporation, estimated using the Meyer formula (Meyer, 1999) and lake area. S_{outflow} is lake discharge, estimated from measured outflow data from a nearby hydrologically similar gauged lake, i.e., Lake Croche, St-Hippolyte, Quebec and transferred to Lake en Coeur under comparable climatic conditions. S_{seepage} represents lake-groundwater exchange losses and is assumed negligible in this study due to data limitations.

The phosphorus mass balance in the lake is governed by:

$$P_{lake}(t) = P_{lake}(t_0) + \int_{t_0}^{t} P_{sep,surf}(t) + P_{sep,gw}(t) + P_{forest}(t) + P_{atm}(t) - P_{settling}(t) - P_{outflow}(t)\ dt \quad (2)$$

where, P_{lake} (kg) is the phosphorus mass. The initial phosphorus mass $P_{\text{lake}}(t_0)$ was estimated by converting observed phosphorus concentrations to phosphorus masses, yielding values clustered around 9 kg. $P_{\text{sep,surf}}$ and $P_{\text{sep,gw}}$ represent phosphorus inputs from septic systems via surface and subsurface pathway, (see following sections for details). P_{forest} represents phosphorus export from forested areas, estimated using the export coefficient method, a commonly used approach in data-limited watersheds (Nuno Gonçalo & Johnes, 2012), based on forest area and literature-derived coefficients. P_{atm} represents atmospheric phosphorus deposition, also estimated using literature-based export coefficients and lake surface area. $P_{settling}$ represents internal phosphorus losses due to sedimentation and is estimated through model calibration due to the lack of site-specific data such as settling velocity. $P_{outlfow}$ is estimated based on outflow discharge and lake phosphorous (see Section S1 in the Supplementary Materials). Since Lake en Coeur is a headwater lake, no upstream phosphorus inflow is considered.

In this study, it is considered that all dwellings around the Lake en Coeur in **Fig. 1** are equipped with conventional septic systems comprised of a septic tank for primary treatment, followed by a drain field for secondary treatment and effluent infiltration, as illustrated in **Fig. 2**. As the drain field is permeable and its main function is to infiltrate the treated effluent, the migration of the phosphorus plume through underground pathways is subjected to attenuation processes such as adsorption (Robertson, 2012).

Septic system contributions are represented based on (i) household characteristics, including household size, occupancy, and influent rate to the septic system; (ii) septic system performance (age, technological failures, distance to the lake, and system density within the watershed); and (iii) soil properties (bulk density and phosphorus adsorption capacity). Since detailed information on the performance of individual systems is unavailable and may change over time, eight conformity cases were defined to represent different combinations of system condition and distance to the lake (**Table 1**), based on the elements of septic system mass balance shown in **Fig. 2** (see Section S1.2 in the Supplementary Materials for details). A Conforming (or Compliant) Septic System (CSS) refers to a system in which wastewater is conveyed from the house to the septic tank, where approximately 52 % of solids are removed (Siegrist, 2017) and then the remaining phosphorus is conveyed to the drain field for secondary treatment and infiltrates exclusively through subsurface pathways, without surface runoff occurring from septic tank overflow or drain field clogging. Septic tank overflow (STO) failure, if it occurs, is represented by a surface discharge of 150 L/d. Under clogged drain field (CDF) conditions, 50 % of the effluent is assumed to infiltrate, while the remainder flows overland. Systems may also experience both failures (STO & CDF). In addition, systems are classified by distance to the lake: compliant systems are located at 15 m, regulatory minimum (MDDELCC, 2015), whereas non-compliant systems are assumed to be located 3 m from the lake. A conforming septic system that respects the minimum setback distance is therefore classified as case CSS15.

The surface and underground phosphorus loads for each configuration in **Table 1** were adopted from Oniga et al. (2026). These loads were estimated using the BioWin model (Liwarska-Bizukojc & Biernacki, 2010), assuming that the phosphorus mass entering the septic system is partitioned between retention within the tank and export from the system, through either surface flow or underground pathways. These estimates are based on a household phosphorus input of approximately 1.47 kg/yr, assuming an average household size of 2.3 persons (Statistics Canada, 2021), and water use of 270 L/d/capita (Quebec Ministry of the Environment, 2013), that generate influent rate of 621 L/d under these conditions. In conforming systems, surface phosphorus is negative, reflecting uptake within the riparian buffer zone. Underground phosphorus loads are the highest under CSS15 and lowest under combined failure scenarios (STO & CDF3 or STO & CDF15).

The reported underground phosphorus does not instantly reach the lake and is delayed by soil adsorption processes (Robertson, 2008). To quantify this effect, soil samples were taken and adsorption capacities were determined in the laboratory by batch tests (ASTM International, 2023), based on six samples collected from the lake's surroundings, given the required consent from local residence (see Section S1 in the Supplementary Material). Six soil types ranging from very low to very high adsorption capacities were identified and shown by Thiessen polygons surrounding lake in **Fig. 1** (Fiedler, 2003). The categories were determined according to the maximum adsorption capacity derived from the Langmuir isotherm (see **Fig. S2**). Accordingly, soil conservation time was determined for each soil type and given the amount of phosphorus generated at the exit of the septic systems for each conformity cases, see **Fig. S3**. The contribution of septic systems to lake phosphorus, P_{total}, depends on the relationship between system age (**Fig. S5**) and soil conservation time (**Fig. S4**) as per Equation 3:

$$P_{total}(t) = \begin{cases} 0 \text{ or } P_{septic,surf}, & Septic\ age_t < Soil\ conserv\ t \\ P_{septic,gw} \text{ or } P_{septic,surf} + P_{septic,gw}, & Septic\ age_t \geq Soil\ conserv\ t \end{cases} \quad (3)$$

If septic system age is less than the soil conservation time, underground phosphorus remains attenuated (underground contribution is zero). Otherwise, it contributes to the lake. Surface phosphorus, when present, i.e., in STO and/or CDF, reaches the lake without delay.

To estimate phosphorus contributions from all septic systems to the lake, a Monte-Carlo approach was adopted (Fisherman, 1996). This is required because, although the number and installation year of systems are known, the exact location and conformity status of each specific system are not. Therefore, conformity cases and soil type for individual systems must be treated as random variables within the model to quantify uncertainty. Each septic system is assigned a conformity case (CC) and a soil type (ST). These variables are modeled as categorical (multinoulli) distributions (Goodfellow et al., 2016) as per Equation 4 and 5:

$$CC \sim Categorical(p^{(1)}), p^{(1)} = (0.80,\ 0.03,\ 0.03,\ 0.03,\ 0.02,\ 0.03,\ 0.03,\ 0.03) \quad (4)$$

$$ST \sim Categorical(p^{(2)}), p^{(2)} = (0.20,\ 0.19,\ 0.09,\ 0.16,\ 0.19,\ 0.17) \quad (5)$$

During the historical period, a probability of 0.80 among *CCs* was assigned to conformity case CSS15 based on previously noted inspections of septic systems in the region few years ago. The remaining 20 %

probability was distributed among the other seven conformity cases. Soil type probabilities were defined according to their spatial distribution shown in **Fig. 1** (see the Supplementary Materials for more information). The lake phosphors model was then run during 1984-2022, the period with available climate data. A total of 1,000 Monte-Carlo simulations were performed to account for uncertainty in system condition and soil type (Scharffenberg & Kavvas, 2011). Therefore, the model produces a distribution of phosphorus concentrations rather than a single deterministic value as a result lake phosphorus concentration values in each year are represented by a probability distribution. **Fig. 3** shows the boxplots of simulated phosphorus concentration in the lake as well as the observed values with dots. The order of magnitude of the simulated concentrations agrees with the observations. Observed values typically fall within the interquartile range, except for 2006 and 2011, when they fall within the full range of simulation. From 2018 onward, observations cluster around the simulated median. The model is subsequently applied under future scenarios.

3.2 Climate projections

An ensemble of climate projections under SSP2-4.5 and SSP5-8.5 was used to simulate future lake conditions over the period 2023-2100. These scenarios represent intermediate and high radiative forcing pathways, respectively, with similar trends in the short term but increasing divergence toward the end of the century due to stronger warming under SSP5-8.5 (Taylor et al., 2012). The selected climate models are listed in **Table S4** in the Supplementary Materials. Daily minimum and maximum temperature and precipitation were obtained from statistically downscaled GCMs at 1/12° resolution in the CanDCS-M6 product (Sobie et al., 2024). The data were downscaled and bias-corrected using the N-dimensional Multivariate Bias Correction method (Cannon, 2018). **Fig. 4** shows the multi-model ensemble of climate projections along with their expected values until end of century. A consistent increase in both minimum and maximum temperature can be observed. Precipitation projections exhibit substantial inter-model and inter-annual variability, although ensemble means suggest modest changes, with slightly higher values under SSP5-8.5 toward the end of the century. These projections were forced to the integrated septic system-lake model to simulate future lake volume and phosphorus concentrations.

3.3 Anthropogenic scenarios

In addition to climate change, potential alterations in anthropogenic conditions were presented in our impact assessment framework through a set of "what-if" scenarios focusing on the most critical factors influencing phosphorus inputs to the lake. These include household characteristics (population density and occupancy) and septic system performance. Population growth was represented by increasing average household size from 2.3 to 3.45 persons per dwelling, consistent with high-growth projections for Quebec

(Government of Quebec, 2025). Residential occupancy was increased from 40 % to 80 %, reflecting a transition from seasonal to predominantly year-round habitation. In parallel, we assume changes in the compliance of septic systems within the watershed relative to historical conditions. Specifically, conformity is reduced from 80 % for CSS to 60%, with the remaining 40 % distributed among other seven conformity cases. **Table 2** presents these anthropogenic scenarios, in which the top row represents the status-quo conditions with similar system characteristics during the historical period.

Given that the considered anthropogenic scenarios are expected to increase phosphorus loading, a management strategy based on source separation technology was evaluated. This approach targets phosphorus removal at the source by separating blackwater from greywater prior to treatment in the septic system. Blackwater represents approximately 12 % to 33 % of household wastewater but contributes up to about 70 % of domestic phosphorus loads (Comber et al., 2013; Zhang et al., 2023). Source separation technologies, defined as systems that isolate blackwater from greywater for targeted treatment (Malila et al., 2019), were represented in the model by modified phosphorus input fluxes. These fluxes were estimated using the BioWin model, consistent with the approach used for conventional systems (**Table 1**), and correspond to greywater-only discharges i.e., wastewater from sinks, showers, and laundry (Zhang et al., 2023). Although the specific technology implementation is site-dependent and subject to cost, feasibility, and stakeholder considerations, its impact on phosphorus loading can be evaluated through these reduced fluxes.

Accordingly, the eight anthropogenic scenarios defined in **Table 2** were re-simulated considering source separation technology to quantify its mitigation potential. The resulting phosphorus fluxes are shown in **Fig. 5** and compared with those with conventional treatment (previously presented in **Table 1**). As can be observed, across conformity cases, source separation reduces underground phosphorus loads by approximately 73 %-80 %. Surface phosphorus loads are reduced by 60 %-100 % when surface discharge occurs, while remaining unchanged (in cases without surface flow, i.e., CSS3 and CSS15). In some configurations (e.g., septic tank overflow at compliant distances), surface phosphorus export becomes negative due to complete interception and uptake within the riparian buffer zone.

3.4 Simulating climate and anthropogenic impacts

The Monte-Carlo framework described in Section S1 was extended to simulate future lake phosphorus dynamics under combined climate change and anthropogenic scenarios. For each scenario, the model was run 100 times over the period 2023-2100 to generate distributions of annual phosphorus concentrations. To assess future lake status, we evaluated the timing of exceedance of key phosphorus thresholds associated with trophic state classification. According to Quebec guidelines, total phosphorus concentrations below 0.01 mg P/L correspond to oligotrophic conditions, values between 0.01 and 0.02 mg P/L indicate moderate enrichment (mesotrophic), and concentrations above 0.02 mg P/L suggest increasing risk of eutrophication (meso-eutrophic), with levels exceeding 0.03 mg P/L indicative of eutrophic conditions (Berryman, 2006). Model outputs were therefore analyzed to identify the timing of exceedance of these thresholds.

A survival analysis framework was used to quantify the probability that lake phosphorus concentrations remain below each threshold over time. Survival analysis provides a robust approach for estimating the timing of threshold exceedance while accounting for right-censored data, i.e., cases where thresholds are not exceeded within the simulation period ending in 2100 (Guo, 2009; Kartsonaki, 2016). One of the several documented techniques is the Kaplan-Meier method, which is widely used to estimate the survival probability, i.e., the probability of not experiencing the outcome of interest (Koletsi & Pandis, 2017). Kaplan-Meier has been previously used in water quality studies (Jørgensen et al., 2013; Vandeberg et al., 2015), in some cases to asses pipe risk of failure (Christodoulou, 2011). In climate analysis, the method was used previously for drought risk assessment associated with climate data (Cetinkaya & Gunacti, 2024). In our study, the outcome of interest is the phosphorus concentration in the lake reaching the aforementioned trophic thresholds. Each scenario has a survival probability associated with this outcome, which needs to be determined to be able to compare scenarios between them and identify the most critical scenario for lake health. Kaplan-Meier is a nonparametric estimator of the survival function as per Equation 6:

$$S(t) = \prod_{t_{j \le t}}^{j} \frac{n_j - d_j}{n_j} \qquad (6)$$

where, d_j is the number of individuals who have an event at time t_j (years where the concentration of critical thresholds is exceeded just before t_j), and n_j the number of individuals at risk just prior to t_j, the number of years still below 0.01, 0.02, or 0.03 mg P/L just before t_j (Kartsonaki, 2016). *S(t)* is the survival probability and is computed for each year and scenario in the future period. This approach enables comparison across scenarios by identifying those with higher probabilities of maintaining acceptable phosphorus conditions, thereby supporting the assessment of climate and anthropogenic impacts on long-term lake eutrophication risk.

4 Results

4.1 Lake volume in the future under a changing climate

Downscaled climate projections under SSP2-4.5 and SSP5-8.5 were used to simulate lake volume and phosphorus concentrations for the study area. **Fig. 6** presents simulated lake volumes for the period 2023-2100. Lake volume shows downward trend reaching 2100, which can be due to increasing temperature causing higher watershed evapotranspiration and lake evaporation reaching the end of century. Although variability exists among ensemble members, the expected lake volume trajectories are almost similar under both radiative forcing scenarios. Higher projected temperatures in SSP5-8.5 resulted in somewhat higher watershed evapotranspiration and lake evaporation compared to SSP2-4.5 and slightly higher precipitation under SSP5-8.5 resulted in higher input to the lake compared to SSP2-4.5. These compensatory processes largely balance the lake water budget between the two pathways. Therefore, the maximum and mean relative divergence in projected lake volume between the two SSPs are 12 % and 3 %, respectively. In the following section, future phosphorus concentrations in the lake are estimated by feeding the projected values into the lake phosphorus model.

4.2 Climate change and anthropogenic impacts on lake phosphorus

This section focuses on the combined impact of changing climate and anthropogenic scenarios on lake phosphorus conditions. Here, we asses the lake phosphorus state relates to previously defined key trophic thresholds: oligotrophic (< 0.01 mg P/L), mesotrophic (0.01-0.02 mg P/L), meso-eutrophic (0.02-0.03 mg P/L), and eutrophic (> 0.03 mg P/L). **Fig.7** presents the frequency of occurrence within each range under SSP2-4.5 and SSP5-8.5. Frequencies were computed as the proportion of simulated years falling within each category across all realizations (2023-2100). The figure shows that, under all scenarios, the lake exceeds the oligotrophic threshold and shifts into mesotrophic conditions, represented by the dark blue colour. In some scenarios, it may eventually reach eutrophic conditions, represented by the red colour. Even under status quo conditions without anthropogenic increase, the lake can reach eutrophic about 40 % of the time, which is significant since rehabilitating the lake from this situation to healthy conditions can be challenging.

Anthropogenic pressures further amplify these effects. Increasing occupancy from 40 % to 80 % raises the frequency of eutrophic conditions in the lake from approximately 40 % to about 60% (see the second bar from left). Increasing household size alone results in eutrophic conditions occurring in more than 80 % of simulations under both climate scenarios, without experiencing any oligotrophic lake conditions. Reductions in septic system conformity alone exacerbate lake quality degradation in less than 2 % of time under oligotrophic conditions and ~60 % of time under eutrophic conditions. Under combined anthropogenic scenarios, the impacts can be significant, almost 90 % of the time eutrophic status (worst water quality state) is reached. Differences between SSPs are relatively minor compared to anthropogenic influences. Under the status quo conditions, SSP5-8.5 shows a slightly higher frequency of maintaining oligotrophic state (~18 %) compared to SSP2-4.5 (~10 %). However, this distinction diminishes as anthropogenic pressures intensify.

To further characterize the timing of likely water quality degradation, a Kaplan-Meier analysis was conducted to estimate the annual probability of remaining below the thresholds of 0.01, 0.02, and 0.03 mg P/L by 2100. Results are presented in **Figs. S7, 8, and S8**, respectively, for all combinations of anthropogenic scenarios under SSP2-4.5 and SSP5-8.5. A probability of 50 % is highlighted in white, allowing identification of critical scenarios where survival probability drops below this threshold in the simulation period. For the oligotrophic threshold (**Fig. S7**), survival probabilities are extremely low under SSP2-4.5, approaching almost 0 % across nearly all scenarios. Similar patterns are observed under SSP5-8.5, with the exception of the status quo and occupancy increase scenarios, where oligotrophic conditions persist for a limited number of years with a relatively high probability.

For the mesotrophic threshold (**Fig. 8**), the status quo scenario indicates that the probability of remaining below 0.02 mg P/L declines below 50 % after approximately 40 years and approaches less than 5 % by the end of the century. Differences between SSPs are relatively small, with most scenarios showing similar temporal patterns. However, combined scenario exhibits the largest divergence (see the bottom row). This limited divergence is consistent with the relatively small differences in projected lake volume with a maximum 12 % discrepancy between SSP2-4.5 and SSP5-8.5 trajectories. Among anthropogenic drivers, increasing household size has the strongest influence on reducing the duration of mesotrophic conditions, shortening the time below the 50 % probability threshold by up to 40 years relative to the status quo. Increased occupancy also reduces this duration, though to a lesser extent, advancing threshold exceedance by approximately 20 %. Decreased system conformity produces a comparable but slightly smaller effect. For the eutrophic threshold (**Fig. S8**), similar temporal patterns as mesotrophic threshold is observed. Under the status quo conditions, the probability of remaining below 0.03 mg P/L is high initially but declines rapidly, indicating that eutrophic conditions may be reached within about 30 years even without additional anthropogenic pressures. Increased population density accelerates this transition, emphasizing its dominant role in driving long-term water quality degradation.

Overall, these results are consistent with the frequency-based analysis, presented in **Fig. 7**. The most detrimental scenario combines increased household size, higher occupancy, and reduced septic system conformity. Under this scenario, the eutrophic threshold can exceed as early as 2030. Among all drivers, population growth exerts the strongest influence, as it directly increases phosphorus loading values presented in **Table 1**. A 50 % increase in population results in a proportional increase in phosphorus exports. In contrast, occupancy primarily affects wastewater flow rates rather than phosphorus generation, leading to a comparatively smaller impact on lake concentrations (see Section S1). These findings were based on using conventional septic system technology and highlight the need to explore mitigation strategies to maintain lake water quality.

4.3 Impact of septic management strategy under changing conditions

This section evaluates the effectiveness of source separation technology in mitigating lake phosphorus enrichment under the defined anthropogenic and climate scenarios. Comparisons between status quo conditions with conventional treatment (**Fig. 7**) and source separation technology (**Fig. 9**) demonstrate that technological upgrades can substantially improve lake water quality. Under status quo conditions, the frequency of maintaining oligotrophic conditions increases from less than 10 % to approximately 90 % under SSP2-4.5 and to almost 100 % under SSP5-8.5. In addition, eutrophic conditions are effectively eliminated in this scenario. Differences between SSP2-4.5 and SSP5-8.5 are relatively modest, with maximum divergences of ~10 %, and slightly poorer water quality outcomes under SSP2-4.5. These results indicate that improved septic system technologies can maintain healthy lake conditions even under changing climate. However, the benefits of source separation diminish as anthropogenic pressures increase.

When population density, occupancy rate, or reductions in system conformity are introduced, either individually or in combination, the technology alone is insufficient to maintain 100 % oligotrophic or even mesotrophic conditions (see **Fig. 9**). As also previously found, among these drivers, population density exerts the strongest influence, followed by occupancy rate. This suggests that maintaining fully oligotrophic conditions is unlikely under scenarios involving 50 % increase in population growth or doubling year-round habitation. Septic system conformity also affects lake response, although its influence is smaller relative to population and occupancy. Nonetheless, maintaining high conformity rates (e.g., ~80 %) through inspections, regulation, and system upgrades remains important for limiting phosphorus inputs and surface runoff of untreated wastewater.

Comparisons between **Fig. 7** and **Fig. 9** further highlight that source separation improves water quality across other scenarios relative to conventional systems, although exceedance of meso-eutrophic and eutrophic thresholds still occur. For example, under increased occupancy alone, the frequency of oligotrophic conditions increases from less than 5 % to approximately 50 %, while eutrophic conditions are reduced substantially. Similarly, under reduced conformity, source separation increases oligotrophic frequency from near 0 % to about 85 % and eliminates eutrophic occurrences. Overall, these results demonstrate that while source separation technology is highly effective as a mitigation measure, it cannot fully offset the combined impacts of population growth, increased occupancy, and reduced conformity to keep the lake healthy.

Survival probability is also computed here for all scenarios given source separations technology, to determine the timeline of lake quality degradation. **Figs. S9**, **10**, and **S10** show the results for 0.01, 0.02, and 0.03 mg P/L survival probabilities, respectively. **Fig. S9** highlights substantial improvements in maintaining oligotrophic conditions due to source separation. Under status quo conditions, the lake remains oligotrophic with high probability throughout most of the simulation period. Compared to conventional systems (**Fig. S9**), scenarios with increased occupancy or reduced conformity also exhibit markedly higher probabilities of maintaining oligotrophic conditions, although this probability declines over time depending on the scenario. Differences between SSPs are minor and primarily reflected in slight shifts (few years) in the timing at which survival probabilities occur. These results indicate that reductions in system conformity can be tolerated to a greater extent, whereas increases in occupancy can only be sustained for a limited period (approximately 30 years) before oligotrophic conditions become unlikely. For the mesotrophic threshold (**Fig. 10**), status quo conditions, and, to a lesser extent, scenarios with reduced conformity, maintain high survival probabilities under both SSPs, even toward the end of the century. Comparison with conventional system results (**Fig. 8**) shows that source separation significantly delays threshold exceedance. For example, in the most impacted scenario (bottom row), the timing at which the probability drops below 50 % is shifted from approximately year 2028-2029 to 2038-2039. Survival probabilities for the eutrophic threshold (**Fig. S10**) are even higher across all scenarios. Under status quo conditions and with 60 % system conformity, the probability of exceeding 0.03 mg P/L remains negligible under both SSPs, indicating that eutrophic conditions are unlikely within the simulation horizon. More generally, most scenarios maintain high survival probabilities through approximately 2050, with near certainty of remaining below mesotrophic thresholds during this period, except in cases with increased population density. Overall, these results are consistent with the frequency-based analysis and reinforce that, although source separation substantially improves water quality, it cannot fully offset the effects of increasing anthropogenic pressure. In particular, population growth remains the dominant driver of degradation, and even advanced treatment technologies provide limited capacity to accommodate 50 % increases in population density.

5 Discussion

Here, we aim to understand the impact of anthropogenic scenarios from a different perspective. **Fig. 11** shows the evolution of the median phosphorus concentration with the gradual implementation of one strategy at a time and their efficiency. The violin plots below show phosphorus concentration distribution obtained by Monte-Carlo sampling with mean behaviour clustering around the median and the extremums at the tails represented by the absolute range boundaries. Assuming the worst-case anthropogenic scenario, increasing the septic system conformity rate to 80 % alone could reduce the median phosphorus concentration by 18 % by the end of the analysis period. Reducing the average household size to 2.3 inhabitants per dwelling could further decrease the median concentration by up to 66 %. Although these measures produce noticeable improvements, the median lake phosphorus would still reach 0.28 mg/L, roughly ten times above the eutrophic threshold. Adding a reduction of the occupancy rate to 40 %, in combination with the previous measures, could further lower the median concentration to 0.09 mg/L, representing an 89 % decrease, yet this remains above acceptable water quality standards under SSP2-4.5. Similar trends are observed under SSP5-8.5. Finally, implementing source separation technology across all septic systems within the next decade could reduce phosphorus concentrations by nearly 99 %, bringing the median into the oligotrophic range under both climate scenarios.

Projections are less alarming if the same analysis is carried out under a shorter horizon. Municipalities often need projections that are not as far into the future, which is why mid-century predictions can also be relevant to plan for more short-term. **Fig. S11** shows that lake health can be preserved if the catchment preserves its historical recreational vocation with same average household size, occupancy rates and 80 % system conformity rate without having to invest in alternative technologies. While **Fig. S11** still shows that keeping the average household size at 2.3 inhabitants per dwelling has the highest efficiency, maintaining current occupancy rate and ensuring an 80 % conformity rate across septic systems are strong enough measures to preserve lake quality until 2050. Straightforward endeavours can greatly preserve septic system's technological integrity such as reducing hydraulic load, nutrient inputs, and sludge carry-over can reduce typical failures such as drain field clogging (Sarac et al., 2001). To reduce hydraulic loads, indoor water efficiency upgrades can be considered and researched, which can also help reduce solids carry-over from septic tank to drain field and help prevent clogging. Without investing into source separation technology, by mid-century the lake's trophic state can remain mesotrophic with a median concentration of 0.016 mg P/L under SSP2-4.5 and 0.013 mg P/L under SSP5-8.5 under status quo conditions.

6 Conclusions

Septic systems can be a critical source of phosphorus to lakes in rural and remote watersheds worldwide, particularly where centralized wastewater-treatment infrastructure is absent. However, their evolving impacts on lake trophic state under changing climatic and anthropogenic conditions remain insufficiently understood. This study addressed this gap using an integrated septic system-lake modelling framework that dynamically simulates phosphorus inputs as a function of system age, distance to the lake, compliance status, and soil characteristics, thereby enabling a more realistic assessment of temporal variability in phosphorus loading. Anthropogenic scenarios incorporated changes in household size, occupancy rates, and septic system performance, while climate projections were based on SSP2-4.5 and SSP5-8.5 scenarios.

The framework was applied to Lake en Coeur Basin, Quebec, Canada, a watershed representative of many rural lake basins where dense lakeshore development relies on septic systems. The basin was selected as septic systems constitute the dominant anthropogenic phosphorus source to the lake, with limited agricultural or urban influences, providing a relatively controlled setting in which observed and projected changes in lake phosphorus concentrations can be more directly associated with septic system impacts. In addition, the lake is already experiencing increasing phosphorus concentrations and growing local concern regarding water quality degradation, making it an appropriate case study to evaluate the effectiveness of septic system management strategies under future environmental change.

The results of the impact assessment demonstrate that human-driven pressures dominate over climate effects in controlling lake phosphorus concentrations in this region. In particular, even conservative increases in population density and occupancy substantially accelerate eutrophication, with critical trophic thresholds frequently exceeded well before mid-century. Under future climate scenarios and conventional septic system conditions, the lake exhibits a high likelihood of progressively transitioning toward meso-eutrophic conditions, even under status quo anthropogenic assumptions. The implementation of source separation technology substantially improves outcomes by reducing phosphorus inputs at the source. Under status quo conditions, this management strategy maintains oligotrophic conditions for most of the simulation period and prevents the occurrence of eutrophic states under future climatic conditions. Nevertheless, technological improvements alone are insufficient to offset the effects of increased anthropogenic pressure to maintain oligotrophic. In particular, scenarios involving population growth show the limited capacity of upgrade of septic systems to compensate for increased loading, although, it can reduce chance of achieving eutrophic lake conditions in short-term. Overall, these findings underscore the importance of integrated watershed management strategies that combine technological upgrades with controls on development and sustained system maintenance. While climate change introduces additional stressors, its influence is secondary to that of human-driven factors.

The importance of investing in alternatives to conventional septic systems is strongly highlighted by this study, particularly given the effectiveness of phosphorus removal through source separation approaches. Several source separation technologies compatible with conventional septic systems already exist. For instance, dry toilets and urine-diversion systems are commonly used for second residences and summer houses in Sweden, particularly in rural areas (McConville et al., 2017). Other approaches, such as anaerobic on-site blackwater treatment systems, have also demonstrated effective phosphorus removal performance (Sharma et al., 2016). Source separation represents an alternative or complementary strategy to tertiary phosphorus treatment, whose cost-effectiveness has also been investigated (Zagklis & Bampos, 2022). These alternative phosphorus removal strategies should be discussed with stakeholders and evaluated in terms of technical, environmental, and economic feasibility, given their strong potential to preserve lake water quality under increasing anthropogenic and climatic pressures.

It should be noted that the applied septic system-lake model has several limitations. First, simulations were conducted at an annual time scale, which limits the representation of seasonal variability and within-year processes occurring in both the catchment and the lake. As a result, processes such as seasonal aquatic vegetation dynamics, biomass growth, and associated evapotranspiration effects were not explicitly represented. In addition, continuous long-term monitoring data for both the watershed and lake are required to improve process representation and reduce uncertainties associated with model assumptions and calibration parameters, including seepage and phosphorus settling estimates. Nevertheless, the proposed methodology is generic and can be applied to other basins to assess the evolving impacts of septic systems on lake water quality under changing climate conditions.

Declaration of competing interest

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

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List of tables

Table 1 Considered eight scenarios for septic system performance and their corresponding underground and surface water phosphorus export to lake

Conformity cases considering the septic system performance and distance from the lake	Underground P generated at the base of the drain field (kg/yr)	Surface P generated at the base of the drain field (kg/yr)
Conforming Septic system in the system at 15 m distance (CSS15)	0.861	-0.144
Septic tank overflow in the system at 15 m distance (STO15)	0.653	0.212
Clogged drain field in the system at 15 m distance (CDF15)	0.385	0.391
Septic tank overflow and Clogged drain in the system at 15 m distance (STO & CDF15)	0.199	0.747
Conforming Septic system in the system at 3 m distance (CSS3)	0.861	-0.036
Septic tank overflow in the system at 3 m distance (STO3)	0.653	0.356
Clogged drain field in a system at 3 m distance (CDF3)	0.385	0.535
Septic tank overflow and Clogged drain in a system at 3 m distance (STO & CDF3)	0.199	0.891

Table 2 Considered anthropogenic scenarios given household population density, residence occupancy rate, overall percentage of conforming septic systems on the watershed, with conventional systems.

Scenario ID	Household size (Person)	Occupancy rate (%)	Conformity rate (%)	Septic system P removal technology
1	2.3	40	80	Conventional
2	2.3	40	60	Conventional
3	2.3	80	80	Conventional
4	2.3	80	60	Conventional
5	3.45	40	80	Conventional
6	3.45	40	60	Conventional
7	3.45	80	80	Conventional
8	3.45	80	60	Conventional

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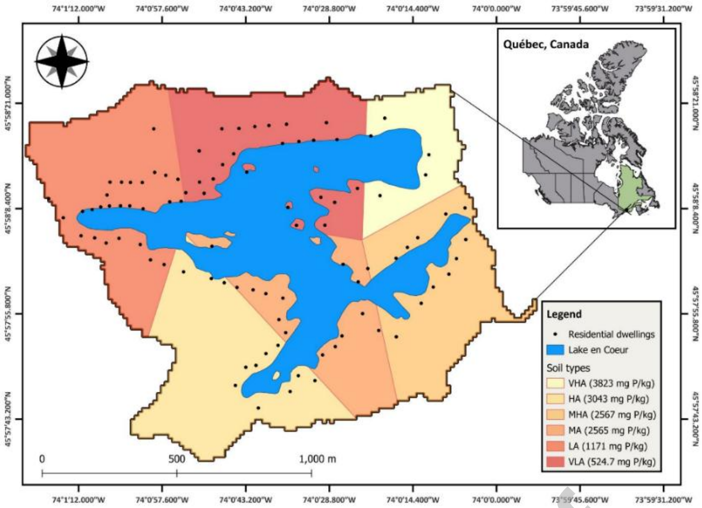


Fig. 1. Lake en Coeur catchment in Quebec, Canada. Circles represent residential dwellings (septic systems). Polygons represent soil phosphorus adsorption capacity classes surrounding the lake, which were estimated from soil sampling, laboratory analyses, and subsequent data interpretation. VHA denotes Very High Adsorption, HA High Adsorption, MHA Medium-High Adsorption, MA Medium Adsorption, LA Low Adsorption, and VLA Very Low Adsorption capacities.

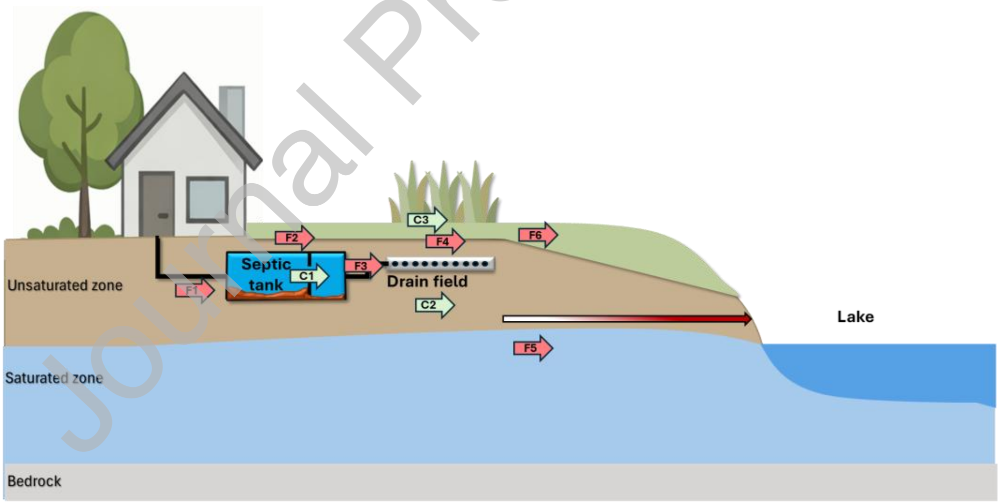


Fig. 2. Conceptual representation of a conventional septic system, including a septic tank and permeable drain field. Phosphorus mass balance components are shown using red (inputs/releases) and green (retention/attenuation) arrows. F1: phosphorus entering the septic system; F2: septic tank overflow; F3: phosphorus transfer from septic tank to drain field; F4: phosphorus accumulation associated with drain field clogging; F5: subsurface phosphorus transport toward the lake; F6: surface phosphorus loading to the lake. C1, C2, and C3 represent phosphorus retention within the septic tank, drain field, and riparian buffer zone, respectively.

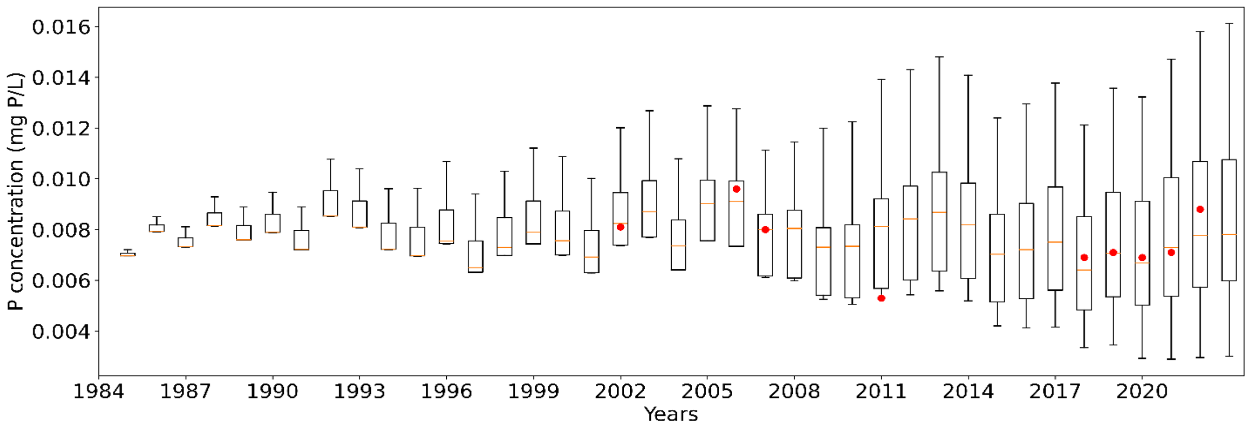


Fig. 3. Simulated phosphorus concentration (boxplots) in the Lake en Coeur using the integrated model versus observed values (dots) for the historical period of 1984-2022.

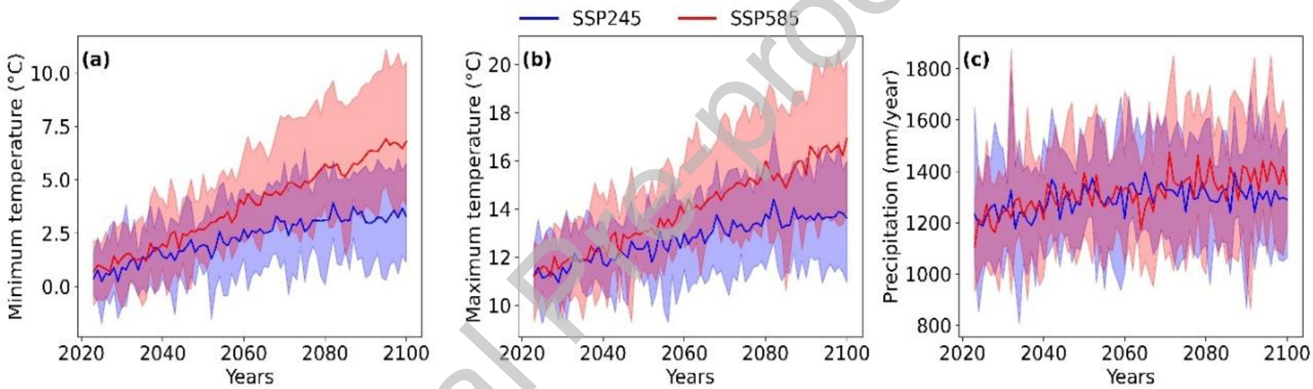


Fig. 4. Envelopes and expected values (lines) of projected minimum and maximum temperature and precipitation based of GCMs under SSP2-4.5 and SSP5-8.5 scenarios in the Lake en Coeur watershed.

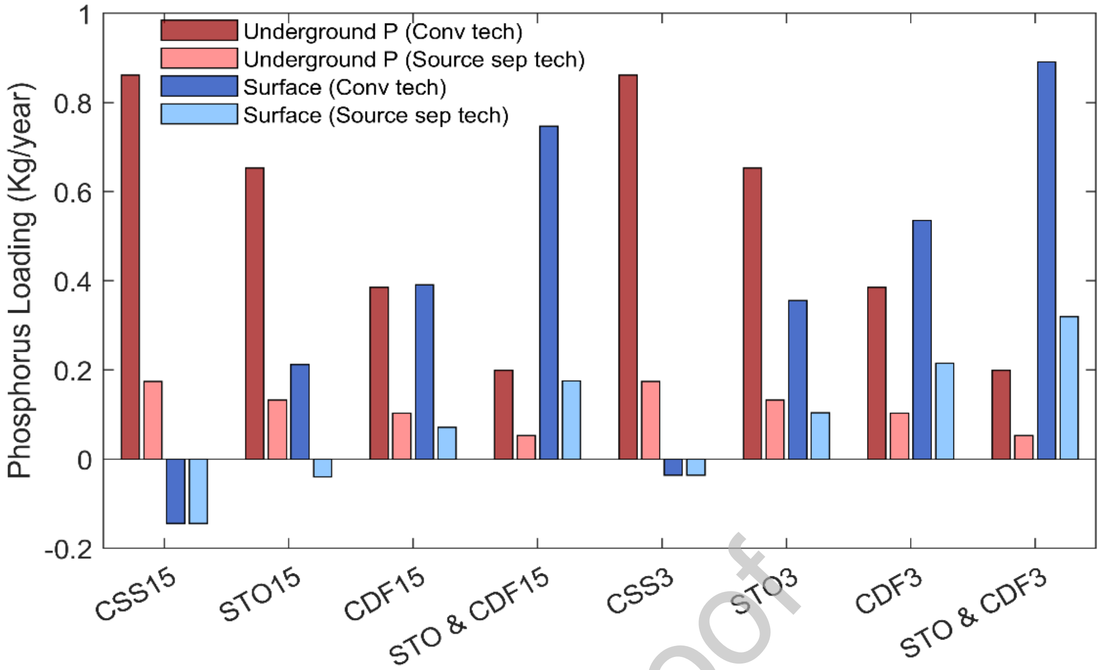


Fig. 5. Underground and surface water phosphorus fluxes to the lake considering conventional versus source separation technology in septic systems.

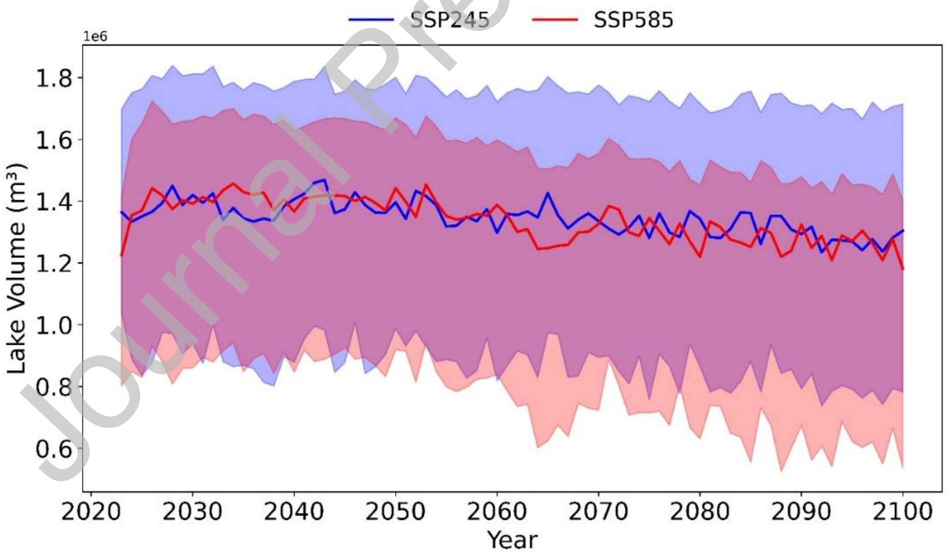


Fig. 6. Envelope of simulated lake volume based on an ensemble of climate projections, with expected lake volume trajectories (lines) under the SSP2-4.5 and SSP5-8.5 scenarios for 2023-2100.

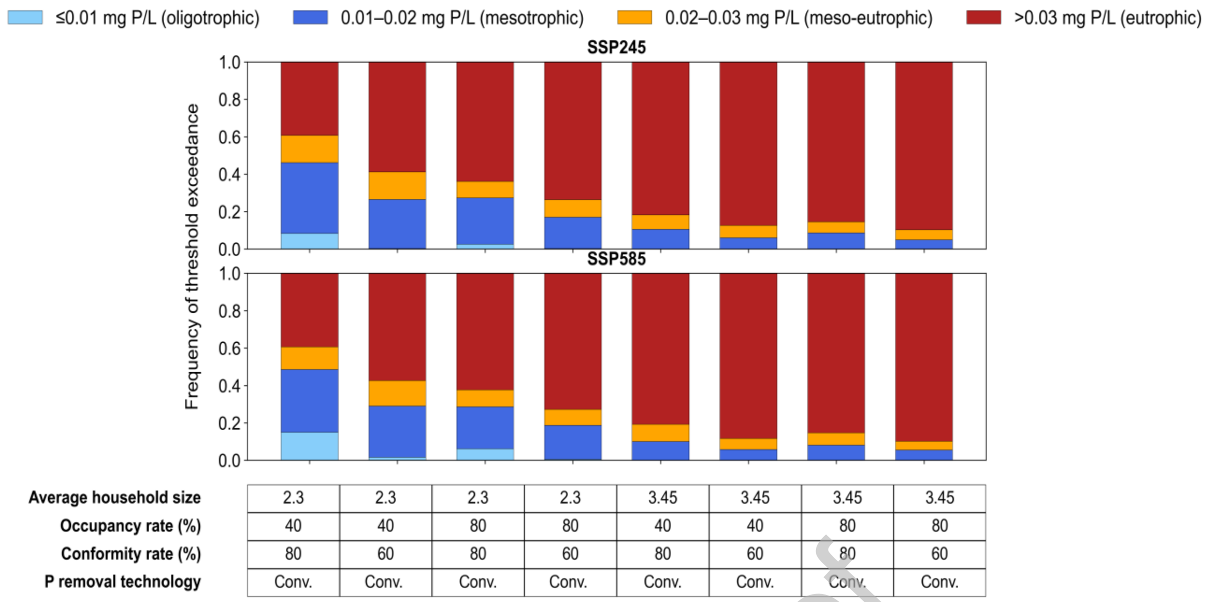


Fig. 7. Frequency of occurrence within trophic state thresholds (oligotrophic, mesotrophic, meso-eutrophic, and eutrophic) under conventional phosphorus removal technology, across changing climate and emission scenarios SSP2-4.5 (top) and SSP5-8.5 (bottom), and anthropogenic scenarios, over the period 2023-2100.

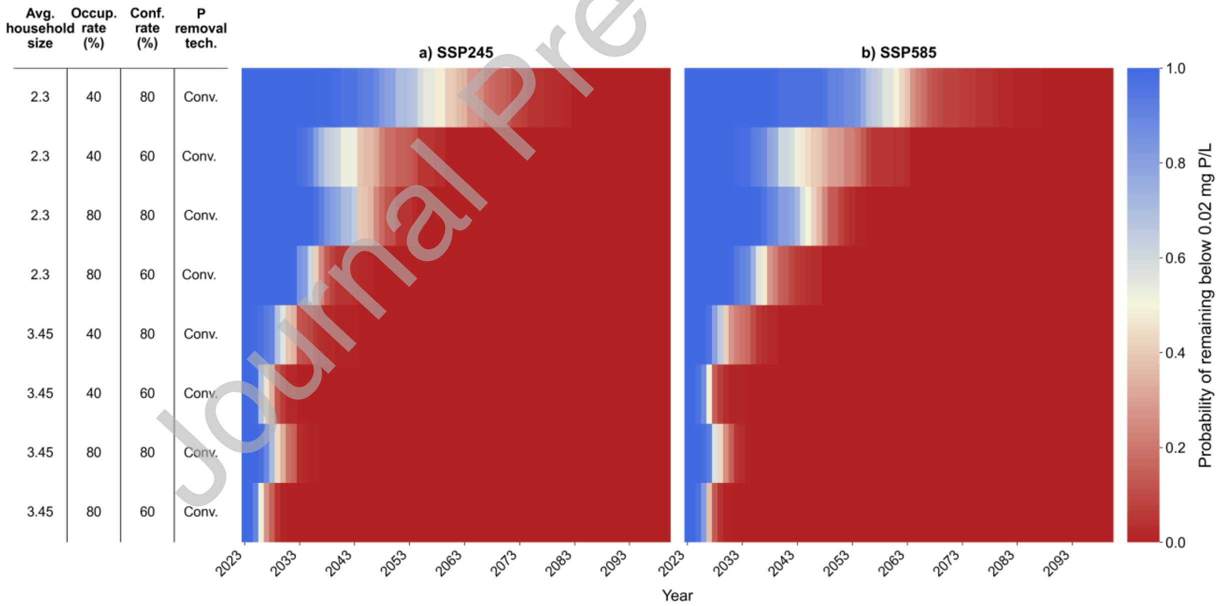


Fig. 8. Survival probability of 0.02 mg P/L, mesotrophic state in the lake, considering the anthropogenic scenarios with conventional phosphorus removal technology in septic systems under SSP2-4.5 and SSP5-8.5 for the period of 2023-2100 using the Kaplan-Meier method.

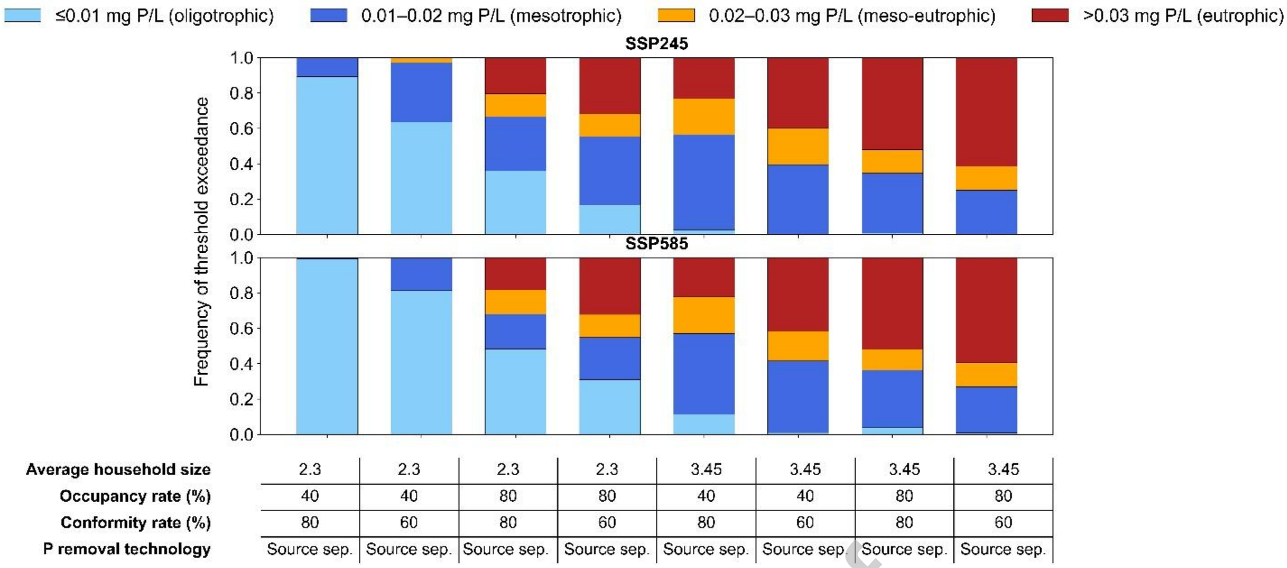


Fig. 9. Frequency of occurrence within trophic state thresholds (oligotrophic, mesotrophic, meso-eutrophic, and eutrophic), given source separation phosphorus removal technology under changing climate and radiative scenarios SSP2-4.5 (top) and SSP5-8.5 (bottom), and anthropogenic scenarios during the period 2023-2100.

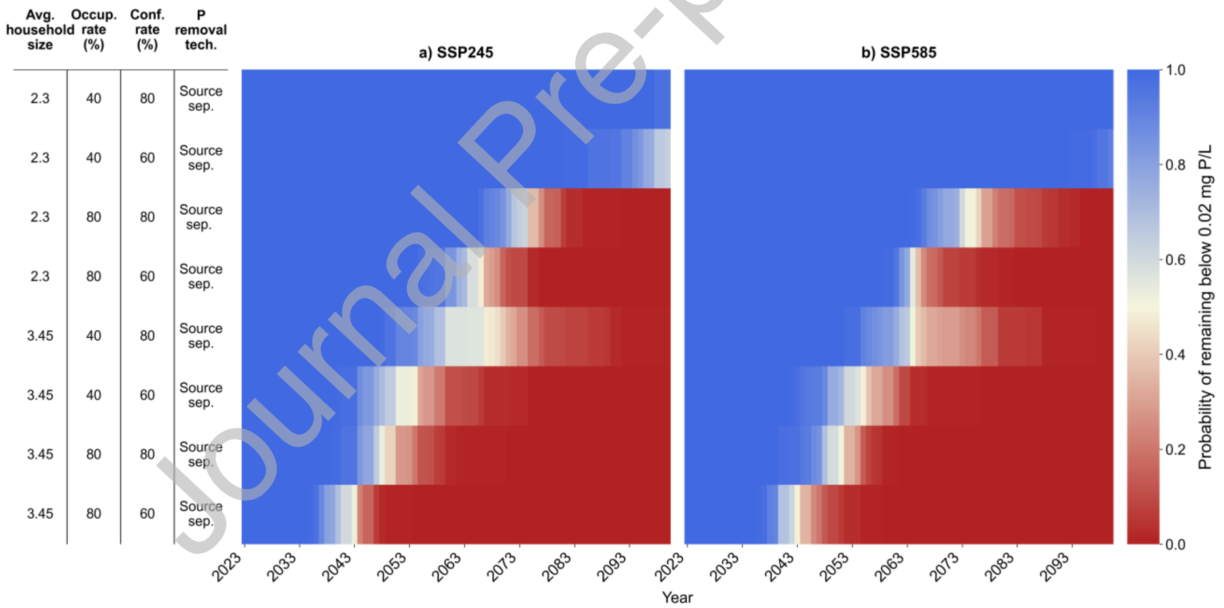


Fig. 10. Survival probability of 0.02 mg P/L, mesotrophic state in the lake, considering the anthropogenic scenarios with source separation phosphorus removal technology in septic systems under SSP2-4.5 and SSP5-8.5 for the period of 2023-2100 using the Kaplan-Meier method.

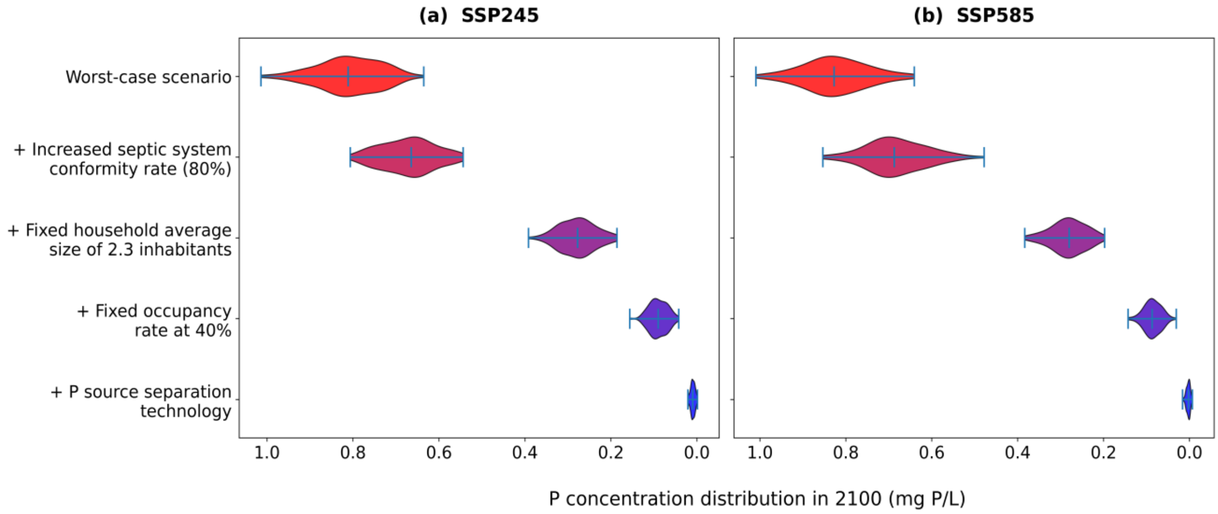
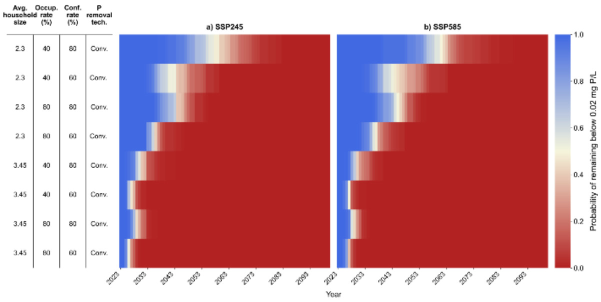


Fig. 11. Evolution of the median phosphorus concentration in the lake with the gradual implementation of mitigation strategies by 2100 under SSP2-4.5 and SSP5-8.5 for the future period 2023-2100.

Graphical abstract



Declaration of Interest Statement

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