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PRIMARY RESEARCH PAPER

Five decades of phosphorus trends in a eutrophic lake: insights from Lake Vombsjön, Sweden

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Abstract We investigated 50 years of total phosphorus trends in Lake Vombsjön, Sweden, to assess changes in phosphorus inputs, outputs, and retention, and to predict the lake's recovery following catchment management efforts. Monitoring data collected in and around the lake are compiled and evaluated using weighted regression on time, discharge, and season to assess long-term trends at the lake's primary inlet and outlet. The analysis revealed a continuous reduction in external phosphorus inputs throughout the study period, with the strongest declines associated with improvements in wastewater treatment. Agricultural management and wetland restoration also contributed to reductions, although these were more gradual. In contrast, reductions in outlet phosphorus concentrations and loads were less pronounced, and indications of internal phosphorus loading were observed, including increasing outlet loads and concentrations after 2015. Our findings highlight the need for restoration strategies that address both catchment and internal phosphorus processes to achieve good ecological status in Lake Vombsjön. These results also demonstrate the broader value of long-term monitoring data for guiding lake managers and understanding a lake's current state.

Keywords Eutrophication · Internal phosphorus loading · Long-term monitoring · Catchment management · WRTDS

Introduction

Anthropogenic pressures are impacting lake ecosystems worldwide (Jilbert et al., 2020). One of the major drivers of change in aquatic ecosystems is eutrophication (May et al., 2011; Orihel et al., 2017; Jilbert et al., 2020), primarily caused by an excess of the macronutrients nitrogen (N) and phosphorus (*P*) (Jilbert et al., 2020). Phosphorus is of particular concern, as it is generally the limiting nutrient for phytoplankton growth in lakes (Søndergaard et al., 2013). Excess *P* can lead to increase phytoplankton biomass, reduce water clarity, and undesirable ecological changes (Søndergaard et al., 2003). Consequently, reducing *P* loading from anthropogenic sources in the catchment has historically been the main restoration approach for eutrophic lakes (May et al., 2011; Lepori

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& Capelli, 2021; Bocaniov et al., 2023). Such sources include fertiliser application, municipal wastewater, and industrial discharges (May et al., 2011; Lepori & Capelli, 2021).

Many lakes have shown improvements in water quality following reductions in external *P* loading (Schindler et al., 2016). However, others have not responded as expected, and their recovery has been delayed by years or even decades (Jeppesen et al., 2005; Søndergaard et al., 2013; Orihel et al., 2017). Examples of such cases include Lake Erie, US (Bocaniov et al., 2023), Loch Leven, Scotland, UK (Spears et al., 2011), and Lake Ringsjön, Sweden (Granéli, 1999). Delayed or partial recovery is often linked to continued diffuse *P* inputs associated with agriculture, land use change, or surface runoff (Schindler et al., 2016) but is more commonly attributed to the internal cycling of *P*, also known as internal *P* loading (Jeppesen et al., 2005; Søndergaard et al., 2013; Orihel et al., 2017). Internal *P* loading may occur when *P* accumulates during prolonged nutrient enrichment, which can, under certain conditions, be recycled back to the overlying water (Orihel et al., 2017). Understanding the present state of a lake, therefore, requires knowledge of its history. This is further supported by Johnes (1999), who argued that understanding catchment history is fundamental to developing sustainable management strategies for nutrient-enriched lakes.

One important means of evaluating the historical trends has been through the use of long-term monitoring data. Long-term monitoring data can identify key patterns, such as trends and infrequent events, that are hard to detect in shorter studies, and which are more influenced by hydroclimatic variability (Burt et al., 2014). As a result, long-term data have been widely used to detect P trends in lakes and catchments (Spears et al., 2011; Salonen et al., 2020; Bocaniov et al., 2023). Long-term studies of restoration actions can also act as reference cases for lake managers (Jilbert et al., 2020). A range of statistical methods has been developed to analyse long-term water quality data, including approaches for describing concentration–discharge (C–Q) relationships that can be implemented in different ways. Initial studies often relied on single, constant slopes in the equations, whereas recent work has enabled the use of more flexible approaches that account for temporal variability and nonlinear behaviour in C–Q relationships, such as generalised additive models (Von Brömssen et al., 2023). Another widely used approach is the weighted regression on time, discharge, and season (WRTDS) method (Canion et al., 2022; Bocaniov et al., 2023; Turner, 2024), which was designed with nutrients in mind and has the goal to increase the amount of information that is extracted from water quality datasets (Hirsch et al., 2010).

Here, we utilise a long-term monitoring dataset from the eutrophic Lake Vombsjön in southern Sweden. The first sampling of the lake was conducted in 1907, which is also the earliest record in the Swedish national database (Miljödata-MVM, 2025). The lake has been monitored at varying frequencies since then. Despite the vast amount of data available, it has, to our knowledge, never been integrated and analysed. Today, the lake exhibits high *P* concentrations and recurrent algal blooms (Elhabashy et al., 2023), despite decades of management efforts to combat this. As a consequence, the lake's ecological status, as defined by the EU Water Framework Directive, is classified as "poor" primarily due to elevated *P* concentrations, which would need to fall by 80% below 27.4 µg/L (Kävlingeåns Vattenråd & Sydvatten AB, 2022). The lake's high *P* concentration has been attributed to internal *P* loading, first identified by Hamrin et al. (1998), and later by Elhabashy et al. (2023). Both studies, however, were based on short-term data, leaving the long-term trends poorly understood.

In this study, we apply the WRTDS method to evaluate long-term trends in TP concentrations and loads at the main inlet and outlet of Lake Vombsjön, Sweden, to assess the effectiveness of historical remediation measures and evaluate the current state of recovery of the lake. This will not only help guide future management of Lake Vombsjön but also provide insights for other eutrophic lakes. Specifically, our objective is to identify (1) how the external *P* inputs to Lake Vombsjön changed historically, (2) how these changes are reflected in *P* export and retention, and (3) what lessons we can draw for future management of Lake Vombsjön.

Materials and methods

Study site

Lake Vombsjön (55°41'N, 13°35'E) is a 12 km^2 eutrophic lake located in Scania, Southern Sweden

(Fig. 1a). The lake is regulated with regard to drinking water production, allowing a water level fluctuation of 2.5 m (VISS, 2025). At the lowest and highest water levels, the mean depth ranges from 5.1 to 5.9 m, with a maximum depth of 16 m (Almestrand & Lundkvist, 1983). Due to the lake's size and wind exposure, stratification is generally weak, and the lake is typically fully circulated (Gelin, 1975; Granéli, 1978; Elhabashy et al., 2023). However, occasional summer stratification does occur, resulting in oxygen depletion (Granéli, 1978; Ekologigruppen Ekoplan AB, 2021). The hydraulic residence time is relatively short, estimated at 0.7–0.8 years (VISS, 2025).

The lake is located in the upper Kävlingeå catchment (Fig. 1b), which covers an area of 447 km^2. The lake catchment is dominated by agricultural land and open fields (~81%), with forests (16%), and urban areas (0.02%) comprising most of the remaining area (Fig. 1b). One wastewater treatment plant is located upstream of Lake Vombsjön; however, all effluents are currently infiltrated, and no direct discharges enter the streams. Three main tributaries flow into the lake: Björkaån, Torpsbäcken, and Borstbäcken, where Björkaån is the largest, accounting for approximately 76% of the total inflow (Li et al., 2018). The lake has one primary outflow, Vombsjöns utlopp, which discharges into the River Kävlingeån (Fig. 1b).

Historically, the Kävlingeå catchment and Lake Vombsjön looked very different. During the 19th and early twentieth centuries, Sweden experienced rapid population growth, leading to the exhaustion of arable land (Krug, 1993). To meet the demands, land within the Kävlingeån catchment started to be drained (Krug, 1993). Streams were straightened and dredged, boulders were removed, the riparian zone and bank habitat were altered through vegetation loss, and even lowering or draining entire lakes became common practice, providing highly fertile soils (Emanuelsson & Möller, 1990; Krug, 1993). Lake Vombsjön was no exception, as its water level was lowered in 1937 to make downstream land available for agriculture (Almestrand, 1968). Wolf (1956) reported that between the

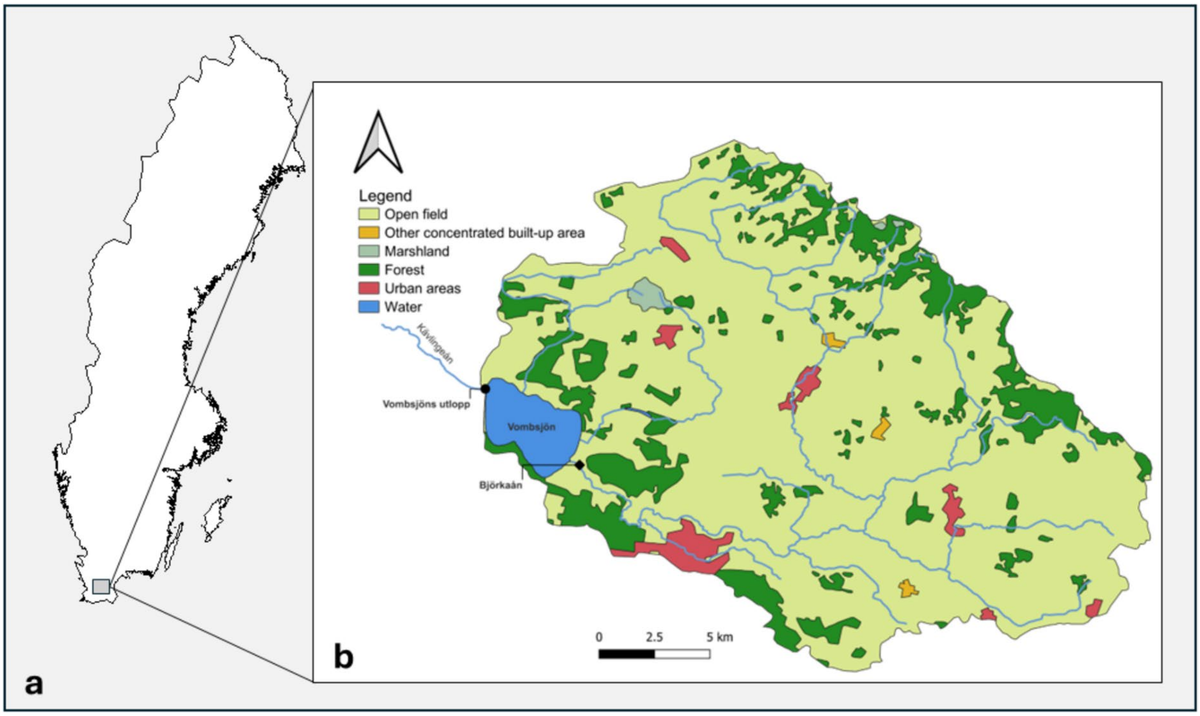

Fig. 1 **a** Map showing the location of Lake Vombsjön in Scania, Southern Sweden. © OpenStreetMap contributors, tiles courtesy of Microsoft Bing Maps. (b) Map of Lake Vombsjön and its catchment showing land use distribution, major streams, and the primary inflow (Björkaån) and outflow (Vombsjöns utlopp). GSD-Översiktskartan vektor © Lantmäteriet. Figure produced using QGIS (version 3.28.6) and Microsoft PowerPoint (Microsoft Office 365)

early 1800s and the mid-1900s, approximately 84% (300 km^2) of wetlands and surface water areas in the Kävlingeån catchment were removed. Furthermore, to increase yields, artificial fertilisers were introduced, and by the beginning of 1900 s, nearly all farmers in Scania used them (Emanuelsson & Möller, 1990). Agriculture was not the only contributor to environmental pressures in the region. Industrial activity and expanding urban areas also played a significant role, particularly through municipal wastewater discharges (Granéli, 1978) and industrial effluents (Kävlingeåns Vattenvårdsförbund, 1970). In 1944, the municipality of Malmö began using the lake as a source of drinking water and has since been subject to various regulatory rulings and variable water abstraction rates (Fig. 2; see also Online Resource 1).

The anthropogenic pressures mentioned above led to the deterioration of water quality. This was seen by, for example, the repeated fish kills in the catchment (Kävlingeåns Vattenvårdsförbund, 1970; Hamrin et al., 1998), the elevated phytoplankton concentrations in Lake Vombsjön (Almestrand, 1951; Andersson et al., 1968), the reduced macrophyte coverage in Lake Vombsjön (Lundh, 1951), and the loss of salmonid fish populations (Krug, 1993). Due to the evident water quality degradation, monitoring began in the catchment in the late 1950s. Similar patterns were observed across Sweden, and monitoring programmes were also set up for the four biggest lakes of Sweden (the lakes Vänern, Vättern, Mälaren, and Hjälmaren) during 1960s (Wilander & Persson, 2001). As a result of the high anthropogenic P loads to basins in Sweden, national regulations on wastewater treatment plants were introduced in the 1950s, and later in the early 1970s, national P removal standards were established, setting a total phosphorus (TP) effluent limit of 0.5 mg/L (Olsson et al., 1998). Within the catchment of Lake Vombsjön, a steep decline in TP concentrations from wastewater treatment plants was observed during 1970s as treatment efficiency improved, before stabilising in the mid-1980s (Fig. 2; see also Online Resource 1). Efforts to reduce industrial effluent also intensified in 1960s, and by 1983, all major industries in the catchment had either ceased discharge or connected to municipal treatment plants (Almestrand & Lundkvist, 1983).

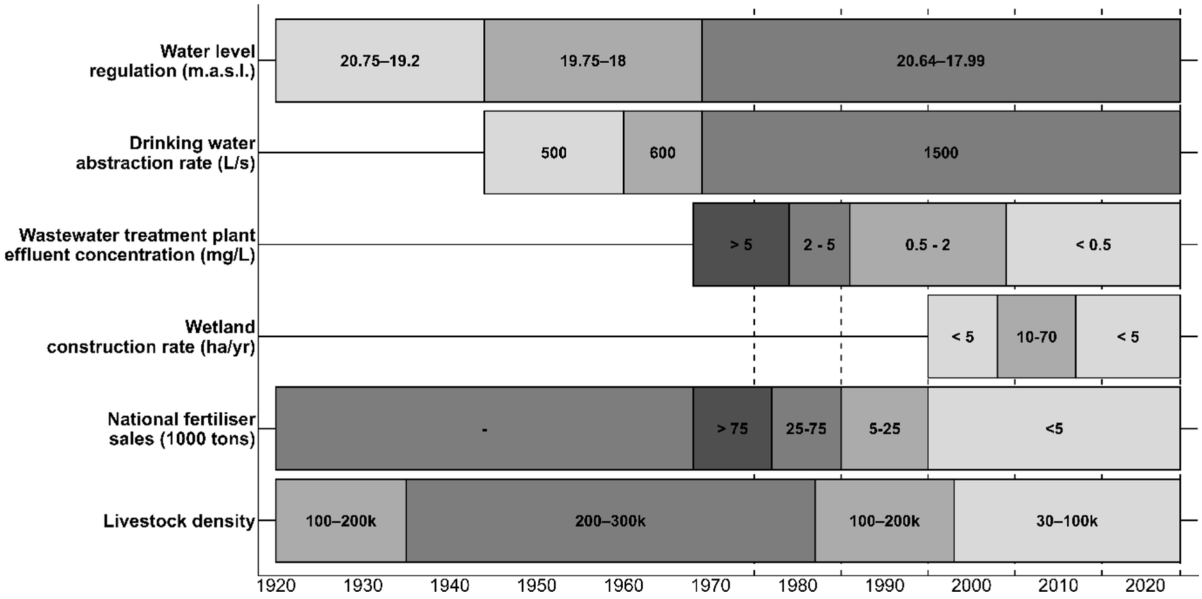

Fig. 2 Historical context of interventions made in the region during and before the study period (1920–2024), supporting data and information can be found in Online Resource 1. **a** Water level amplitude of Lake Vombsjön in m.a.s.l., **b** drinking water abstraction rates from Lake Vombsjön, **c** wastewater treatment plant mean TP concentration for the plants in the runoff area to Lake Vombsjön in mg/L, **d** wetland construction intensity in the runoff area to Lake Vombsjön in ha/yr, **e** national sales of P fertilisation in Sweden in 1000 tonnes, **f** livestock density in the runoff area to Lake Vombsjön. Figure produced in R (version 4.4.1; R Core Team, 2024)

In the1990s, catchment management in the Kävlingeå catchment began mitigating diffuse sources, primarily through the construction of wetlands (Ekologgruppen, 2013). In total, 91 wetlands were established within the Lake Vombsjön catchment, with the highest construction rate occurring in the middle of the 2000 s (Fig. 2; see also Online Resource 1), contributing to approximately 370 ha of newly created wetlands across the entire Kävlingeå catchment. Agricultural practices also changed during this period. Fertiliser use declined, and the area of arable land decreased, while crop yields continued to increase (Hushållningssällskapet, 2014). Phosphorus fertiliser application in Scania peaked in 1970s at around 30 kg P/ha (Krug, 1993), a trend consistent with national fertiliser sales, which also began to decline after 1970s (Fig. 2; see also Online Resource 1). The livestock density also changed considerably, reaching its highest of 200–300k in the 1980s, then declining to 100–200k until the end of the 1990s, and at present approximately 30–100k (Fig. 2; see also Online Resource 1).

Water quality dataset

Water quality data were collected from Lake Vombsjön, its primary inflows (Björkaån, Torpsbäcken, Borstbäcken), and the lake outlet (Vombsjöns utlopp) over the period 1937–2024. The primary data source was the Miljödata-MVM database (Miljödata-MVM, 2025). To fill temporal gaps and improve completeness, supplementary historical data were digitised from monitoring reports and publications in the area. Several of these sources were not publicly available and were obtained through archival research. A complete account of all sources, digitisation procedures, and dataset structure is provided in Online Resource 2. Although the compiled dataset includes a broad range of water quality parameters, this study focuses on TP, representing all forms of P in the water. TP concentrations are also often used as an indicator of water quality in lakes (Nürnberg, 1998; Brett & Benjamin, 2008). All other parameters were retained in the complete dataset for potential use in future studies.

Estimating daily TP concentration and load

Daily TP concentrations and loads were estimated using the WRTDS method developed by Hirsch et al. (2010). Analyses were performed with the EGRET package (version 3.0.10) in the R software environment (version 4.4.1; R Core Team, 2024). The WRTDS model is a flexible regression model based on the premise that the concentration is a function of discharge, season, and long-term temporal trend (Green et al., 2025). The regression equation is

$$\ln(c) = \beta_0 + \beta_1 t + \beta_2 \ln(Q) + \beta_3 \sin(2\pi t) + \beta_4 \cos(2\pi t) + \varepsilon$$

where the fitted coefficients are the β values, c is the concentration, Q is the discharge, t is the time in decimal years, and ε is the unexplained variation. While the regression equation itself is relatively simple, the key feature of WRTDS lies in how it is fitted (Hirsch et al., 2010). Unlike a traditional regression model with fixed coefficients, WRTDS generates a unique local regression for each estimation point by dynamically recalibrating weights and coefficients (Zhang et al., 2026). These weights are determined by the distance of each observation from the estimation point in time, discharge, and season, as well as by user-defined half-window widths (Hirsch et al., 2010; Zhang et al., 2026). Thus, observation points closer to the observation points are assigned higher weights, whereas points beyond the half-window widths are excluded from the local fit (Zhang et al., 2026). The regression equation is evaluated over a grid of points spanning time and discharge using weighted regression on the observations, and the resulting coefficients define a continuous surface of expected concentration as a function of time and discharge, often referred to as the "regression surface" (Green et al., 2025; Zhang et al., 2026). Hence, WRTDS can capture local conditions and nonlinear patterns (Zhang et al., 2026).

The WRTDS method requires a dataset consisting of more than 200 samples, a collection period exceeding 20 years, a complete record of daily discharge, all analyses above detection limits, samples representative of the entire river cross-section, and minimal "flashy flow" (Hirsch et al., 2010). Based on these requirements, only two sites met the inclusion criteria: Vombsjön utlopp (hereafter, lake outlet) and Björkaån (hereafter, lake inlet).

These sites also represent the primary hydrological input and output of Lake Vombsjön. The TP dataset for the lake outlet included 523 observations (1969–2024), and for the lake inlet, 500 observations (1969–2024). Possible effects of changes in field or laboratory methods were considered before the trend analysis to avoid introducing systematic bias and misleading trends (Smith & McCann, 2000). Observations reported below the detection limits were excluded. In total, four measurements were removed (two per location), all from 1969. Because censored values were few and confined to the beginning of the record, changes in detection limits were considered unlikely to influence the long-term trends. In addition, visual inspection of the time series revealed no apparent step changes indicative of major methodological shifts.

Potential outliers were evaluated cautiously, and a conservative upper threshold of 0.75 mg/L was applied to avoid extreme values distorting temporal trends. In total, two measurements were removed (one per location), both from the beginning of the study period.

Corresponding discharge data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI): Vombsjöns Övre (Station ID: 2018; 1969–2024) for the outlet and Eggelstad (Station ID: 2125; 1973–2024) for the inlet. Although the Eggelstad station is located upstream of the inlet monitoring site, it provides the most representative and complete discharge record available. After accounting for data availability and excluding observations below the detection limit and outliers, the final TP datasets comprised 520 observations at the outlet and 469 at the inlet, which were used to generate daily TP concentrations with WRTDS.

Default half-window widths of 2 log Q units for discharge, 7 years for time, and 0.5 years for season were used. The modelled estimates of TP concentration and load were evaluated against the observed TP concentration and load by using built-in diagnostic functions in EGRET. The evaluation included the coefficient of determination (R^2), root mean square error (RMSE) of the logarithmic concentration, and standard error of prediction (SEP) of the logarithmic concentration. Even though the RMSE and SEP are based on log-transformed concentrations, the same value would apply to the load. Furthermore, a visual comparison of observed and estimated TP concentrations and loads was conducted by computing scatterplots. Residuals and fitted values were also visually inspected to assess temporal consistency and potential systematic bias. No flow normalisation was used, as the objective was to evaluate observed long-term variability and management effects rather than trends adjusted for flow variability.

Long-term trends

Estimated TP concentrations and loads for the lake inlet and outlet were analysed for the period 1975–2024, which defines the study period. Earlier data were excluded due to insufficient observations at the inlet. Annual mean TP concentrations and loads were calculated as the average of daily estimates, and corresponding standard deviations were determined. To examine C–Q relationships, a contour plot of the lake inlet was generated using the EGRET package. Following the recommendations of Hirsch and De Cicco (2015), the flow range was constrained to the 5th and 95th percentiles to avoid unreliable extrapolations at extreme high and low discharges.

To assess long-term trends, the dataset was divided into five time periods: 1975–1984, 1985–1994, 1995–2004, 2005–2014, and 2015–2024, hereafter referred to as time periods 1 to 5. The cumulative change in TP concentration was determined by comparing the annual mean concentration in 1975 with that of the final year in each time period, expressed as a percentage. Mean TP load, mean TP retention, and mean retention coefficient were also calculated for each time period as the average of the annual values.

The TP retention for Lake Vombsjön was calculated as a mass flux, defined as the difference between *P* input to and P output from the lake on an annual basis (Hupfer & Lewandowski, 2008; Nürnberg, 2020). Specifically, annual TP load estimates for the lake inlet were subtracted from the annual TP load estimates for the lake outlet to determine annual TP retention. The retention coefficient was calculated annually as the ratio of the TP retention to TP load at the lake inlet, representing the proportion of external TP retained in the lake (Hupfer & Lewandowski, 2008; Nürnberg, 2020). Mean TP retention and retention coefficient were subsequently calculated for each time period. We acknowledge that *P* retention can be defined and estimated in multiple ways. In this study, we adopted a mass balance approach due to data limitations that prevented the application of alternative methods across the whole study period.

To quantitatively assess the relationships between the management interventions within the catchment of Lake Vombsjön (Fig. 2) and the estimated TP concentrations, multiple linear regression models were fitted separately for each of the five time periods. Annual mean log TP concentrations were used as the response variable in all models. Explanatory variables included *P* emissions from wastewater treatment plants discharging into Björkaån, cumulative constructed wetland area (ha) upstream of Lake Vombsjön, and national *P* fertiliser sales to Swedish agriculture (Fig. 2; see also Online Resource 1). Atmospheric deposition of *P* was not included in the analysis, as Swedish monitoring indicates generally low deposition levels (Linderholm & Mattsson, 2013), and since previous studies suggest no clear long-term temporal trend for *P* deposition in Sweden (Knulst, 2001).

Table 1 Model performance statistics for the WRTDS model at the lake inlet and outlet

Site	R^2 (logC)	R^2 (logF)	RMSE (logC)	SEP (logC)
Lake inlet	0.684	0.953	0.336	34.5
Lake outlet	0.564	0.894	0.454	47.8

Shown are the coefficients of determination (R^2) for both the log TP concentration (logC) and TP load (logF), root mean square error (RMSE), and standard error of prediction (SEP). RMSE and SEP are based on log-transformed concentration, but the same value would apply for the load

Results

Model performance

Model performance was evaluated for both the lake inlet and outlet by comparing the observed and estimated daily values from the WRTDS model, presented in Table 1. The lake inlet showed higher predictive ability than the lake outlet, as reflected by higher R^2 values, lower RMSE, and lower SEP. Model performance was also higher for TP load than for concentration, indicated by the higher R^2 values. Overall, these results suggest that the model adequately captured the main temporal patterns of observed concentrations and loads, with moderate prediction uncertainty.

Scatterplots of observed versus predicted TP concentrations are presented in Fig. 3. The model performance was generally better at lower concentrations for both the lake inlet and outlet, where observations clustered more closely around the 1:1 line. Overall,

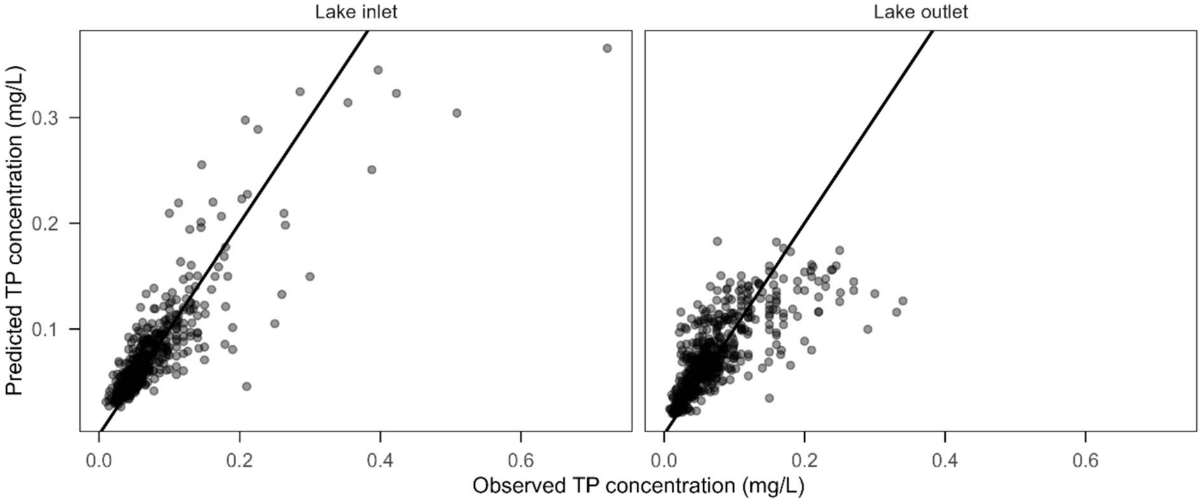

Fig. 3 Observed versus predicted TP concentrations at the lake inlet and outlet of Lake Vombsjön. The solid line represents the 1:1 relationship, indicating perfect agreement between observed and predicted values. Figure produced in R (version 4.4.1; R core team, 2024)

the lake inlet showed closer agreement between observed and predicted values compared to the lake outlet.

Concentration trends

Between 1975 and 2024, a decreasing trend in annual TP concentration was identified at both the lake inlet and outlet, presented in Fig. 4. The largest reduction occurred at the lake inlet, where TP concentrations declined continuously throughout the study period, decreasing by a total of 72%, from a mean concentration of 0.21 mg/L in 1975 to 0.058 mg/L in 2024. The changes within each time period are summarised in Table 2. The most pronounced decrease occurred during the first period (1975–1984), with a 38% reduction, followed by smaller decreases of 16% and 15% in the subsequent two periods. Thereafter, the decline stabilised, with only a 5% decrease and a minor 2% increase during the most recent period.

In contrast, annual TP concentrations at the lake outlet showed a less consistent pattern, alternating between periods of increase and decrease (Fig. 4). During the first two time periods, TP concentrations declined by 10% and 11%, respectively (Table 2), followed by an increase of 7% in the next period. A 30% reduction occurred during the subsequent period, followed by a 19% increase in TP concentrations in the final period. Overall, the outlet showed a 25% decrease from 1975 to 2024, from 0.098 mg/L to 0.074 mg/L.

Load trends and retention

Estimated TP loads for the lake inlet and outlet are presented in Fig. 5, with positive bars representing inlet loads and negative bars representing outlet loads. A general decline in TP loads occurred at both sites, consistent with the concentration trends, although with more pronounced annual variability. At the lake inlet, mean annual TP loads decreased from 15.8 tonnes/year in 1975–1984 to 8.2 tonnes/year in 2015–2024, corresponding to an overall reduction of 48%. At the outlet, TP loads also declined from 10.4 tonnes/year in 1975–1984 to 7.8 tonnes/year in 2015–2024, representing a 25% reduction.

Annual mass TP retention estimates for Lake Vombsjön are also presented in Fig. 5, with bars

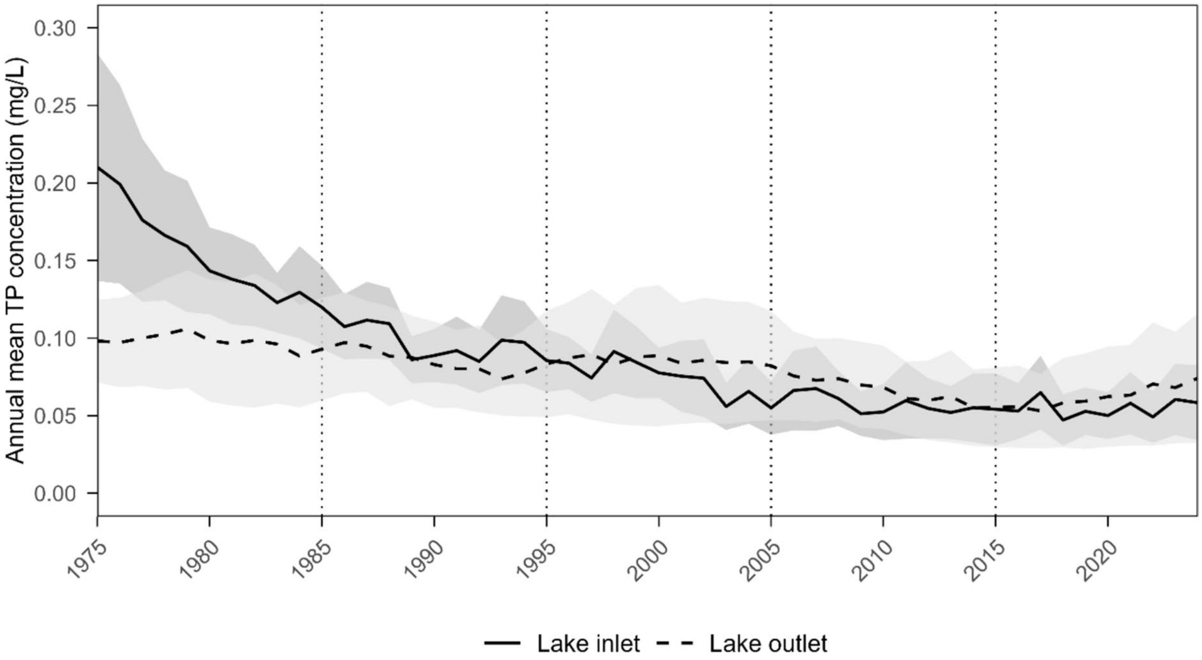

Fig. 4 Annual mean TP concentrations (mg/L) at the lake inlet (solid line) and outlet (dashed line), with standard deviation shown as shaded ribbons (grey), for the period 1975–2024. Vertical dotted lines indicate the time period boundaries (1985, 1995, 2005, and 2015). Figure produced in R (version 4.4.1; R core team, 2024)

Table 2 Summary of temporal changes in estimated TP concentrations from 1975, mean loads, and retention for the five defined time periods

Time period	Change in TP concentration (%)		Mean TP load (tonnes/year)		Mean retention (tonne/year)	Mean retention coefficient (%)
	Lake inlet(%)	Lake outlet(%)	Lake inlet	Lake outlet		
1975–1984	−38	−10	15.8	10.4	5.43	33
1985–1994	−54	−21	14.4	8.95	5.43	34
1995–2004	−69	−14	10.9	9.02	1.88	9.4
2005–2014	−74	−44	8.38	7.99	0.39	−0.0089
2015–2024	−72	−25	8.72	8.38	0.34	1.3

Shown are cumulative changes in annual TP concentration, mean TP load (tonnes/year), mean mass retention (tonnes/year), and mean retention coefficient (%)

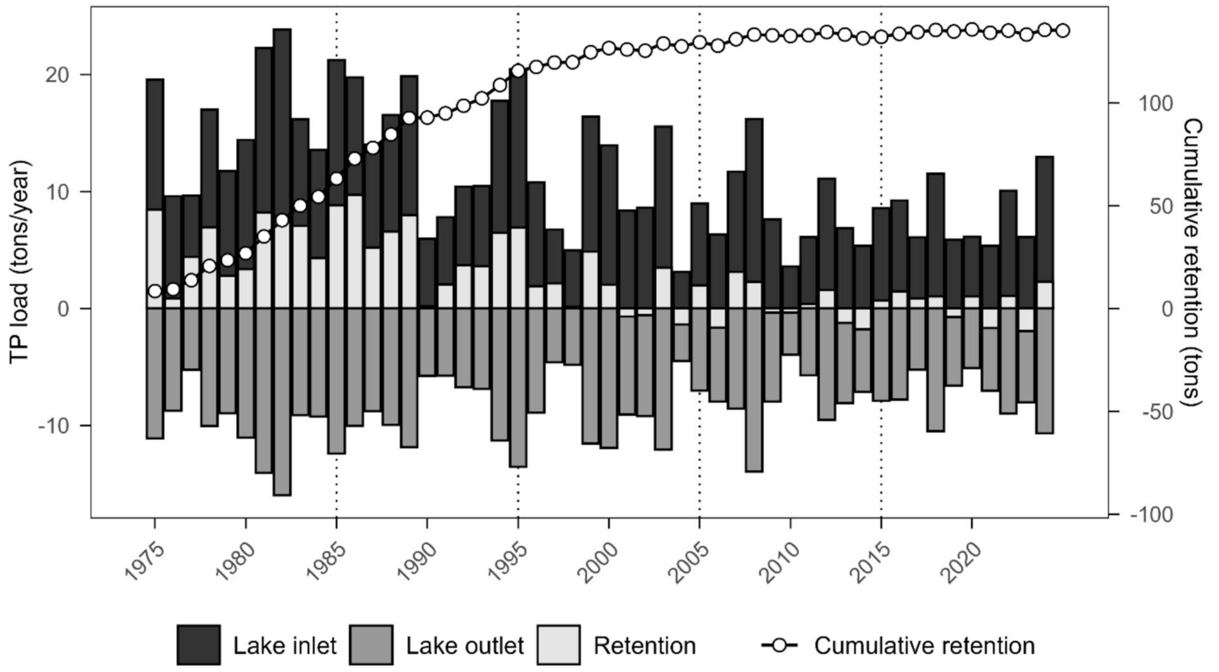

Fig. 5 Annual TP load (tonnes/year) at the lake inlet (black bars) and outlet (dark grey bars), together with annual TP retention (light grey bars) and cumulative net TP flux (line with points) shown on the secondary y-axis, for the period 1975–2024. Vertical dotted lines indicate the time period boundaries (1985, 1995, 2005, and 2015). Figure produced in R (version 4.4.1; R Core Team, 2024)

representing the difference between inlet and outlet loads. The cumulative retention over the study period is shown on the secondary y-axis, indicating that approximately 130 tonnes of TP were retained between 1975 and 2024. The highest retention occurred during the earlier time periods and reached equilibrium at the fourth time period (2005–2014). Although some years exhibited net negative retention, retention was positive in most years throughout the study period. Both annual TP retention and the corresponding retention coefficients are summarised in Table 2.

The retention coefficient followed a similar pattern (Table 2). Approximately 33–34% of external

TP input was retained during the first two periods, but retention thereafter decreased to 9.4% in the third period. In the two most recent periods, the retention coefficient approached zero, with values of -0.0089 and 1.3%, respectively.

Concentration-discharge relationship

A contour plot showing the relationship between TP concentration and discharge at the lake inlet is presented in Fig. 6. During the first time period, high TP concentrations were observed under both low and high flow conditions. By the second time period, TP concentrations during low-flow events had weakened. Elevated concentrations during high flow events persisted, although they declined gradually throughout the study period.

Seasonal variability

The estimated monthly mean TP concentrations for the different time periods are presented in Fig. 7. At the lake inlet, TP concentrations decreased from winter to spring, followed by a gradual increase towards late summer and autumn. Seasonal variability was most pronounced during the first time period, when concentrations during summer and autumn were higher than in subsequent periods.

At the lake outlet, a clear seasonal pattern was observed, with lower concentrations during winter and spring and higher concentrations during late summer and early autumn, where peak values occurred. The decline between the time periods was consistent for winter and spring months but less stable during summer, when both increases and decreases were observed. Similar to the annual concentration trends, this summer increase was particularly evident during the third and fifth time periods.

Management interventions

The results of the multiple linear regression analysis are presented in Table 3, where the relationship between TP concentration and management interventions varied depending on the different time periods. Wastewater treatment plant effluent concentration was significantly ($p < 0.05$) and positively associated with TP concentrations in the first time period (1975–1984), but this relationship weakened and was not significant in subsequent periods. National fertiliser sales showed a positive and statistically significant ($p < 0.05$) relationship with TP concentrations during the second time period

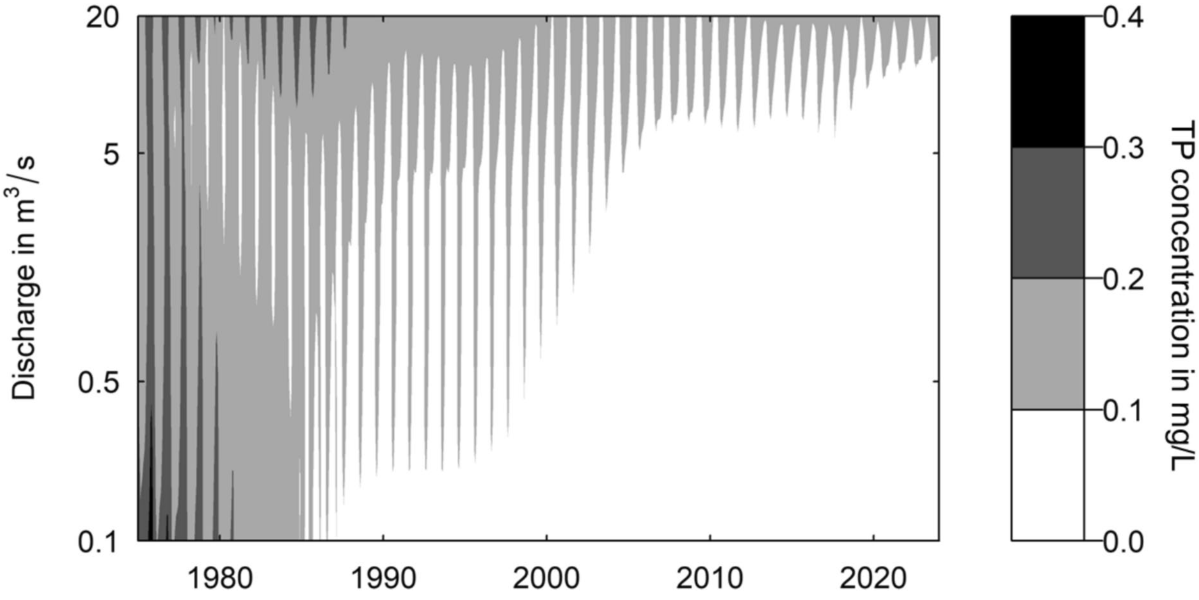

Fig. 6 Contour plot of TP concentration (mg/L) as a function of discharge and time at the lake inlet. Darker shades indicate higher TP concentrations. The flow range is constrained between the 5th and 95th percentiles. Figure produced in R (version 4.4.1; R core team, 2024)

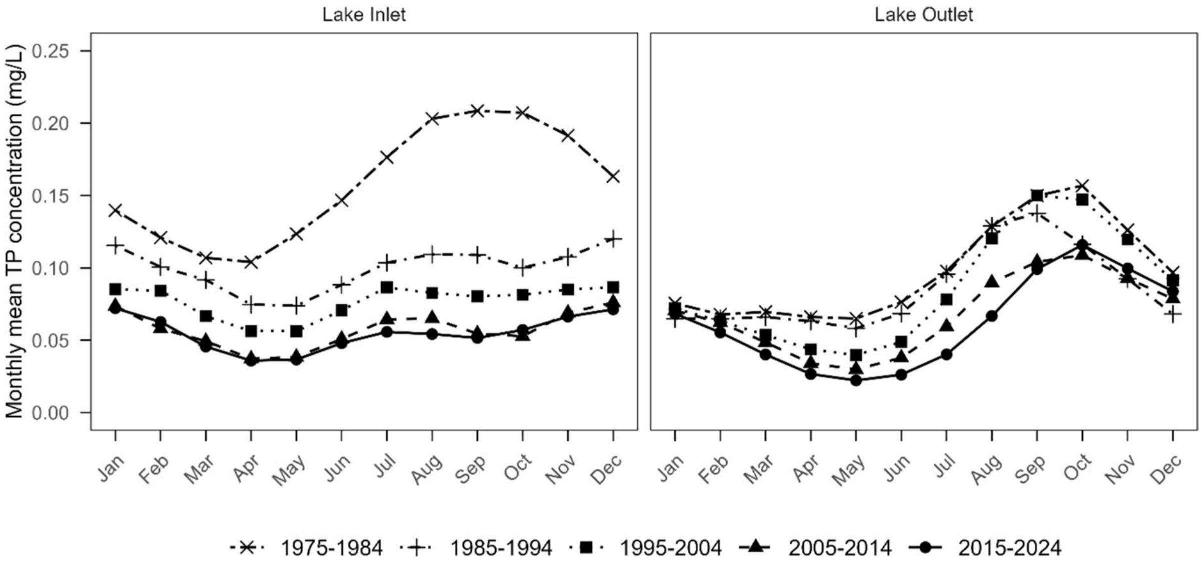

Fig. 7 Monthly mean TP concentration in mg/L at the lake inlet and lake outlet, for each time period (1970–1984, 1985–1994, 1995–2004, 2005–2014, 2015–2024). Figure produced in R (version 4.4.1; R core team, 2024)

Table 3 Multiple linear regression coefficients for log TP across different time periods

	1975–1984	1985–1994	1995–2004	2005–2014	2015–2024
Wastewater treatment plant effluent concentration	0.2*	− 0.07	− 0.03	−0.3	− 0.08
National fertiliser sales	0.002	0.017*	0.006	NA	NA
Constructed wetland area	NA	NA	− 0.008*	− 0.0009(.)	0.0024
R^2	0.9	0.5	0.7	0.5	0.008

Significance levels: *** $p<0.001$, ** $p<0.01$, * $p<0.05$, (.) $p<0.10$. NA = not applicable

Explanatory variables include wastewater treatment plant effluent concentration, national fertiliser sales, and cumulative constructed wetland area. R^2 indicates model explanatory power

(1985–1994). Cumulative wetland construction showed a significant ($p<0.05$) and negative relationship in the third time period (1995–2004) and a marginally significant negative relationship ($p<0.10$) in the fourth period (2005–2014). Model explanatory power varied between time periods, with the highest R^2 observed in 1975–1984 ($R^2=0.9$) and the lowest in 2015–2024 ($R^2=0.008$), indicating a strong decline in the ability of the selected drivers to explain TP variability in recent decades.

Discussion

The WRTDS model indicates that the management interventions implemented in the catchment have been effective in reducing TP concentrations at the inlet and outlet of Lake Vombsjön over the past 50 years. Overall, the model demonstrated satisfactory performance, with higher predictive ability at the lake inlet than at the lake outlet, as indicated by higher R^2 values and lower RMSE and SEP (Table 1). Scatterplots of observed versus predicted concentrations (Fig. 3) showed generally good agreement, particularly at lower concentrations, while higher variability was observed at the lake outlet. This higher variability at the outlet is likely due to in-lake processes not represented in the WRTDS model. Furthermore, although no clear discontinuities indicative of methodological changes were observed in the raw TP dataset, the potential effects of changes cannot be entirely excluded. Therefore, the observed trends are interpreted with this uncertainty in mind.

In addition, this study only focuses on the primary inflows and outflows of Lake Vombsjön, thereby neglecting minor tributaries (Fig. 1) and other sources and sinks. While this does not capture the full scale of *P* inputs and outputs, these main hydrological inputs and outputs are still expected to represent overall *P* trends on a longer time scale. Despite these limitations, clear trends in *P* were identified. To better interpret them, the discussion is organised into three parts reflecting the three research objectives: (1) historical changes in *P* inputs, (2) responses in *P* export and retention, and (3) future management of Lake Vombsjön.

Historical changes in *P* input

Between 1975 and 2024, a continuous decline in TP inputs to Lake Vombsjön, corresponding to reductions of 72% in TP concentration and 48% in TP load, was identified (Fig. 4 and Fig. 5). These estimates are however likely underestimated, since monitoring began after several wastewater and industrial management measures had already been implemented (Fig. 2). Nevertheless, the magnitude of TP reduction observed in Lake Vombsjön is like that of other lakes that have undergone similar catchment management efforts. For example, Loch Leven (Scotland) achieved a 60% reduction in TP loads (May et al., 2011), Lake Müggelsee (Germany), a 52% reduction (Köhler et al., 2005), nearby Lake Ringsjön (~ 20 km away) approximately 50% (Granéli, 1999), and for the four biggest lakes in Sweden (the lakes Vänern, Vättern, Mälaren, and Hjälmaren) reductions of approximately 50–60% were reported (Wilander & Persson, 2001).

The largest decrease in TP concentration (38%) and highest mean TP load (15.8 tonnes per year) occurred during the first time period (1975–1984), coinciding with the introduction of wastewater treatment plants and reductions in industrial discharges (Fig. 2). During this time period, high TP concentrations were associated with low-flow conditions (Fig. 6), indicating a system dominated by point sources (Bowes et al., 2008). This relationship weakened over time, most likely because point sources were successfully mitigated. This interpretation is supported by the regression results (Table 3), where wastewater treatment plant emissions were significantly and positively associated with TP concentrations in 1975–1984 ($p < 0.05$), but became weaker and non-significant in later periods. Similar findings were also reported by Krug (1993), who documented a 35% reduction in TP loads in the Kävlingeån catchment between 1960 and 1988, primarily due to improved sewage treatment and industrial regulation.

During the second and third time periods, TP concentrations declined at a slower rate than in the previous time period, while the mean TP load also decreased (Table 2). The previously strong relationship between high TP and low flow was further weakened (Fig. 6), indicating that diffuse sources rather than point sources were the main contributors to external *P* loading. The trends also align with the measures implemented during these periods. During the second time period, fertiliser use and livestock density were still relatively high (Fig. 2), resulting in a higher mean TP load of 14.4 tonnes per year. By the third time period, the fertiliser usage and livestock density decreased, along with the start of wetlands reintroduction (Fig. 2), resulting in a lower mean TP load of 10.9 tonnes per year. Collectively, these findings suggest that improvements in diffuse sources primarily drove the continued TP reduction during these time periods. These interpretations are supported by the regression results (Table 3), where fertiliser sales showed a significant positive relationship with TP concentrations during 1985–1994 ($P < 0.05$), while wetland area showed a negative relationship during 1995–2004 ($P < 0.05$). However, the R^2 of these models was lower than in the earlier period dominated by point-source controls.

In the two most recent time periods, the decline in TP concentration stabilised, with minor decreases and even slight increases observed. Mean TP load during these years was approximately 8 tonnes/year, and diffuse sources remained as the primary contributor to external loading (Fig. 6). Only constructed wetlands showed a marginally significant relationship with TP concentrations ($p < 0.10$) during the fourth study period, whereas in the final period, none of the management interventions were significant, consistent with the low R^2 values observed (Table 3). Wetland construction peaked between 2003 and 2012 (Fig. 2), which may help explain the marginal significance observed in the fourth period; however, the associated reduction in TP concentrations was small compared to earlier periods (Table 2 and Fig. 4).

Overall, the long-term decline in TP inputs to Lake Vombsjön was initially driven by reductions in point sources, followed by more gradual improvements associated with reduced fertiliser use, lower livestock density, and wetland construction. This pattern is consistent with the greater difficulty of reducing diffuse pollution compared to point sources (Macintosh et al., 2018). For example, the effect of diffuse-source measures such as wetland construction has been shown to vary, as their effectiveness depends strongly on factors such as landscape position and hydraulic and nutrient loading conditions (Djodjic et al., 2022), highlighting the challenges of mitigating diffuse nutrient inputs.

Responses in *P* export and retention

TP concentrations and loads at the lake outlet decreased by approximately 25% over the period 1975–2024, showing a smaller and less consistent reduction than at the inlet (Fig. 4 and Fig. 5). During the first two time periods (1975–1984 and 1985–1994), TP concentrations at the lake outlet decreased by approximately 10% in each time period, indicating that the initial reductions in external *P* inputs were reflected in the lake outlet. However, this early response was followed by an increase in TP concentrations and loads during 1995–2004, diverging from the continued decreasing trend at the inlet. In the subsequent time period (2005–2014), concentrations decreased again by roughly 30%, before increasing once more in the most recent period (2015–2024).

The differing behaviour between the lake inlet and outlet likely reflects the difference in hydrological residence time, which slows nutrient transport, prolongs biotic processing, and dampens the amplitude of seasonal nutrient fluxes. One process influenced by this extended residence time is the release of *P* from historically accumulated sediments, i.e. internal *P* loading (Søndergaard et al., 2013). Internal *P* loading has been shown to be pronounced during the first years after a reduction in the ingoing *P* load, delaying the recovery by approximately 10–15 years (Jeppesen et al., 2005; Søndergaard et al., 2013).

Cumulative retention estimates indicated that approximately 130 tonnes of TP have accumulated in the lake from 1975 to 2024 (Fig. 5), representing a substantial pool available for release to the water column. This estimate is likely conservative, as monitoring began during a period of already elevated *P* loading that had persisted for several decades (Fig. 2), and it accounts for only one of the lake inflows (Fig. 1b). The largest TP accumulation occurred during the first two time periods, amounting to roughly 110 tonnes, coinciding with a large decrease in external *P* load and retention coefficients of 33 and 34% (Table 2). Thereafter, both the external load and retention coefficient declined, while annual outlet concentrations and loads began to rise. This pattern suggests a growing influence of internal *P* loading during this period, consistent with the dynamics described by Jeppesen et al. (2005) and Søndergaard et al. (2013), in which internal loading is pronounced after a considerable reduction in external loading.

The increase in annual TP concentrations and loads during 1995–2004 was primarily driven by early autumn concentrations (Fig. 7). This seasonal pattern supports the influence of internal *P* loading, as late summer and early autumn TP peaks are commonly observed in recovering shallow lakes (Spears et al., 2011). In such systems, recovery typically begins with declining winter and spring concentrations, while internal recycling sustains higher summer values due to sediment release (Spears et al., 2020). Over time, these seasonal peaks gradually diminish as internal stores are depleted, and the lake approaches a new equilibrium. This progression was evident in Lake Vombsjön, as annual outlet TP concentration and load decreased again during 2005–2014, particularly in early autumn (Fig. 7). The delay is consistent with the expected 10–15 year lag between external load reduction and recovery. By this time period, annual TP retention values also approached zero, indicating that the lake had reached a new equilibrium. However, this does not necessarily mean that the lake is recovered. Studies have shown that in eutrophic shallow lakes, internal P loading may persist, particularly in summer, even though the lake acts as a sink on an annual scale (Søndergaard et al., 2013).

By the fourth study period (2004–2015), annual TP at the outlet had decreased by approximately 50% (Table 2). However, by the last time period, outlet TP concentrations exhibited an upward trend, interrupting the expected recovery trajectory. Søndergaard et al. (2013) suggested that in lakes with a high mobile *P* pool, there is a risk of a shift back to negative feedback and increased sediment *P* release if the lake reverts to a turbid state. In addition, climate-related factors such as rising temperatures have been shown to enhance internal *P* release by intensifying stratification and anoxia (Nürnberg, 2025). At the outlet of Lake Vombsjön, water temperature showed a weak increasing trend, while dissolved oxygen showed a slight decreasing tendency (See Online Resource 3). However, the relationship between TP concentration and these variables was weak, and the R^2 value was low (Online Resource 3 – Table S1). Thus, the drivers of the recent increase remain uncertain and warrant further investigation.

Taken together, the accumulation of TP in Lake Vombsjön until the late 1990s reflects a system primarily driven by high external *P* loading. As catchment interventions have effectively reduced these external inputs, internal processes now appear to play a more dominant role, and full recovery remains ongoing. Previous studies by Hamrin et al. (1998) and Elhabashy et al. (2023) identified internal *P* loading as a key driver of elevated TP concentrations in Lake Vombsjön, and our long-term analysis confirms this while further demonstrating how the relative influence of internal versus external loading has changed over the past five decades.

Future management of Lake Vombsjön

Our historical analysis of the in and outflow *P* trends in Lake Vombsjön reveals patterns that provide important insights for future lake management. A shift from a point source to a diffuse-source-dominated system in Lake Vombsjön was identified. The most pronounced reductions occurred during the early period, while later changes associated with diffuse-source management were more gradual. Since reduction of external nutrient loading is a fundamental premise for lake restoration (Jilbert et al., 2020), future measures should be specifically targeted towards the remaining diffuse sources. These include measures such as precision agriculture, vegetated buffer strips, contour cultivation, and constructed wetlands (Macintosh et al., 2018).

Internal *P* loading has and continues to influence the lake's TP concentration, especially during the late summer and autumn period. Special focus should be placed on better understanding the mechanism driving the increase in outgoing *P* load observed after 2015 and determining whether it represents a temporary fluctuation or an emerging trend. This is especially important given that the mean annual TP concentration of the lake outlet still exceeds the restoration target (74 µg/L compared to the goal of 27 µg/L).

Our findings emphasise the broader value of historical and continuous monitoring data available around Lake Vombsjön. The use of long-term monitoring data combined with the WRTDS model, therefore, enabled the identification of these trends. While models or statistical methods, such as WRTDS, can help extract temporal trends from noisy datasets, a model is only as good as the data it is fed. Thus, modelling can complement, but never replace, actual data (Burt, 2014), highlighting the need for continuous monitoring in Lake Vombsjön and in other affected lakes worldwide. Continued monitoring, additional assessment of diffuse-source contributions, and targeted investigations into the drivers of recent internal loading dynamics will be essential for guiding effective future interventions. Such investigations can be supported by decision-support frameworks for assessing and managing internal *P* loading in Swedish lakes, such as those developed by Huser et al. (2023).

Conclusion

This study shows that the catchment management interventions in the Lake Vombsjön catchment reduced the external TP loads by 48% and inlet concentrations by 78% over the past five decades. The most substantial reductions occurred early in the study period (1975–1984), following the introduction of wastewater treatment and a decrease in industrial discharges. Subsequent changes in TP were more gradual and increasingly associated with diffuse-source management, including fertiliser reductions and wetland implementation, which showed a significant but more modest effect. A shift from a point-source-dominated to a diffuse-source-dominated system was identified, highlighting the need for future management to focus on strategies that effectively mitigate diffuse inputs.

An estimated 130 tonnes of *P* have accumulated in lake sediments since 1975, forming a substantial legacy pool that can delay recovery through internal *P* loading. Since the mid-1990s, internal *P* loading has influenced lake TP concentrations, and signs of recovery were initially observed. However, since 2015, this trajectory appears to have reversed, with increasing early autumn and annual outlet concentrations. Although the drivers of this recent increase remain uncertain, it is possible that increased internal *P* loading is driving this trend. These findings highlight the need for restoration strategies that simultaneously reduce external inputs and address internal loading to support progress towards good ecological status in Lake Vombsjön.

Finally, this study demonstrates the value of long-term monitoring and historical datasets. Such records enable the detection of slow or nonlinear recovery trajectories, the identification of emerging trends, such as the post-2015 increase, and the evaluation of the effectiveness of past management. These insights are hard to obtain from short-term studies and are essential for guiding future lake management.

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Data availability Data and R code are available upon request to the corresponding author.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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