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PRIMARY RESEARCH PAPER

Nutrient dynamics following 50 years of reduced loading in the large and shallow Lake Arresø

Kaj Sand-Jensen · Jonas Stage Sø · Theis Kragh

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Abstract Motivated by a citizens group to improve the ecological quality in Denmark's largest lake, we examined 50 years of measurements to evaluate the scope for improvement. We found that external inputs in the early 2020s contained only 10% of phosphorus (P) compared to the mid-1980s, mainly due to effective purification of urban wastewater. Although in-lake P and chlorophyll concentrations decreased four–fivefold, summer Secchi depths are only 40–60 cm, but not because large sediment nutrient pools causes high internal loading and long-term delays upon load reductions. Rather, frequent sediment resuspension ensures intimate contact between nutrient pools in surface sediments and the water and close correspondence between P inputs and in-lake concentrations. Thus, costly attempts to remove surface sediments or add chemicals to bind P will not have long-term effects. Instead, predictions show that reducing the external P input twofold would increase Secchi depths to about 1 m and might bring waterplants back to Lake Arresø. For this to happen would require appreciable reduction in nutrient runoffs from the farmland by means of larger uncultivated lowland areas, wider buffer strips along the streams and reduced fertilizer application.

Keywords Limnology · Nutrient dynamics · Phosphor · Nitrogen · Lake

Introduction

A citizens group revived discussions in 2024 regarding the unacceptable bad ecological quality of Denmark's largest lake, Lake Arresø (Fig. 1, Sand-Jensen et al., 2025). Despite remarkable improvements in urban wastewater treatment, the lake has remained turbid due to dense phytoplankton blooms and frequent sediment resuspension. During summer, the Secchi depth can be 30 cm and rarely rises above 70 cm. The group urged full consideration of the possibility of reducing urban nutrient losses even further and immobilizing phosphate with lanthanum by adding the bentonite-clay, Phoslock, which they suggested would transform phosphate (P) into the inert mineral rhabdophane ($LaPO_4$-nH_2O) in the lake sediments. However, Phoslock treatment would

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K. Sand-Jensen
Freshwater Biological Section, Department of Biology, University of Copenhagen, Universitetsparken 4thfloor, 2100 Copenhagen, Denmark

J. S. Sø (✉) · T. Kragh
University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark
e-mail: Jonassoe@biology.sdu.dk

Fig. 1 Map of Lake Arresø, outline of the catchment and subcatchments (stippled red) and location of the two main cities (Hillerød and Helsinge in gray). The four main stream-inlets (Ramløse Å, Pøleå, Æbelholt Å and Lyngby Å, blue lines), the outlet (A) to Roskilde Fjord and forests (green) are also shown. The area is some 40 km north of central-Copenhagen. From Frederiksborg Amt (2005)

be extremely costly in the 40-km^2 large lake and it would not target organic P which is the main form in the water.

The group arranged a large public meeting with invited politicians, farmers, nature representatives and local citizens. We welcome the initiative and offer new limnological insights, since extensive data from the last fifty years has been analyzed in a comprehensive manner that may shed light on the possibility of improving the water quality.

Paleoecological studies showed that Lake Arresø had been a clear-water lake with luxurios submerged vegetation for 4000 years in the past, but had turned eutrophic in the eighteenth century and hypereutrophic during the last 100 years due to high nutrient inputs of domestic sewage from 60–70,000 residents and nutrient losses from cultivated fields (CowiConsult, 1989; Klein, 1989). The lake was already very turbid by the 1930s from dense phytoplankton blooms and frequent resuspension of sediment particles due to the low mean water depth relative to the large lake surface area and the high wind exposure (Olesen, 1976).

Plans to restore the lake by sediment removal, for example as in Lake Trummen, Sweden (Björk, 1985), were debated in the 1980s (CowiConsult, 1989). It was suspected that nutrient release from lake sediment pools (internal loading) would prevent or delay improvements many years after reduction in external nutrient inputs. CowiConsult (1989) concluded that costs were too high and the chance of success was too low due to the frequent resuspension of the upper 2 cm of fine sediments on about three-quarters of the lake's floor (about 31.6 km^2) and the spatial shifts in sedimentation of the material depending on wind velocity and direction. Despite careful sediment analyses, CowiConsult (1989) did not quantify the lake's mobile nutrient pools in surface sediments and water, the internal nutrient loading and the significance of short water retention time (mean 3.4 years) that leave lake ecology highly dependent on external nutrient input (Kalff, 2002).

Many studies of the response of shallow lakes after the reduction in external nutrient sources show substantial net release of nutrients from sediments for several years, slowing the improvement of lake qualities (Søndergaard et al., 1993; Welch & Clarke-Cooke, 2005). Phosphorus retention in winter may be replaced by total phosphorus (TP) release in summer and raise in-lake TP concentrations two–sixfold (Phillips et al., 1994; Søndergaard et al., 2003). Phosphorus may be released from adsorbed P, redox-sensitive Fe–P compounds and labile organic P compounds primarily at the sediment surface, while Ca–P, Fe–P minerals and Al–P minerals and certain organic P compounds are recalcitrant and increase with sediment depth (Ketsev et al., 2006; Søndergaard et al., 2013).

We know that P release from aerobic surface sediments is stimulated by organic degradation at low nitrate concentrations as temperatures increase, but reduced by high nitrate concentrations elevating redox levels in surface sediments and improving Fe–P binding, while the pH influence is smaller and more variable (Jensen & Andersen, 1992; Jensen et al., 2006). Lakes with high Fe/TP ratios (> 15) in surface sediments may show a reduced P release during summer, possibly due to firm P binding in Fe–P minerals (Jensen et al., 1992a, b; Kommana et al., 2023).

The long-term development of nutrient pools in sediments during nutrient abatement has been measured in only a few lakes (Søndergaard et al., 1993). Instead, internal loading by nutrient release from sediments is often calculated from the difference between nutrient inputs and outputs (Søndergaard et al., 2013). The common finding is that shallow lakes that experienced decades of high nutrient inputs have accumulated large sediment pools, which gradually release nutrients to lake waters over several years following nutrient abatement, thus markedly slowing the improvement of lake nutrient status. However, the story may be different in large shallow lakes such as Lake Arresø, which experiences almost permanent resuspension; lake water and surface sediments are in much closer contact, and nutrient pools in lake water and surface sediments may decline in concert.

Following the substantial reduction in external P from domestic sewage in the 1990s, in-lake chlorophyll concentrations rapidly declined in Lake Arresø (Sand-Jensen, 2014). Thus, we concluded that, perhaps, the perception of a large mobile sediment pool preventing lake ecological improvement for many years, underlying the former idea of removing the upper sediment layers and the contemporary idea of treating the lake with Phoslock, is unwarranted. Recent studies also supported the view that shallow lakes and lakes with short water retention time may show limited resilience and hysteresis of in-lake nutrient concentrations upon pronounced reductions in external nutrient loading, allowing fast improvement of lake quality (Jeppesen et al., 2005; Chorus et al., 2020; Frenken et al., 2023).

Over recent decades, nutrient inputs from domestic sewage have been reduced even further in Lake Arresø by gradually replacing more than 30 small sewage treatment plants (Olesen, 1976) with two newly built and very effective water treatment plants. Combining mechanical, advanced biological, and chemical treatments, they remove about 98% of TP and 90% of total nitrogen (TN) from the raw sewage (PULS-Danmarks Miljøportal; Sand-Jensen et al., 2025). Moreover, to facilitate the improvement of Lake Arresø and assist biodiversity, four new, small, shallow lakes were constructed in the catchment during the 1990s with the goal of retaining runoff nutrients in their sediments and reducing TP inputs to Lake Arresø (Sand-Jensen, 2001).

Nutrient inputs from cultivated fields have remained much less regulated than sewage treatment, though legislations prior to 2016 required nutrient application per surface area to be below certain thresholds, and cultivation of follow-up crops during winter as well as uncultivated 10-m-wide buffer zones along streams may have reduced nutrient inputs appreciably. In 2016, however, the 10-m-wide buffer zones were reduced to only 2 m and farmers were allowed to increase nutrient application on their fields (Landbrugspakken, Lov nr. 186, March 2016). As a likely consequence, nationwide measurements in 153 lakes found significant increases in TP, TN and chlorophyll from 2011–2016 to 2017–2022 (Johansson et al., 2024). The details of development in Lake Arresø have remained unexplored (Sand-Jensen et al., 2025).

While not a focus to the citizens group and the public discussions, we note that Lake Arresø's outflow empties into the saline, Roskilde Fjord, and thus contributes to its eutrophication. We urge consideration of interventions aimed at improving the entire eutrophic ecosystems. Phytoplankton and macroalgal growth in Roskilde Fjord are mainly N-limited according to bioassay experiments (Geertz-Hansen et al., 1993; Pedersen & Borum, 1996). While most studies of Lake Arresø's ecological quality emphasize the influence of P, the main catchment effect on Roskilde Fjord is the N emerging from the lake. Nitrogen in Lake Arresø has been reduced thanks to better sewage treatment and denitrification in the sediments of Lake Arresø and the newly constructed lakes. The combined effect of these efforts is unknown, but appears to benefit Roskilde Fjord.

Our main objectives here are to quantify the external nutrient sources, the nutrient inputs and nutrient outputs from Lake Arresø as well as the coupled in-lake water–sediment dynamics of nutrients during the last 50 years. Specifically, we evaluate: (i) the coupling between N and P inputs and outputs, (ii) N and P removal in Lake Arresø and newly constructed lakes in the catchment, (iii) sediment P release during summer (internal loading) and the potential contribution of sediment P pools to the lasting eutrophication, and (iv) the possibility of improving the ecological quality of Lake Arresø and reducing its N loss to the downstream estuary.

Materials and methods

Lake Arresø's water transparency, phytoplankton and nutrient dynamics were studied by several authors and agencies in the 1970–1980s (Andersen, 1976a, b; Olesen, 1976; Hovedstadsrådet, 1982; CowiConsult, 1989). From the late 1980s to the early 2000s, detailed measurements following a common protocol were conducted by Frederiksborg County and, thereafter, by the Environmental Protection Agency, presently the Agency for Green Transition and Aquatic Environment (https://ecos.au.dk/forskningraadgivning/fagdatacentre/ferskvand;https://miljoegis.mim.dk/). The measuring protocol includes mid-lake integrated water sampling with depth as well as sampling at specific depths in the usually well-mixed water column at monthly intervals during winter and bimonthly from March to October for the main physical (i.e., temperature and Secchi depth), biological (phytoplankton composition and chlorophyll *a* (Chl)), and chemical conditions. The vertical light attenuation coefficients (K_d, m^{-1}) were estimated assuming that 15% of subsurface light remained at the Secchi depth (SD) and $K_d = 1.897\ (SD)^{-1}$ measured by Olesen (1976). Chlorophyll was initially measured by acetone extraction on GF/C filters (Golterman, 1969) and later by ethanol extraction (Jespersen, 1987). The chemical analyses follows Danish and international standards and are in accordance with the mentioned methods. TP and TN were analyzed by spectrophotometry after persulfate digestion (Koroleff, 1968; Solorzano, 1969). Inorganic phosphate, ammonia and nitrate were measured using methods introduced by several authors (Murphy & Riley, 1962; Strickland & Parsons, 1972; Solorzano, 1969). Organic P and organic N were calculated by subtracting inorganic ions from total P and N. Total alkalinity was measured by acidimetric titration (Rebsdorf, 1972).

Sediment cores were sampled from the three main sediment areas outlined by CowiConsult (1989) in transparent Perspex tubes (inner diameter 56 mm) using a Kajak sampler (Kajak et al., 1965). In 1988, four separate sediment cores were analyzed from each of the three main sediment areas, but later analyses available in Miljøportalen used only single cores from the main sediment areas. Sediments were sliced into six-cm-depth strata (0–2, 2–5, 5–10, 10–20, 20–30 and 30–40 cm), carefully mixed and analyzed for wet weight, dry weight (DW at 105 °C) and organic dry weight (org DW as loss on ignition at 550 °C). Organic carbon was estimated as org DW*0.44, assuming that organic matter contains 49% C and that 5% water is lost by dehydration of clay and Fe– and Al–oxyhydroxides at 550 °C (Santisteban et al., 2004); the exact conversion factor is not important to our evaluations and conclusions. Total nitrogen was analyzed on dried material as above. Total P and total Fe (Fe) in the ash content were measured after dissolution and heating in hydrochloric acid (HCl) (Andersen, 1976a, b), dissolved P using the molybdate method (Murphy & Riley, 1962) and dissolved Fe using the bipyridyl method (Heaney & Davidson, 1977). Calcium content was measured on the ash after dissolution in HCl and titration with EDTA (Freshwater Biological Laboratory, 1972). The calcite content ($CaCO_3$) was calculated assuming that it includes all Ca. Calculations of pools of TP and organic content with sediment depth require knowledge of sediment density. These data were not available, so we used an estimate—mean density of 1.1 g cm^{-3}—in all calculations. This approximates the values (1.07–1.11 g cm^{-3}) calculated for the 1988 data set setting density of inorganic matter at 2.6 g cm^{-3} and organic matter at 1.05 g cm^{-3}, following Søndergaard et al. (1993).

Mass balance calculations were based on 18–24 measurements of TP and TN concentrations annually in the four main inlets and the single outlet from Lake Arresø. Daily nutrient concentrations between measurements were calculated by linear interpolation. Nutrient transport was calculated by multiplying daily nutrient concentrations with water discharge (Q). Discharge was calculated daily at permanent hydrometric stations that constantly record water level (H) in the streams and apply calibrated Q-H relationships. A small part of the catchment with forests on sandy soils drains by subsurface flow into Lake Arresø. Its nutrient input was added using typical nutrient losses from such areas (Frederiksborg Amt and o. M. L. , 2004). The lake's water balance was calculated accounting for surface inlets and outlets, changes in lake water volume (according to continuous measurements of lake water levels) as well as precipitation measured at a meteorological station 30 km away and evaporation from the lake surface calculated from lake water temperature and wind velocity (Hovedstadsrådet, 1982; Miljøstyrelsen, 2000; Miljøportalen.dk). Atmospheric nutrient inputs applied by Frederiksborg County and in subsequent calculations for the entire period were assumed to be consistent with nationwide measurements, 0.1 kg P ha^{-1} and 15 kg N ha^{-1} (Ellermann et al., 2011) and small later changes (Ellermann et al., 2024).

A linear regression model can describe the relationships between annual input and mean in-lake summer concentrations (May–September) of N and P. A multiple linear mixed-effects model was used to relate K_d to the three predictor variables: org P, org N and Chl. During summers, inorganic P and N were very low, and org P and org N were only slightly lower than TP and TN, respectively. Year was treated as a random variable, accounting for annual differences by inferring that two measurements from the same year are more similar than those from different years. To facilitate comparisons among the estimates, all predictor variables were scaled prior to modeling. R^2 is reported as both marginal and conditional, which refers to cases where the random factor is not considered and where it is considered, respectively. The multiple linear mixed-effects model was made using the *lme4*-package, while *P*-values and R^2 values were computed using the *lmerTest* and *MuMIn* packages, respectively. All data analysis were performed in *R* (R Core Team, 2025).

The simple relationships (either linear, logarithmic, exponential or power) accounting for most of the variability (i.e., highest R^2 and lowest *P*-values) of K_d as a function of each of the three predictor variables (org P, org N and Chl) were determined using all individual summer measurements over the last 20 years (>300 observations). All analyses were made in R.

Results

Lake characteristics and land use

Lake Arresø is alkaline, 40-km^2 large, mean depth 3 m and mean water retention time 2.4 years (Table 1). Land use in the catchment in 2003 was divided between towns and infrastructure (17%),

Table 1 Basic characteristics of Lake Arresø. Water retention time and alkalinity values are presented as mean (median, min–max)

Catchment area (km^2)	215
Cultivated area (km^2)	116
Lake area (km^2)	39.9
Mean depth (m)	3.1
Max depth (m)	5.9
Water retention time (years)*	3.4 (3.0, 1.2–10.8)
Alkalinity (meq. l^{-1})**	2.47 (2.47, 1.75–3.35)

[*] Water retention time is calculated from discharge values from 1989 to 2021

[**] Alkalinity is calculated from summer values between 2000 and 2024

cultivated land (52%), forests (23%), wetlands (5%) and nature areas (3%) (Frederiksborg Amt and o. M. L. , 2004). Summer measurements of Secchi depth in 1934 and 1957–1958 and more frequent measurements in 1973 showed very low values as a reflection of hypertrophy (about 0.30 m; Andersen, 1976a, b; Olesen, 1976), while many measurements in the 2000s showed slightly higher mean values (about 0.40–0.60 m) but persistently turbid waters and dense phytoplankton populations (Fig. S1).

Input and output of P and N

Both input and output of TP and TN declined considerably from the 1970s to the early 2000s (Fig. 2).

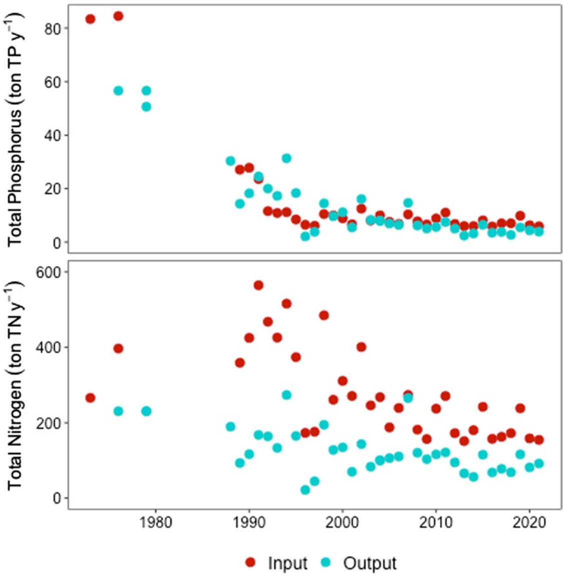

Fig. 2 Annual input and output of TP and TN in Lake Arresø over 50 years

Annual TP input to the lake decreased from about 82 metric tons in the 1970s (Andersen, 1976a, b) to about 6–8 tons in the 2000–2020s (Table 2). Annual TP output followed the same time course and magnitude as TP input. Outputs mostly exceeded inputs in the 1980–1990s, but around 2020s, inputs have slightly exceeded outputs, although the result is within the uncertainty of calculations.

Markedly reduced TP inputs from 1973 and onward were mainly due to reduced input from domestic sewage by gradually transferring treatment from many small to two modern plants with high purification effectiveness. Comparative data from 1985 to 87 and 2018–21 shows a drop in annual output in the treated water: from 62.6 tons TP and 199 tons TN to only 2.2 tons TP and 23.3 tons TN. Annual input into Lake Arresø dropped from 72 to 6.8 tons TP and 449 to 247 tons TN over the same period (Table 2). Thus, TP content from treated sewage, including overflow from buildings, roads and pavements in the cities, decreased to only 3.5% of its former levels, and its contribution to total input to Lake Arresø dropped from about 87% to 32% (Table 2).

Mean annual TN input to Lake Arresø decreased by half from the 1970s to 2018–21 (Table 2). Over the period 1985–87 to 2018–21, the new treatment plants captured 90% more TN than their predecessors, and urban contribution to total TN input to Lake Arresø declined from about 44% to just 9%, while most comes from open land.

Mean summer concentrations of org P and org N (after 1989, individual data not shown) were linearly related to the annual inputs measured in the same year according to the two regressions: (1) org P (μg P L^{-1}) $= 16.0$ TP_{IN} (ton P $year^{-1}$, $R^2 = 0.85$, $P < 0.01$) and (2) org N (μg N L^{-1}) $= 6.86$ TN_{IN} (ton N $year^{-1}$, $r^2 = 0.89$, $P < 0.01$).

Table 2 Mean annual input of TP and TN to Lake Arresø and outlets from sewage treatment plants in 1970s, 1985–1987 and 2018–2021. Outlets during storm flow events in the two main cities are included in the sewage outlets in 2018–2021 (PULS-database https://arealdata.miljoeportal.dk)

Sources and proportions	Ton year^{-1}					
	1970s	1985–1987			2018–2021	
	TP	TN	TP	TN	TP	TN
Input to Lake Arresø	82	508	72	449	6.84	247
% in 2018–21 of 1985–87					9.5	55
Output from water treatment plants and stormflow			62.6	199	2.22	23.3
% input from urban areas relative to lake inlets			87	44	32	9
% urban input in 2018–21 of urban input in 1985–87					3.5	11.7

Retention of P and N in Lake Arresø and new lakes

Annual input and output of TP changed almost in concert over the years, though long water retention time retained some TP in the lake, while short water retention time released some TP (Fig. 3). In contrast, TN input to Lake Arresø exceeded TN output every year (Fig. 2, Fig. S2). The annual retention of TN in the lake as a percentage of the input was high and increased with water retention time, leaving more time for TN removal to take place within the lake (Fig. 3). Over the years, N removal decreased almost linearly along with the reduced input (from 580 to 160 tons), causing approximately a 60% loss of input (Fig. S2). Relative to the 31.6 km^2 with soft sediments, the annual loss was 8.7–2.4 g N m^{-2}. Because the N pool in the upper sediments decreased from 1988 to 2018 (see later), this removal represents a minimum net loss by denitrification because neither the reduction of the sediment's N pool nor N fixation by cyanobacteria were accounted for.

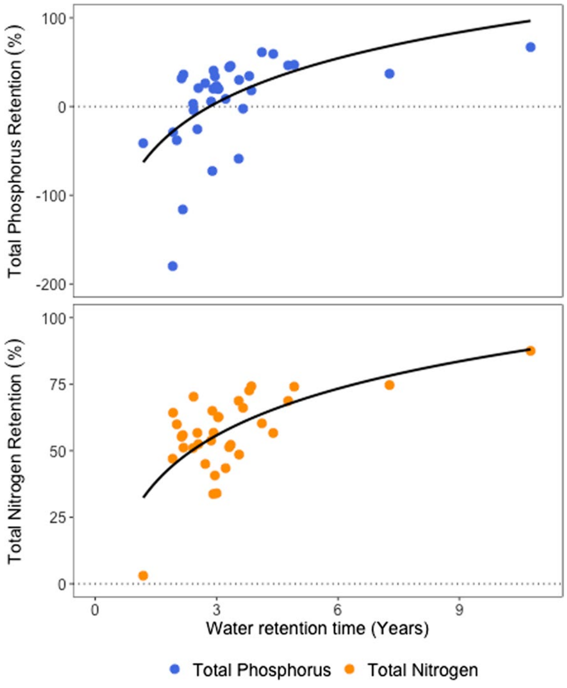

Fig. 3 Annual retention of TP and TN relative to input (in %) versus water retention time (WRT) in Lake Arresø from 1989 to 2021. Nutrient retention (=nutrient removal) is shown with positive value

During the first two years after constructing the nearby shallow Lake Strødam and Lake Solbjerg, they removed a high proportion of TP and TN input from the inlet stream (Fig. 4). The loss of TP during passage was probably due to net particle sedimentation and P-adsorption in the submerged terrestrial soils. After the first two years, however, TP retention in the new lakes became minimal, as a balance between particle sedimentation–resuspension and P-adsorption and release was established. The initial loss of TN may have been due to net particle sedimentation and denitrification in the sediments. After these two initial years, nitrogen loss continued in Lake Solbjerg in years 3, 4 and 5 at a mean rate of 14.5 g N m^{-2} year^{-1}, likely due to ongoing denitrification.

Assuming that the annual loss per sediment area in the four constructed shallow lakes in the catchment to Lake Arresø was the same as the annual mean loss in Lake Solbjerg in years 3, 4 and 5 after its construction, the combined annual loss would be 21.5 tons N from the four lakes (total surface area 147.8 ha). This is obviously a coarse calculation, but it is not critical to the total N loss, which is mainly determined by the large Lake Arresø. The mean annual N loss by passage of Lake Arresø in the recent 10 years 2012–2021 was 95.4 tons N. Thus, total reduction in annual N

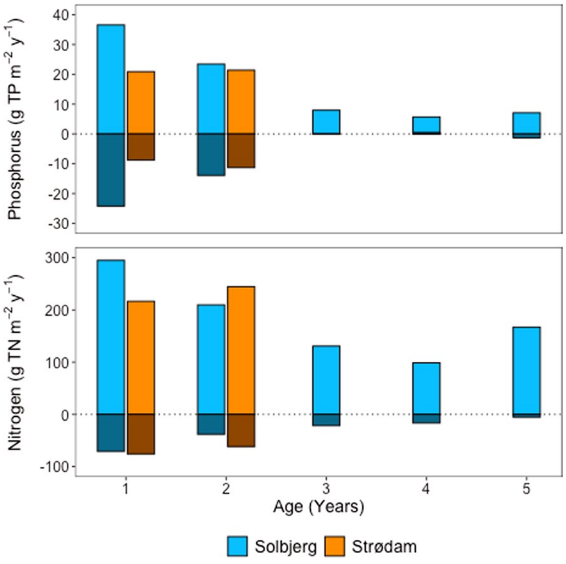

Fig. 4 Annual input (above zero line) and removal (input–output, below zero line) of TP and TN in Lake Solbjerg and Lake Strødam in the years following their construction along the Stream Pøleå

transport was 117 tons N in all five lakes compared to the recent mean annual TN output of 84 tons from Lake Arresø to the downstream estuary.

In-lake P and N concentrations

Mean summer TP and TN concentrations (in mg L^{-1}) was maximal in 1973 to mid-1980s (app. 0.75 TP and 3.50 TN). TP decreased fivefold to a mean concentration of 0.138 between 2000 and 2024, while TN dropped to 1.70 in 2000–2016 and then increased to 2.37 in 2018–2024 (Fig. 5). When dominated by the early TP-rich input (Lønholdt 1973), the in-lake TN/TP mass ratio was about 4–5, but with later smaller total inputs from sewage treatment plants of effective P-purification, in-lake TN/TP mass ratios increased to 15–30 in recent years (Fig. 5).

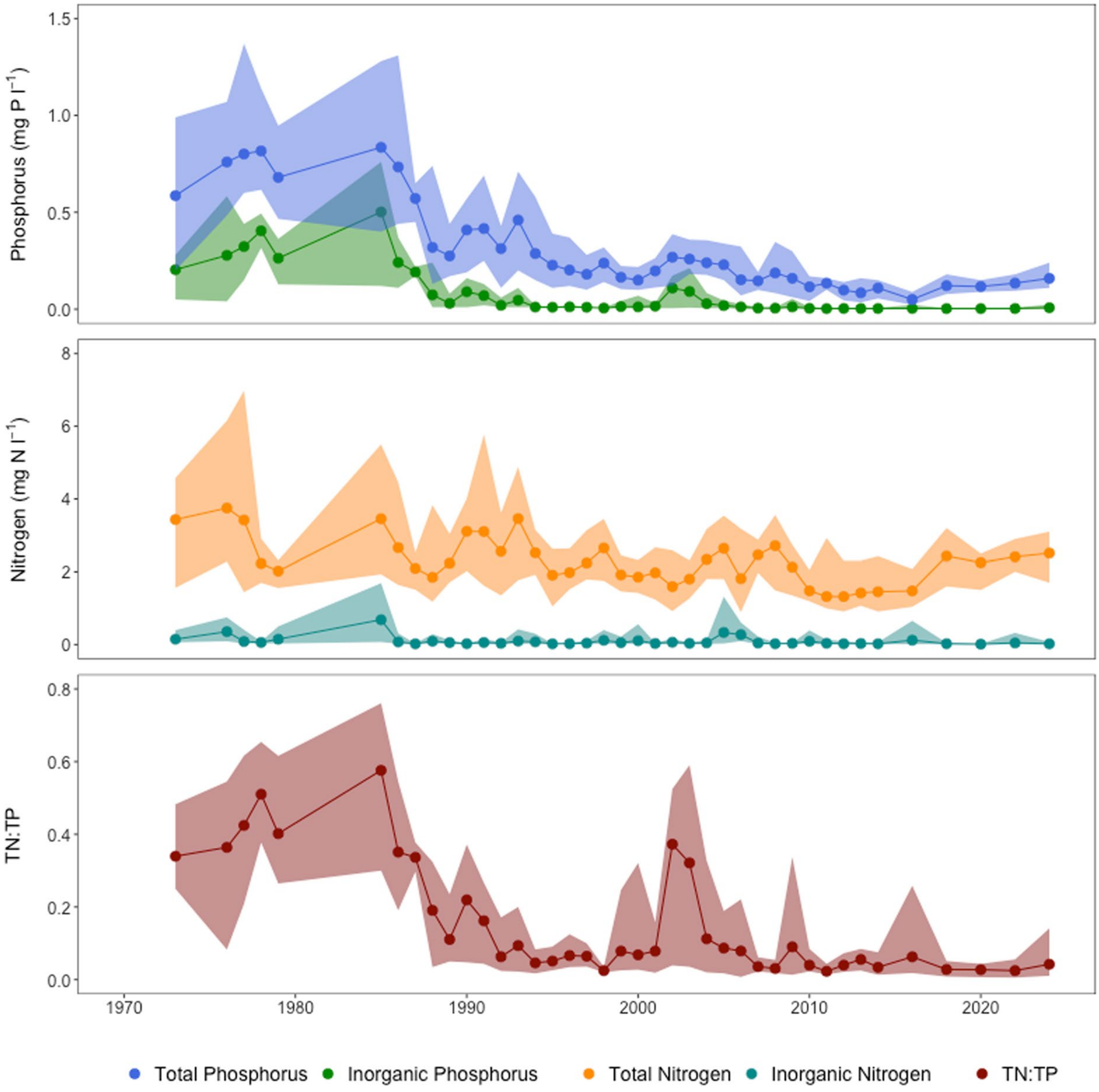

Fig. 5 Summer concentrations (May–September) of TP, inorganic P, TN, inorganic N and TN/TP ratio in Lake Arresø over 50 years. Mean values (the line) and ranges are shown

During summer, when external input of water and TP is the lowest, concentrations of TP markedly increased in the water column from June to September, mainly due to mineralization of sediment organic matter and, possibly, release of adsorbed P from surface sediments at high water pH (often 9–10) and low oxygen and low redox potential. The increase in TP concentration in the water (in µg L^{-1}) from May to September in the selected examples was 570–880 in the 1970–1980s, 270–320 in the 1990–early 2000s and only 95 in 2014 (Fig. 6). The summer net increase in the 3 m-deep water column of the 40-km^2 lake corresponded to a TP pool of 70–105 tons in the early period falling to 11 tons P in 2014. The decreasing sediment release during summer over the 50-year period corresponds to the gradually decreasing ranges (maximum-minimum) of summer TP concentrations (Fig. S3).

Relationships between in-lake nutrients, chlorophyll and light attenuation

During summer, inorganic nutrients were close to zero and chlorophyll concentrations in the water column were significantly positively related to concentrations of org P and org N (linear model: org P: estimate = 453.7, std. error = 96.4, t-value = 4.7, P-value < 0.001, org N: estimate = 86, std. error = 20.5, t-value = 4.2, P-value < 0.001). Moreover, concentrations of Chl, org P and org N were significantly related to the light attenuation coefficient (K_d; Table S1). Chlorophyll accounted for a larger proportion of K_d's variability, and all three variables together accounted for 51% of total K_d variability and 63% when differences between years were included in the analysis (Table S2). To attain an improved water quality with a Secchi depth of 1 m (K_d of 1.9 m^{-1}) possible to be estimated with the available data, it would require nutrient levels of 75 µg org P $L^{-1}$and 1305 µg org N L^{-1} according to the relationships: Org P (µg P L^{-1}) = 61.1 ln K_d (m^{-1}) + 35.6 ($r^2 = 0.23$, $P < 0.01$). Only the P-relationship included permitted interpolation to a low required annual TP input of 3.7 tons TP (about half the contemporary TP input) to reach the lower org P level and a predicted Secchi depth of 1 m.

Sediment composition and dynamics

Lake Arresø's sediments were sampled in late November–early December from spatially homogenous sediment areas covering 31.6 km^2 of the lake (CowiConsult, 1989). The remaining sediment areas have hard sediments that exchange few nutrients with

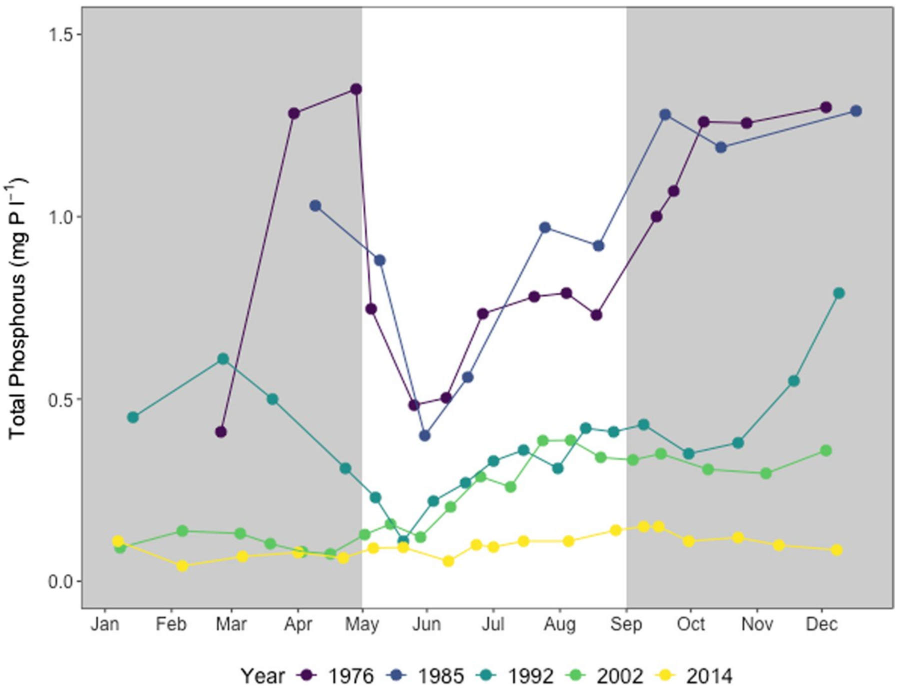

Fig. 6 Mean TP concentrations in the water column as summer (white background) progresses in five years over the 50-year period. The TP concentrations increase generally from June to September

the water. The examined sediment strata in 1993 were rich in calcium (mean 126–165 mg DW^{-1}) and organic matter (220–372 mg DW^{-1}), but poor in Fe (9.7–14.1 mg DW^{-1}). The Fe/TP ratio was low at the sediment surface (mean 7.2), suggesting low permanent Fe-binding here, but increased to 20.8 at 30–40 cm depth in the sediment, suggesting the existence of Fe–P minerals (Table S3).

Surface sediments were modestly rich in TP and organic matter. However, variability among duplicate-triplicate samples as well as spatial variability resulted in estimates of changes of TP (per DW) between years and over the full 40-cm range of sediment depth that did not follow a systematic directional course over the 30 years (Fig. 7). Total P (per DW) in the surface sediments (0–10 cm) was the highest in 1988 and lower in all later measurements.

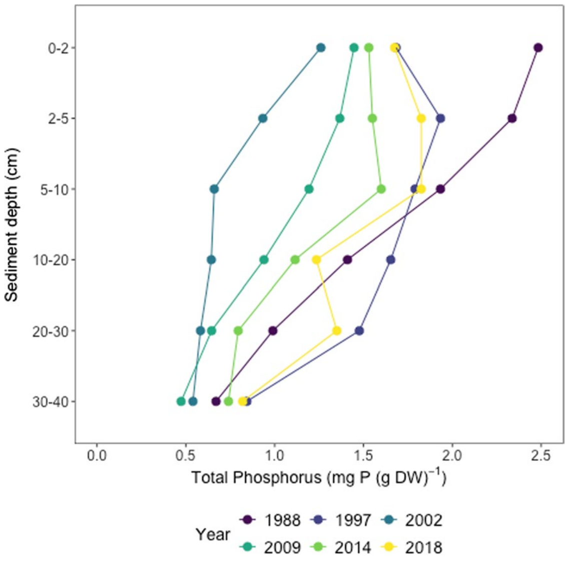

Fig. 7 Sediment TP concentrations (per DW) with depth in six years. Values are means of sediment cores from 2 or 3 sampling stations representing the predominant areas with soft sediments (CowiConsult, 1989)

The TP and organic content followed each other and decreased with sediment depth. The change of the org C:P ratio (org C; organic carbon) from 0–2 cm to 2–5 cm was small and not significant and the decrease to the 5–10 cm stratum was only about 10% (Table 3). Averaged over the entire period, TP (per DW) decreased to 42% at 30–40 cm relative to the content in the surface sediment (Fig. 7). The mean org C:P mass ratios across all measurements remained within a narrow range (94–99) in the upper 10 cm of the sediments, suggesting that this pool was a main source of mobile TP. The org C:P ratio was markedly higher (149) at 30–40 cm depth reflecting a depletion of TP relative to org C (Table 3). The org C:N ratios were 6.8–10.0 independent of sediment depth, while N:P ratios were 7.8–16.0 across all measurements (Table 3).

Measurements of TP and org C content relative to dry weight over the entire period (1988–2018) were most reproducible and distinct in the upper 5 cm of sediment in closest contact with the lake water (Fig. 8). The TP and org C concentrations (per DW) in the upper 5 cm, as well as the concentration of TP relative to org C, decreased to a minimum in 2009 when the TP concentration in the water was also low (Fig. 5). The significant decrease over 30 years from 1988 to the latest sampling in 2018 was 17–32% for the three measures (Fig. 8).

The TP pool in the upper 5 cm of the sediment was 110–180 tons in the lake over the study period (Table 4). A comparison of magnitudes suggested that this surface pool interacted with the increasing TP pool in the water column during summer. Comparing the first measure in 1988 with the two last measures

Table 3 Mean org C:N, N:P and org C:P ratios with depth in sediments over the years

Sediment depth	Org C:N			N:P		Org C:P						
	1988	1993	1997	1988	1997	1988	1993	1997	2002	2009	2014	2018
0–2	10.0	8.1	7.6	7.83	12.1	78.3	83	98.0	96.7	108.7	100.7	91.2
2–5	9.64	7.4	7.3	8.14	12.3	78.4	98	94.5	111.7	101.1	95.8	100.9
5–10	9.43	7.5	7.2	9.18	12.9	86.2	141	94.3	111.7	104.5	79.1	77.8
10–20	8.06	7.4	7.7	10.5	11.3	93	142	90.6	123.2	118.2	107.5	82.3
20–30	6.81	7.7	6.3	12.1	11.4	107	123	76.3	143.1	125.2	125.4	137.9
30–40	8.18	7.9	8.0	16.0	13.1	138	141	105.5	153.2	240.7	156.1	110.8

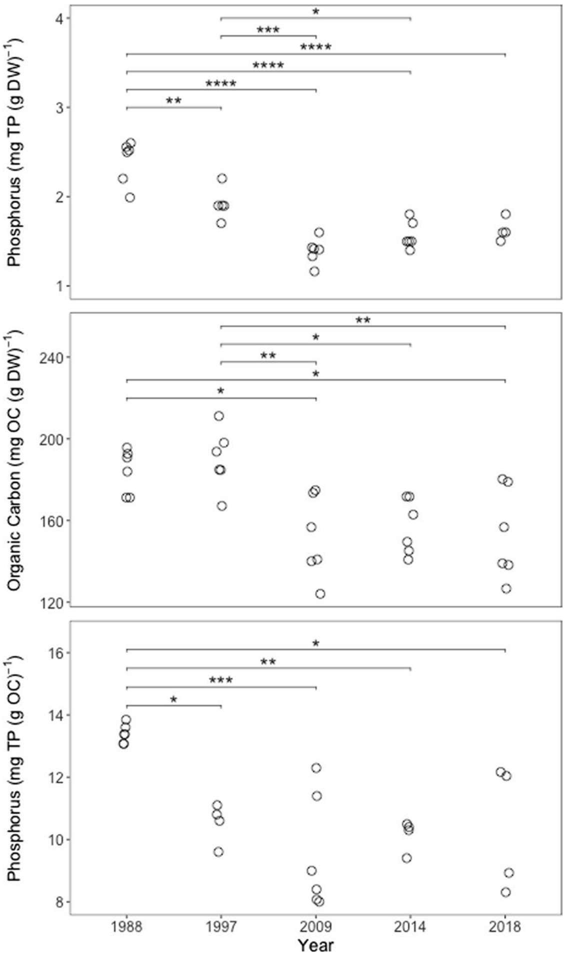

Fig. 8 Decrease in concentrations of TP (per DW), organic carbon (per DW) and TP (per organic carbon) in surface sediments (0–5 cm depth) from 1988 to 2018. Values are means of sediment cores from 2 or 3 sampling stations representing the predominant areas with soft sediments. Significant differences between the first (1988) and later measurements are shown with horizontal lines and levels of significance ($P < 0.05$ *, $P < 0.01$ **, $P < 0.001$ ***)

in 2014 and 2018 showed a decline of the TP pool in the upper 5 cm sediment of 15–33 tons TP for the entire lake (Table 4). If we instead applied the 32% decline of TP per DW in the period 1988–2018 to the initial sediment TP pool in the upper 5 cm of the sediment (Fig. 8), the decrease in the surface P pool in the lake would be 45 tons P for a constant density and no change in sediment depth levels and net burial. The three estimates correspond to a mean reduction in the sediment pool in the lake of only 0.5–1.5 tons P per year. These rates are very small relative to annual mean TP inputs of 72 tons in 1985–87 and 6–8 tons P in recent years. The results agree with the parallel course and similar magnitudes of inputs and outputs from Lake Arresø over the 50-year period and with the reduction over the same period of the magnitudes of mobile TP released from sediments to lake waters as summer progresses (Fig. 6).

Discussion

Nutrient loading from urban and rural areas

The ratio of urban and rural nutrient loading to Lake Arresø has undergone profound changes during the last 50 years. In the 1970–1980s, the high emissions from numerous sewage treatment plants with traditional mechanical and biological purification dominated the large P input to Lake Arresø, while N input from rural areas slightly exceeded urban N input. The transfer of most domestic sewage treatment to two new water treatment plants and improved control of storm flow brought the combined annual urban outlets in 2018–2021 down to 2.2 tons P and 23 tons N (3.5% for TP and 11.7% for TN of former levels). This profound reduction took place despite rising numbers of residents and industrial activity in the catchment cities over the period.

Table 4 TP pools in sediment depth strata in Lake Arresø over the period. Estimates in tons P in soft sediments (31.6 km^2) for the entire lake

Sediment depth	1988	1997	2002	2009	2014	2018
0–2 cm	42.98	44.91	47.96	30.89	33.13	35.47
0–5 cm	140.3	179.7	175.8	111.1	107.5	125.3
0–10 cm	338	459	350	276	275	335
0–20 cm	730	1111	749	607	599	781
0–40 cm	1616	2719	1499	1206	1289	1716

Nutrient losses from cultivated fields have been less firmly regulated, and the lack of direct measurements of the different routes of losses makes quantification difficult. Nonetheless, it is important to compare measured losses from urban areas and estimated losses from cultivated fields because large sums of money have been invested to reduce urban losses, bringing the sewage outlets close to the best technical practice.

Using different methods and data, it is possible to estimate contributions from rural areas (with agriculture as the main land use and by far the main nutrient source), calculated as the difference between total inlets minus urban outlets, to the total influx into Lake Arresø are presently about 90% for TN and 68% for TP. The estimated annual P input from cultivated areas into Lake Arresø was 5.5 tons in 1986 (CowiConsult, 1989). Assuming that the present input is of the same order, it exceeds urban losses 2.5-fold. A third estimate using recent models of annual losses at 20–30 kg P km^{-2} from cultivated fields in the catchment yields 2.3–3.5 tons P (Andersen and Heckrath, 2020, Fig. 4.9.6). Overall, the data suggest that the most cost-effective investment to reduce P input into Lake Arresø would be to reduce P transport from cultivated fields.

While urban and rural areas both contribute to external P loading of Lake Arresø, rural areas by far are the main contributor to external N loading. Though P is considered the main limiting element of the phytoplankton biomass, phosphate, nitrate and ammonium all decrease below limiting thresholds during summer (e.g., 5 µg P L^{-1} and 10– 20 µg N L^{-1}, Maberly et al., 2020) for the phytoplankton biomass and those low nutrient levels have become more frequent during the last 30 years (Sand-Jensen et al., 2025). However, the uncertainty of responses of light attenuation to in-lake TN and TP concentrations at the lower level of actual measures makes it difficult to estimate the exact external nutrient inputs that may lead to substantial improvement of the light climate in Lake Arresø. Our calculations suggest that the annual TP input must be reduced to 3.7 tons, half the present level, to obtain a summer mean in-lake concentration of 75 µg org P L^{-1} and a Secchi depth of 1 m, which may facilitate the spread of submerged macrophytes, increase sediment stability and reduce sediment resuspension. To achieve this improvement, P input from the fields must be markedly reduced.

Since 2016, the permissible nutrient application of TP and TN from inorganic fertilizers and liquid manure on the fields has been allowed to increase by 20% and the 10-m-wide uncultivated buffer zones along streams reduced to just 2 m (Landbrugspakken, Lov nr. 186, March 2016). Accordingly, higher losses of dissolved nutrients and soil particles from fields and stream banks next to the fields are enabled (Fraser et al., 1999; Kronvang et al., 2012). This may have contributed to 17–55% increases in TP, TN, Chl and K_d in Lake Arresø from 2010 to 2022, while input from urban sources continued to decline. Thus, there is apparently no scope of achieving a good ecological status in Lake Arresø unless rural inputs are markedly reduced.

Nitrogen reduction and downstream losses

Annual N losses to the downstream N-limited estuary via the outlet from Lake Arresø have been reduced about threefold from the 1970s to the recent 2011–2021 primarily due to improved sewage treatment and construction of four new lakes in the catchment (removing N by denitrification). The main goal of constructing the four new shallow lakes in the catchment was to reduce P-inlets to Lake Arresø, but the new lakes turned out to have no lasting effect on P-retention as they lacked deep sedimentation basins. However, the new lakes developed rich populations of waterfowl feeding on benthic invertebrates and plants (Sand-Jensen, 2001) and also generated a positive downstream effect. Thus, denitrification in the new lakes has contributed to lower N loading to Lake Arresø and to the estuary, which faces N eutrophication due to detrimental oxygen depletion and growth of nuisance filamentous macroalgae (Geertz-Hansen et al., 1993; Pedersen and Borum, 1996).

Denitrification rates estimated in the shallow Lake Solbjerg (14.6 g N m^{-2} year^{-1}) were high, and rates in Lake Arresø (2.4–8.7 g N m^{-2} year^{-1}) were positively related to N inputs and in-lake concentrations. The magnitudes in Lake Arresø are supported by measurements applying ^{15}N-nitrate (Madsen, 1979). The calculated denitrification rates in Lake Arresø are lower than in other hypertrophic shallow Danish lakes receiving higher N input relative to lake surface area (i.e., 13–76 g N m^{-2} year^{-1}; Andersen, 1974, 1977; Jensen et al., 1992a, b). Denitrification is enhanced by coupled nitrification–denitrification in the shallow lakes by shifting sediment particle resuspension in the oxic water column, producing nitrate as the essential element for denitrification when particles resettle and sediment anoxia develops (Zhu et al., 2021).

Sediment–water dynamics over time

Surface sediment and water are in close contact, and they decreased in concert over time with the reduced nutrient input to Lake Arresø. The P concentrations was maximum in the upper 5 cm of surface sediments, which had the highest proportions of P relative to org C and mobile P (about 60% of TP) compared to deeper sediment with most P associated with recalcitrant organic matter and aluminum, carbonate and iron minerals (CowiConsult, 1989). The P concentrations in the upper 5 cm of surface sediments decreased significantly from 1988 to 2014–2018 by about 15–45 tons P (0.5–1.5 tons P year^{-1}). These values are subject to considerable uncertainty due to sampling and measuring error, but magnitudes are definitely within these narrow ranges.

The decline of mobile sediment concentrations of TP and organic matter from the 1988 to 2018–2021 accord with the gradually smaller summer TP increase in the water column in later years compared to early years. The magnitudes of reductions in sediment surface pools, increase in TP pools in the lake water during summer and the annual TP input are all within the same range. Thus, net internal P loading during summer has declined over the long-term period and they do not represent a prominent delay to the reduction of in-lake P concentrations after a cut down of external loading due to the frequent sediment resuspension and P mobilization across the lake. This situation is in contrast to the prominent delay to reduce in-lake nutrient concentrations accompanying lowered loading of many lakes after several decades of excessive loading (Björk, 1985; Søndergaard et al., 2003; Sand-Jensen et al., 2017). However, net P release from the sediments during summer is still appreciable (i.e., 11 tons P in 2014) and stimulates ongoing phytoplankton growth. Earlier proposals to spend many million Euros to remove surface sediments across the nutrient-rich lakebed (CowiConsult, 1989) and recent proposals to treat Lake Arresø with expensive Phoslock to bind mobile P (Sand-Jensen et al., 2025) cannot be recommended as external loading was and still remains the main regulator of its water and ecological quality. Thus, in order to improve the ecological quality of Lake Arresø, we argue that annual external P loading must be reduced further, estimated at 3.5 tons or half its present level.

Sediment stability and vegetation

At present, the frequent resuspension of sediment particles reducing water transparency and inhibiting the rooting of submerged plants may be countered by building barriers in restricted near-shore areas, to dampen waves and stimulate the spread and consolidation of submerged vegetation that previously dominated the lake (Klein, 1989). Realistically, it may be difficult to diminish nutrient input to the lake sufficiently due to lack of political support to resume effective reduction of nutrient losses from rural areas. However, there may be some support for pilot experiments with artificial barriers, to evaluate the influence of sediment stabilization on submerged macrophyte colonization and particle resuspension. Well-established vegetation may substantially increase water transparency in shallow eutrophic lakes despite an unaltered nutrient input and induce a better ecological state (Moss et al., 1996; van den Berg et al., 1998). The relevant submerged angiosperms and charophytes are still present in Lake Arresø in small populations at shallow protected sites. Some hope for improvement is alive.

Conclusions

With respect to the initial questions, we found that over the years: 1) dissolved inorganic P and N in the lake decreased during summer to near zero and potentially biomass-limiting concentrations for phytoplankton, 2) while rural areas and particularly the losses from cultivated fields by far dominated N inputs to Lake Arresø, the P losses likely exceeded urban losses and 3) to obtain good ecological quality in Lake Arresø will not be possible without a coordinated effort to markedly reduce nutrient losses from fields and to further reduce urban losses. Water quality in Lake Arresø responds quickly to ongoing nutrient inputs. Public proposals to remove lake sediments or treat them with Phoslock are extremely costly, technically difficult and without lasting effects.

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Data availability All data are publicly available in the references or can be downloaded from Miljøportalen (https://kemidata.miljoeportal.dk) and PULS database (https://arealdata.miljoeportal.dk).

Declarations

Conflict of interest The authors have no financial or proprietary interests in any material discussed in this article.

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