FUTURELAKES
For Nature, Climate and People

Demonstrating Successful Restoration

Demonstration Site Descriptions

Deliverable D4.1 Annexes A - F

Publication Date: 28 February 2026

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Annexes

a) Lake Vesijärvi

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[1] Finnish Environment Institute (Syke)

[2] University of Helsinki, Lammi Biological Station

[3] Lake Vesijärvi Foundation

1.1 Lake details

Lake name: Lake Vesijärvi, Finland		
Type of characteristics	**Characteristics**	**Value**
Geographical characteristics	Geographical coordinators (WGS84): Longitude Latitude Altitude (m a.s.l.)	25.53305E 61.09569N 81.4
Lake characteristics	Area [km^2]	107
	Maximum depth [m]	40
	Mean depth [m]	6.1
	Water volume [m^3]	700 000 000
	Depth index (mean depth to maximum depth ratio)	0.15
	Water residence time (τ) [years] Residence type (short < 1 year, moderate >1 year, long > 10 years)	Moderate, basin specific from 0.7 to 9 yrs. Average 6.8 yrs
	Shoreline development index $K = \frac{shoreline\ lenght}{2\sqrt{\pi}\ \cdot lake\ area}$	6.2
	Mixing type	Basin-spesific from bradimictic to polymictic
	Stratification	Stratified

Lake name: Lake Vesijärvi, Finland		
Type of characteristics	**Characteristics**	**Value**
Catchment characteristics	Total catchment area [km2]	514
	Direct catchment area [km2]	
	Land-use (CORINE)	**% of total catchment area**
	Agriculture	18
	Urban	8
	Forests	51
	Wetlands	2
	Water bodies	20
	Schindler's index (sum of total catchment and lake areas to lake volume ratio)	4.7
Climate characteristics (30 year average; 1991-2020)	Mean annual air temperature Mean annual precipitation Maximum summer air temperature Days number > 15°C mean daily air temperature per year Days with snow per year	Mean annual temp. 4.8 °C Mean annual precip. 600-650 mm Max summer temp. 32-35 °C Days with > 15°C temp. 60-106 days, mean 78 days (2019-2025) Days with snow 115-135 (Dec 6-16 – April 10-20; 1991-2020)
Hydrochemistry and trophic type (situation in 2025)	Alkalinity (meq/L), Alkalinity type (low - <0.2, medium 0.2-1.0, high - > 1.0)	Medium (alkalinity 0.6 mmol/L. NB, no information on the ionic composition available; conversion from mmol/L to meq/L cannot be conducted)
	Colour type (colour in HAZEN units – clear < 30, humic 30-90, polyhumic >90)	Clear (mean colour 13 mg Pt/L)
	Trophic type (oligotrophic, mesotrophic, eutrophic, hypertrophic)	Mesotrophic (mean epilimnetic 15 µg P/L)
	Calcium level (water hardness – softwater <25 mg Ca/L, hardwater ->25 mg Ca/L	No information on Ca available. Presumably softwater based on low conductivity (mean 12 mS/m)

1.2 Restoration Programme

1.2.1 Background

Lake Vesijärvi (lake no. 14.241.1.001) is a 107-km^2 seepage lake located in Southern Finland. It is surrounded by the City of Lahti and municipalities of Hollola and Asikkala. The lake has four main basins: Enonselkä (max. depth 33 m), Kajaanselkä (42 m), Komonselkä (10.5 m) and Laitialanselkä (18.5 m). In addition, there are two smaller, shallower bays, Paimelanlahti-Vähäselkä (Paimelanlahti max. 14.5 m, Vähäselkä max. 2 m) and Kirkonselkä (3 m). Kajaanselkä is the only basin that has reached good ecological status, and the rest remain in moderate status based on the latest river basin management planning (RBMP) assessment in 2019 (Figure 1). For the ongoing 4th RBMP cycle, L. Vesijärvi is divided into three water bodies: Vesijärvi 1, Vesijärvi 2 and Vesijärvi 3. Vesijärvi 1 refers to basins Enonselkä together with Komonselkä and Paimelanlahti-Vähäselkä; Vesijärvi 2 to Kajaanselkä; and Vesijärvi 3 to basins Laitialanselkä and Kirkonselkä. L. Vesijärvi belongs to a national water body type SVh (large clear water and oligohumic lakes, corresponding to an EU broad type L-02 lowland, silicious).

The lake flows through the River Vääksynjoki into L. Päijänne in the north, from where the waters discharge to R. Porvoonjoki and, eventually, to the Gulf of Finland in the Baltic Sea.

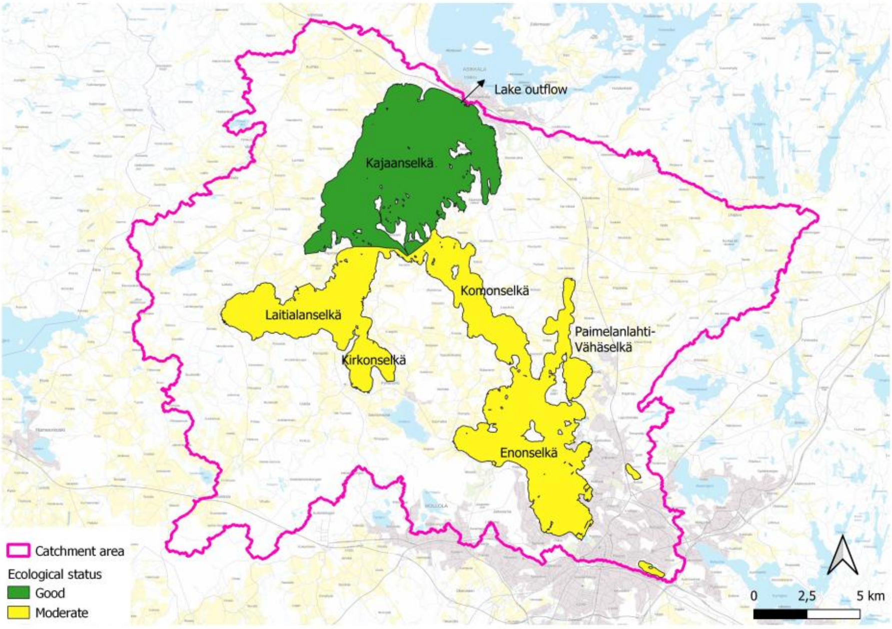

Figure 1. The catchment area of Lake Vesijärvi and the ecological status of the lake's separate basins (water bodies) in the RBMP assessment in 2019: Vesijärvi 1 (Enonselkä, Komonselkä and Paimelanlahti-Vähäselkä); Vesijärvi 2 (Kajaanselkä); and Vesijärvi 3 (Laitialanselkä and Kirkonselkä). Contains data from the National Land Survey of Finland and from the Finnish Environment Institute (License CC BY 4.0)

Lake Vesijärvi was formed after the ice age in between the two Salpausselkä I and II ice marginal formations. Based on ancient remains identified in the catchment area, the shorelines of the lake and its surroundings were inhabited already during the stone age. It has been estimated that the number of inhabitants within the catchment area was around 4,000 in the beginning of the 19th century (Keto et al. 2010). The borough of Lahti was established in 1878, after which the population grew rapidly. Currently, around 100,000 inhabitants live in the catchment area.

Due to both international and national importance of lake to waterfowl, parts of it belong to the designated Natura 2000 -network ("Kutajärven alue", FI0306006) both as Special Areas of Conservation (SAC) and as Special Protection Areas (SPA) (Figure 2). The Natura 2000 -area includes the largely overgrown Lake Kutajärvi on the south side of L. Vesijärvi and its five distinct bays that represent the HD Annex I habitat type Natural eutrophic lakes with Magnopotamion or Hydrocharition -type vegetation (3150). Of these bays, Laasonpohja and Kutajärvi belong to the national waterfowl protection programme and Laasonpohja also to The Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat. In addition to its importance to waterfowl, the Natura 2000-area has exceptionally representative and versatile vegetation, which is threatened by eutrophication and overgrowth. L. Kutajärvi was formerly a part of L. Vesijärvi, but it was detached during the 18th and 19th centuries when the water table of L. Vesijärvi was lowered by an estimate of 3 m in total (Salminen et al. 2021).

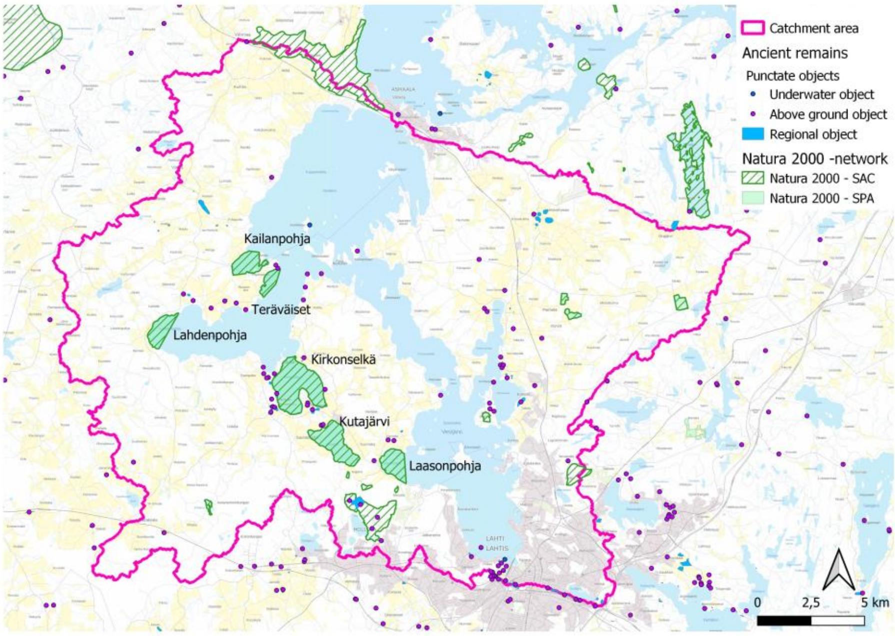

Figure 2. Identified ancient remains and the delimitations of Nature 2000-area at L. Vesijärvi and its catchment area. Contains data from the National Land Survey of Finland, the Finnish Environment Institute and the Finnish Heritage Agency (License CC BY 4.0).

Originally, L. Vesijärvi was a clear-water lake with some naturally eutrophic features present (Järnefelt 1929). In the 20th century, the population growth, industrialization, mechanization of agriculture, intensive drainage and utilization of artificial fertilizers all affected the lake that began to experience water quality deterioration. The first signs of eutrophication of L. Vesijärvi, along with a first incidence of cattle poisoning in Finland due to cyanobacteria, were recorded during the late 1920s and became obvious in 1960s when the lake became known as one of the most eutrophic large lakes in Finland (Keto 1982). The most southern part of the lake, Enonselkä basin in the vicinity of the City of Lahti, experienced the worst deterioration as it was subject to domestic sewage and industrial wastewaters for 60 years (Horppila et al. 1998; Keto 1982). Still in the beginning of the 1970s, the wastewaters of 60,000 inhabitants were discharged to the basin almost untreated (Salonen et al. 2020).

In 1976, a first step in the improvement of L. Vesijärvi water quality was taken with the establishment of a wastewater treatment plant and sewage diversion, after which the effluent load was subsequently cut to third (Keto 1982; Salonen et al. 2020). In the 1980s, the diversion of industrial wastewaters further reduced the nutrient load by ~ 15% (Horppila et al. 1998). However, annual mass occurrences of harmful cyanobacteria remained in the 1980s, prohibiting the recreational use of Enonselkä basin and calling for additional measures to advance the lake recovery from past loading. Consequently, an extensive series

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of restorative in-lake measures and preventative external measures have been undertaken since mid-1970s (Figure 3) in that are described in more detail in sections 1.2.2 and 1.2.3.

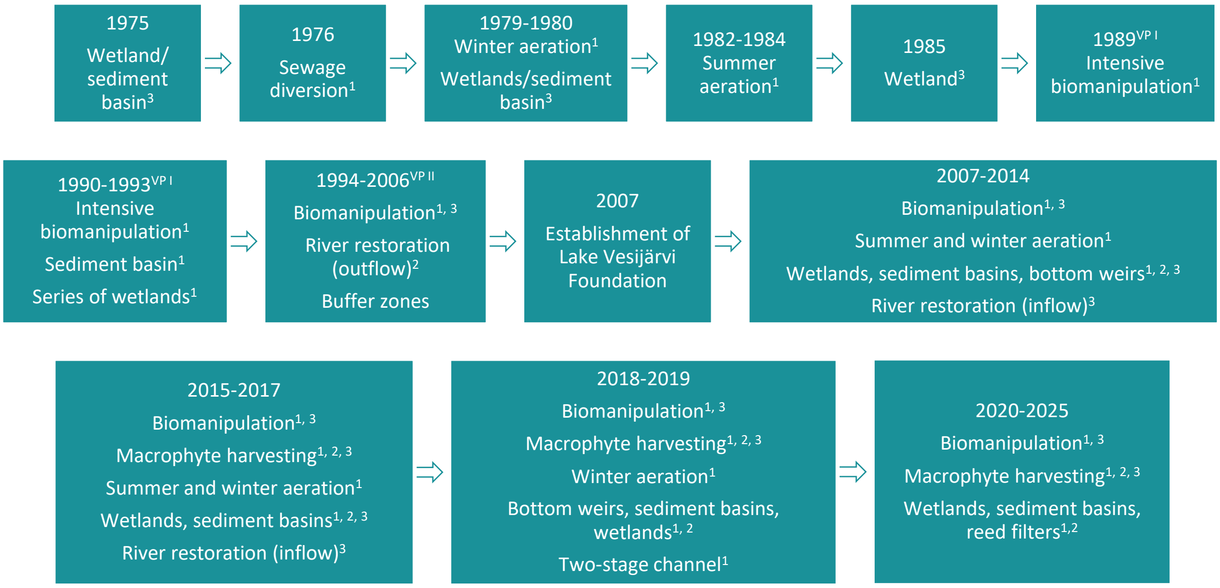

Figure 3. Water protection and restoration measures conducted at Lake Vesijärvi since the establishment of wastewater treatment plant in 1976. Upper indices display the basins to which measures have been targeted (1 = Vesijärvi 1 (basins Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä); 2 = Vesijärvi 2 (Kajaanselkä); 3 = Vesijärvi 3 (Laitialanselkä and Kirkonselkä)). Please refer to Figure 1 for information on the location of these basins. The timing of the pioneering Vesijärvi Project I (VP I) and Vesijärvi Project II (VP II) are indicated by upper indices.

1.2.2 In-lake measures

The sewage inputs in the 20th century caused deoxygenation of L. Vesijärvi, due to which the first in-lake restoration measure initiated in the late 1970s was aeration of the hypolimnetic water to both prevent winter-time fish kills and to reduce internal nutrient loading promoted by periodic hypolimnetic anoxia and hypoxia (Salonen et al. 2023). At first, aeration was applied during the winter 1979, when epilimnetic water was pumped from 1 m depth to the hypolimnion only in the deepest part of the Enonselkä basin (Vesijärvi 1). Between 1983 and 1985, aeration was extended to summer months (Keto and Sammalkorpi 1988; Salonen et al. 2023), which, however, turned out to be less efficient than winter aeration and the equipment was disturbed by wave action (Keto and Sammalkorpi 1988).

After the first aeration period, a large-scale biomanipulation was carried out by mass removal of planktivorous and benthivorous fish (mainly roach (Rutilus rutilus) and smelt (Osmerus eperlanus)) and by stocking of predatory pikeperch (Sander lucioperca) (Anttila et al. 2013; Salonen et al. 2020; Salonen et al. 2023). As part of the extensive "Vesijärvi project I" that was implemented in 1987–1994, more than 1000 tons of cyprinid fish were removed from Enonselkä basin (Vesijärvi 1, Figure 4) and 208,700 pikeperch fry were introduced to the lake (Sammalkorpi 1988). Ever since, the fish removal in Vesijärvi 1 (basins Enonselkä, Komonselkä, Paimelanlahti) has continued with an average catch of 2,000 kg/ha/a. Biomanipulation and stocking of pikeperch has also been conducted in the other basins of L. Vesijärvi (Vesijärvi 2; Kajaanselkä and Vesijärvi 3; Laitialanselkä) since 1996. In Vesijärvi 3, the catch during late 1990s and 2000s has corresponded to that of Vesijärvi 1. In Vesijärvi 2, in turn, the catch has been more modest (Figure 4).

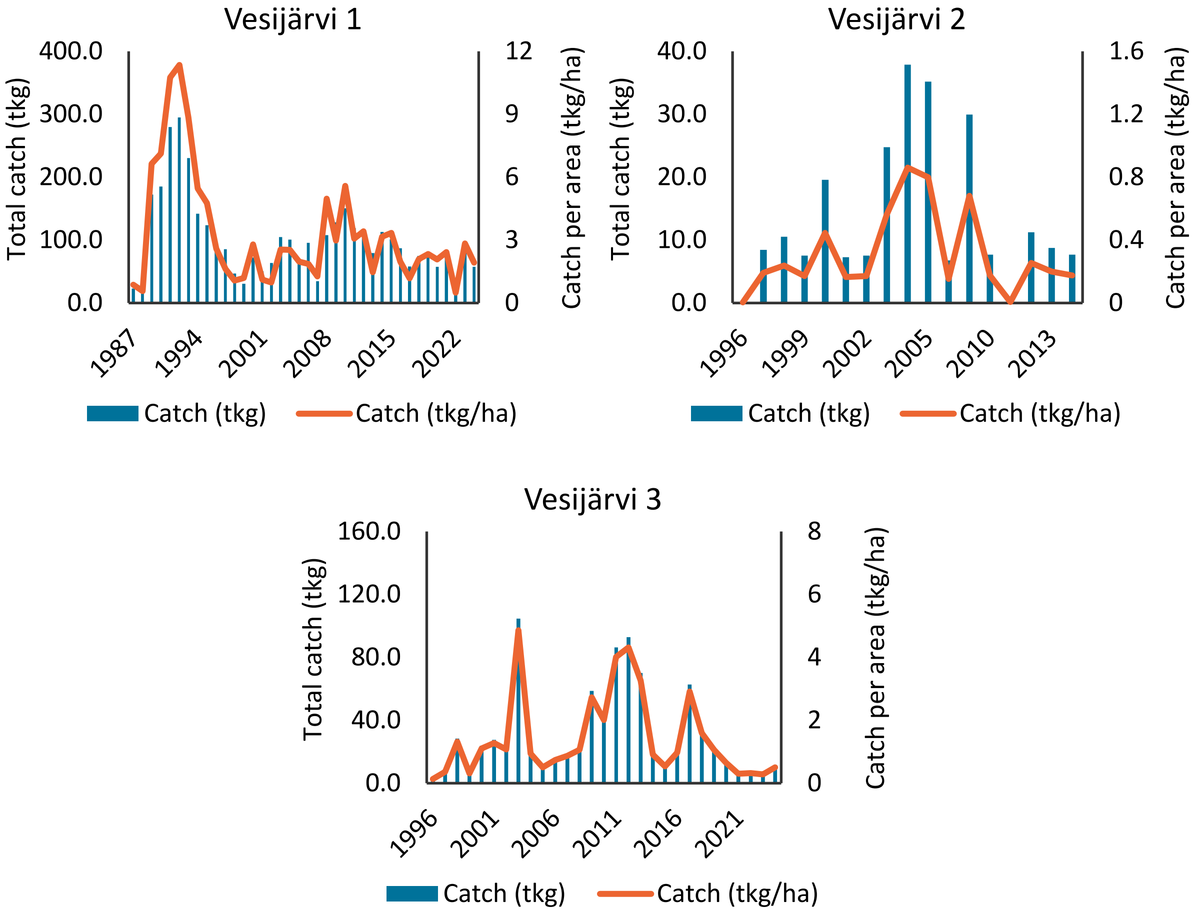

Figure 4. Annual biomanipulation catch of fish at the distinct RBMP water bodies of L. Vesijärvi (Vesijärvi 1 = Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä; Vesijärvi 2 = Kajaanselkä; and Vesijärvi 3 = Laitialanselkä and Kirkonselkä basins). Please refer to Figure 1 for information on the location of these basins. Data from the City of Lahti. Note the different scales on x- and y-axes.

Another period of hypolimnetic aeration in Enonselkä basin by nine aeration stations (Mixox pumps) was conducted between the years 2010 and 2017. This time, aeration was implemented not only during the winter but also in the summer during periods when the hypolimnetic oxygen concentration decreased below 4 mg/L (Ruuhijärvi et al. 2020). Due to aeration, the volume of hypoxic water and duration of hypoxia decreased, but the temperature in hypolimnion expectedly increased, with consequent implications for increased mineralisation of organic matter and increased P recycling (Niemistö et al. 2016). Despite high water temperature, the young-of-the-year smelt reached exceptionally high abundance and increased predation pressure on zooplankton by smelt (Ruuhijärvi et al. 2020). Additionally, the summer aeration and the increase in hypolimnetic water temperature (up to 5 °C) increased the release of carbon dioxide, methane and nutrients from the sediment (Salonen et al. 2023).

Due to these adverse impacts, the summertime aeration was terminated after 2017 and aeration was continued only during the winter until 2019, after which it was finally terminated as the water column nutrient concentrations were not affected despite improved hypolimnetic oxygen concentrations (Salmi et al. 2014; Salonen et al. 2023). Additionally, it was observed that the shallower, oxygenated depths also had a substantial impact to the release of sedimentary P, suggesting limitations to the usability of aeration in lake restoration in general (Tammeorg et al. 2017; Tammeorg et al. 2013).

Since 2015, harvesting of macrophytes (mainly common reed (Phragmites australis), but also the invasive reed sweet-grass (Glyseria maxima) has been conducted on the shoreline areas around L. Vesijärvi to prevent macrophyte overgrowth for both preserving the habitat value in Natura 2000-areas and securing the recreational amenities elsewhere.

1.2.3 External measures

To decrease the external loading and improve agricultural water management, 16 (series of) wetlands have been constructed in the catchment since 1970s, 11 of which in 2006-2013 (Figure 3, Figure 5). Most wetlands include a separate sedimentation basin. In addition, 18 individual sedimentation basins have been constructed, 17 of which in 2007-2014. To decrease channel erosion and thus the transport of suspended sediment and particulate substances, 7 bottom weirs/rocky sills have been constructed in streams mostly in 2018. Most of these structures have been maintained, typically by removing the deposited sediment approximately every 7 years. Ten rapid sections in streams discharging to the lake have also been restored by constructing dam bypasses and spawning areas, improving the sheltering, and rearing habitats of particularly the locally naturally reproducing trout (Salmo trutta) in River Hammonjoki.

Additionally, the City of Lahti has a designated stormwater management programme established in 2011, to enhance, plan and implement stormwater management at several locations (Lahden seudun ympäristöpalvelut 2010). It has been estimated that 30% of P loading to the Enonselkä basin originates from urban runoff (Järveläinen 2014). The stormwater management includes treatment of stormwaters on site via different infiltration systems such as permeable pavements, green roofs, biofiltration systems, vegetated depressions, meandering channels, and designated stormwater wetlands. An example of advanced stormwater treatment system is from Hennala subarea in the City of Lahti, where substantial amount of stormwaters are first treated in a combined biofiltration/wetland system and then diverted to River Porvoonjoki to completely bypass L. Vesijärvi (see details in Section 1.3.1.3.1).

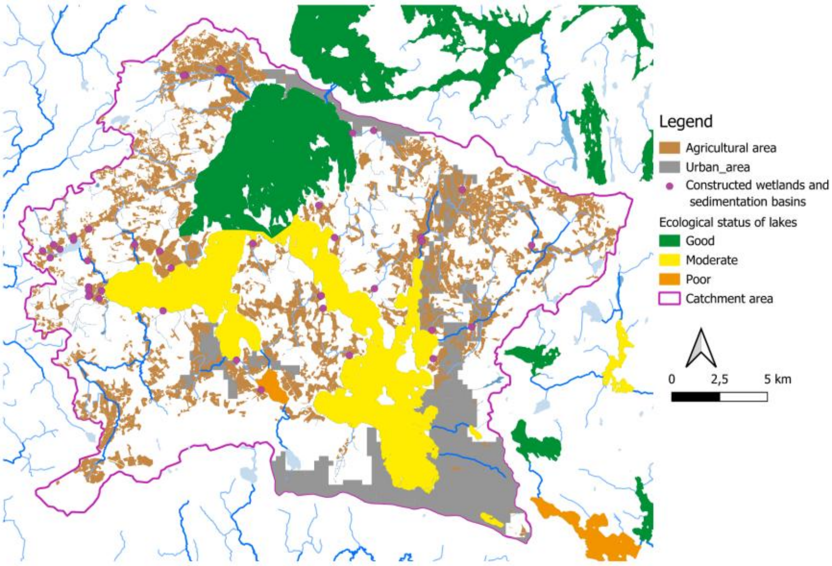

Figure 5. Urban and agricultural areas, and constructed wetlands and sedimentation basins along streams discharging to Lake Vesijärvi. Contains data from the Finnish Environment Institute, The Centre for Economic Development, Transport and the Environment, National Land Survey of Finland, and the Finnish Food Authority (License CC BY 4.0).

1.2.4 Costs of restoration

The annual costs realized for “Vesijärvi project I” implementing extensive in-lake measures (aeration and intensive biomanipulation) during 1989-1994 were around M€0.46/a (Porra & Mäkelä 1995, Lehtoranta 2013). Based on the costs of Vesijärvi Project I, a monetary evaluation on the benefits of L. Vesijärvi restoration efforts was carried out in 2013, when the improvement of Enonselkä basin’s water quality was estimated to have a monetary benefit of at least M€0.58 annually (M€0.77 converted in the value of 2025) exceeding the annual costs realized for the project (Lehtoranta 2013).

The total costs for a sequence, “Vesijärvi project II” in 2002-2007 were M€1.58, i.e. M€0.23/a (Lahden Kaupunki 2007). These included both external measures, such as establishment of wetlands and buffer zones, education about proper wastewater treatment in sparsely populated areas, and in-lake measures such as biomanipulation, macrophyte harvesting and restoration of spawning areas by small-scale dredging. Additionally, the project included planning of aeration, extensive monitoring and different engagement activities such as organising different lake restoration related events, and multichannel communications.

Since these two projects, the costs of restoration have been divided into numerous various sources and have been financed from various sources including contributions from e.g., municipalities, support from the state, national and EU-projects, and private sector through donations. In the following sections, we provide estimated costs for individual restoration and water protection measures since the two pioneering Vesijärvi projects (Vesijärvi Project I and II).

1.2.4.1 In-lake measures

During the 2000s, the estimated costs for biomanipulation have been €1.00-1.20/kg depending on the method used (trawling, fyke nets, seining). Hence, based on the total catch from L. Vesijärvi (all basins), the estimated annual costs of biomanipulation since 2007 after the “Vesijärvi project II” have varied between c. €11,200-43,600/a depending on the fish biomass removed. Since 2007, an estimate of M€2,2 in total has been used for biomanipulation. Unfortunately, no representative data could be obtained on the costs of fish stocking. In 2023, introduction of predatory fish (eels (*Anguilla anguilla*), pikeperch and trout (*Salmo trutta*)) to L. Vesijärvi costed €40,336, and €30,000 in 2018. In 2008, information is only available for the introduction of eels, when the stocking of 27,500 individuals costed c. €30,000.

The annual total costs for aeration in 2007-2009 was €8,000/a with one operational pump in use in the Enonselkä basin; €80,000/a in 2010-2015 with eight operational pumps at Enonselkä basin; and €35,000/a in 2016-2020 when the number of pumps was four (I. Malin pers. comm. on 29 Sept. 2025). Consequently, the total amount of funding spent on aeration since the two Vesijärvi projects I and II has been c. €644,000.

1.2.4.2 External measures

The estimated costs of implementing constructed wetlands are shown in Table 1, and are based on unit costs from comparable Finnish cases. The unit cost of construction was estimated at ~€13 000/ha (2024 value), which agrees with the average costs in Finland (Ortamala 2012). The estimated unit costs of sedimentation ponds are rather similar as excavation masses are the largest cost factor. The lost earnings for farmers and benefits were estimated following the methodology of Västilä et al. (2021). Farmers lost field area, decreasing the value of the land by a maximum of ~€12,000/ha based on region-specific selling prices. The lost crop value was roughly €800/ha/a (based on cereal crops constituting 60% of the field area). Currently, the €500/ha/a of CAP subsidy is provided for maintaining the wetland, which is in most cases higher than the areal subsidies for crop cultivation but is needed for covering the costs of the actual maintenance works. Wetlands are typically established on locations suffering from floods and thus poor agricultural productivity. Hence, the lost earnings are actually lower, as the alternative to the wetland implementation would be to invest in improved water management, which would generate alternative costs. The cost estimate does not include e.g. monitoring.

Those sites that fulfilled the criteria have been financed by CAP-AES as non-productive investments. Other sites have been financed e.g. by the municipalities of the L. Vesijärvi catchment and by public and private sector through various projects implemented by e.g. Lake Vesijärvi Foundation.

The estimated financial benefits of external water protection measures include decreased loading to L. Vesijärvi, but the available data does not allow reliable direct evaluation of the P retention by the wetlands. The share of wetland surface area is small with respective to the total catchment area (0.05%) while the benefits are valued at €300/retained kg P (based on KUTOVA background data, 2024 value). Since the agricultural practices have also changed (Section 1.3.1.11), we consider the cost-effectiveness of well-performing soil amendments (€56/kg P) as a reference (Ollikainen et al. 2024). Based on this range in benefit valuation, the decreased P loading to L. Vesijärvi (see Section 1.3.1.3) has had a monetary environmental benefit of M€3-17 the 33-y time frame, i.e., M€ 0.1-0.5/a.

Table 1. Estimated costs of constructed wetlands (2024 value) over a period of 30 years based on representative conditions in Southern Finland.

Variable	**Units**	**Unit costs / quantities**	**Costs**	**Data source**
Time frame	years	30		
Total area of wetlands	ha	20		Lake Vesijärvi Foundation 2025
Project management (planning, stakeholder collaboration, securing financing)	€/ha	24,000	480,000	Ortamala 2012
Construction	€/ha	13,000	260,000	Ortamala 2012
Maintenance	€/ha/a	500	300,000	CAP 2023-2027
Land price	€/ha	12,000	240,000	Västilä et al 2021
Lost crop value	€/ha/a	800	480,000	Västilä et al 2021
Total costs within 30 years	**€**		**1,760,000**	
Total costs within 30 years	**€/ha**		**88,000**	

1.3 Evaluation of existing restoration programme

1.3.1 WFD

1.3.1.1 Water quality and chlorophyll a

The sewage diversion in 1976 remarkedly decreased the epilimnetic growing season total phosphorus (TP) and chlorophyll a (Chl *a*) concentrations of Vesijärvi 1 (Enonselkä, Komonselkä, Paimelanlahti-Vähäselkä basins) that was the area most subjected to wastewater loading. In between the sewage diversion (1976) and the begin of biomanipulation (1989), the median TP concentrations (41 µg/L) were on a level displaying poor status. After the period of intensive biomanipulation in 1989-1993, the epilimnetic TP concentrations in the 1990s declined to levels indicating moderate status (26 µg/L) and have further declined during the recent years (since 2020) to a level indicating good status (16 µg/L) (Figure 6). Similarly, the Chl a in Vesijärvi 1 has experienced a substantial decline from the concentrations in 1980s after the onset of consistent. However, elevated Chl a concentrations have been observed during the 2010-2020s despite the reduced TP concentrations due to changes in phytoplankton communities (Figure 6, Section 1.3.1.1.2). The aeration of Enonselkä basin in 2010-2019 increased the hypolimnetic oxygen concentration (Horppila et al. 2015) but did not affect the epilimnetic nutrient concentrations (Salmi et al. 2014; Salonen et al. 2023). However, increased temperature and oxygen concentration in the hypolimnion promoted the benthic N removal via increased denitrification and reduced the accumulation of ammonium in the hypolimnion during stratification (Holmroos et al. 2016).

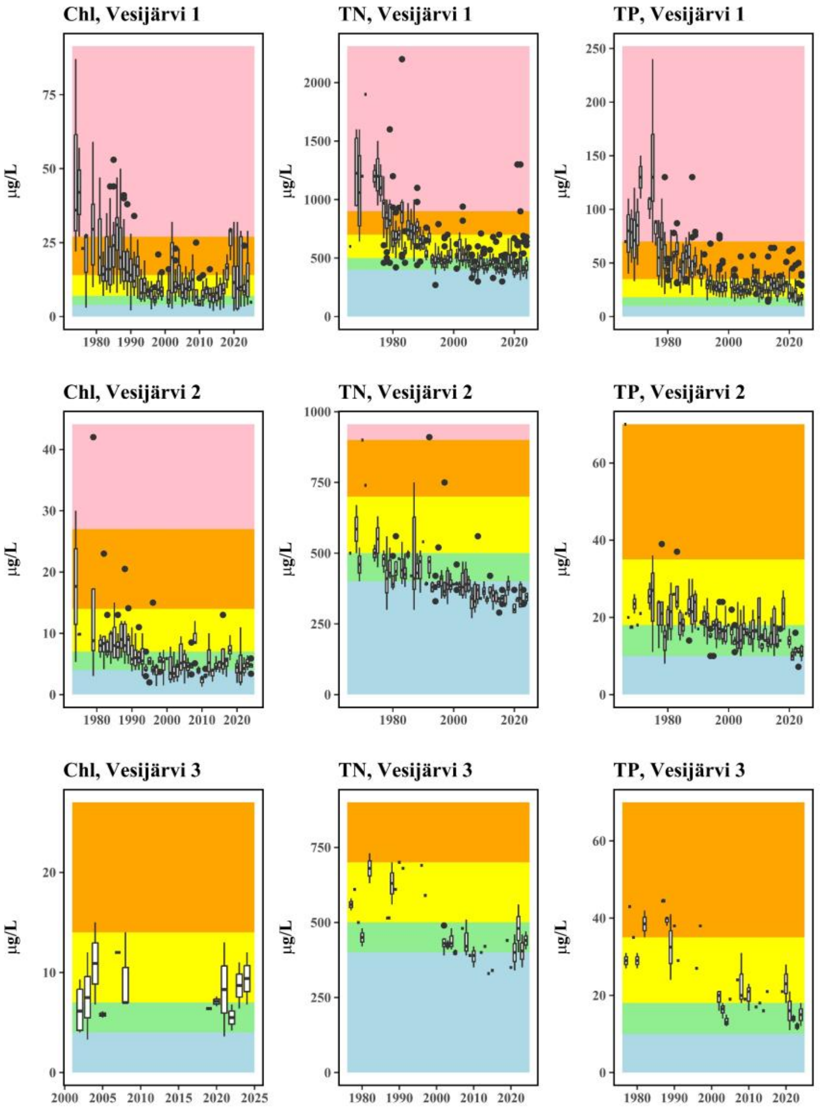

Figure 6. Development of chlorophyll a (Chl a), total nitrogen (TN) and total phosphorus (TP) concentrations in the three RBMP water bodies of L. Vesijärvi since the beginning of monitoring. Vesijärvi 1 refers to basins Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä; Vesijärvi 2 to Kajaanselkä; and Vesijärvi 3 to Laitialanselkä and Kirkonselkä. The reader is suggested to refer to Figure 1 for information on the location of these basins. Note the different scales on x- and y-axes. The colours represent status class boundaries for phytoplankton metric Chl a and the supporting elements TN and TP (blue = high; green = good; yellow = moderate; orange = poor; red = bad).

In Vesijärvi 2 (Kajaanselkä), the median TP, TN and Chl a concentrations during the 1980s mainly indicated moderate status. Since the 1990s, the Chl a concentration has mainly remained on a level indicating good status, whereas the TP concentration has fluctuated between moderate and good

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status. Chl data from Vesijärvi 3 (Laitialanselkä and Kirkonselkä) are rather sparse and only available from the 21st century. Since then, the Chl a concentration has been on a level mainly indicating moderate ecological status.

In regards of TN, the median growing season (May-September) concentrations at all L. Vesijärvi RBMP water bodies (Vesijärvi 1-3) have mainly indicated good or high ecological status since the 1990s.

Considering nutrient limitation, L. Vesijärvi has earlier been estimated as P limited in a national assessment based on TN/TP-ratios of Finnish lakes (Pietiläinen and Räike 1999). This is supported by a comparison of monthly concentrations of soluble reactive phosphorus (SRP), dissolved inorganic nirogen (DIN; i.e. the sum of nitrate, nitrite and ammonium nitrogen) and total organic nitrogen (TON; difference between TN and DIN) in different subbasins (Figure 7). According to Maberly et al. (2002), P limitation would be possible in months when SRP is < 10 µg/L, whereas the threshold for N limitation could be DIN < 0.1 mg/L. In Vesijärvi subbasins, the concentrations of TON substantially exceed this limitation threshold, whereas the SRP concentrations are below the P limitation threshold especially during the phytoplankton growing season (June-August), also suggesting P limitation. However, it must be noted that the thresholds suggested by Maberly et al. (2002) display the conditions in upland lakes an may not fully repserent the conditions at the lowland L. Vesijärvi. Indeed, a more recent study by (Ojala et al. 2003) combining results of long-term enrichment experiments with natural phytoplankton, lake nutrient and chlorophyll a concentrations, elemental ratios (N:P, C:P, C:N) of particulate matter, and analysis of P uptake using [33P] did not support P limitation in the Enonselkä basin. Instead, the N:P ratios usually suggested the occurrence of N limitation (Ojala et al. 2003). Fluctuations between P and N limitation were also observed in the growing season during 2024 (KVVY Tutkimus Oy 2025).

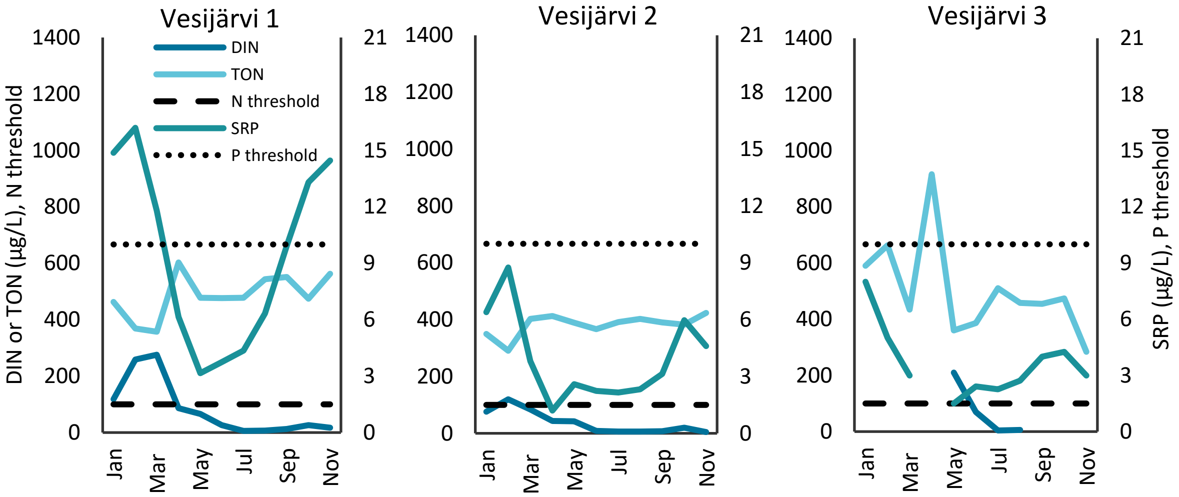

Figure 7. Seasonal changes in surface water (0-4 m) soluble reactive phosphorus (SRP), dissolved inorganic nitrogen (DIN) and total organic nitrogen (TON) average concentrations in L. Vesijärvi subbasins in 1990–2025. The threshold values for P (10 µg/L, dotted line) and N (100 µg/L, dashed line) are presented following Maberly et al. (2002). Vesijärvi 1 refers to the basins Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä; Vesijärvi 2 to Kajaanselkä; and Vesijärvi 3 to Laitialanselkä and Kirkonselkä. The reader is suggested to refer to Figure 1 for information on the location of these basins.

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1.3.1.2 Phytoplankton

Before the sewage diversion and first restoration efforts taken in late 1970s, the phytoplankton BQE metrics total biomass, proportion of harmful cyanobacteria and the phytoplankton trophic index (TPI) in the subbasin Vesijärvi 1 indicated bad status (Figure 8). Since the mid-1990s, the phytoplankton biomass metric in Vesijärvi 1 has fluctuated between levels indicating poor or moderate status. The proportion of harmful cyanobacteria in phytoplankton biomass in Vesijärvi 1, in turn, has mostly remained <16% indicating as a single phytoplankton metric good status with some exceptions in the 21st century. For instance, in 2002, 2009, 2016 and 2018 the median proportion of cyanobacteria indicated poor status (Figure 8), as both the N-fixing cyanobacteria and cyanobacteria in general were abundant (Figure 9, Figure 10). During the periods of summer aeration in 2010–2017, it was estimated that the turbulence tolerant Planktothrix agardhii probably benefited from the aeration-induced mixing (Ruuhijärvi et al. 2020). The phytoplankton trophic index (TPI) indicated bad to poor status before the sewage diversion and extensive biomanipulation. Ever since, this metric has fluctuated between levels indicating good to poor status (Figure 8).

Although the sewage diversion in 1976 reduced the TP concentration in the Enonselkä basin's epilimnion by circa 40%, the cyanobacterial blooms were still frequent in the early 1980s (Salonen et al. 2023). Further reduction of TP by about 30-40% due to intensive biomanipulation in 1989-1993 reduced the phytoplankton biomass and the percentage of cyanobacteria remarkably (Horppila et al. 1998; Kairesalo et al. 1999; Salonen et al. 2023). Aeration periods did not have major impacts on phytoplankton communities. Prior to biomanipulation, the most abundant cyanobacterial genera in Enonselkä basin were Planktothrix, Aphanizomenon and Dolichospermum. The turbulence tolerant Planktothrix formed high biomass especially in 1970s and 1980s, as well as during and a few years after the first aeration period. Since 1990, after the "Vesijärvi project I", the proportion of cyanobacteria declined and the N2-fixing cyanobacterium Dolichospermum replaced the non-N2-fixing cyanobacterium Planktothrix. However, in some years during the second aeration period, Planktothrix has been the most abundant cyanobacterium.

Since the 1960s, the total biomass of phytoplankton has been markedly higher in Enonselkä compared to Kajaanselkä basin (Vesijärvi 2)(Figure 8, Figure 9). In Vesijärvi 2, the phytoplankton metrics total biomass, the proportion of cyanobacteria and the TPI have mainly indicated good to moderate status during the last couple of decades (Figure 8). In Kajaanselkä basin, the proportion of cyanobacteria has also been markedly lower compared to the Enonselkä basin. However, in 2016 and 2018, the proportion of cyanobacteria was high also in Vesijärvi 2, similar to Vesijärvi 1. This was attributed to the abundance of both N-fixing cyanobacteria and other cyanobacteria (Figure 9). Although the phytoplankton biomass is significantly lower in Kajaanselkä, the species succession has been rather similar in both basins (Salonen et al. 2023). In addition to cyanobacteria, diatoms, cryptomonads and dinoflagellates dominate the phytoplankton community in both basins (Figure 9) (Salonen et al. 2023).

In Vesijärvi 3, where data are much sparser and only dates back to the beginning of the 2000s, the phytoplankton total biomass metric has indicated moderate to poor status, and the proportion of cyanobacteria and the TPI mainly good ecological status, respectively (Figure 8).

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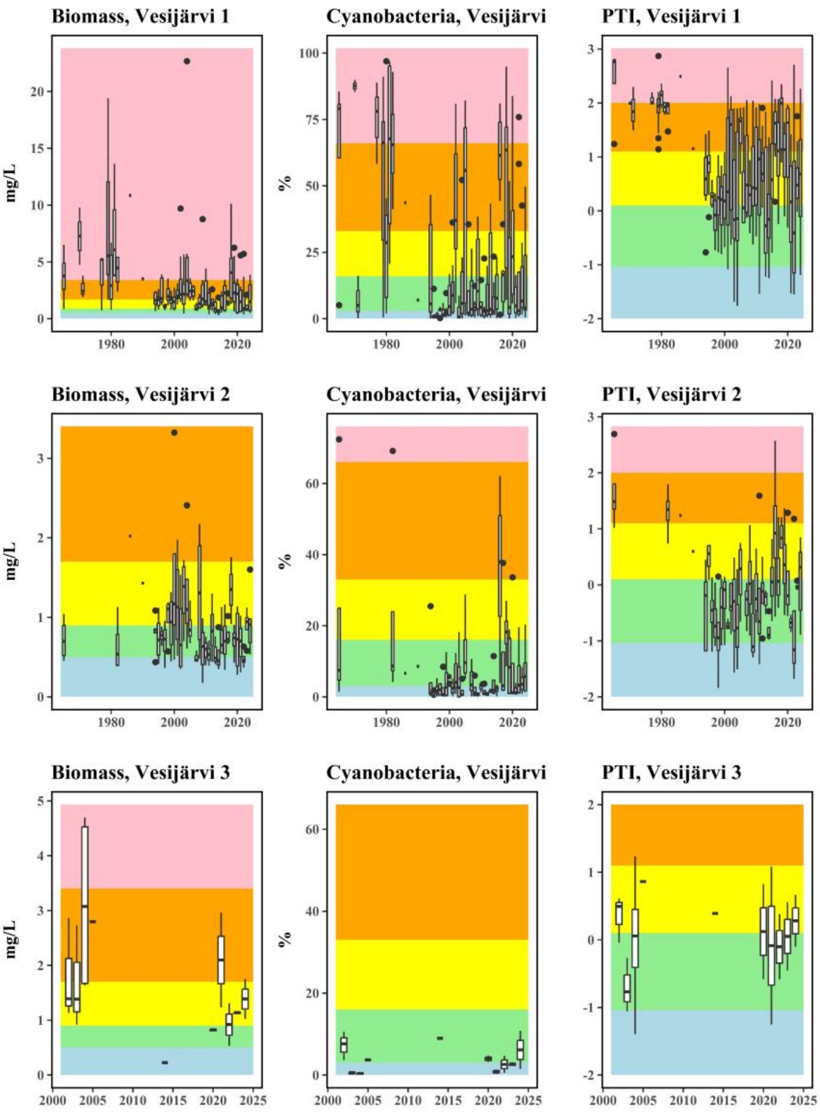

Figure 8. Phytoplankton total biomass, proportion of harmful cyanobacteria of phytoplankton biomass and phytoplankton trophic index (TPI) in the three RBMP water bodies of L. Vesijärvi since the beginning of monitoring. Vesijärvi 1 refers to basins Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä; Vesijärvi 2 to Kajaanselkä; and Vesijärvi 3 to Laitialanselkä and Kirkonselkä. The reader is suggested to refer to Figure 1 for information on the location of these basins. Note the different scales on x- and y-axes. The colours represent status class boundaries for the phytoplankton metrics (blue = high; green = good; yellow = moderate; orange = poor; red = bad).

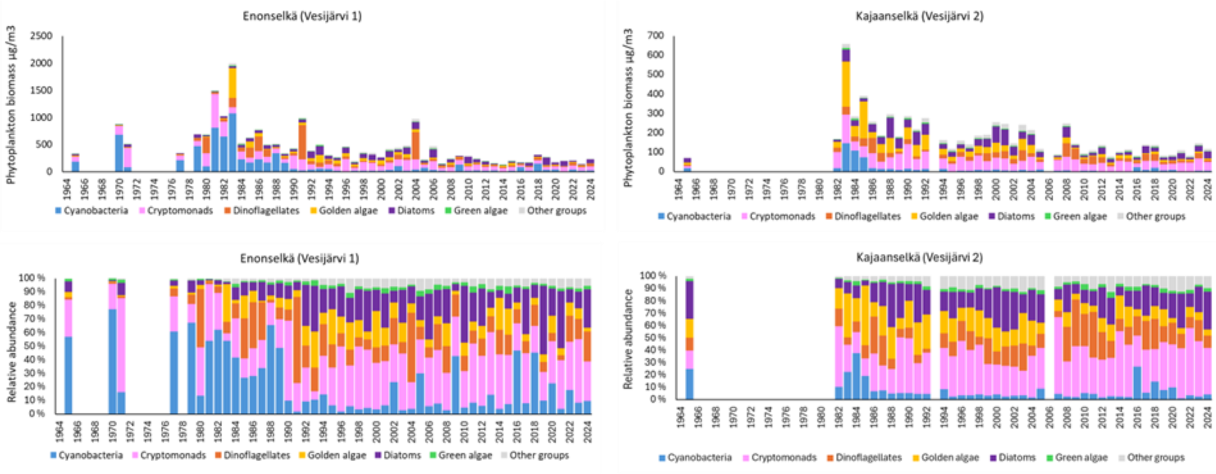

Figure 9. The development of phytoplankton communities at L. Vesijärvi's Enonselkä (Vesijärvi 1) and Kajaanselkä (Vesijärvi 2) basins since the beginning of monitoring in 1965. The data represent average biomasses from June to August. Note the different scales on y-axis.

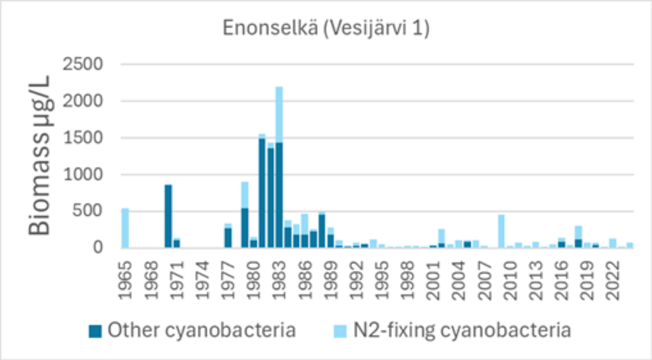

Figure 10. The development of N2-fixing and non-N2-fixing cyanobacteria (other cyanobacteria) at Enonselkä basin (Vesijärvi 1) since the beginning of monitoring 1965. Data represent average cyanobacterial biomass from June to August. The data represent average yearly biomasses from June to August.

1.3.1.3 Fish

The fish community structure in L. Vesijärvi Enonselkä basin has been evaluated since 2007 by random sampling with Nordic multi-mesh survey nets following standard methods described in Olin et al. (2002). The catch as number per unit effort (CPUEn (ind./net/night)) and biomass per unit effort (CPUEw (g/net/night)) has been used as an index of fish abundance. Despite continuous biomanipulation and trawling, the abundance of fish in Vesijärvi 1 has been such high both in terms of CPUE, that it has mainly indicated bad ecological status (Figure 12). However, the proportion eutrophication-indicative cyprinid species, in turn, has often been on a low level indicating high status. Compared to the reference values of large non humic lakes, the fish community in L. Vesijärvi is abundant and indicates impacts of eutrophication. However, the structure of the fish stock is good, as perch are abundant in relation roach and the proportion of predatory fish is high (Ruuhijärvi et al. 2023). Changes in fish communities correspond to the management goals of L. Vesijärvi.

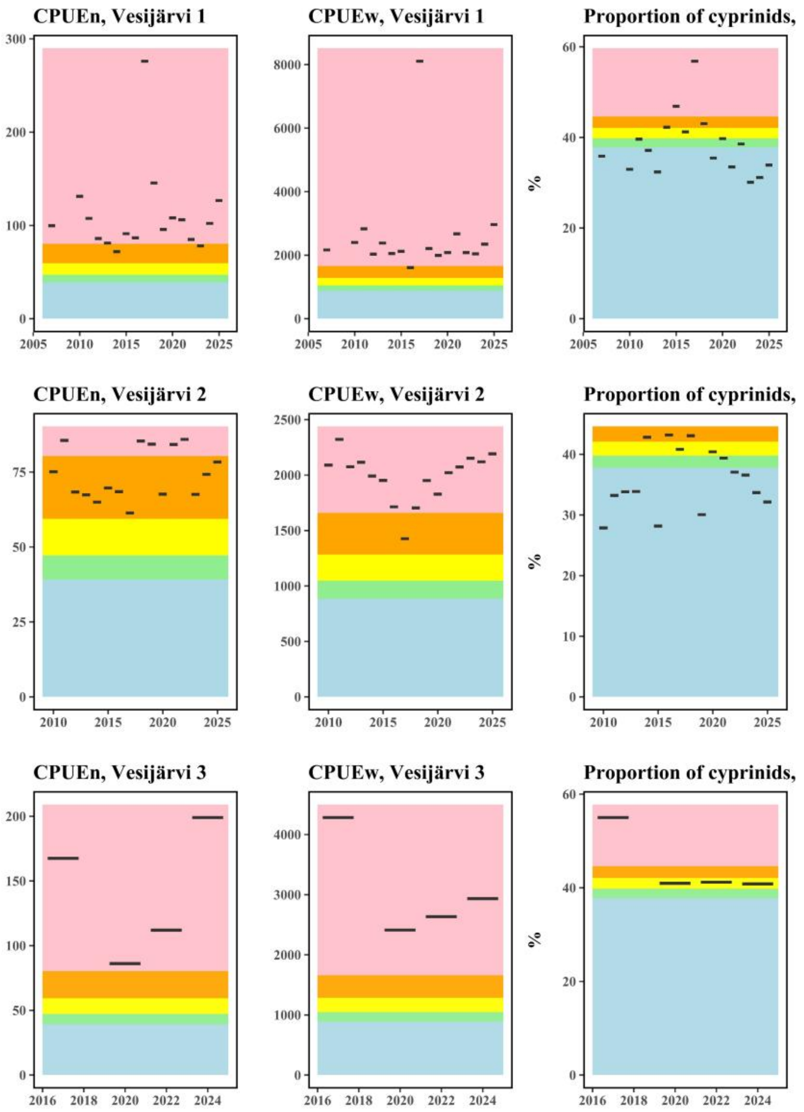

Figure 12. Fish community composition in L. Vesijärvi subbasins based the number of fish per gillnet (CPUEn), biomass (g) of fish per gillnet (CPUEw) and proportion of eutrophication-indicative cyprinids in CPUEw. The colours represent status class boundaries for the respective fish metrics (blue = high; green = good; yellow = moderate; orange = poor; red = bad).

In general, the most abundant fish species based on standard multimesh gillnetting in L. Vesijärvi 1, 2 and 3 during the 21st century have been perch (Perca fluviatilis), smelt and occasionally roach (Figure 13, Figure 14). Gillnetting at Vesijärvi 3 has been conducted only since the late 2010s, after which perch, ruffe (*Gymnocephalus cernua*), bleak (*Alburnus alburnus*) and roach have been the most abundant species within the catch. However, it must be noted that some of the species are systematically underestimated by standard gillnetting, whereas the species with spiky structures (e.g. perch) are being caught more easily. Hence, the size of the L. Vesijärvi smelt population is remarkably higher when estimation is conducted by hydroacoustic assessment and trawling, according to which smelt has been by far the most abundant species in the pelagial of L. Vesijärvi since 2009 (Malinen and Vinni 2025). Subsequently, changes in smelt population have affected the functioning of the lake's food web (Section 1.3.1.2.4). Fluctuations in the smelt population have originated from the changes in water temperature and oxygen conditions both during hot summers and operation of summer aeration (Malinen and Vinni 2025; Ruuhijärvi et al. 2020), and also the strength of predatory fish stock (Malinen and Vinni 2025), which is being supported by annual stocking of whitefish (*Coregonus lavaretus*), trout, salmon (*Salmo salar* m. *sebago*), pikeperch and eel (*Anguilla anguilla*).

The endangered eel population in L. Vesijärvi is completely dependent on its introduction and c. 10,000 fry are being introduced annually (Ruuhijärvi et al. 2023). Additionally, the departure of L. Vesijärvi eel population on their reproductive migration to the Sargasso Sea is prohibited by Vääksy canal, which forms a migration barrier. In 2023-2024, a pilot for promoting the eels' migration was carried out using the assistance of professional fishermen who trapped and transported more than 900 individuals to R. Kymijoki (KVVY Tutkimus Oy 2025), which drains to the Baltic Sea. Currently, there are to continue the and expand the operation to new areas.

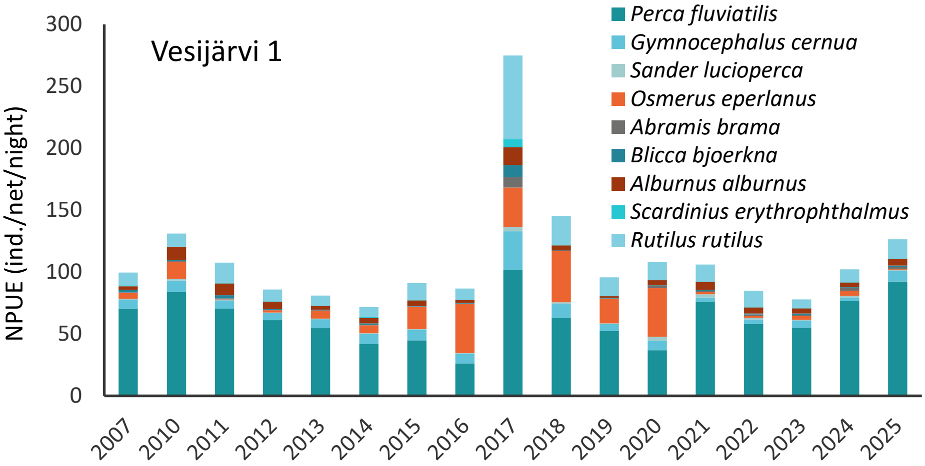

Figure 13. Fish community composition of L Vesijärvi RBMP water body Vesijärvi 1 (Enonselkä, Komonselkä, Paimelanlahti-Vähäselkä basins) based on the number of most abundant fish species per gillnet (NPUE).

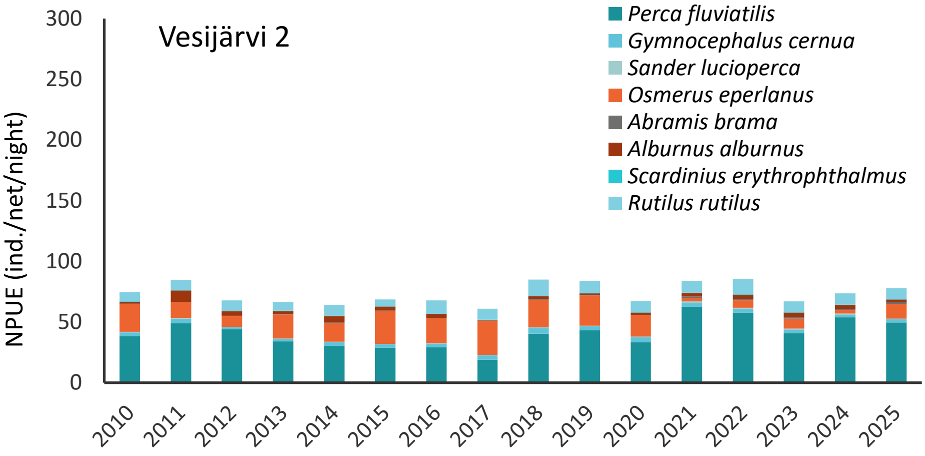

Figure 14. Fish community composition of L. Vesijärvi RBMP water body Vesijärvi 2 (Kajaanselkä basin) based on the number of most abundant fish species per gillnet (NPUE).

1.3.1.4 Macroinvertebrates

In Vesijärvi 1 (Enonselkä basin), data on benthic macroinvertebrates is available since 2010, after which the most abundant species have been *Chironomus plumosus*, *Limnodrilus* sp, *Potamothrix/Tubifex* sp., *Procladius* sp. and *C. antracinus* (Figure 15). The benthic macroinvertebrate percent model affinity (PMA

(Novak and Bode 1992)) and the profundal invertebrate community metrics (PICM) metrics in Vesijärvi 1 have mainly indicated moderate status since the beginning of 2000s.

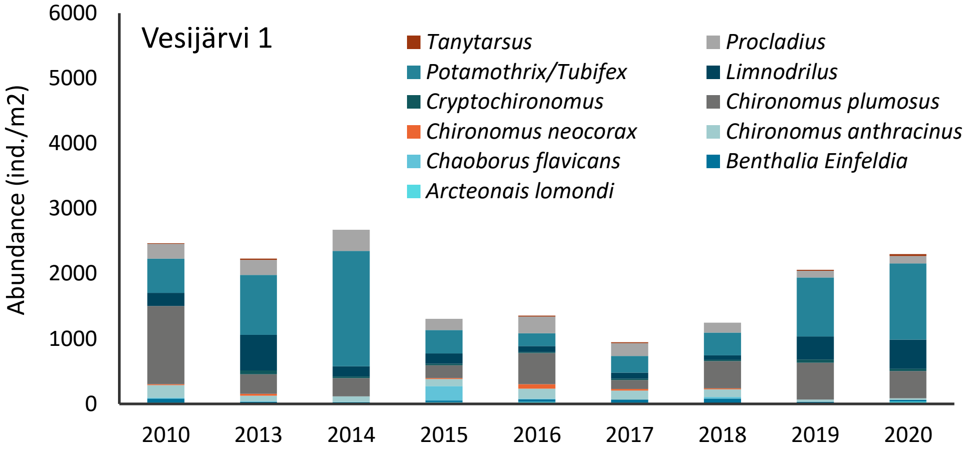

Figure 15. The abundance of selected macroinvertebrate species in 9-32 m depths of L. Vesijärvi Enonselkä basin in between 2010-2020. Only the species that have occurred almost during all the years of sampling are presented. Aeration of Enonselkä both during the winter and summer took place in 2010-2017, and during the winter 2018-2019.

In Kajaanselkä basin (Vesijärvi 2), data are only available from 2008, 2014 and 2020 and from the deepest areas of the basin (depths from 35-37 m). The most abundant genera have been *Potamothrix/Tubifex* sp., and *C. anthrasinus* (Figure 16). In Vesijärvi 2, the PMA and PICM metrics since 2008 have mainly indicated moderate status.

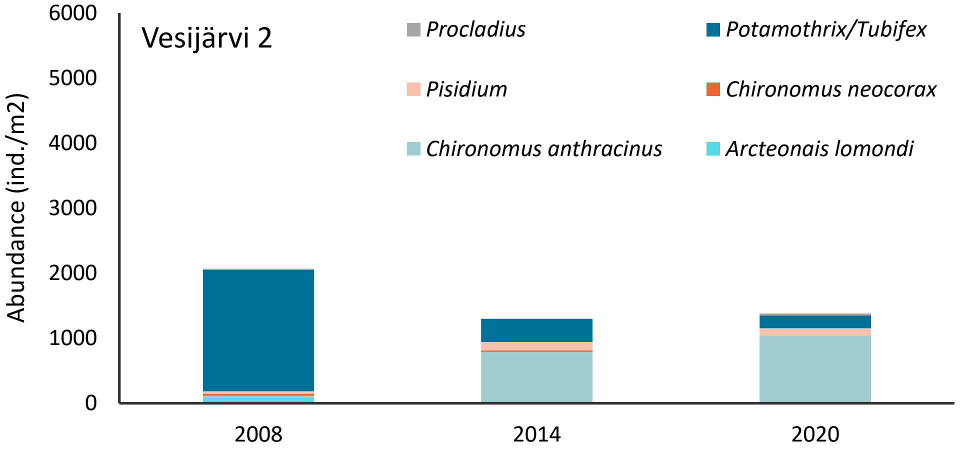

Figure 16. The abundance of selected macroinvertebrate species in 35-37 m depths of L. Vesijärvi Kajaanselkä basin in between 2008-2020. Only the species that have occurred almost during all the years of sampling are presented.

In Vesijärvi 3 (Laitialanselkä basin), where data are available for the depths 16-18 m, the most abundant genera in have been *Procladius* sp., *C. plumosus*, *Potamothrix* sp., and *Tubifex* sp (Figure 17). The PMA metrics in Laitialanselkä have mainly indicated moderate status and the PICM, instead, has mainly indicated poor status.

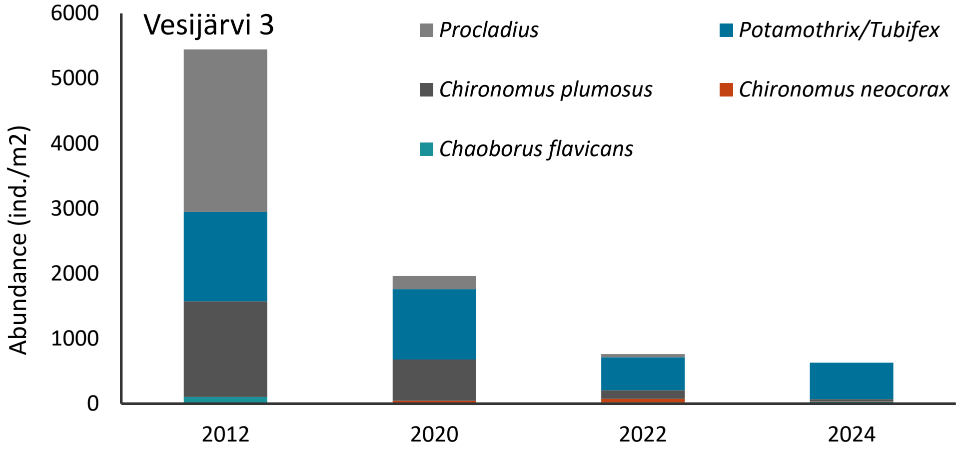

Figure 17. The abundance of selected macroinvertebrate species in 16-18 m depths of L. Vesijärvi Laitialanselkä basin in between 2012-2024. Only the species that have occurred almost during all the years of sampling are presented.

Impacts of aeration on L. Vesijärvi Enonselkä basin zoobenthos were evaluated in the early 2010s. In 2009, before the aeration, the number of profundal mid-depth (0–15 m) macroinvertebrate taxa was on average 9.5 (Tolonen and Hynynen 2012). After the onset of aeration (9 Mixox-pumps, operation during winter and summer) in 2010, the number of mid-depth taxa reduced to an average of 7.5 in 2010 and 6.5 in 2011 (Tolonen and Hynynen 2012). In the deepest parts of Enonselkä basin (20–30 m), the number of taxa in 2009 was on average 5.7, increased to 6.5 in 2010 after the onset of aeration and again reduced to 4.5 in 2011 (Tolonen and Hynynen 2012). Before the aeration in 2009, the most abundant genera in Enonselkä basin were *Potamothrix* sp. and *Tubifex* sp. together with *Procladius* sp. and *Chironomus* sp. After the onset of aeration, the abundance of *C. plumosus* increased remarkably, as the species is well adapted to warm water (Self et al. 2011). The formerly observed species *C. salinarius, Polypedilum* sp., *Tanypus villipennis*, *Aulodrilus piqueti*, *Slavina appendiculata*, *Arcteonais lomondi* and *Vejdoskyella comata* were, in turn, no longer recorded in 2011 and the abundance of Einfeldia sp. had clearly decreased. The diversity of genera after the onset of aeration was still scarce and typical of eutrophied lake depths (Tolonen and Hynynen 2012).

The total abundance and biomass of macroinvertebrates, however, increased remarkably after the onset of aeration. The total abundance in mid-depth during 2009 was on average 950 ind./m2, whereas in 2011 it had increased to c. 2900 ind./m2. In the deepest parts of the basin, the total abundance in 2009 was c. 1500 ind./m2 and increased to c. 5000 ind./m2 by 2011 (Tolonen and Hynynen 2012). The total biomass in mid-depth were 3-fold, and in the deepest parts 11-fold in 2011 compared to the situation in 2009 (Tolonen and Hynynen 2012). The increments in total abundance and biomass were mainly attributed to the increase of *C. plumosus* and Oligochaeta (*Potamothrix* sp., *Tubifex* sp.) both in mid-depth and in the deepest areas, resulting from increased temperature and increased oxygen concentrations in the hypolimnia (Tolonen and Hynynen 2012). It was concluded that the aeration did not improve the ecological status of the lake based on PMA and PICM macroinvertebrate metrics (Tolonen and Hynynen 2012). In turn, the increased temperature in the hypolimnion favored *C. plumosus*, which is a species indicative of eutrophy.

1.3.1.5 Zooplankton

Zooplankton in general is not being monitored as part of WFD, despite its significance in lake foodweb dynamics (Jeppesen et al. 2011). Nevertheless, zooplankton of the Enonselkä basin (Vesijärvi 1) has been monitored since the onset of consistent biomanipulation in the late 1980s and early 1990s. Based on long-term data, both the total zooplankton biomass and *Daphnia* sp. biomass during the growing season (June-September) experienced a decline in mid-2000s, after which the total zooplankton biomass has remained constant (Figure 19). *Daphnia* sp. biomass, in turn, has slightly increased after 2010s and the biomass in 2024 was closer to the levels observed in early 2000s. According to Kuoppamäki (2025), the biomass of cladocerans, such as *Daphnia* sp., and copepods such as *Eudiaptomus gracilis* and *Limnocalanus macrurus* have increased since 2015, while at the same time the biomass of rotifers has decreased as an indication of a recovering food web. During the years when the biomass of *Daphnia* sp. has been lowest (2004, 2009), an increase in the phytoplankton biomass could expectedly be observed (Figure 8).

Biomanipulation in the 1990s had a positive impact on the abundance of nutritionally high-quality phytoplankton, crucial for supporting *Daphnia* production, and the biomass of this keystone species, while the opposite was found following the hypolimnetic aeration in 2010's (Taipale et al. 2020; Taipale et al. 2019). Another plausible reason for the low biomass of *Daphnia* during 2010's was the disappearance of the dark and low-oxygen deep-water refuge against fish predation following the mixing of water column (Ruuhijärvi et al. 2020). It has earlier been reported that the fluctuations in L. Vesijärvi's planktivorous smelt population have substantially affected the zooplankton community (Anttila et al. 2013; Nykänen et al. 2010; Ruuhijärvi et al. 2020) and the presence of dense smelt stock inversely correlates with the size of herbivorous cladocerans (Ruuhijärvi et al. 2020). These impacts have also been observed in the subfossil cladoceran zooplankton samples taken from the sediment in Enonselkä basin, where the mean size of *Daphnia* and *Eubosmina crassicornis* ephippia and carapaces increased significantly after the period of intensive biomanipulation in 1989–1992 (Nykänen et al. 2010). Also, the abundances *Diaphanosoma brachyurum* and *Limnosida frontosa* increased significantly, while that of *Ceriodaphnia* and rotifers decreased. Increased water clarity due to biomanipulation was also reflected to a recovery of littoral vegetation with consequent implications for the concentration of littoral species in the deep sediment core (Nykänen et al. 2010).

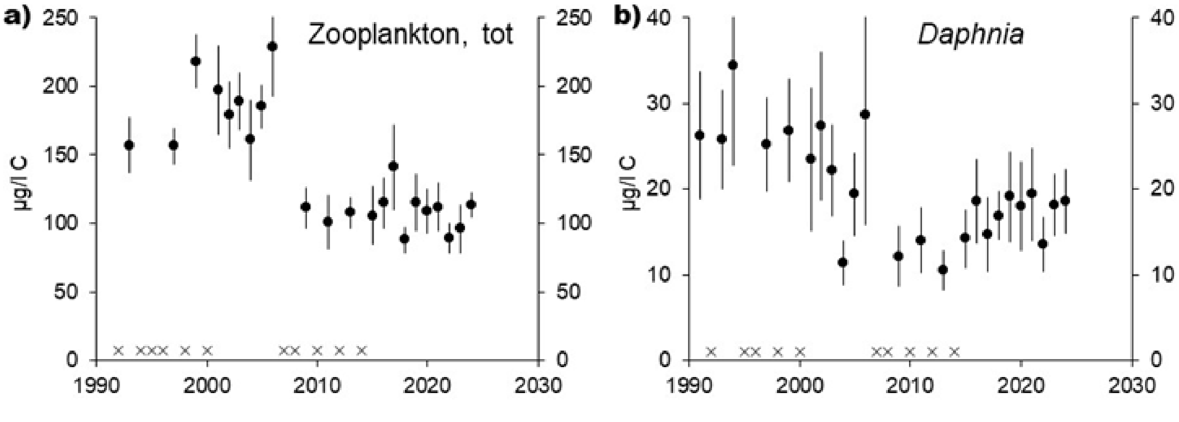

Figure 19. The volume-weighted average (±SE) annual carbon biomass of a) total zooplankton (cladocerans, copepods and rotifers) and b) all Daphnia species in samples collected from Enonselkä basin (Vesijärvi 1) from the depth of 0-30 m between years 1991–2024. The years when samples have not been analysed are marked with an x.

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1.3.2 Biodiversity net gain

1.3.2.1 Waterfowl

The waterfowl population of L. Vesijärvi has been monitored since the late 1970s, when the lake was considered as a substantial waterfowl lake (Lammi and Kolunen 2010). During the 1970s, piscivorous waterfowl were abundant due to eutrophication, abundant planktivorous fish stock, and dense reed beds. Especially the number of breeding and resting *Podiceps cristatus* was exceptionally high, and the large shoals of small fish attracted gulls, common terns (*Sterna Hirundo*), common mergansers (*Mergus merganser*) and red-breasted mergansers (*M. serrator*) to the lake during their autumnal aviation (Lammi and Kolunen 2010). Additionally, demanding species such as the herbivorous *Fulica atra*, and the dabbling ducks *Aythya ferina, A. fuligula*, *Spatula querquedula*, and *S. clypeata* were abundantly breeding at the lake together with large colonies of black-headed gulls (*Chroicocephalus ridibundus*) (Lammi and Kolunen 2010).

The waterfowl population in L. Vesijärvi in general began to experience changes in mid-1980s after the sewage diversion that took place in 1976, due to changes in agriculture as the number of cattle started to decline with subsequent implications for reduced shoreline grazing and pinching of former pastures, and due to increased recreational boating at the lake near Laasonpohja where e.g. *P. cristatus* were abundant (Lammi and Kolunen 2010). During the 1990s when the water quality of L. Vesijärvi began to improve as a result of water protection and restoration efforts, the abundance and density of common reed started to decline with subsequent negative implications for the breeding success of *P. cristatus, F. atra* and C. ridibundus (Lammi and Kolunen 2010). At the same time, the abundance of *Equisetum fluviatile* declined, and *Typha* sp. started to expand to the rare, flooded meadows that were left. Since 1990s, breeding of more tolerant species such as *Anas platyrhynchos*, *A. crecca* and *Bucephala clangula* has become more common and *Cygnus cygnus* has settled down to the lake. A similar trajectory has continued during the 2000s (Lammi and Kolunen 2010).

In general, the decline in breeding waterfowl populations observed in L. Vesijärvi is in line with the general trend in Finland during the last decades (e.g., Lehikoinen et al. 2016). The identified reasons behind this trajectory are, amongst others, the general water quality deterioration and excess eutrophication of surface waters due to changes in land use, and the predation pressure exerted by invasive alien predators (*Neogale vision* and *Nyctereutes procyonoides*) (e.g., Holopainen and Lehikoinen 2022; Lehikoinen et al. 2016; Pöysä et al. 2013). In general, the breeding numbers of many waterbird species are also shown to track the long-term changes in the size of black-headed gull colonies due to its aggressive nest defence behaviour that benefits many other waterfowl species to gain protection against predators (Pöysä et al. 2019).

The substantial decline in L. Vesijärvi breeding waterfowl populations after mid-1990s can be clearly observed in the data from the Natura 2000-area (Figure 19). The endangered species (*P. cristatus, A. ferina*) have substantially declined and the number or breeding black-headed gulls in the Natura 2000-areas during the 2020s has been negligible. In general, it has been estimated that the numbers of breeding birds at the Natura 2000 -area may species-specifically represent 30-60% of the numbers in the whole L. Vesijärvi (Lammi and Kolunen 2010). However, the number of breeding black-headed gulls only represents an estimate of 10% of the total numbers in the whole lake area (Lammi and Kolunen 2010). The breakwater at L. Vesijärvi harbour, Enonselkä basin, is a large artificial island that hosts one of Finland's largest colonies of black-headed gulls (Kekki et al. 2018).

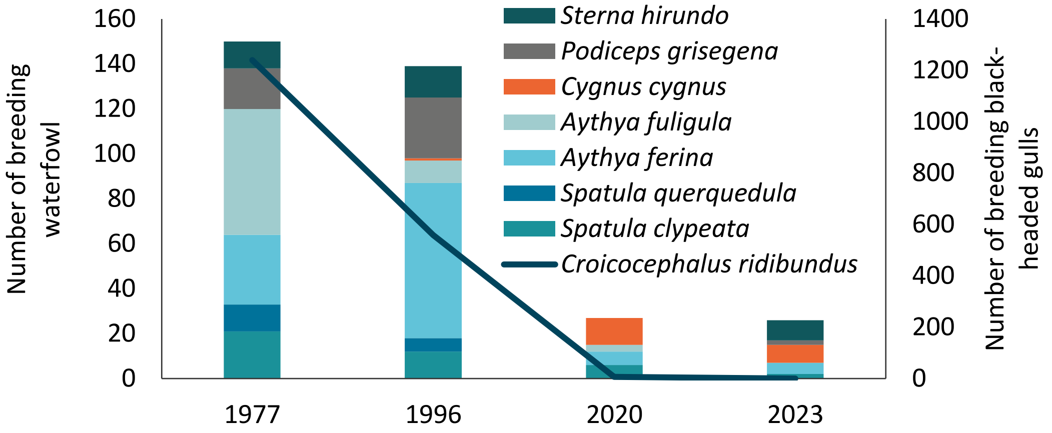

Figure 19. The numbers of selected breeding waterfowl and black-headed gulls (Croicocephalus ridibundus) that are behind the protection of Natura 2000-area FI0306006 ("Kutajärven alue") since the beginning of monitoring in 1977.

1.3.1.2.2 HD Annex IV species

The dragonflies in Kutajärvi 2000-area were mapped in 2007 when a total of 19 species were discovered from L. Vesijärvi bay areas (Kailanpohja, Teräväiset, Lahdenpohja, Kirkonselkä, Laasonpohja) including *Leucorrhinia caudalis* and *L. pectoralis* that are listed in Annex IVa of the European Union's Habitats Directive (Mäkinen 2007). The latter is also listed as one of reasons for the protection of Kutajärvi Natura 2000-area. Both species were also observed in all these bay areas during the mapping in 2019 (Metsänen and Saikko 2019). This time, however, the occurrence of other dragonflies was not systematically evaluated nor recorded.

These two species generally inhabit ponds, lakes and bays with abundant submerged vegetation. In larger lakes such as L. Vesijärvi, they occur in fertile bays. Both species have declined sharply in Western Europe but are rather common in Southern Finland, at the northern limit of their range, where they may be more sensitive to changes in the environment. However, in Finland, the conservation status of both species has been favourable in 2019 and 2025. The species favour eutrophied lakes and bonds with floating-leaf vegetation, but can be absent from hypertrophic, overgrown lakes and bonds. *L. pectoralis* favours relatively higher water transparency. In addition to the breeding site, the resting site includes the protective vegetation surrounding the water area, in which the dragonflies take shelter at night and during cloudy weather (Metsänen and Saikko 2019; Nieminen and Ahola 2017). Long-term time series data on the occurrence of species in the area are not available. However, based on their habitat requirements, both species may have benefited from the improvement in the water quality of L. Vesijärvi. Both species have become more abundant in Finland since the early 2000s (www.laji.fi/en [accessed on 30 Sept 2025]).

Among the HD annex IVa species, the moor frog (*Rana arvalis*) has also been observed in the Kutajärvi Natura 2000 area including L. Vesijärvi bay areas (Laasonpohja, Kirkonselkä, Lahdenpohja, Teräväinen and Kailanpohja) (Lammi and Vauhkonen 2021). The species is found almost throughout Finland, but it is most abundant in the southern and central parts of the country (Nieminen and Ahola 2017). The species can be found in moist meadows, forests, and bogs (www.laji.fi/en [accessed on 30 Sept 2025]). In L. Vesijärvi, Lahdenpohja is a particularly suitable area for the reproduction of the moor frog where hundreds of spawning individuals have been observed (Lammi and Vauhkonen 2021).

1.3.1.2.3 Macrophytes

L. Vesijärvi is one the most valuable lakes in Finland in terms of representative and versatile aquatic flora, especially within the four bays (Kirkonselkä, Laasonpohja, Lahdenpohja, Teräväiset and Kailanpohja) that are designated to Natura 2000 -network. The endangered *Myriophyllum sibiricum*, *Callitriche hermaphroditica*, *Chara braunii*, and *Rhynchostegium riparioides* have been recorded from the lake (Järnefelt 1929), and *Najas flexilis* and *N. tenuissima* are among the justification for protection of the Natura 2000 -area. As a special feature, some brackish water species, such as *C. hermaphroditica*, *Potamogeton filiformis* and *P. pusillus* inhabit the lake as a remnant from the era when the lake was a former bay of the Baltic Sea (Keto et al. 2010).

Eutrophication and the general water quality deterioration have affected the macrophyte communities at L. Vesijärvi. For instance, *Ceratophyllum demersum*, which generally benefits from eutrophication, formed mass occurrences during the 1970s and 1980s when the symptoms of eutrophication were most severe (Keto et al. 2010). Another species that begun to spread along with increasing eutrophication was *Phragmites australis* whereas *P. rutilus* was abundant at the lake in mid-1900s but started to decline remarkably in the 1980s (Keto et al. 2010). Although the water clarity increased during the 1990s due to restoration efforts, the water quality improvement alone has not benefited *P. rutilus* which has suffered from the shoreline construction and small-scale dredging, harvesting of reed belts, and exhaustion of sheltered habitats (Keto et al. 2010). Similarly, *N. flexilis* and *N. tenuissima* have severely suffered from eutrophication, and the construction and dredging of shoreline habitats that are linked to increased recreational activities and increased occurrence of summer housing (Keto et al. 2010).

At the end of the Vesijärvi Project II in 2006, the aquatic flora of Enonselkä basin had clearly changed since the 1990s with increased abundances of *Myriophyllum alterniflorum, Ranunculus peltatus, P. crispus, Fontinalis hypnoides* and *F. antipyretica* (Lahden Kaupunki 2007). The abundances of *Ceratophyllum demersum, Phragmites australis, Nuphar lutea* and *Equisetum fluviatile*, in turn, had remained more or less constant. In general, the abundance of oligo-mesotraphents/mesotraphents such as *M. alterniflorum* and *R. peltatus* had increased, whereas eutraphents had decreased (Lahden Kaupunki 2007). In total 81 species have been recorded from the lake with a majority of them (43) abundant with several habitats around the lake. Additionally, 17 species only inhabit certain areas of the lake, and 12 species have extremely limited occurrence (Keto et al. 2010). The invasive *Elodea canadensis* was first observed in the lake in 1890s and *Glyseria maxima* in 1960s (Keto et al. 2010), and they can be considered as long-known nuisance.

The latest vegetation survey of L. Vesijärvi was done along transects in 2018, when the macrophyte-EQR indicated good ecological status (0.6).

1.3.1.3 Zero pollution

1.3.1.3.1 Nutrients

The external loading to Vesijärvi has substantially decreased already by the establishment of the wastewater treatment plant in Lahti in 1976. Additionally, further decreasing trends in TP and TN loads are observed in all the Vesijärvi sub-catchments between 1991 and 2024, likely caused by both the implementation of extensive water protection measures (see Section 1.2.3) and changes in agricultural practices (see Section 1.3.1.11). Gradual decreases in external loading since ~2008 could be expected following the establishment of several wetlands and sedimentation basins. The influence of the water protection structures on the external loads is expected to have reached an approximately constant level since 2020 as only one major measure has been implemented after that (FutureLakes' Innovation site; combined sand filter and wetland in Hollola's subarea Sorvanen during 2023-2024).

Based on linear regression, the predicted total TP load to L. Vesijärvi has declined significantly between 1991 and 2024 with the decline being 27% (3.4 t/a) (Figure 20). For TN, in turn, the total loads to L. Vesijärvi in 2024 are 23% (62 t/a) lower compared to the level in 1991, but the decline is insignificant. For both nutrients, the lowest annual loads were estimated for the year 2013, as modelled by the operational watershed model WSFS-Vemala (Huttunen et al. 2016), which has been recently updated and calibrated with 3000-4000 observations of TP and TN between years 1987 and 2022 from ~50 ditches/streams and constructed wetlands across the L. Vesijärvi catchment (Narikka and Huttunen 2023). The model also considers the diversion of part of the stormwater from the L. Vesijärvi catchment to another catchment through the Hennala stormwater treatment system. The calibrated water quality model is expected to capture the potential trends in loads more reliably than water sampling that is known to be biased to low flows and typically lacks concurrent discharge data. Based on the water samples only, there has been no clear trend in TP and TN concentrations in the ditches and streams discharging to L. Vesijärvi since 2002 (Ketola et al. 2024).

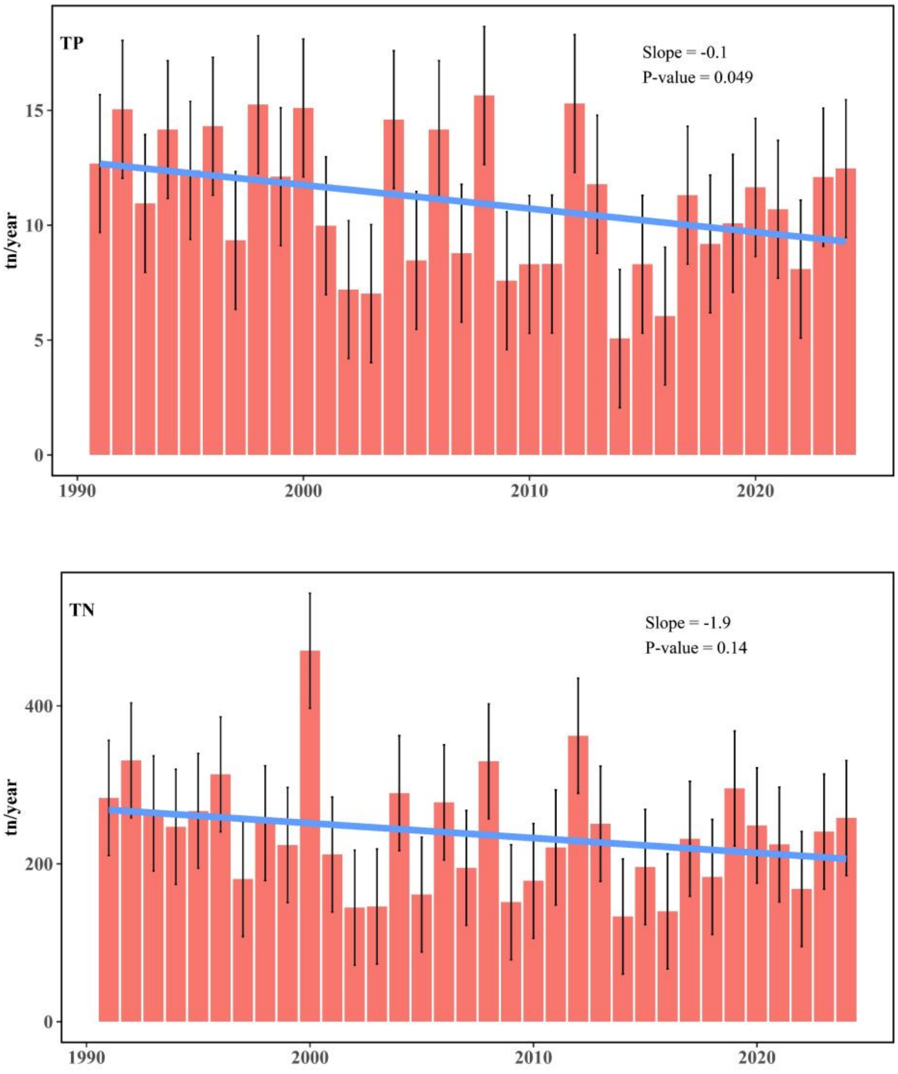

Figure 20. Changes in external TP and TN loading to Lake Vesijärvi from 1991 to 2024 based on the Water quality and nutrient load model system for Finnish watersheds WSFS-Vemala (Huttunen et al. 2016).

1.3.1.3.1.1 Stormwater treatment

The Hennala stormwater diversion and treatment project has been operational since 2020 and has since then decreased the catchment-scale loads to the lake by 1.9% for TP and 0.4% for TN (Table 2) simply by diverting the stormwater to another catchment by using an existing backup sewer connection. The average annual reductions have been more substantial for TP (6.6%) and TN (1.7%) when considering only the most polluted Enonselkä part of the lake to which the stormwater was priorly discharged to. In 2015-2024, stormwater constituted on average 23% of the TP and 8% of TN loading to the lake, and 50% of TP and 19% of TN loading to Enonselkä basin. Thus, the diversion decreases the stormwater load to the lake by 8.3% for TP and 5.5% for TN. These figures were estimated based on flow-weighted sampling of the stormwater prior to the construction of the stormwater treatment system (Lahden kaupunki 2018) and on the diverted water volume averaging 328,000 m3/a in 2021-2024.

Table 2. Load reductions to L. Vesijärvi and its Enonselkä basin resulting from diversion of stormwater to Hennala treatment plant.

	Storm-water volume (m^3/a)	TN (kg/a)	TP (kg/a)	Cd (kg/a)	Cr (kg/a)	Cu (kg/a)	Ni (kg/a)	Zn (kg/a)	Pb (kg/a)	SS (t/a)	TOC (t/a)	E. coli (CFU/100 ml)	Enterococcus (CFU/100 ml)	PO4-P (kg/a)	NO3-N (kg/a)
Mean annual reduction	328,000	1020	196	0.02	0.51	3.05	0.83	10.4	0.17	46	3.83	797	463	6.73	530
Reduction to L. Vesijärvi (%)		0.4	1.9	0.3	1.9	2.1	0.6	1.3	0.3	3.8	0.3			0.2	0.4
Reduction to Enonselkä (%)		1.7	6.6												

The Hennala stormwater treatment system with its sedimentation pond, biofiltration area, wetland and the channel network was established in 2018 and resulted in concentration reductions particularly for TP (17%), TN (8.5%), copper (36%) and lead (46%) in the first 2 years of operation (Figure 21). However, the performance appears to have generally weakened in the 3rd-4th operational years, resulting in outgoing concentrations exceeding the ingoing ones. This is likely resulting from the filling up of the sedimentation pond, which enables fine sediment to be transported further downstream, leading to decreases in the conductivity of the biofilters, and to deposition and subsequent re-suspension from the wetland and channels. For bacteria, the performance has improved after the 1st year. These results are based on a limited number of water samples (15), several of which had concentrations lower than the detection limit for lead.

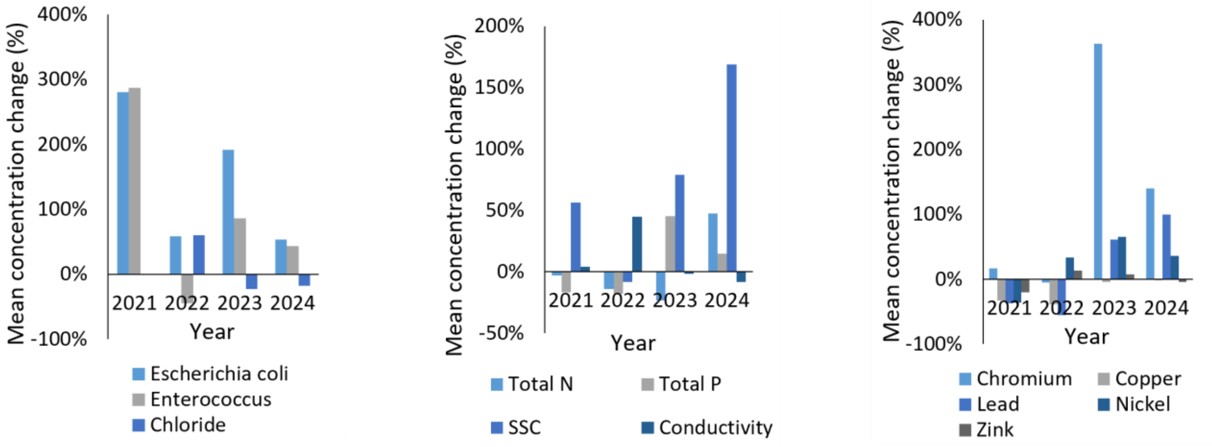

Figure 21. Average concentration changes between the outlet and inlet of the Hennala stormwater treatment system (negative values indicate reductions). Data from the City of Lahti.

1.3.1.3.2 Emerging pollutants

Microplastics (MPs) are not routinely monitored but have been detected in the sediments near the urban areas of L. Vesijärvi shorelines at concentrations of 400 MPs/kg in a study by Scopetani et al. (2019). Concentrations have also been measured from snow and ice at L. Vesijärvi with concentrations of 120 MPs/l/snow and 8 MPs/l/ice, respectively. In all these three sample matrices, synthetic fibres have constituted >99% and fragments <1% while no film, granule or pellet type MPs have been found (Scopetani et al. 2019). Main sources of the MPs in these samples were assumed to be the release of fibres from clothes during recreational activities and stormwater discharge from the City of Lahti. The occurrence of MPs is likely lower in most other, less urban parts of the lake shores. Nevertheless, fibres and other types of MPs have also been observed during inspection of zooplankton samples collected from the Enonselkä basin by inverted microscopy, but their abundance has not been estimated (K. Kuoppamäki, unpublished).

The trend in PFAS cannot be evaluated as there is only one PFAS analysis result available from the Vesijärvi catchment. The PFAS level of 3070 ng/g (with 2150 ng/g of PFOS) has been recorded in perch muscle in Kajaanselkä basin (Vesijärvi 2), due to which L. Vesijärvi has been denoted as a PFAS hot-spot area of which presumptive contamination sites include 2 sewage treatment plants, 2 pulp mills and a waste incineration plant in the catchment (The Forever Pollution Project, https://foreverpollution.eu/ [accessed on 3 Oct 2025]).

1.3.1.4 Climate regulation

The predicted annual methane (CH_4) emissions from L. Vesijärvi subbasins based on annual growing season Chl a values have declined from the period of most severe eutrophication in the late 1970s (Figure 22). Highest CH4 emissions are predicted to originate from Vesijärvi 1 that contains the Enonselkä basin that was most subjected to wastewater loading during the 20th century.

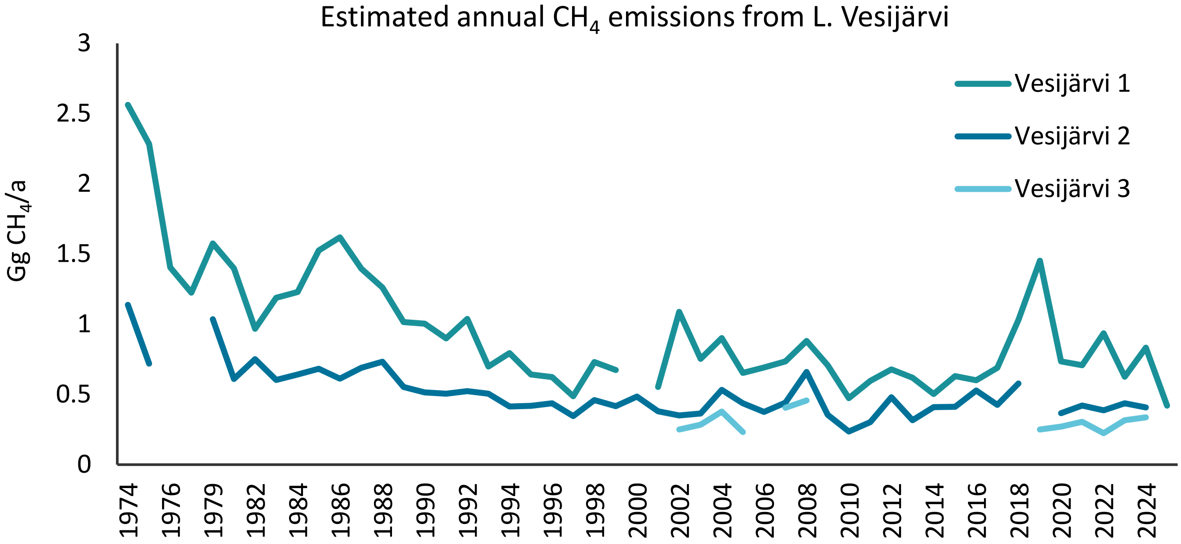

Figure 22. Predicted sum of ebullitive and diffusive methane (CH_4) emissions from the three subbasins of L. Vesijärvi based on average annual growing season (June-August) chlorophyll a concentration. The diffusive and ebullitive methane predictions were made using a Bayesian model constructed from a global dataset of ground-based methane measurements and satellite-derived chlorophyl-a data. The data used to construct the Bayesian model is available as supplementary information in DelSontro et al. (2018). Predictions conducted by E. Kitson, UKCEH.

Based on water samples and gas chromatography, the Enonselkä basin (Vesijärvi 1) acted as a source of CO_2 and CH_4 to the atmosphere in the mid-2000s during the open-water period with fluxes of 2.10 mol/m2 and 0.04 mol/m2, respectively (Linnaluoma 2012; López Bellido et al. 2011). The highest CO_2 concentrations in the epilimnion and hypolimnion were recorded in late summer, i.e. at the time of maximum water temperatures and hypolimnetic hypoxia (Linnaluoma 2012). On average, the surface water concentrations (0–30 cm) of CO_2 in Enonselkä basin were 1.7-fold to that of the atmospheric equilibrium. The CH_4 concentration in Enonselkä basin, in turn, were highest during early autumn and in the periods of hypoxia with remarkably higher CH_4 concentrations in the hypolimnion compared to the epilimnion (Linnaluoma 2012). The surface water concentrations (0–30 cm) of CH_4 varied from 0.020 to 0.460 µM in Enonselkä basin, being 45 times greater than that of the atmospheric equilibrium. Consequently, the estimated total annual global warming potential (GWP) for Enonselkä basin during the stratification period was 3.10 mol CO_2 equivalent/m2, of which the contribution of CH_4 was 33%. It was concluded that the degradation of autochthonous organic matter contributes to the carbon cycling in the Enonselkä basin and the productive lake sediments have a higher capacity to produce CO_2 and CH_4, which is reflected in the carbon gas fluxes (Linnaluoma 2012). Furthermore, the estimated annual CO_2 and CH_4 flux from the Enonselkä basin to the atmosphere was approx. 0.70 mol C/m2/a, corresponding to 7% of the terrestrial net ecosystem exchange (NEE) of forests and peatlands in southern Finland (Riutta et al. 2007; Suni et al. 2003).

The impact of summer aeration on Enonselkä basin's CO_2 and CH_4 fluxes were evaluated in 2013 in a separate study by Zhang (2014), who found that the mean CO_2 flux was >2.5 times higher than in the reference year 2005 when the aeration was not implemented (López Bellido et al. 2011; Zhang 2014). Zhang (2014) concluded that the aeration-induced mixing of water column enhanced the release of CO_2 from surface water to the atmosphere. The hypolimnetic CH_4 concentrations, in turn, were on average 1/100 of that from the concentrations in summer 2005 with prolonged hypoxia/anoxia and no aeration in operation (López Bellido et al. 2011). Consequently, the CH_4 fluxes were slightly decreased in 2013, which was probably attributed the higher rate of CH_4 oxidation in the hypolimnion but also to a limited CH_4 production under oxygenation (Zhang 2014). Earlier, it has been estimated that aeration may play a significant role in limiting methanogenesis in the hypolimnion (Huttunen et al. 2001). However, despite aeration, Enonselkä basin still acted as a source of CH_4 to the atmosphere (Zhang 2014).

1.3.1.5 Climate resilience

The area of constructed wetlands in L. Vesijärvi catchment area has increased during the last decades due to advances in external pollution control (Section 1.2.3) and change in agriculture (Section 1.3.1.11) subsequently increasing the resilience to floods and droughts via increased water storage capacity within the catchment areas. Currently, there are c. 30 constructed wetlands and sedimentation basins in L. Vesijärvi catchment, having an estimated total maximum area of ~20 ha. Assuming a maximum mean depth of 1.5 m, their maximum storage volume is 0.3 Mm3. Considering the catchment area excluding the lake, the theoretical maximum storage volume corresponds to an average design rain of 0.7 mm. However, the storage capacity is centred mostly to Laitialanselkä (Vironjoki-Matjärvi and Mustoja sub-catchments) and to Northern Kajaanselkä basins (agricultural sub-catchment Häränsilmänoja) (Vesijärvi 3 and Vesijärvi 2, respectively). However, the stormwater management programme in the City of Lahti facing the Enonselkä basin (Vesijärvi 1) on its part contributes to climate resilience via increased management of stormwaters on site and reduced volume of stormwaters discharged to the lake (Section 1.3.1.3.1).

L. Vesijärvi has been regulated since 1925 by a dam in the outflow to keep the water level in between 81.06–81.35 m above the sea level, due to which there have been no changes in the lake water volume during the last century. Moreover, the restoration of L. Vesijärvi itself has not contributed to the lake's water storage or retention.

The City of Lahti has a distinct Climate programme, established in 2023, with 9 indicators (https://lahdenymparistovahti.fi/indicators [accessed on 14 Oct 2025]) including actions and targets related to emissions from heating, traffic, industry and also agriculture that has potential to indirectly impact the climate resilience of L. Vesijärvi through changes in land use practices. Since the beginning of 2025, the municipalities of Hollola and Asikkala have also had their own Climate programs guiding their climate and sustainability work in the upcoming years.

1.3.1.6 Health & Well-being

The establishment of the wastewater treatment plant and sewage diversion remarkably affected the swimming water quality of L. Vesijärvi, as the bacteriological defects were eliminated within one year (Keto 1982). Unfortunately, the data on the abundance of faecal enterococci, coliform bacteria and Escherichia coli in L. Vesijärvi water before and after the sewage diversion is rather sparse. However, during the 1960s and early 1970s, when the lake was still subject to untreated wastewaters, the number of faecal enterococci in Enonselkä basin was on average 14 ind./100 mL (range 0–40 ind./100 mL), and coliform bacteria 120 ind./100 mL (range 0–450 ind./100 mL). Data on E. coli before the sewage diversion are not available. One year after the diversion in 1977, the number of faecal enterococci was 0.2 ind./100 mL, coliform bacteria 0 ind./100 mL and E. coli 0 ind./100 mL, respectively. Since then, the abundance of only faecal enterococci was measured in the Enonselkä basin until 1997, being on average 6 ind./100 mL (range 0-21 ind./100 mL).

Vesijärvi has three EU beaches (Ankkuri, Mukkula and Messilä), all of which are located in Enonselkä basin (Vesijärvi 1). There are also two public beaches, Mukkula in Enonselkä basin and Kalmari in Kajaanselkä basin (Vesijärvi 2). The EU Bathing Water Directive (Directive 2006/7/EC (BWD)) requires monitoring of E. coli and intestinal enterococci in bathing water, as they are important indicators of faecal contamination. They pose a risk to human health due to the potential presence of pathogens. Following BWD, the quality of bathing water is classified as excellent, good, sufficient, or poor based on the monitoring results. In general, based on the BWD assessment, the quality of the bathing waters of Ankkuri, Messilä and Mukkula (Vesijärvi 1) have been good or excellent since 2014. In 2014-2016, the status of Kalmari (Vesijärvi 2) beach was sufficient or poor, improved to good in 2017 and has remained excellent since 2018 (State of bathing waters in 2024 | European Environment Agency [accessed on 26 September 2025]).

The cyanobacterial bloom situation on these public beaches is also being regularly monitored by trained municipal health authorities at the same time with bathing water status assessment. The cyanobacterial observations are recorded in Järvi-meriwiki as part of a national cyanobacterial monitoring programme. Monitoring has been conducted since 1998 with a weekly frequency in June-September evaluating the bloom intensity by visual inspection from the beach on the scale of 0 = no cyanobacteria, 1 = some cyanobacteria, 2 = abundant bloom, and 3 = very abundant bloom. In Mukkula beach, Enonselkä basin, the recorded cyanobacterial intensities since 1998 have mainly represented the level 1 (some cyanobacteria) with some cyanobacteria observed (Figure 23). In Kalmari, Kajaanselkä basin, in turn, the recorded intensities have been higher despite the generally lower proportion of cyanobacteria in phytoplankton biomass (Figure 8). This could perhaps be explained by the location of these public beaches and the prevailing wind direction in Finland which is southwest or between south and west caused by low pressure from the Atlantic. As the Kalmari beach is located in the northeastern part of Kajaanselkä basin and Mukkula in the eastern side of Enonselkä basin, it is likely that the prevailing winds have affected the cyanobacterial intensities at these sites.

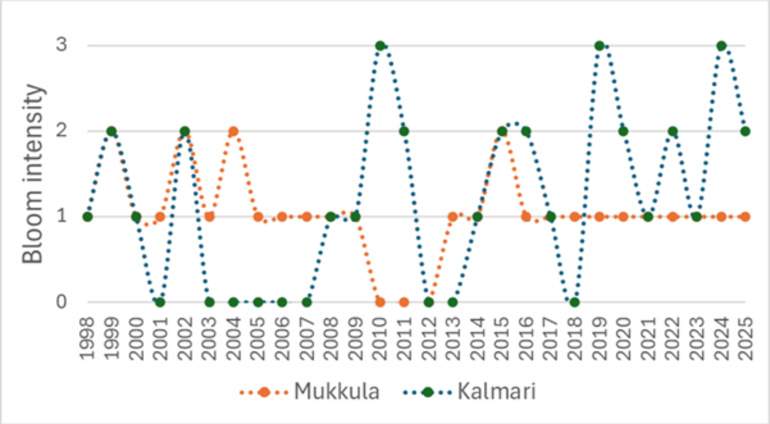

Figure 23. Annual maximum cyanobacterial bloom intensities on the public beaches of Mukkula (Enonselkä basin) and Kalmari (Kajaanselkä basin). 0 = no cyanobacteria, 1 = some cyanobacteria, 2 = abundant bloom, and 3 = very abundant bloom.

1.3.1.7 Inclusivity

After the impacts of eutrophication became visible in L. Vesijärvi during the 1960, the City of Lahti decided to take serious actions to restore the lost recreational amenities of the lake. The development of the City of Lahti as the strongest expert and implementer in lake basin management amongst the Finnish municipalities began in 1971, when Finland's first municipal environmental protection committee was established in Lahti. The committee prepared the city's environmental protection programme, the core of which was the protection of L. Vesijärvi. Due to the committee’s proposal, a first municipal limnologist position in Finland was also established in the City of Lahti in 1975.

Since then, the city has been pioneering lake management and taking care of environmental issues for decades. In 2007, L. Vesijärvi restoration programme was revolutionized as a dedicated Lake Vesijärvi

Foundation for the protection and restoration of the lake was established by the three municipalities (Lahti, Asikkala, Hollola), and three private sector bodies (Kemppi Ltd, a society of industrial enterprises in Lahti and the press company Esan kirjapaino) to coordinate the management of L. Vesijärvi (Szulecka 2025).

The Lake Vesijärvi Foundation with its administrative bodies actively collaborate with various stakeholders such as municipalities, consultants and water area owners to promote the protection and restoration of the lake. A regularly meeting academic expert group consisting of researchers from universities and research organisations has been established by the Foundation to share expertise and recent results from the lake to map future lake protection and restoration needs and to support their planning. Additionally, the regional Centre for Economic Development, Transport and the Environment also regularly organises working group meetings with representatives of stakeholders related to the implementation of the WFD. Overall, c. 100 concrete actions to enhance public knowledge and understanding on the lake status, pressures and restoration needs, and to promote restoration are taken by the Foundation annually. These are arranged, for instance, in the form of educational campaigns for high school kids, communicational Vesijärvi week each summer, and voluntary events for e.g., harvesting invasive macrophyte species and repairing fishing gear. The local media have also been active in supporting the Foundation for generating public discussions and increasing the general understanding of L. Vesijärvi (Szulecka 2025).

Since 1970s, a total of c. 100 stakeholder organisations, including university researchers, governmental, regional authorities, and municipal authorities, non-profit and non-governmental organizations, private companies, consultants, land owners, farmers, water area owners, fishery owners, fishing communities, local media, artists from different fields, and general public have participated in improving the ecological status of the lake (Szulecka 2025).

Engagement with stakeholders has been stressed as a pivotal factor for the success of restoration projects (Poikane et al. 2024). Indeed, the wide participation, cooperation and engagement of local people, stakeholders and authorities were considered to secure the comprehensive management approach of L. Vesijärvi by Suoraniemi et al. (2000) already before the establishment of Lake Vesijärvi Foundation. Participatory water management practices organized by the Foundation have also increased the awareness of general public about the lake, its ecosystem, status and management targets. The Lake Vesijärvi Foundation is the only inland water management body in Finland that continuously and actively seeks new corporate sponsors and partners to expand the funding base for water management in the area. As the needs for water management increase due to climate change, and state funding decreases, the local business community must take more responsibility for the future condition of the waters. On the other hand, land and water area owners need to be made even more interested in discussing measures to reduce the external nutrient load originating from their areas and to take part in implementing restoration and management measures within the lake.

1.3.1.8 Recreation

As a result of the improvement of L. Vesijärvi water quality and reduced frequency of HABs, the recreational amenities have recovered and the recreational activities at the lake have increased substantially. Still in the 1970s and 1980s, swimming in the public beaches was occasionally banned due to HABs. Currently, there are several public beaches (Section 1.3.1.6) with water quality compliant with the EU BWD, thus allowing for swimming both during the summer and in the winter. The improved status of L. Vesijärvi was one of the reasons why the City of Lahti was able to host international triathlon events for seven years until 2023 with circa 10,000 athletes and supporting staff attending, as the swimming segment of the race was held in L. Vesijärvi.

Within the City of Lahti, there are around 180 km of outdoor routes and skiing tracks near L. Vesijärvi. During the winters, when the lake ice is thick enough, the skiing track also goes around the Enonselkä basin. Additionally, around 30 km of nature trails have been established in the shorelines of Enonselkä basin. There are four bird hides located around the lake, in addition to which several shoreline areas are suitable for observing birdlife (Kekki et al. 2018). There is also a passenger harbour in the City of Lahti facing the Enonselkä basin, around which plenty of recreational services are being centred (Section 1.3.1.10, also Section 1.3.1.12).

Additionally, the impacts of eutrophication in 1970-1980s were reported to weaken the possibilities for fishing via staining and gluing the fishing gear and by causing muddy taste to fish, which hindered the sales of fish catch (Lahden Kaupunki 2007). Since the improvement of L. Vesijärvi water quality in 1990s, the private sector, municipalities, and different fishing organisations have greatly developed fishing opportunities and fishing grounds (Kairesalo and Vakkilainen 2004) and the number of recreational fishermen at the lake has increased. For instance, in 1987, it was estimated that c. 7400 recreational fishermen operated at L. Vesijärvi, of which on estimate >90% conducted winter-time fishing on ice (Vesijärven kalastusalue 1987). In 2019, in turn, it was estimated that there are c. 9000 recreational fishermen visiting L. Vesijärvi annually, out of which 75% conduct winter-time fishing on ice (Haro 2020). Increased opportunities for fishing also create a link to blue economy (Section 1.3.1.10).

Improved status of the lake has presumably also affected the number of summer cottages at the lake. In 1987, it was estimated that there are 1,200 summer housing in the catchment area of L. Vesijärvi (Vesijärven kalastusalue 1987). In 2002-2007 during Vesijärvi project II, the estimated number of holiday apartments in L. Vesijärvi catchment area had increased to 1,300 (Lahden Kaupunki 2007). Unfortunately, no data can be obtained on the number of summer housing to date within the catchment area. In general, the total number of free-time residences in the City of Lahti, and the municipalities of Asikkala and Hollola has not remarkably changed since 2005 (https://stat.fi/tup/tilastotietokannat/index_en.html [accessed on 30 September 2025]).

1.3.1.9 Circular economy

Lake Vesijärvi restoration programme represents a pioneering link of biomanipulation to circular economy with commercial utilization of the cyprinid catches by the local food industry (Tammeorg et al. 2024). Approximately 20% of catch ends up in food production, thus providing a link to the transition to a blue bioeconomy (Section 1.3.1.10). Although cyprinids are not usually targeted in commercial and recreational fishing, they offer quality protein and fatty acids for human consumption (Taipale et al. 2022).

1.3.1.10 Blue economy

The restored recreational value of the lake has stimulated the tourist sector in the local economy, and ship and boat traffic has proliferated (Kairesalo and Vakkilainen 2004). Due to the lake’s recovery, building activity, as well as the value of land around the lake, have risen with an estimated value of M€0.3/m2 for the built-up lakeside districts in Lahti (Kairesalo and Vakkilainen 2004). The improvement of the water quality has estimated to affect the economic profit/value of not only those estates directly on L. Vesijärvi shorelines but also of those that are not situated directly on the lakeside (Kairesalo and Vakkilainen 2004). The City of Lahti has built a new harbour. Also, a concert and congress centre, the Sibelius Hall, was established in 2000 on the lakeshore in a former pulp mill. In the Sibelius Hall, various events from concerts, private parties to symposiums, are being organised with the global LahtiLakes-symposium for lake restoration amongst them. Lahti harbour is especially lively during the summer months with several cafés, restaurants, and shops centred near the harbour (Figure 24).

Figure 24. Sunset at L. Vesijärvi harbour during June 2025. © Laura Härkönen

Both recreational and commercial fishermen have also benefited from the improvement of L. Vesijärvi water quality and from the ongoing restoration programme. In 2019, it was estimated in a survey-based thesis that there are c. 9000 recreational fishermen visiting L. Vesijärvi annually, out of which 75% conduct winter-time fishing on ice (Haro 2020). Furthermore, it was estimated that recreational fishing at L. Vesijärvi can generate up to M€4.6/a for the Lahti region in the form of purchasing boats and fishing equipment locally (Haro 2020). Commercial biomanipulation (see also Section 1.3.1.9) provides additional income for the professional fishermen who provide part of the cold-water season catch for food industry. For instance, in 2024, 26% (18,000 kg) of the annual catch of cyprinids was delivered to further processing to e.g., canned roach, which is currently the most important end product of commercial biomanipulation (Lahden Kaupunki 2025). Additionally, catch is being offered to anyone interested, free of charge, and is being utilised by households for e.g., food, feed and as carrion. The rest of the catch is being utilised in biogas production.

The framework for commercial biomanipulation in L. Vesijärvi dates back to 2012 and “Järvi Hoi”-project, since when the circular use of catch has been promoted. Since 2014, the City of Lahti has maintained an emailing list open to the general public to communicate about available catch during the days of biomanipulation. In 2024, distinct facilities were established near one of L. Vesijärvi marinas for the professional fishermen who sort their catch in cold rooms securing the fresh processing.

1.3.1.11 Sustainable Agriculture

The reductions in the agricultural area, total number of livestock and changes towards more sustainable agricultural practices are expected to be the main reasons for the decreased external TP and TN loading to Lake Vesijärvi (see Section 1.3.1.3). Agriculture currently comprises 18% of the catchment land use and is the main external nutrient source to the lake generating 42% and 37 % of TP and TN loading according to the WSFS-Vemala model. The proper agricultural areas with the highest expected specific loading, i.e. non-wooded fields/pastures and fruit tree/berry plantations, have decreased by 9.8% in 2000-2018 according to Corine land cover classification (Figure 25), and by a further ~3.6% reduction in 2018-2024 based on municipal statistics. Most of the decommissioned agricultural area is slowly changing to forests and semi-natural areas with lower specific loading.

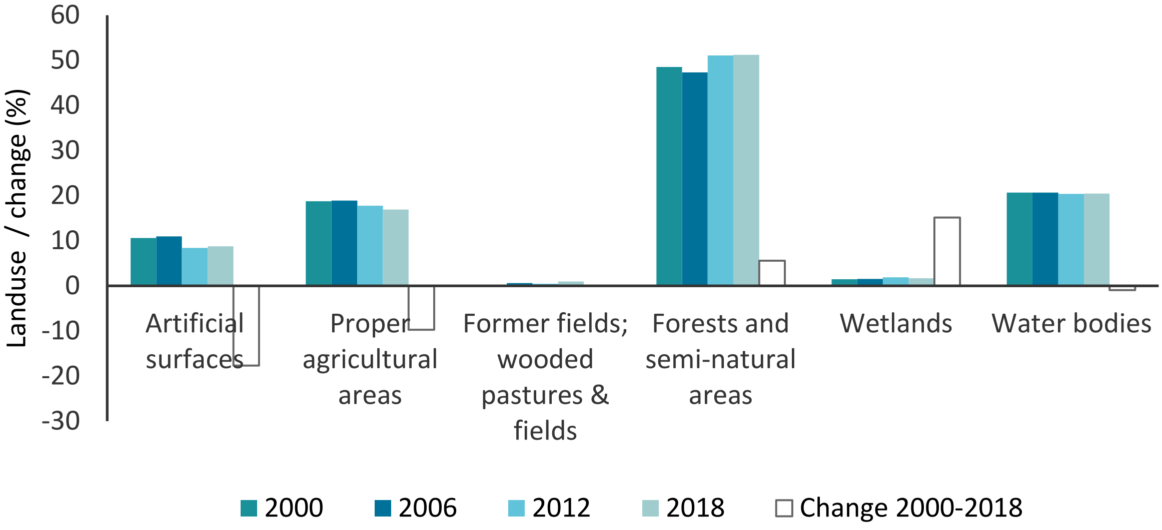

Figure 25. Changes in catchment land use between 2000 and 2018 based on Corine classification. Data from Finnish Environment Institute, Natural Resourses Institute Finland, Finnish Food Authority, LIVI, DVV, EU, MML Maastotietokanta 01/2017).

The numbers of cattle and pigs have decreased by 46% and 41%, respectively, while the number of poultry has practically decreased close to 0 in 2000-2024 according to regional and sub-regional statistics (Figure 26). Only the number of sheep has increased by 57% in 2000-2024. Although the regional statistics cover a region substantially larger than the catchment, they are expected to be roughly representative of the catchment. Considering 1975-2000, the total number of cattle likely substantially decreased in the catchment (43% decrease nationally) while the number of pigs (25% increase nationally) and poultry (no statistics available before 1995) likely increased.

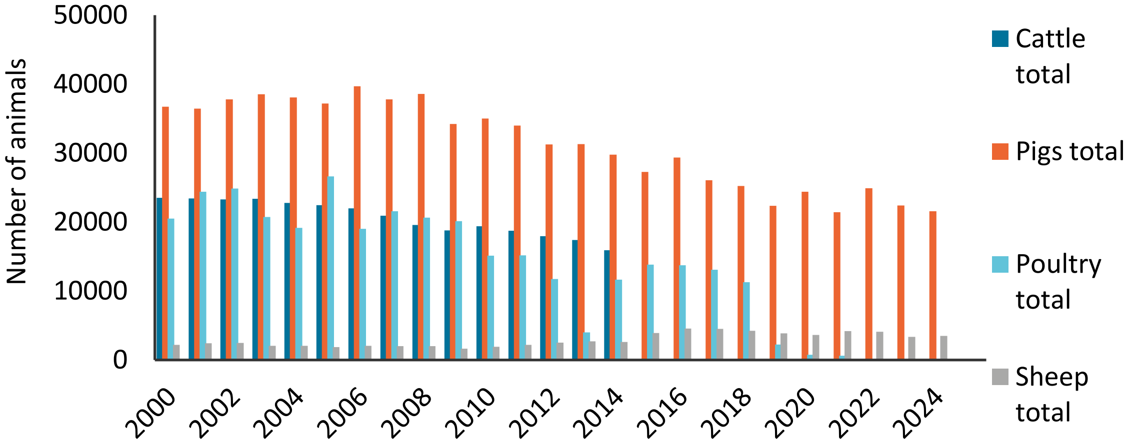

Figure 26. Regional changes in number of livestock. Statistics from Natural Resources Institute Finland.

The agricultural practices have also changed to a direction expected to result in decreases in nitrogen, phosphorus and pesticide loads. Applied fertilizers per hectare farmland have decreased by 26% for N and 74% for P in 1992-2022, and pesticide usage by 21% in 2013-2018 nationally (Figure 27). Thus, the regional N and P balances in farmland soil have systematically decreased: N balance decreased from 86% in 1990 to ~30% in 2020s while P balance decreased from 27% in 1990 to an average of 0 since 2009. The winter-time bare soil has decreased from 19 to 11% and ploughing from 50% to 32% in 2010-

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2023 regionally, which are expected to decrease erosion and thus the leaching of particularly particulate P.

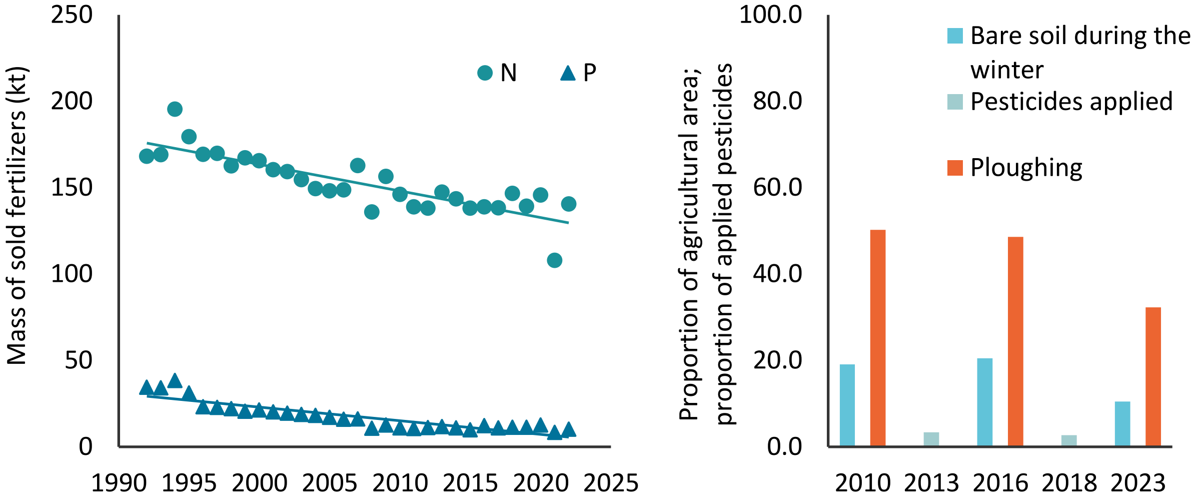

Figure 27. Masses of nitrogen (N) and phosphorus (P) fertilizers sold to farms (national figures), and the proportion of fields with environmentally harmful agricultural practices (bare soil during the winter, ploughing; regional figures) and of applied pesticides (national figures; only available for the years 2013 and 2018). Statistics from Natural Resources Institute Finland.

1.3.1.12 Sustainable Transport

The Vesijärvi harbour locates in the City of Lahti, at the southern shore of Enonselkä basin, and it was first established in the late 1800s. The Vääksy canal in between L. Vesijärvi and L. Päijänne (in the lake outlet in the north, See Figure 1) was constructed in R. Vääksynjoki, and was opened in 1871 (Pekkarinen 2010). A couple of years earlier, a railway station had been established in the City of Lahti right near the harbour (Pekkarinen 2010). Since the opening of Vääksy canal, L. Vesijärvi was frequently used for navigation. A steamboat operated between these two lakes during the 20th century and the shipping was at its busiest in the 1920s (Pekkarinen 2010). While the road traffic in Finland and Lahti region started to increase in 1930s, the shipping in L. Vesijärvi started to slowly decrease. However, the freight traffic in Vääksy canal remained substantial and the shipping lane passing through L. Vesijärvi from the City of Lahti to Vääksy was in frequent use still in late 1980s when six passenger ships operated regularly on the lake (Vesijärven kalastusalue 1987). The transportation of lumber and agricultural products by barges was active all the way until 1986, when the operation of a sawmill in the City of Lahti was finally terminated (Pekkarinen 2010; Vesijärven kalastusalue 1987).

The current Lahti railway station further away from the harbour was established in 1935 to better serve the increased population within the Lahti region. The old railway station at the harbour was in use until the 1960s. Today, the old station serves as a café and the boating traffic in L. Vesijärvi mainly consists of recreational boating during the summer months (Pekkarinen 2010). In addition to Vesijärvi harbour, there are where five marinas around L. Vesijärvi and several smaller marinas for rowing boats.

1.3.1.13 Sustainable Energy

The energy company of the City of Lahti (Lahti Energia Ltd) has an environmental permit to use L. Vesijärvi water as a cooling and condensing liquid for the Kymijärvi power plants. The permit also sets requirements for additional monitoring (water temperature, fish, Chl a).

The volume of water taken from the Enonselkä basin is substantial (Figure 28, Table 3), and it is directed back to L. Vesijärvi via the River Joutjoki. It has been estimated that the annual heat content of the returning liquid could increase the water temperature at Enonselkä basin 0.2-1.8 ˚C (Table 3 (KVVY Tutkimus Oy 2025)). In 2024, a total of ca. 15.3 Mm3 of cooling and process water was taken from L. Vesijärvi, and 15.2 Mm3 of cooling liquid was directed via R. Joutjoki back to L. Vesijärvi. According to the environmental permit of Kymijärvi power plants, the maximum flow of R. Joutjoki can be 3.5 m3/s. In 2024, maximum discharge was 1.41 m3/s and the mean discharge 0.48 m3/s (KVVY Tutkimus Oy 2025). The heat load in 2024 was highest in May-July (Figure 28).

The heat load and volume of cooling liquid have clearly decreased from 2010 as a result of shutdown of Kymijärvi-I steam boiler in 2019 and the introduction of Kymijärvi-III bio heating plant (Table 3) (KVVY Tutkimus Oy 2025). Cooling waters of Kymijärvi power plants keep the mouth of R. Joutjoki open in the Niemi city district, which attracts overwintering waterfowl.

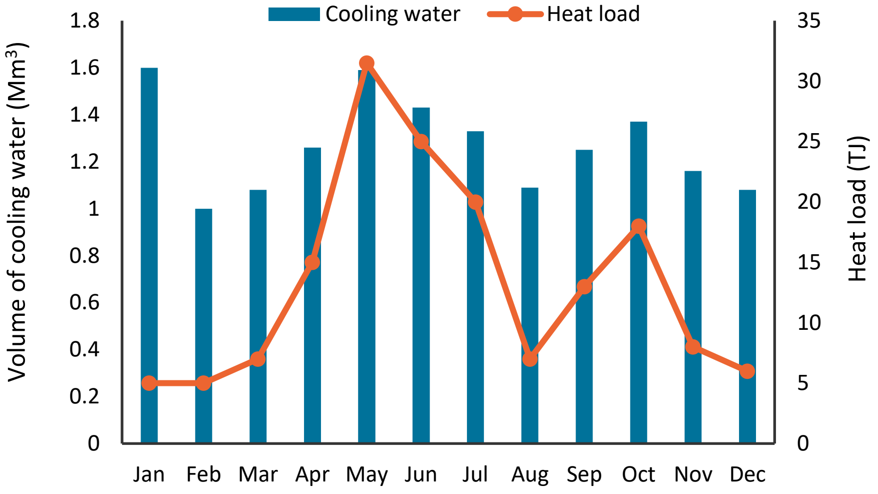

Figure 28. Monthly volume and heat load of cooling water directed to River Joutjoki from Kymijärvi power plants in January-December 2024. Modified from: KVVY Tutkimus Oy (2025).

Table 3. Volume of cooling liquid from the Kymijärvi power plants to L. Lake Vesijärvi in 2010-2024, and estimated heat load transferred to the lake if happened at once. Source: KVVY Tutkimus Oy (2025).

Year	Volume of cooling liquid million m^3	Energy conducted to Vesijärvi TJ	Increase of temperature in Enonselkä basin ˚C	Increase of temperature in L. Vesijärvi ˚C
2010	61.0	1071	1.5	0.4
2011	59.0	1246	1.7	0.4
2012	47.4	911	1.2	0.3
2013	76.0	1293	1.8	0.5
2014	74.6	878	1.2	0.3
2015	80.0	600	0.8	0.2
2016	63.0	519	0.7	0.2
2017	55.0	278	0.4	0.1
2018	60.0	807	1.1	0.3
2019	31.0	249	0.3	<0.1
2020	15.3	121	0.2	<0.1
2021	17.1	225	0.3	<0.1
2022	17.3	278	0.3	<0.1
2023	15.5	136	0.2	<0.1
2024	15.2	159	0.2	<0.1

1.3.1.14 Sustainable Tourism

The City of Lahti and the province of Päijät-Häme have long profiled themselves as trendsetters in sustainable development. The City of Lahti was the European Green Capital in 2021 and aims for nature positivity by 2030. In 2021, the Lahti region was also nominated in the category of best responsible destinations by European Best Destinations travel website (https://www.europeanbestdestinations.com/destinations/lahti/ [accessed on 15 Oct 2025]), as the region attracts tourists to outdoor activities such as cycling, skiing, swimming and hiking. Visit Lahti (Lahti Region Ltd), which is the key regional tourism organisation, is committed to the Sustainable Travel Finland programme (https://www.visitfinland.fi/en/liiketoiminnan-kehittaminen/vastuullinen-matkailu/sustainable-travel-finland [accessed on 14 Oct 2025]) to develop the sustainability of the tourism industry and encouraging businesses in the region to obtain sustainable tourism certificates. Subsequently, there are several accommodation and experience services within L. Vesijärvi region that are labeled with a national Sustainable Tourism Finland certificate which is awarded to companies and destinations that meet the criteria of sustainable tourism. In addition, the Salpauselkä UNESCO Global Geopark, which operates in the six municipalities of Päijät-Häme (with Lahti, Hollola and Asikkala amongst them), has played a significant role in the development of sustainable tourism in the region. The European Capital of Smart Tourism competition recognizes European cities for sustainable tourism practices. Lahti has demonstrated a strong commitment to sustainable tourism development – the goal is to achieve the Sustainable Travel Finland Destination status by 2025.

1.3.1.15 Water supply & sanitation

1.3.1.15.1 Water supply

L. Vesijärvi is a seepage lake that is located in between one of the largest areas of groundwater in Finland, the Salpausselkä Ridges. Accordingly, there are several groundwater areas in the catchment area of L. Vesijärvi. The water of L. Vesijärvi is partly infiltrated from the shoreline areas thus forming groundwater. However, the lake water itself is not directly used for water supply.

According to the latest assessment in 2019, both the quantitative and qualitative status of these groundwater areas was good. There are seven water intakes located at the groundwater areas near L. Vesijärvi, which have valid environmental permits. Based on authorization orders, these intakes could theoretically abstract on average 2.8 Mm3/d of groundwater. In between 2015-2024, the reported groundwater abstraction has been on average 1.0 Mm3/d with some of the intakes having zero abstraction.

1.3.1.15.2 Sanitation

In 2003-2006 during Vesijärvi Project II, there were 4,614 households that were not connected to the sewage (Lahden Kaupunki 2007). The estimated number of households that are not connected to the sewage in the City of Lahti within L. Vesijärvi catchment area to date is just a few and if they are found, they are obliged to connect to the sewage by the authorities (J. Järveläinen, pers. comm 13 Feb 2025). The whole area of the City of Lahti that is located within L. Vesijärvi catchment area currently belongs to the water supply area and is thus connected to the sewage following the national Act on Water Services (119/2001). The Act obliges that, at a reasonable cost, enough sanitary and impeccable domestic water, as well as appropriate sanitation must be secured in terms of health and environmental protection.

However, the water supply's operating area covers smaller districts in the municipalities of Hollola and Asikkala (Figure 29), in which the number of households not connected to the sewage is higher. The estimated number of households outside the sewage in Asikkala to date is c. 1,700 and has presumably increased since the Vesijärvi Project II that ended in 2006 as the water supply area only covers a limited area near the L. Vesijärvi outlet in Vääksy canal and the construction of holiday housing has increased (A. Jäntti pers. comm on 7 Oct 2025).

Unfortunately, no estimation could be obtained from the municipality of Hollola. However, the sewage network has expanded during the 2000s and it can be estimated that most of the properties within the neighbourhood areas of L. Vesijärvi (Figure 29) are connected to the sewage (R. Johansson pers. comm. on 7 Oct 2025). Nevertheless, a vast majority of the catchment area is sparsely populated and outside the operational areas of water supply. Consequently, the number of households not connected to the sewage is likely close to that reported by Lahden Kaupunki (2007), and the importance of providing advice and education about the proper treatment of wastewaters in areas of sparse settlement remains severe.

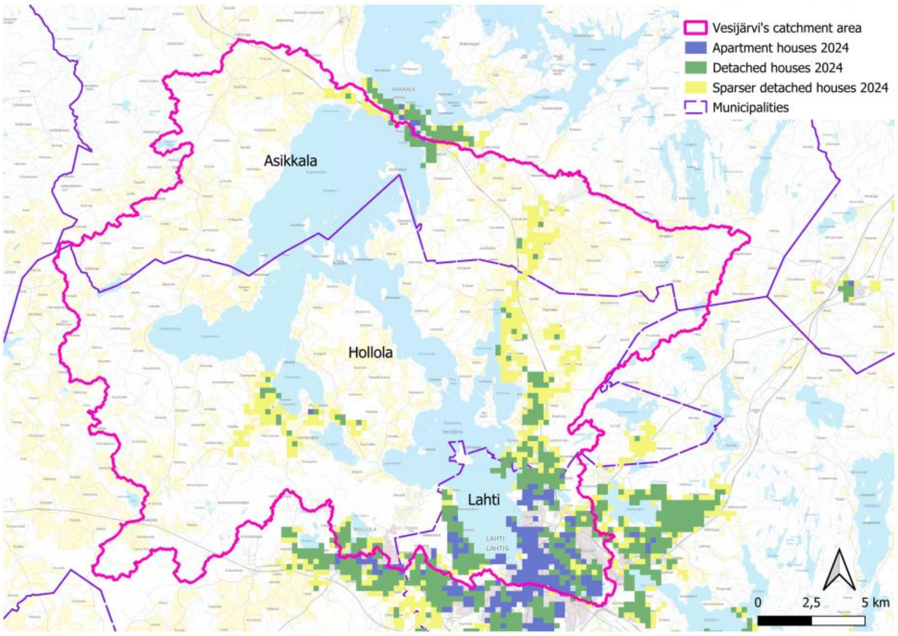

Figure 29. The neighbourhoods of the City of Lahti and the municipalities of Asikkala and Hollola in L. Vesijärvi catchment area during 2024. These areas are mostly within the water supply areas and are presumably connected to the sewage.

1.4 Unexpected results across criteria, synergies and trade-offs

Increased recreational use, disturbance by boating and construction of shorelines were estimated to hamper the breeding success of vegetation-dependent fish such as bream in the densely populated shoreline areas already in late 1980s when the water quality of L. Vesijärvi started to improve (Vesijärven kalastusalue 1987). Similarly, these factors have limited the occurrence of such macrophyte species that depend on sandy bottoms that are increasingly being harnessed to recreational activities (Section 1.3.1.2.3). Increased harvesting of macrophytes and the reduced eutrophication and subsequent implications for the abundance of common reed have estimated to negatively affect some of the locally breeding waterfowl populations (Lammi and Kolunen 2010), while it must be noted that the declining trend in L. Vesijärvi waterfowl populations is well in line with their national plight (Section 1.3.1.2.1).

Contradictory to initial expectations, the concentrations of nutrients were not affected by hypolimnetic aeration despite the disappearance of anoxia in deep water (Salmi et al. 2014; Salonen et al. 2023). While the complete loss of oxygen in the hypolimnion was prevented, at the same time the temperature and turbulence within the hypolimnion increased (Niemistö et al. 2016) with consequent negative implications for organic matter mineralisation, P recycling, cold-stenothermic fish, zooplankton, eutrophy-indicative macroinvertebrates, and GHG emissions (e.g., Niemistö et al. 2016; Ruuhijärvi et al. 2020; Salonen et al. 2023; Tolonen and Hynynen 2012; Zhang 2014).

1.5 Summary of effectiveness of restoration programme

As stated by the EEA (2024), L. Vesijärvi can be considered as a European flagship example of successful restoration of a eutrophied lake. Establishment of wastewater treatment plant and the sewage diversion 1976 first initiated the gradual recovery of L. Vesijärvi from nutrient loading. Since then, multiple measures have been taken on both the catchment area and within the lake to reduce the internal loading and improve the condition of habitats. While aeration did not result in anticipated reductions in nutrient concentrations (Salmi et al. 2014; Salonen et al. 2023), the large-scale, consistent biomanipulation since 1989-1993 has led to remarkable reductions in both P concentrations and HABs (e.g., Horppila et al. 1998; Salonen et al. 2020; Salonen et al. 2023). Additionally, the introduction of predatory pikeperch has successfully restored its naturally reproducing population (Ruuhijärvi et al. 2005), which is secured by fishing restrictions that are set to prohibit catching individuals <50 cm in total length. Implementation of extensive water protection measures and changes in agricultural practices have managed to reduce the diffuse external loading to the lake.

Despite these improvements, however, it is evident that the recovery of L. Vesijärvi is still in progress. Although the water quality in Enonselkä basin has improved considerably since 1976, the surface sediment enrichment of P is still far in excess of the pre-industrial background (Jilbert et al. 2020). It has been estimated that, despite ongoing restoration actions, the magnitude of internal P flux in L. Vesijärvi from deeper reactive sediment layers is similar to that of external P loading to the lake (Jilbert et al. 2020). Consequently, the combined incoming fluxes of P are likely to retard the complete recovery of L. Vesijärvi from eutrophication still by decades (Jilbert et al. 2020), which is essential to recognise in the changing climate.

With the expansion of residential areas, and increase in road traffic (Kuoppamäki et al. 2014) the stormwater management in L. Vesijärvi becomes more and more central in addition to the management of diffuse pollution originating from agriculture and forestry. In this context, it is crucial to apply such catchment water management, cropping and forest management strategies that prevent pollutants from entering the water cycle while at the same time providing multiple co-benefits for several policy goals (Härkönen et al. 2025). Additionally, continued establishment of effective NbS, such as constructed wetlands and two-stage channels, are needed to improve water and nutrient retention within the catchment areas. However, their efficacy is likely hampered by climate change and increased runoff outside the growing season when the vegetation provides less protection against erosion and biological processes of the water protection structures are weaker. The external P and N loads are projected to increase by 15-20% and 14-15%, respectively, to the different sub-basins of L. Vesijärvi in the next 30-y period compared to the last 10-y period according to the WSFS-Vemala simulations with the RCP4.5A climate scenario. In fact, slightly increasing annual TP and TN loads can already be seen during the recent years (Figure 20) while the annual air temperatures and precipitation during the summer months have increased and the snow cover during late autumn has decreased within the Lahti region during the last ~30 years (Figure 30).

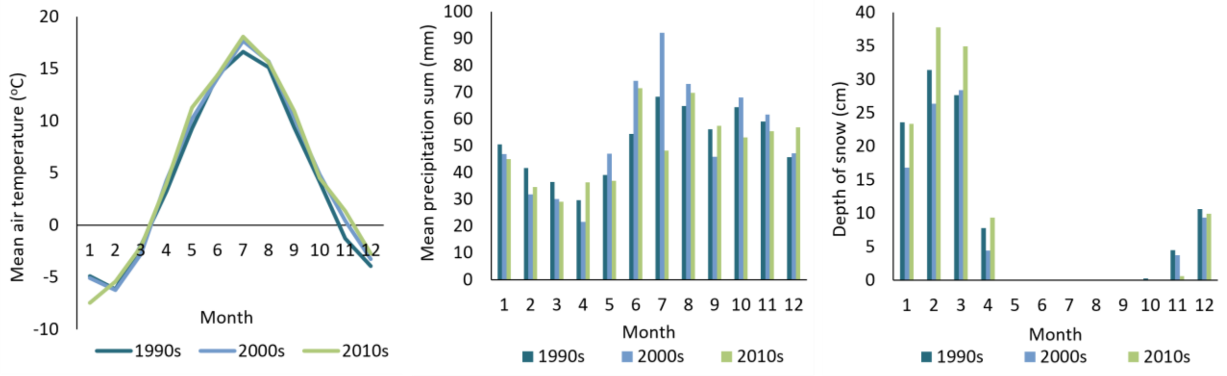

Figure 30. Mean monthly air temperature, precipitation sum and depth of snow in Lahti region (Lahti Laune monitoring station) in 1990-2024. Contains data from the Finnish Meteorological Institute, Licence CC BY 4.0.

Another visible impact of climate change is the shortening of L. Vesijärvi ice-cover period since the beginning of monitoring in early 1900s (Figure 31). In general, the lake has been ice-covered from December to early May, but there has been high variation in the number of days between ice-on and ice-out especially during the last couple of decades when the shortest ice-cover periods have been recorded. For instance, during the winter of 2019–2020, the number of ice-covered days was only 61 as the permanent ice-cover over the whole horizon was not recorded until 23 January 2020 and disappearance from the entire horizon already on 24 March 2020. In contrast, the duration of ice-cover period 100 years before in 1919–1920 was 169 d with the ice-on recorded on 11 November 1919 and ice-out on 28 April 1920, respectively. Similarly, the epilimnetic water temperature during the growing season (June-September) has increased during the monitoring period since the 1960s (Figure 32).

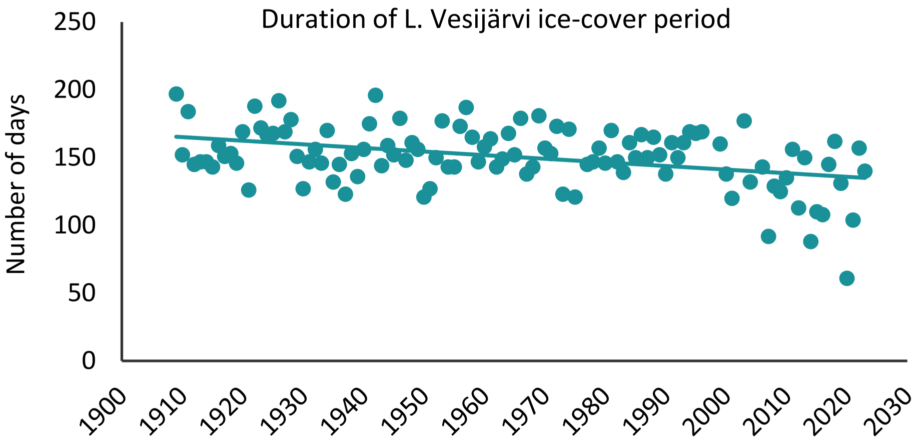

Figure 31. The duration of ice-cover period in L. Vesijärvi Enonselkä basin since the beginning of the 20th century expressed as days between the formation and disappearance of permanent ice cover in the horizon.

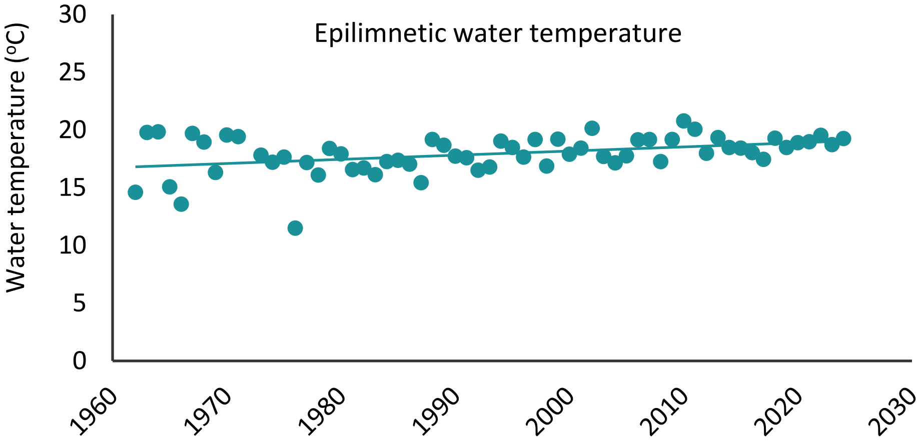

Figure 32. Mean epilimnetic (0-4 m) water temperature during the growing season (June-September) in L. Vesijärvi since the beginning of 1960s.

Despite the overall reduced nutrient concentrations in L. Vesijärvi, the climate change-induced increasing water temperatures may increase the risk for the proliferation of HABs, as cyanobacteria may thrive also in oligotrophic freshwater systems under favourable temperature conditions (Reinl et al. 2021). In contrast, the shortening ice-cover period may benefit under-ice oxygen conditions in L. Vesijärvi due to prolonged ventilation in fall and shortening of the oxygen drawdown period in winter similar to what has been observed in large northern hemisphere lakes (Jansen et al. 2025). However, changes in ice-cover period and the thickness of ice have already impacted the feasibility of winter-time fishing (Ruuhijärvi et al. 2023) and earlier ice-off in spring may lead to steepening thermal stratification and increase the associated hypoxia. The adverse, uncertain implications of climate change for L. Vesijärvi must be considered when setting future environmental targets for the management of the lake. It is also important to inform both the general public and the funding organisations how climate change influences – and likely prolongs – the recovery of L. Vesijärvi, while at the same time demonstrate that without management actions the status and the recovery of the lake would be worse.

Lake restoration with durable outcomes requires the re-establishment of in-lake processes improving and stabilizing water quality and ecological diversity (e.g., Moss 1990). Due to the resistance of lake ecosystems to disturbance, eutrophication often takes decades before the symptoms come apparent. Similarly, restoration of a eutrophied lake can be considered as a disturbance to the prevailing conditions, due to which a re-oligotrophication is expected to take at least as much time. Despite the expected delays in L. Vesijärvi recovery from past loading, the gradual positive response trajectories in water quality, phytoplankton communities and the structure of food web since the diversion of wastewaters in late 1970s due to management of diffuse external loading and biomanipulation predict that L. Vesijärvi is slowly on its way to re-oligotrophication. However, a positive development trajectory requires managing the external loading within tolerable boundaries. Additional measures to tackle the long-lasting internal loading are still to be determined to provide L. Vesijärvi with the needed nudge towards its full recovery. Additionally, the possible occasional N-limitation must be taken into account when considering future restoration efforts.

All in all, the combined management approach with multiple measures on external and internal scales have substantially benefited L. Vesijärvi. Sustainability of this comprehensive lake basin management strategy is secured by the coordination of Lake Vesijärvi Foundation, with its wide inclusion of stakeholders from researchers to practitioners, environmental authorities, private companies, and general public to the planning and implementation of restoration and water protection measures. As concluded by the EEA (2024), the example of L. Vesijärvi showcases the four key pillars for successful lake restoration (WWQA 2023) including a good scientific understanding of the causes of lake deterioration and effectiveness of restoration measures; effective policy and governance for lake management; public-private finance partnerships to sustain lake monitoring and management programs over decades; and widespread local awareness of the social and economic benefits of restoration.

1.6 Acknowledgements

In memory of Ismo Malin, whose contributions to the protection and restoration of Lake Vesijärvi remain deeply valued.

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b) Kartuzy Lakes

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1.1 Lake details

Table b.1. Mielenko Lake basic data

Lake name: Mielenko Lake		
Type of characteristics	**Characteristics**	**Value**
Geographical characteristics	Geographical coordinators:	
	Longitude	E: 18°10’54.25’’
	Latitude	N: 54°19’55.26’’
	Altitude (m a.s.l.)	203.7
Lake characteristics	Area [km^2]	0.078
	Maximum depth [m]	1.9
	Mean depth [m]	1.3
	Water volume [m^3]	102.9 x 10^3
	Depth index (mean depth to maximum depth ratio)	0.68
	Water residence time (τ) [years] Residence type (short < 1 year, moderate >1 year, long > 10 years)	0.43 year short
	Shoreline development index	1.3

	$K = \frac{shoreline\ lenght}{2\sqrt{\pi}\ \cdot lake\ area}$	
	Mixing type Bradimictic – short spring and autumn mixing, long stratification, thin epilimnion, steep and thin thermocline Tachymictic – long spring and autumn mixing, shorter stratification, thick epilimnion, not steep thermocline Eumictic – between tachy- and bradymixis Polymictic – shallow, all season mixing except ice cover presence period Meromictic	polymictic
	Stratification	non-stratified
Catchment characteristics	Total catchment area [km^2]	3.82
	Direct catchment area [km^2]	0.221
	Land-use (CORINE)	**% of total catchment area**
	Agriculture (meadows)	35 %
	Urban (112 – loose built-up)	Excluded (because of the presence of storm sewerage)
	Forests (313 mixed forest)	65%
	Wetlands	
	Water bodies	
	Schindler's index (sum of total catchment and lake areas to lake volume ratio)	37.9
Climate characteristics (30 year average; 1991-2020)	Mean annual air temperature Mean annual precipitation Maximum summer air temperature Days number > 15°C air temperature per year Days with snow per year	8.5 °C 661.7 mm 31.4 °C 23 days 38.5 days
Hydrochemistry and trophic type (situation in 2025)	Alkalinity (meq/L), Alkalinity type (low - <0.2, medium 0.2-1.0, high - > 1.0)	high
	Colour type (colour in HAZEN units – clear < 30, humic 30-90, polyhumic >90)	humic
	Trophic type (oligotrophic, mesotrophic, eutrophic, hypertrophic)	eutrophic
	Calcium level (water hardness – softwater <25 mg Ca/L, hardwater ->25 mg Ca/L	hardwater

Table b.2. Karczemne Lake basic data

Lake name: Karczemne Lake

Type of characteristics	**Characteristics**	**Value**
Geographical characteristics	Geographical coordinators: Longitude Latitude Altitude (m a.s.l.)	E: 18°11’26.35’’ N: 54°19’42.23’’ 203.2
Lake characteristics	Area [km^2]	0.404
	Maximum depth [m]	3.2
	Mean depth [m]	1.97
	Water volume [m]	798.3 x 10^3
	Depth index (mean depth to maximum depth ratio)	0.62
	Water residence time (τ) [years] Residence type (short < 1 year, moderate >1 year, long > 10 years)	1.69 moderate
	Shoreline development index $K = \frac{shoreline\ lenght}{2\sqrt{\pi}\ \cdot lake\ area}$	1.4
	Mixing type Bradimictic – short spring and autumn mixing, long stratification, thin epilimnion, steep and thin thermocline Tachymictic – long spring and autumn mixing, shorter stratification, thick epilimnion, not steep thermocline Eumictic – between tachy- and bradymixis Polymictic – shallow, all season mixing except ice cover presence period Meromictic	polymictic
	Stratification	non-stratified
Catchment characteristics	Total catchment area [km^2]	5.15
	Direct catchment area [km^2]	0.449
	Land-use (CORINE)	**% of direct catchment area**
	Agriculture	
	Urban	Excluded (because of the presence of storm sewerage)

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	Forests	44.9
	Barren lands	21.0
	Water bodies	
	Schindler's index (sum of total catchment and lake areas to lake volume ratio)	7.00
Climate characteristics (30 year average; 1991-2020)	Mean annual air temperature Mean annual precipitation Maximum summer air temperature Days number > 15°C air temperature per year Days with snow per year	8.5 °C 661.7 mm 31.4 °C 23 days 38.5 days
Hydrochemistry and trophic type (situation in 2025)	Alkalinity (meq/L), Alkalinity type (low - <0.2, medium 0.2-1.0, high - > 1.0)	high
	Colour type (colour in HAZEN units – clear < 30, humic 30-90, polyhumic >90)	humic
	Trophic type (oligotrophic, mesotrophic, eutrophic, hypertrophic)	hypertrophic
	Calcium level (water hardness – softwater <25 mg Ca/L, hardwater ->25 mg Ca/L	hardwater

Table b.3. Klasztorne Małe Lake Basic data

Lake name: Klasztorne Małe Lake		
Type of characteristics	**Characteristics**	**Value**
Geographical characteristics	Geographical coordinators: Longitude Latitude Altitude (m a.s.l.)	 E: 18°11'26.35'' N: 54°19'42.23'' 202.3
Lake characteristics	Area [km^2]	0.137
	Maximum depth [m]	20.0
	Mean depth [m]	8.1
	Water volume [m]	1,106.0 x 10^3
	Depth index (mean depth to maximum depth ratio)	0.40
	Water residence time (τ) [years] Residence type (short < 1 year, moderate >1 year, long > 10 years)	0,52 year short
	Shoreline development index $K = \frac{shoreline\ lenght}{2\sqrt{\pi \cdot lake\ area}}$	1.4

	Mixing type Bradimictic – short spring and autumn mixing, long stratification, thin epilimnion, steep and thin thermocline Tachymictic – long spring and autumn mixing, shorter stratification, thick epilimnion, not steep thermocline Eumictic – between tachy- and bradymixis Polymictic – shallow, all season mixing except ice cover presence period Meromictic	meromictic
	Stratification	stratified
Catchment characteristics	Total catchment area [km^2]	7.45
	Direct catchment area [km^2]	22.1
	Land-use (CORINE)	**% of direct catchment area**
	Agriculture	
	Urban	Excluded (because of presence of storm sewerage)
	Forests	100%
	Wetlands	
	Water bodies	
	Schindler's index (sum of total catchment and lake areas to lake volume ratio)	
Climate characteristics (30 year average; 1991-2020)	Mean annual air temperature Mean annual precipitation Maximum summer air temperature Days number > 15°C air temperature per year Days with snow per year	8.5 °C 661.7 mm 31.4 °C 23 days 38.5 days
Hydrochemistry and trophic type (situation in 2025)	Alkalinity (meq/L), Alkalinity type (low - <0.2, medium 0.2-1.0, high - > 1.0)	high
	Colour type (colour in HAZEN units – clear < 30, humic 30-90, polyhumic >90)	humic
	Trophic type (oligotrophic, mesotrophic, eutrophic, hypertrophic)	eutrophic
	Calcium level (water hardness – softwater <25 mg Ca/L, hardwater ->25 mg Ca/L	hardwater

Table b.4. Klasztorne Duże Lake basic data

Lake name: Klasztorne Duże Lake		
Type of characteristics	**Characteristics**	**Value**
Geographical characteristics	Geographical coordinators: Longitude Latitude Altitude (m a.s.l.)	E: 18°12’10.33’’ N: 54°20’52.36’’ 202.3
Lake characteristics	Area [km^2]	0.575
	Maximum depth [m]	8.5
	Mean depth [m]	4.8
	Water volume [m]	2780.0 x 10^3
	Depth index (mean depth to maximum depth ratio)	0.59
	Water residence time (τ) [years] Residence type (short < 1 year, moderate >1 year, long > 10 years)	1.21 moderate
	Shoreline development index $K = \frac{shoreline\ lenght}{2\sqrt{\pi}\ \cdot lake\ area}$	1.5
	Mixing type Bradimictic – short spring and autumn mixing, long stratification, thin epilimnion, steep and thin thermocline Tachymictic – long spring and autumn mixing, shorter stratification, thick epilimnion, not steep thermocline Eumictic – between tachy- and bradymixis Polymictic – shallow, all season mixing except ice cover presence period Meromictic	eumictic
	Stratification	stratified
Catchment characteristics	Total catchment area [km^2]	12.25
	Direct catchment area [km^2]	103.0
	Land-use (CORINE)	**% of direct catchment area**
	Agriculture	
	Urban	Excluded (because of the presence of storm sewerage)

	Forests	100%
	Wetlands	
	Water bodies	
	Schindler's index (sum of total catchment and lake areas to lake volume ratio)	
Climate characteristics (30 year average; 1991-2020)	Mean annual air temperature Mean annual precipitation Maximum summer air temperature Days number > 15°C air temperature per year Days with snow per year	8.5 °C 661.7 mm 31.4 °C 23 days 38.5 days
Hydrochemistry and trophic type (situation in 2025)	Alkalinity (meq/L), Alkalinity type (low - <0.2, medium 0.2-1.0, high - > 1.0)	high
	Colour type (colour in HAZEN units – clear < 30, humic 30-90, polyhumic >90)	humic
	Trophic type (oligotrophic, mesotrophic, eutrophic, hypertrophic)	eutrophic
	Calcium level (water hardness – softwater <25 mg Ca/L, hardwater ->25 mg Ca/L	hardwater

1.2 Restoration Programme

1.2.1 Description of geographical conditions of Kartuzy Lakes complex

The topographic total drainage basin of the Kartuzy Lakes group (Fig. b.1), in the closing cross-section, which represents the outflow of the Klasztorna Struga stream from Lake Klasztorne Duże, has an area of 12.25 km². The main stream of the basin, defining a distinct hydrographic axis of the area, is the Klasztorna Struga. It is a natural stream, 10.27 km long (based on records of water and land improvement facilities), whose origin is at the outlet from Lake Mielenko.

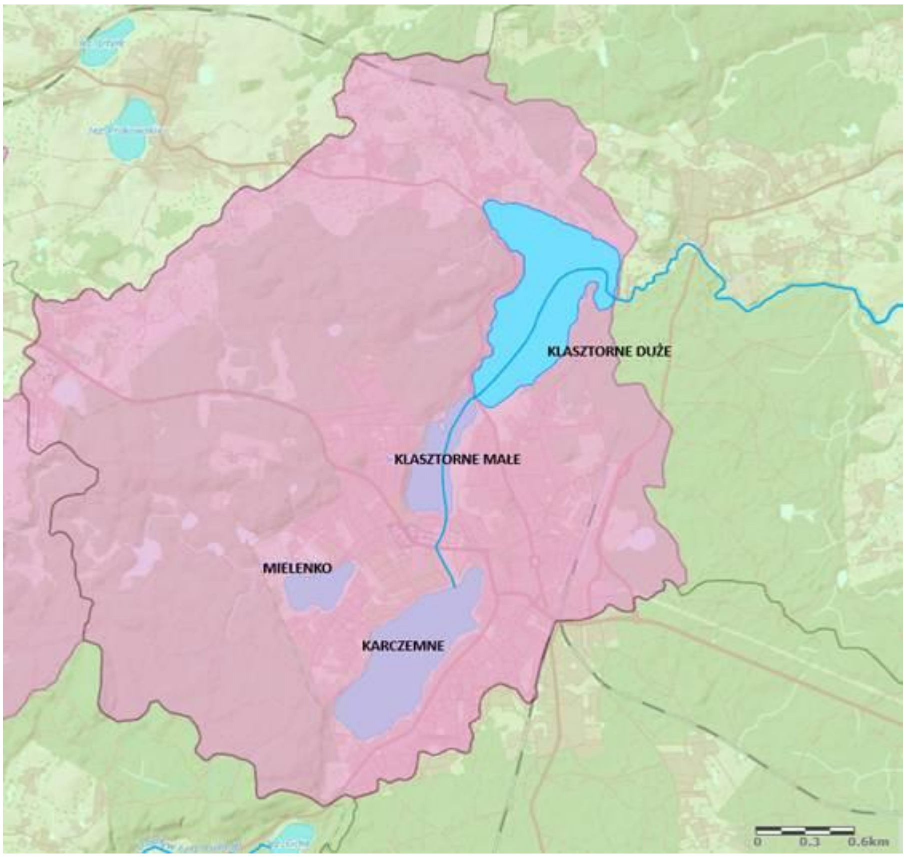

Figure b.1. The total drainage basin of the Kartuzy Lakes (Hydroportal - ISOK)

In urbanized areas, defining the direct catchment area is very difficult due to its exclusion from the surface runoff supply area and its connection to the storm sewer system. Therefore, in cities, the boundaries of lake catchments are uncertain and are essentially formed by storm sewer catchments. Furthermore, developing the areas directly supplying lakes is very difficult due to the dynamic and constant changes they undergo. This requires constant adjustments. Changes in the use of lake catchments in urban areas primarily involve the phasing out of cultivation and the conversion of arable land into urbanized areas and wasteland. When defining the direct catchment area of the Kartuzy Lakes, areas included in the storm sewer system were excluded.

The direct catchment area of Lake Mielenko has an area of 22.1 ha. Forests predominate, covering 65.1% of the area (14.4 ha). Meadows and pastures are the secondary land cover (34.9%) (Fig. 2). The direct catchment area of Lake Karczemne covers 44.9 ha. 20.7% of its area is wasteland and 79.3% is forest (Fig. b.2). The direct catchment area of Lake Klasztorne Małe has an area of 13.0 ha, and that of Lake Klasztorne Duże has an area of 103.0 ha. The areas directly supplied to these reservoirs are 100% covered by mixed forest (Fig. b.2).

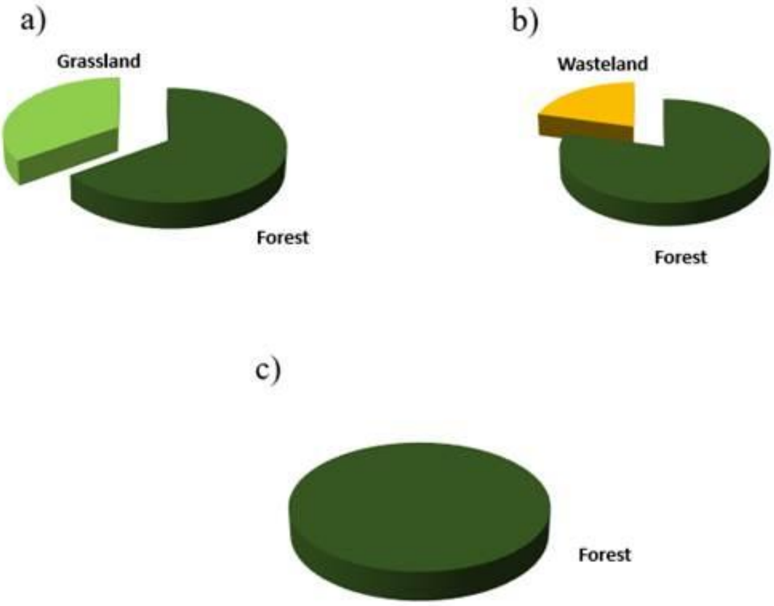

Figure b.2. Development of the direct catchments: a) Lake Mielenko, b) Lake Karczemne, c) Lakes Klasztorne Małe and Klasztorne Duże

1.2.2 History of Kartuzy Lakes pollution

In Kartuzy, the storm sewer system covered only 17% of the city's area, and most streets had no storm sewer system at all. Some rainwater and meltwater were discharged into the combined sewer system (the combined sewer system then transported them to the sewage treatment plant). Furthermore, the storm sewer system was partially connected to the sanitary network via combined sewers. The storm sewer system discharged stormwater into the Kartuzy Lakes through 23 stormwater outlets, nine of which discharged untreated. The storm sewer system that existed until 2018 was in poor condition due to advanced operation and insufficient capacity. Connecting the existing storm sewer system with the sanitary sewer system caused pollutants to enter the lakes with domestic sewage. The lack of retention and regulation reservoirs meant that during heavy rains, high concentrations of pollutants entered the lakes with the first wave of runoff. Furthermore, the lack of effective pre-treatment systems at the outlets meant that polluted rainwater and meltwater discharged into receiving bodies of water with their full load of pollutants (with the exception of 14 collectors equipped with separators, which, however, did not eliminate all pollutants). Improper water and sewage management in the city contributed to the complete degradation of the Kartuzy Lakes. A study of the catchment area and an analysis of the external load of basic nutrients in the lakes showed that in the case of Lake Mielenko, the total phosphorus load introduced during that period was 17.2 kg P year^{-1}, and nitrogen load 202.6 kg N year^{-1}, which, when converted per unit of reservoir surface area, was equal 0.22 g P m^{-2} year^{-1} and 2.60 g N m^{-2} year^{-1}. Comparing this pollutant load entering the lake with the loads calculated using Vollenweider's hydrological model (1976), it was found that the permissible load for phosphorus (0.050 g P m^{-2} year^{-1}) was more than four times higher than the permissible load and more than twice the critical load (0.100 g P m^{-2} year^{-1}), accelerating the reservoir's degradation process. The total phosphorus load entering Lake Karczemne at that time was 161.7 kg P year^{-1}, while the total nitrogen load was 1,333.9 kg N year^{-1}, or 0.400 g P m^{-2} year^{-1} and 3.302 g N m^{-2} year^{-1} when converted to the load per unit of reservoir surface area. This result indicated that the permissible load (0.030 g P m-2 year-1) was exceeded by more than 13 times and the critical load (0.060 g P m^{-2} year^{-1}), causing accelerated eutrophication. In the case of Lake Klasztorne Małe, the phosphorus load was 516.8 kg P year-1, and the nitrogen load was 1,571.5 kg N year^{-1} (3.772 g P m^{-2} year^{-1} and 11.471 g N m^{-2} year^{-1}). This indicated that the permissible load (0.267 g P m^{-2} year^{-1}) and the critical load (0.533 g P m^{-2} year^{-1}) were exceeded by 14 times and the critical load (0.533 g P m^{-2} year^{-1}) were exceeded by 7 times. Lake Klasztorne Duże received 976.7 kg of phosphorus per year, and 5,186.5 kg of nitrogen per year, which equated to 1.699 g of phosphorus per square meter (m^{2}) and 9.020 g of N per square meter (m^{2}) per year when converted to a unit of reservoir surface area. Comparing the lake's actual phosphorus load with the model-calculated loads, it was determined that the permissible phosphorus load (0.083 g of phosphorus per square meter (m^{2}) per year) was over 20 times higher than the permissible load (0.167 g of phosphorus per square meter (m^{2}) per year), and the critical load (0.167 g of phosphorus per square meter (m^{2}) per year was 10 times higher, causing rapid eutrophication. Data analysis revealed the need for protective measures in the Kartuzy Lakes catchment area to reduce pollutant emissions into the water bodies (Grochowska 2024).

Comprehensive studies of the water and bottom sediments in the Kartuzy Lakes enabled the selection of optimal restoration measures. A phosphorus inactivation method was planned for all lakes, which involves reducing the availability of this element to primary producers (primarily planktonic algae and cyanobacteria) using coagulants. This occurs by precipitating phosphorus compounds from the water column (immediately after treatment), and above all, by inhibiting the long-term release of this element from bottom sediments by increasing their sorption capacity. The coagulant introduced into the lake settles on the bottom in the form of flocs, creating a barrier that prevents the release of phosphorus from the sediments into the water. The effectiveness of the method depends on maintaining the surface layer of lake sediments relatively intact. Two types of coagulants were used for the reclamation of the Kartuzy Lakes: the iron-based PIX 111 and the aluminum-based PAX 18. The iron-based coagulant was applied to the coastal zones of the lakes, where good oxygen conditions prevailed year-round. The aluminum coagulant, insensitive to low redox potential, was used in the central zones of the lakes, so that after sedimentation, it would settle on the profundal lake sediment (Grochowska et al. 2023, Grochowska 2024)

1.2.3 Protective measures

The protection of the Kartuzy Lakes included a series of comprehensive measures involving the construction and reconstruction of the stormwater and combined sewer systems in the town of Kartuzy, the construction of three stormwater retention reservoirs and pretreatment facilities at existing stormwater outlets. Furthermore, the main pumping station for excess stormwater was modernized. Protective measures were implemented before the main restoration beginning.

The coagulant amounts determined individually for each lake were divided into four equal doses to maintain ecological safety and, furthermore, in accordance with the lake's annual cycle, ichthyofauna protection requirements, and fisheries management (Tab. b.5).

1.2.4 Restoration programme

Table. b.5. P inactivation agents' doses, which were applied on Kartuzy Lakes

	Mielenko	**Karczemne**	**Klasztorne Małe**	**Klasztorne Duże**
Aluminium coagulant PAX 18				
Total dose	9 940 kg	70 787 kg	75 356 kg	148 398 kg
Single application	2 485 kg	17 697 kg	18 839 kg	37 100 kg
Iron coagulant PIX 111				
Total dose	9 040 k	74 433 kg	28 216 kg	93 137 kg
Single application	2 260 kg	18 608 kg	7 054 kg	23 284 kg

The doses of the preparations given above were introduced into the water of the Kartuzy Lakes on the following dates: Lake Mielenko - March and November 2020 and 2021, Lake Karczemne - November 2022, April, October, and November 2023, Lake Klasztorne Małe - March and November 2021 and 2022, Lake Klasztorne Duże - March and November 2021 and 2022.

In Lake Karczemne, which has the highest degree of degradation, and sediment contains concentrations of pollutants never seen in other reservoirs, additional removal of the most polluted layer of bottom sediments was planned. 240,000 m^3 of sediment was removed from the lake. In order to maintain the effects of technical and chemical reclamation, biomanipulation was carried out in parallel, consisting of appropriate control of the ichthyofauna population – cyprinid fish were caught, and the lakes were stocked with predatory fish (pike, pikeperch, and asp).

The cost of restoration is given in the table below:

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Table b.6. Costs of Kartuzy Lakes restoration (www.kartuskiejeziora.pl)

Restoration method	Costs
Phosphorus inactivation (chemical method)	€ 327,755.6
Biomanipulation (regulatory fish catching and introduction of predatory fish: pike, pikeperch, asp)	€ 73,511.06
Sediment dredging and treatment	€ 10,941,672.80
Environmental land development - construction of recreational infrastructure - promenade along Lake Klasztorne Małe and a path along Struga Klasztorna	€ 2,326,266.06
Total	€ 13,669,205.08

- Costs for individual measures: **sediment dredging – € 278,833 per ha; P inactivation – € 2,745 per ha, biomanipulation – € 616 per ha.**
- Costs for lost earnings (euros per year) - no data available
- Estimated financial benefits of restoration – in euros per year- no data available

1.3 Evaluation of existing restoration programme

1.3.1.1 WFD

The effectiveness of the restoration measures implemented can be assessed based on changes in nutrient content, primarily phosphorus and nitrogen, as well as primary production indicators such as chlorophyll a concentration and water transparency. Extensive data was collected during environmental monitoring, conducted monthly from April 2019 to December 2023.

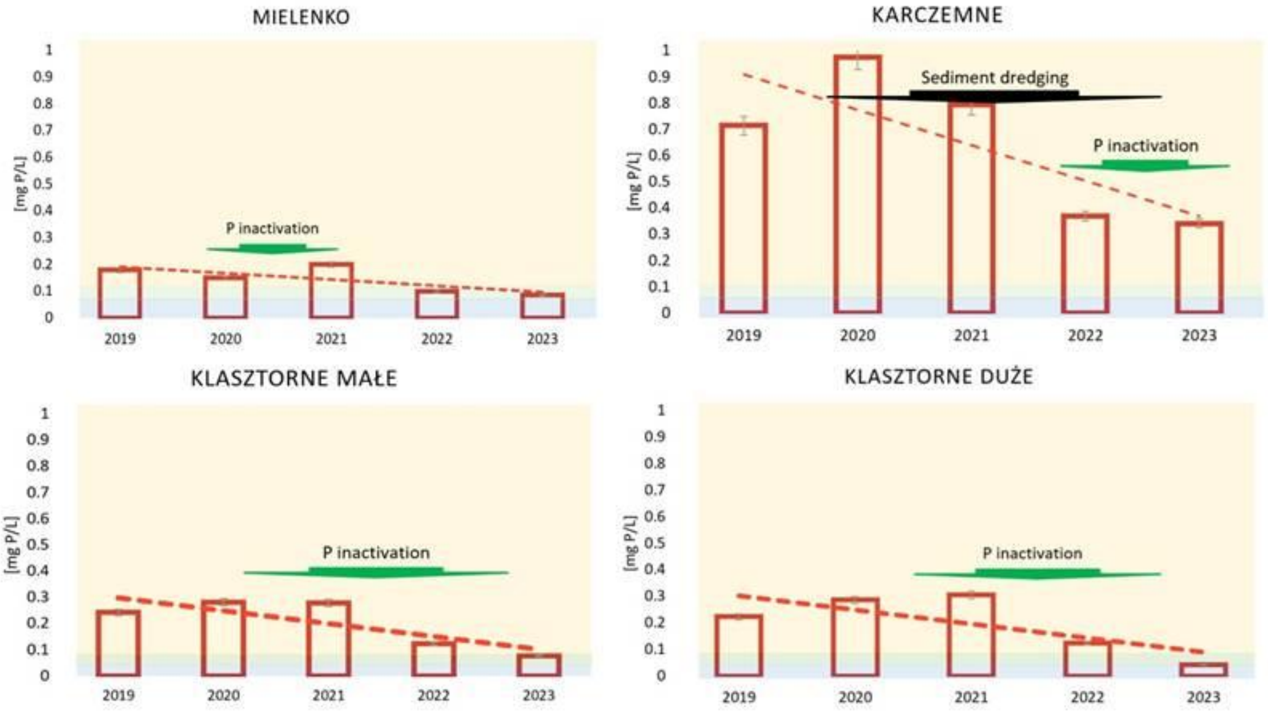

Figure b.3. Changes in average annual concentrations of total phosphorus in Kartuzy Lakes during restoration treatments

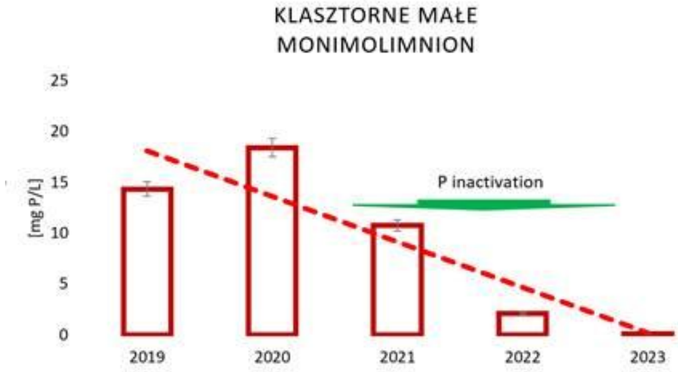

Figure b.4. Changes in average annual concentrations of total phosphorus in monimolimnion of Klasztorne Małe Lake during and after restoration treatments

There were very marked differences in total phosphorus content between the lakes in the Kartuzy region. The most polluted lake was Lake Karczemne, where TP concentrations exceeded 1 mg P/L (Fig. b.3). Lake Klasztorne Małe is also noteworthy. Due to sewage inflow, it developed complete meromixis, and extremely high nutrient concentrations – approximately 20 mg P/L – were observed in the monimolimnion zone water (Fig. b.4). Applied P inactivation method in case of this lake caused radical decrease in TP content especially in the monimolimnion zone. Lakes Mielenko and Klasztorne Duże were significantly less polluted. Restoration measures resulted in a significant reduction in total phosphorus content in lakes Mielenko, Klasztorne Małe, and Klasztorne Duże (Fig. b.3). Less effective treatments were observed in the saprotrophic Lake Karczemne. Analysis of trends in mean annual total phosphorus content indicates a systematic improvement in water quality and a progressive stabilization of environmental conditions. In Mielenko and Klasztorne Duże lakes TP content corresponds to the ranges typical of Class II water quality standard – good water state (Fig. b.3).

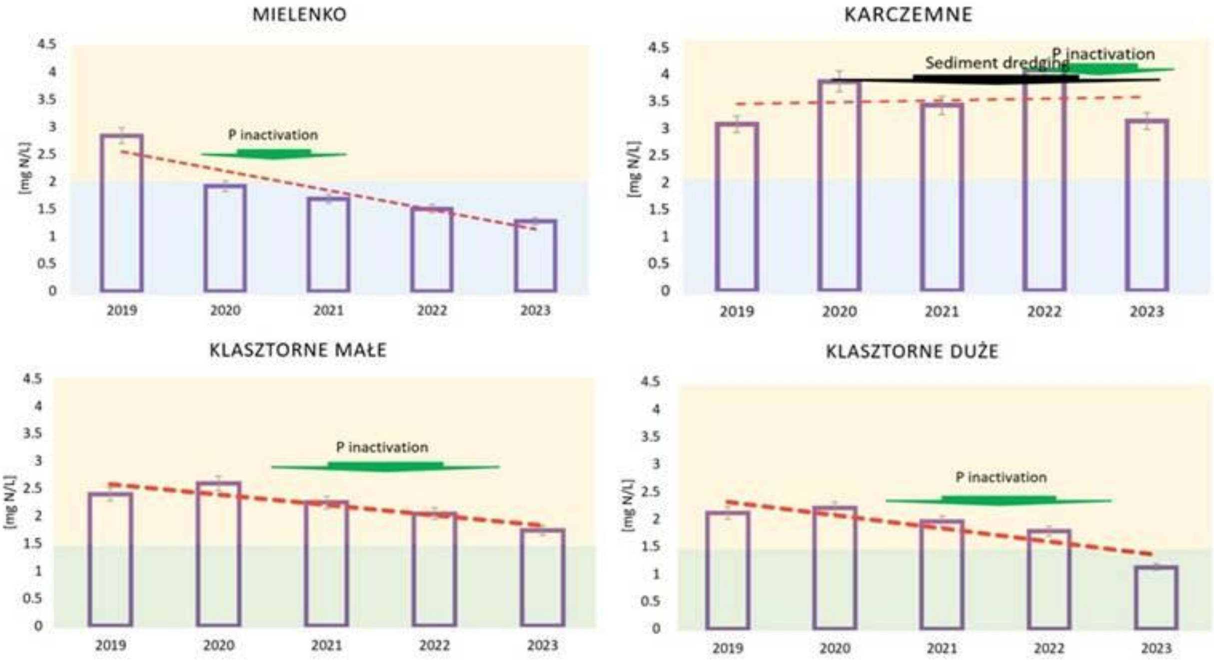

Figure b.5. Changes in average annual concentrations of total nitrogen in Kartuzy Lakes during restoration treatments

As with phosphorus, the most polluted lake in terms of nitrogen content was Lake Karczemne (>7 mg N/L) and the monimolimnion waters in Lake Klasztorne Małe (>50 mg N/L) (Figs. b.5, b.6). As a result of reclamation measures, a decrease in total nitrogen content was observed in Lakes Mielenko, Klasztorne Małe, and Klasztorne Duże. Less effective treatment was again observed in the saprotrophic Lake Karczemne. Analysis of trends in average annual total nitrogen content indicates a systematic improvement in water quality and a progressive stabilization of environmental conditions, with the exception of Lake Karczemne. Nitrogen content in lakes Mielenko and Klasztorne Duże corresponds to the ranges typical of Class II water quality – good water quality (Fig. b.5). In Lake Klasztorne Małe, it is slightly below good, while in Lake Karczemne, it remains within the range typical of poor water quality (Fig. b.5).

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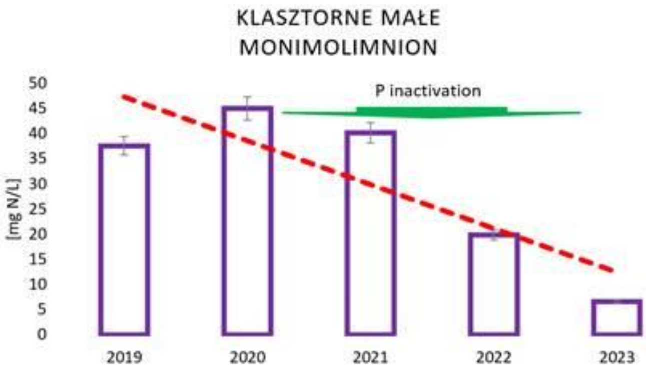

Figure b.6. Changes in average annual concentrations of total nitrogen in monimolimnion of Klasztorne Małe Lake during and after restoration treatments

Figure b.7. Changes in average annual concentrations of chlorophyll a in Kartuzy Lakes during restoration treatments

Chlorophyll a is an indicator of primary production. Before restoration treatments, the least intense primary production processes were observed in Lake Mielenko, a shallow, turbid lake. Photosynthesis was most intense in Lake Karczemne, where chlorophyll a concentration exceeded 170 µg/L (Fig. b.7). Lake restoration caused a reduction in the availability of nutrients in the water, resulting in a significant reduction in phytoplankton blooms. This is confirmed by the decrease in chlorophyll a, whose concentrations in Lakes Mielenko, Klasztorne Małe, and Klasztorne Duże generally do not exceed 20 µg/L. In Lake Karczemne, where nutrient concentrations could not be reduced to photosynthesis-limiting values, production processes decreased slightly, and cyanobacterial blooms continue to occur, with chlorophyll a concentration reaching 100 µg/L (Fig. b.7).

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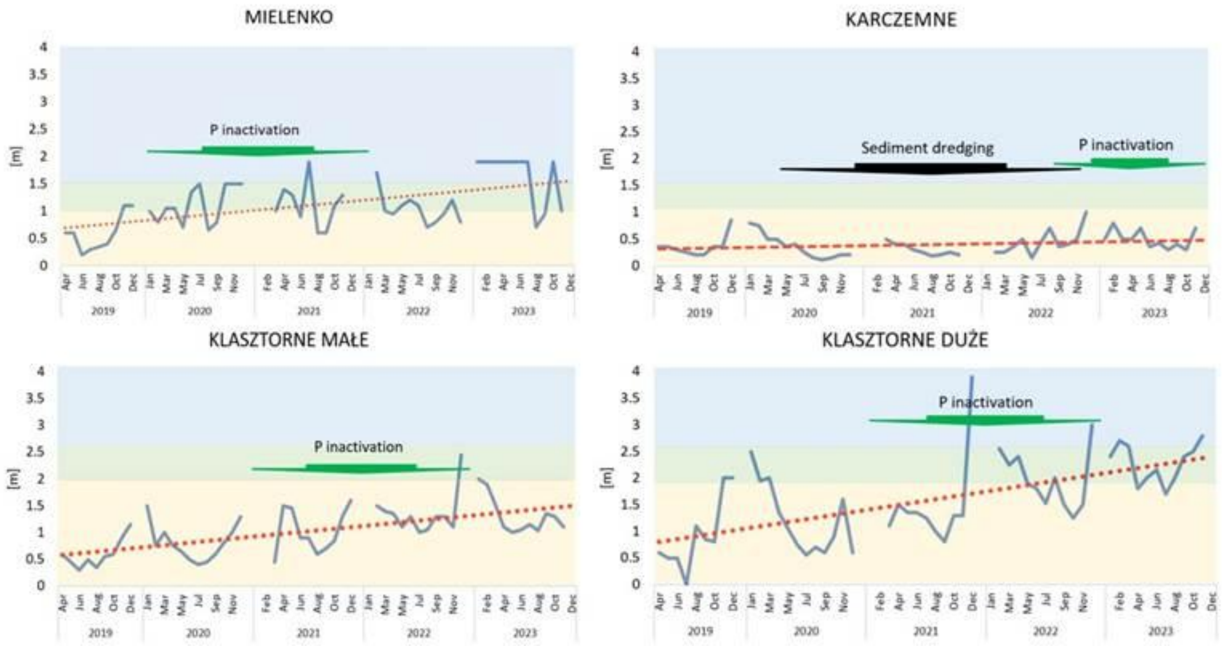

Figure b.8. Changes in average annual values of Secchi disc visibility in Kartuzy Lakes during restoration treatments

Before restoration treatments, Lake Klasztorne Duże had the best water clarity, while Lake Karczemne had the worst light conditions (Fig. b.8). Restoration treatments caused general improvement in water quality, resulting in a significant increase in water transparency. In Lakes Mielenko and Klasztorne Duże, the Secchi disk visibility remains at a level typical of Class II water quality – good water state. In Lake Klasztorne Małe, this indicator is slightly below the values typical of Class II water quality, while in Lake Karczemne, it is still within the range typical of hypertrophic lakes (Fig. b.8). Improved light conditions resulted in the expansion of vascular vegetation, particularly in Lake Mielenko. In that lake the presence of *Chara delicatula (syn. Chara virgata)* was recorded in 2025.

Lake Mielenko has transitioned to a clear-water state with a dominance of macrophytes and transparency to the bottom maintained throughout most of the year. It should be emphasized that submerged vegetation is an indicator of good water quality and its presence is beneficial, as it absorbs phosphorus and nitrogen from both the water column and bottom sediments for growth, accumulating these elements in its tissues. This vegetation thus competes for nutrients for phytoplankton, which, due to the lack of nutrients in the water column, cannot reproduce and form algal blooms. Recently, the appearance of submerged macrophytes has also been observed in the Klasztorne lakes. The first submerged macrophytes were also found in Lake Karczemne in 2025.

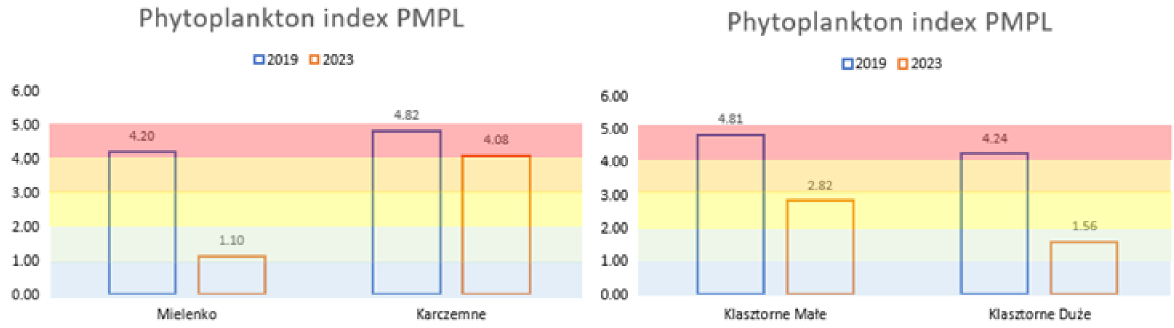

Figure b.9. Phytoplankton index (PMPL) before and after restoration measures (Grochowska et al. 2019, Grochowska et al. 2023)

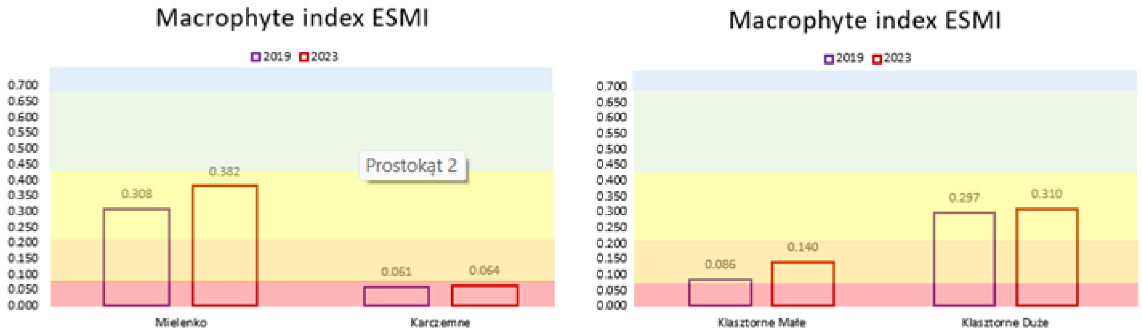

Figure b.10. Macrophyte index (ESMI) before and after restoration measures (Grochowska et al. 2019, Grochowska et al. 2023)

The progress in the biological elements improvement such as phytoplankton or macrophytes can be noticed, analysing indices such as phytoplankton index PMPL or macrophyte index ESMI changes (Figs. b.9, B.10). Considering experiences from other restoration projects it is known, that biological parameters improvement rate is much slower, than improvement observed in hydrochemical properties (eg. Długie Lake restoration case in Olsztyn, Grochowska et al. 2017). Biological elements need time for reaction for physico-chemical environment conditions changes.

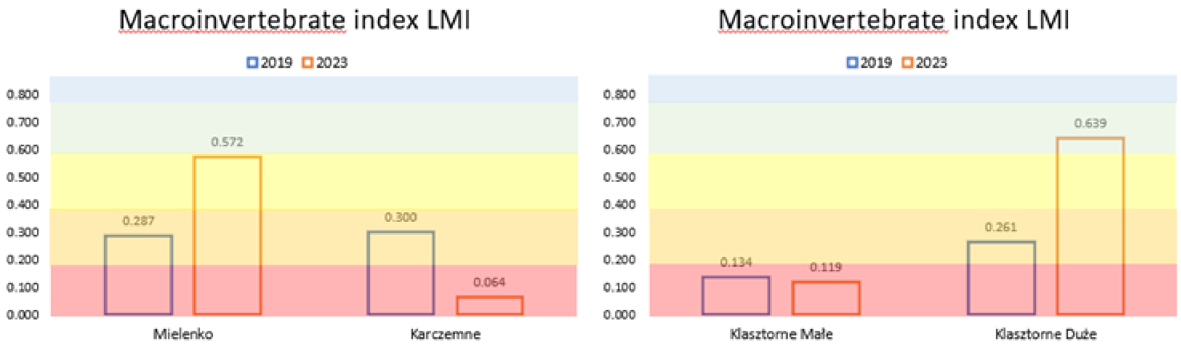

Figure b.11. Macroinvertebrate index (LMI) before and after restoration measures (Grochowska et al. 2019, Grochowska et al. 2023)

Analysis of macroinvertebrate index values before and after restoration measures revealed, that sediment dredging had negative effect on macroinvertebrates in Karczemne Lake (Fig. b.11). Dredging causes increase in water turbidity and locally oxygen depletion in the bottom zones, which caused limits macroinvertebrates range. Probably the conditions for benthic organisms will be better in elapsing time, with continuous improving water quality. Positive effects of restoration (increasing LMI index values) were noticed for Mielenko and Klasztorne Duże Lakes (Fig. b.11).

1.3.1.2 Biodiversity net gain

https://niva365.sharepoint.com/:f:/r/sites/int_HorizonMISSIONLakerestoration/Shared Documents/WP4 Demonstration/4.1_Demonstrating-success/Literature-Evaluating-Restoration-Success/Biodiversity-assessment?csf=1&web=1&e=sydQ2w Before restoration, the lakes in Kartuzy were characterized by poor ecological condition, with sparse submerged vegetation communities, or their complete absence (in lakes Karczemne and Klasztorne Małe) and massive phytoplankton blooms. After completing restoration, the new spots of submerged macrophytes are observed (Figs. b.12, b.13, b.14).

Figure b.12. New place with submerged Potamogeton perfoliatus in the Klasztorne Małe Lake nearby inflow from Karczemne Lake, spotted in summer 2025 (©R. Augustyniak-Tunowska).

Figure b.13. New place with blooming Potamogeton natans nearby east shore of Karczemne Lake, spotted in summer 2025 (© R. Augustyniak-Tunowska).

Figure b.14. Chara delicatula, spotted in summer 2025 in Mielenko Lake (©R. Augustyniak-Tunowska, A. Hutorowicz)

The ichthyofauna structure was also unfavorable, dominated by cyprinid species, characteristic for highly eutrophic waterbodies. During the study, the presence of the invasive gibel carp (*Carassius auratus gibelio*) was also noted. A biological method of biomanipulation of fish communities was used in the Kartuzy Lakes as a supporting method. Predatory fish species (pike, zander, and asp) were introduced into the lakes. Furthermore, regulatory harvesting of excess cyprinid fish was conducted. These activities were conducted in consultation with the fishing user (Polish Angling Association). After biomanipulation, a reduction in the percentage of invasive gibel carp relative to native species was observed. (Fig. b.15). Biomanipulation also changed the share of predatory fish in the ichthyofauna of Kartuzy Lakes – that effect was noticed mainly in the shallow lakes – Mielenko and Karczemne. In the deeper lakes (Klasztorne lakes) due to higher angling pressure on predators' relation between Cyprynids and predatory fish remained similar, possibly due to higher angling pressure on predators.

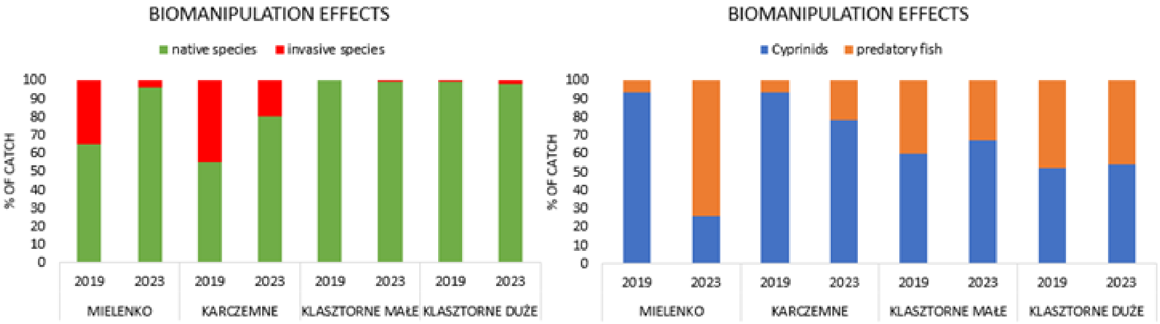

Figure b.15. Changes in the percentage of invasive gibel carp species in the ichthyofauna of Kartuzy Lakes, and in the percentage of predatory fish in the ichthyofauna of Kartuzy Lakes

1.3.1.3 Zero pollution

Monitoring studies conducted in the Kartuzy Lakes catchment area between 2019 and 2023 have shown that the external load of nutrients, particularly phosphorus, the main element responsible for the ongoing eutrophication process, has significantly decreased. In 2023, the total phosphorus load introduced into Lake Mielenko was 6.9 kg P year^{-1}, and nitrogen 173.0 kg N year^{-1} (per unit of reservoir surface area - 0.088 g P m^{-2} year^{-1} and 2.218 g N m^{-2} year^{-1}). Comparison of the actual phosphorus load to the lake with permissible and hazardous loads showed that for phosphorus, the permissible load was exceeded 1.8 times, while the hazardous load was not exceeded (Fig. b.16).

The total nutrient load flowing into Lake Karczemne over the course of 2023 was 31.0 kg P and 587.2 kg N (0.076 g P m^{-2}·year and 1.453 g N m^{-2}·year). Comparison of the current phosphorus load to the lake with the loads calculated using the Vollenweider model (1976) indicates that in the case of phosphorus, the hazardous load, causing accelerated eutrophication, is exceeded by 1.3 times (Fig. b.16).

The total nutrient load reaching Lake Klasztorne Małe from the catchment in 2023 was 34.0 kg P and 439.3 kg N – calculated per unit of lake surface area: 0.248 g P m^{-2}·year and 3.206 g N m^{-2}·year. Comparison of the actual phosphorus load to the lake with the permissible and hazardous loads calculated using Vollenweider’s hydrological model (1976) showed that the current actual load is lower than the permissible load, which, according to Vollenweider's theory, is safe and does not cause accelerated eutrophication. It is noteworthy that the actual load is half the critical phosphorus load that triggers avalanche eutrophication (Fig. b.16).

The external load on Lake Klasztorne Duże in 2023 was 70.0 kg P year^{-1}, and for nitrogen 1,121.3 kg N year^{-1}, or, when converted to a unit of reservoir surface area, 0.121 g P m^{-2} year^{-1} and 1.950 g N m^{-2} year^{-1}. Comparing the actual phosphorus load to the lake with the permissible and hazardous loads calculated from the model showed that for phosphorus, the permissible load was exceeded by 1.4 times, but the hazardous load, which would cause accelerated eutrophication, was not exceeded (Fig. b.16).

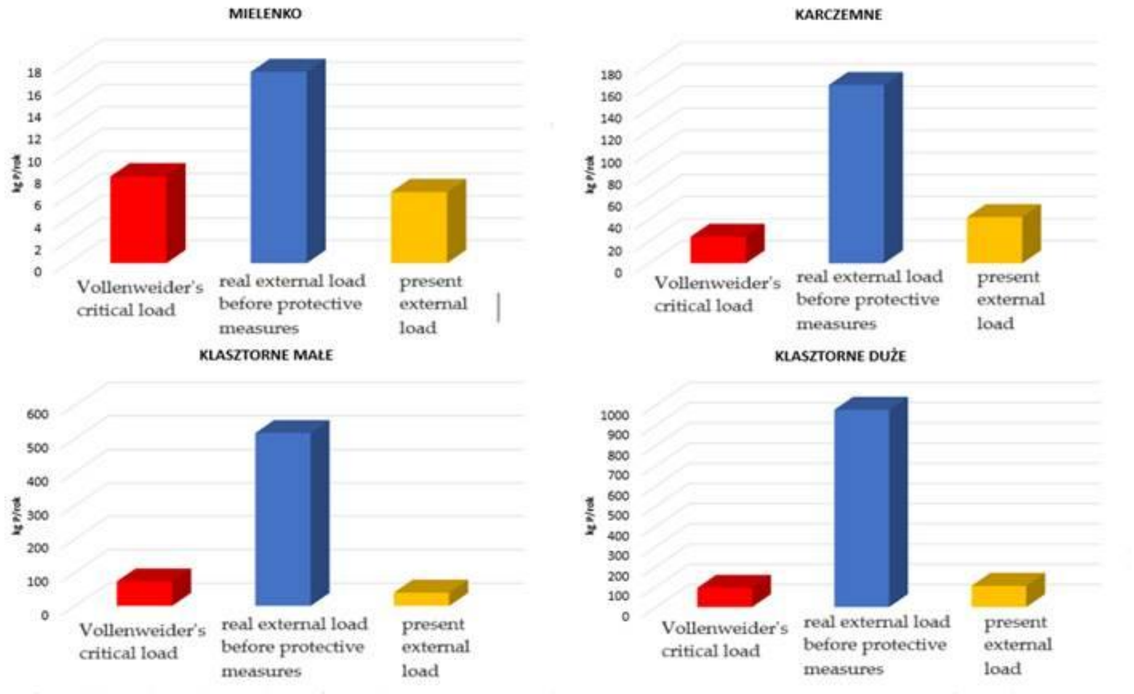

Figure b.16. Changes in the external load of the Kartuzy Lakes with pollutant loads from the catchment area

1.3.1.4 Climate regulation

The assessed annual methane emissions from Kartuzy Lakes showed differences between lakes. The lowest emissions were calculated for Mielenko Lake (0.002 - 0.003 Gg CH_4/a), and the highest emissions were assessed for Karczemne Lake (0.043 Gg CH_4/a in 2020, during the first year of sediment dredging). The total methane emissions from the whole lake complex was in the range between 0.073 Gg CH_4/a (in 2020) and 0.025 Gg CH_4/a (in 2024). The application of the whole lake restoration procedures on Kartuzy Lakes caused decrease in annual methane emissions in all lakes, proving that implemented lake restoration methods (P inactivation with assistance of biomanipulation and combination of sequential sediment dredging, P inactivation and biomanipulation) seems to be effective tools for limiting GHG emissions from lakes.

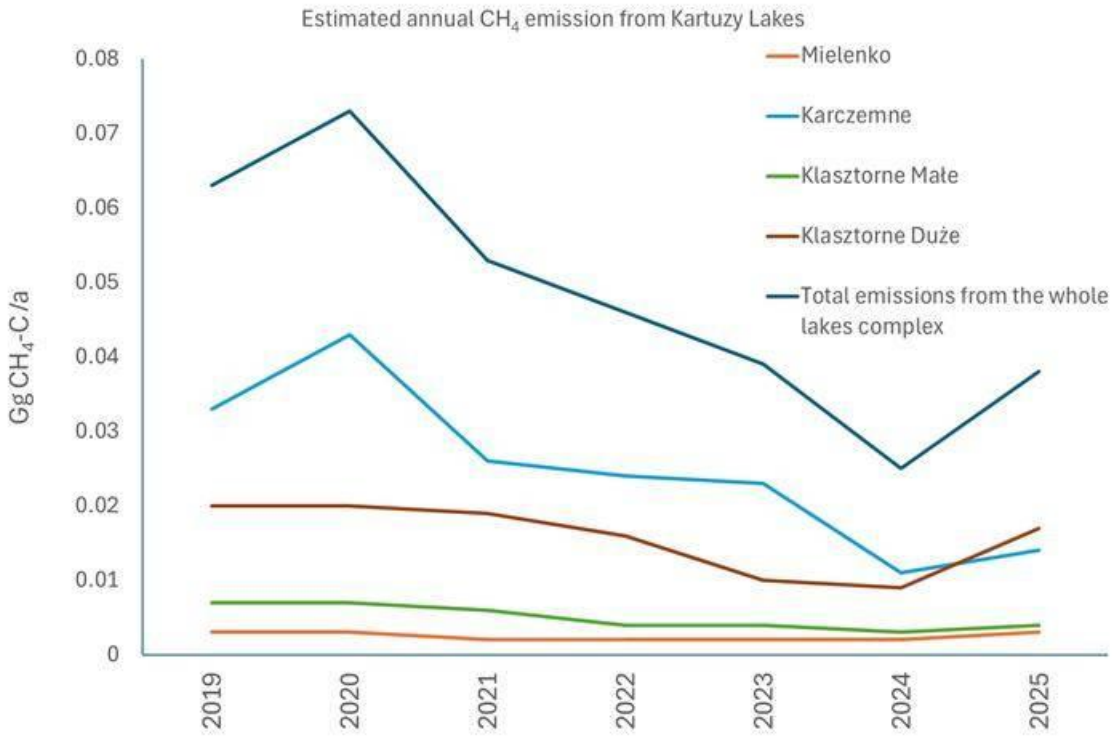

Figure b.17. Predicted sum of ebullitive and diffusive methane (CH_4) emissions from the Kartuzy Lakes based on average annual chlorophyll a concentration. The diffusive and ebullitive methane predictions were made using a Bayesian model constructed from a global dataset of ground-based methane measurements and satellite-derived chlorophyl-a data. The data used to construct the Bayesian model is available as supplementary information in DelSontro et al. (2018). Predictions conducted by E. Kitson, UKCEH.

1.3.1.5 Climate resilience

The Kartuzy water supply system is an open-circuit ring system, directed to the city and nine surrounding villages from seven wells (140-150 meters deep). The KPWiK operates a total of 37 deep wells and 13 water treatment plants. Water is supplied to approximately 32,000 residents. The water supply network is 484 km long, and approximately 1,900 hydrants are installed in the network. The scheme of water supply net is presented on Fig. b.18.

Figure b.18. Water supply system in Kartuzy Commune (source: KPWiK website, https://www.kpwik.kartuzy.pl/)

In Kartuzy area surface water are not used for water supply. According to Polish Geological Institute, Kartuzy area are not endangered by groundwater resources exhaustion (https://www.pgi.gov.pl/)

1.3.1.6 Health & Well-being

The cut off sewage pollution and comprehensive restoration opened new chapter in the recreation on Kartuzy Lakes. Very important part of restoration was arrangement of area around lakes. The hiking path (promenade) was constructed on the shores of Karczemne, Klasztorne Małe and Klasztorne Duże lakes.

The comprehensive works included: renovation of existing and construction of new pedestrian paths, installation of area lighting; planting of trees, shrubs, grasses, and perennials as well as construction of recreation areas, including the installation of small-scale architecture elements – eg. benches, information boards, and signposts. (www.kartuskiejeziora.pl) (Figs. b.19, b.20) .

The path is safe for wheelchair users and cyclists, as well as for pedestrians. The total length of paths is equal ca. 5 km (Fig. b.19).

Figure b.19. Recreational path in Kartuzy around lakes (www.geoportal2.gov.pl , changed)

Figure b.20. Path and ponds arranged as a part of Klasztorna Struga River reclamation, between Karczemne and Klasztorne Małe lakes

1.3.1.7 Inclusivity

Kartuzy Lakes restoration project was comprehensive, initiated by the local authorities, with a high collaboration and personal engagement of the researchers from the University of Warmia-Mazury in Olsztyn. Additionally, Polish Angling Association (Polski Związek Wędkarski - PZW), was a partner and beneficiary of the project. The association actively engaged in the project execution. Members of the local branch – angling circle no. 57 – were on site and took an active part in the restoration measures related to fish manipulation.

An important part of the engagement activities was dedicated to the civic dialogue and environmental education. The local Kartuzy Culture Centre was a meeting place for the project discussion, along with a dedicated project website. An important element were clear and shared goals to improving the water quality, environmental status and recreational values of the lakes.

Lake restoration needs to bring together many institutions, with diverse competences. For the Kartuzy Lakes restoration, intensive collaboration between the authorities, research and the PZW as well as the local public could be observed. Less engagement was documented from the State Water Holding 'Polish Waters', that can be explained with competence division and some institutional barriers. The institution is relatively new (established in 2018), its branch suffered from personnel discontinuation, with the dialogue on the project and issuing the necessary permits taking more than expected by the project partners (Szulecka et al., 2025 – FutureLakes D2.1)

Table b.6. Stakeholders – Kartuzy Lakes (Szulecka et al. 2025).

Stakeholder name	Stakeholder category	Sector/ fields of interest	Stakeholder level	Interest	Power
EU	EU	EU legislation and funding	International	H	H
Consortium INORA	Business	Contractor for restoration	Polish-Latvian	H	L
Czerwony Szkwał Maritime Works	Business	Contractor for restoration	National	H	L
National Fund for Environmental Protection and Water Management	Governmental	Environmental protection, funding	National	H	H
University of Warmia-Mazury in Olsztyn	Research and development	Lake water quality and restoration	National, regional	H	H
National Water Holding – 'Polish Waters', Regional Board of Water Management	Governmental	Surface water management	Regional (Gdańsk)	L	H
The General Directorate for Environmental Protection	Governmental	Environment protection	National	H	H
Regional Directorate for Environmental Protection	Governmental	Environment protection	Regional (Gdańsk)	H	H
Chief Inspectorate for Environmental Protection	Governmental	water quality monitoring, environmental intervention	Regional (Gdańsk)	H	H
Polish Forests	Governmental	Forest management	Regional (Gdańsk)	L	L
Polish Angling Association PZW	NGO	Angling on surface waters	Regional (Gdańsk)	H	H
Kartuzy Municipality	Local authorities	Responsible for lake management, initiated lake restoration	Local	H	H
Kashubian Landscape Park	NGO	Tourist service	Local	L	L
Private owner of Karczemne Lake	Private person	Karczemne Lake	Local	H	H
Kartuzy Water and Sewerage Company	Municipal	water and sewage management	Local (Kartuzy)	H	H
Residents	Permanent residents	Accommodation & amenities	Local	H	L
Tourists	Seasonal residents	Accommodation & amenities	Local	H	L
Kashubian Tourist Association	Governmental	Management of protected Kashubian landscape area	Local	H	L
Kartuzy Culture Center	Municipal	Culture	Local	H	L
Express kaszubski	Media	Articles	Local	H	L

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Community fisheries guard/ Spoleczna straz rybacka	Citizen	Fish	Local	H	L
Collegiate Church in Kartuzy/ Kartuska Kolegiata	NGO	Religious	Local	H	L
SOS for Kartuzy Lakes/ SOS dla Kartuskich Jezior	Citizen	Environment, culture	Local	H	L
Grzybno	Downstream stakeholders	a village in the administrative district of Gmina Kartuzy	Downstream		

1.3.1.8 Recreation

Long history of Kartuzy Lakes pollution limited their recreational use. Mielenko Lake and Klasztorne Duże Lake, as less polluted, were used for recreational angling. The pollution of Karczemne and Klasztorne Małe Lake caught less interest of anglers. The swimming was not recommended due to sanitary issues.

Figure b.21. Recreational path on the shore of Klasztorne Małe Lake (©P. Kuchta, www.kartuskiejeziora.pl)

Since 2023 the promenade is constructed on Klasztorne Duże Lake shore (Fig. b.21). One of the element of recreational area development is the construction of beach infrastructure. Two piers were made for recreants and the official opening of city beach is planned before summer 2026 (Fig. b.22).

Figure b.22. Beach arrangement construction on the shore of Klasztorne Duże Lake in spring 2025 (©R. Augustyniak-Tunowska)

Figure b.23. Recreational summer event on Klasztorne lakes in Kartuzy (https://dziennikbaltycki.pl/deski-sup-wyplynely-na-kartuskie-jeziora-tak-zakonczyli-lato/gh/c2-17903549 , ©UM Kartuzy)

On the shore of Klasztorne Małe Lake a renting of water bikes is possible. Also, other recreational events are organized, eg. boating on SUP paddle boards during summer (Fig. b.23).

1.3.1.9 Circular economy

The Kartuzy Lakes complex, located in northern Poland (Kashubian Lakeland), consists of four lakes (Mielenko, Karczemne, Klasztorne Małe and Klasztorne Duże), connected by Klasztorna Struga River. Karczemne Lake (area 40.4 ha, max depth 3.2 m) is the second lake in the cascade of the river. In the past, Karczemne Lake was the recipient of raw wastewater from Kartuzy city (via six sewerage inlets), which led to massive degradation of the entire ecosystem and its transformation into a saprotrophic lake type. Dense cyanobacterial blooms, low Secchi depth (10-20 cm), and very high N and P concentrations (3.3 mg TN/l and 1.2 mg TP/l, respectively) proved terrible water quality. Bottom sediment analysis (2018) revealed extremely high TP concentrations (12 –16 mg P/g DW in the deepest point of lake, and even more than 30 mg P/g DW in the polluted hot-spot nearby the east shore. Therefore, it was clear that the bottom sediment of Karczemne Lake acted as a huge internal source of nutrients (Thiemer et al. 2025, FutureLakes M 1.2).

Figure b.24. Sewer No 17 - example of inflow to Karczemne Lake in 2012 (before restoration) (photo: J. Grochowska)

Figure b.25. Karczemne Lake before restoration - intensive cyanobacterial bloom (Photo: R. Augustyniak-Tunowska)

After sewerage modernization in the city (2015), the raw sewage was cut from the lake, but due to high P internal loading and P abundance in the bottom sediment, the only way to improve water quality in Karczemne Lake was to remove polluted sediment. High phosphorus level in the sediment opened the possibility of recycling the removed sediment for P reuse. Preliminary assessment of sediment volume dedicated to removal was 240,000 m^3 (Grochowska et al. 2019, Thiemer et al. 2025)

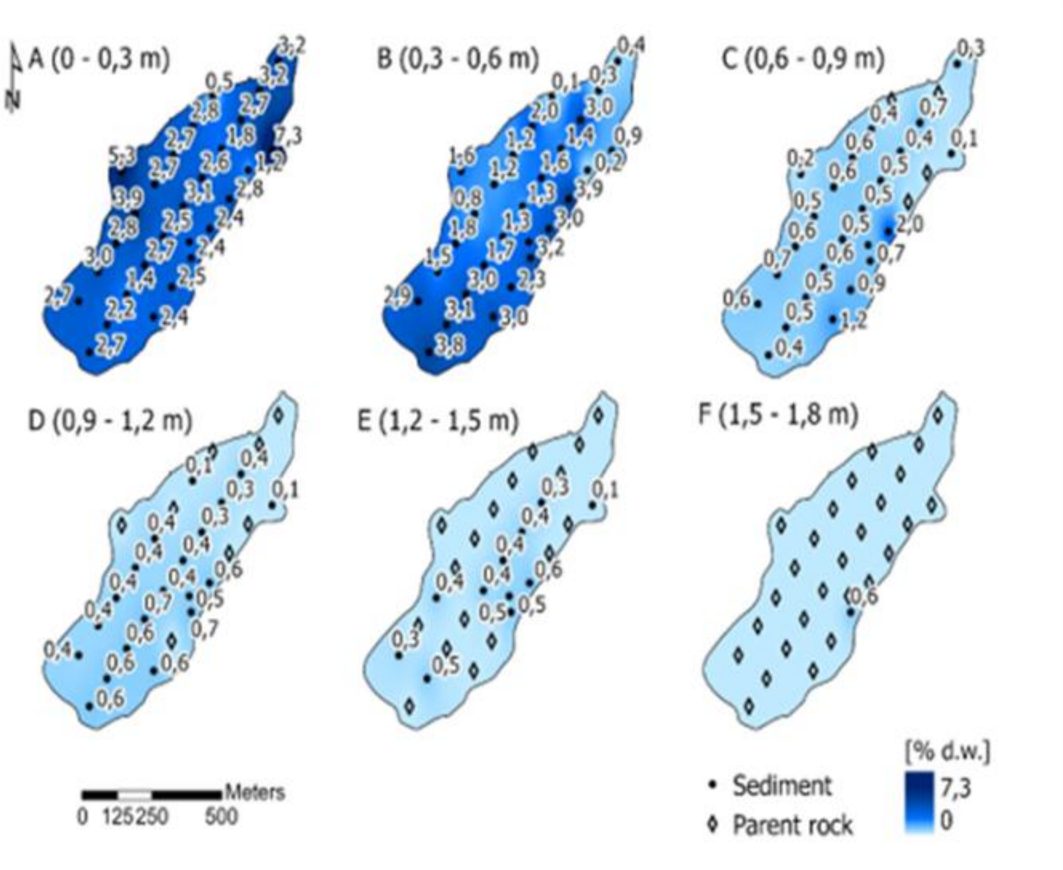

Figure b.26. Spatial P distribution in the sediment of Karczemne Lake before restoration (source: Grochowska et al. 2021, Archives of Environment Protection, DOI 10.24425/aep.2021.139501)

In cooperation with Kartuzy WWTP, the whole technological line was constructed for sediment treatment in the first half of 2020. Watered sediment was removed from the lake by refuler, and the sediment was directly hydrotransported via 4.5 km long pipeline into Kartuzy WWTP and stored in the large sedimentation tanks for preliminary dehydration. The removed pore water was directed to main sewage biological and chemical treatment line in WWTP. Preliminary dehydrated sediment was dehydrated again using grit chamber and centrifuges. The final product of dehydration was mixed with excessive active sludge from the main Kartuzy WWTP sewage technological line and stabilized. The physicochemical and microbiological parameters were checked according to standards, and the final soil-like product was dedicated for agricultural use beyond Kartuzy Lakes catchment.

Figure b.27. Pipeline for sediment hydrotransport to Kartuzy WWTP (photo: J. Grochowska)

Figure b.28. Kartuzy WWTP aerial view during lake sediment treatment (Source: Kartuzy WWTP)

The process of sediment removal ended in 2023. The restoration of Kartuzy Lakes complex was financed by Kartuzy Municipality and EU (Infrastructure and Environment Operational Program). The total volume of processed mixture of water and sediment amounted to 1 mln m^3 .

Figure b.29. Sediment removal from the part of Karczemne Lake – geomembrane curtains were used for separation of regulation area from the rest of lake (source: Kartuzy WWTP)

Figure b.30. Final product of sediment treatment in the storage shed (source: Kartuzy WWTP)

1.3.1.10 Blue economy

Fisheries, eco-tourism, nature-friendly recreation businesses based around lake, services (café's restaurants).

Kartuzy Lakes are used for angling. On three lakes, belonged to National Water Holding Polish Waters (Mielenko, Klasztorne lakes) Polish Angling Association gives permissions for angling. Karczemne Lake is private property and the owner gives permission for angling.

In Kartuzy and nearby villages fourteen hotels and apartments are functioning (Table b.7). Several of them are agrotourtistic businesses. The Center of Tourist Information recommends ten restaurants located in Kartuzy, but there are more small cafeterias. The proximity of Tricity (Gdańsk, Sopot and Gdynia) is also favourable for recreational businesses.

In last years, several apartment buildings were constructed nearby lakes. According to info from Kartuzy Municipality (Ms Natalia Lekner, personal comm), those apartments are used for short-term rent for tourists. But Kartuzy Municipality has no information about tourists number visiting Kartuzy. The common info about tourists number is available for the whole Pomeranian Voivodeship, but it is impossible to extract data for Kartuzy in particular. Hence, the informational gap exists in this area, and this is suggestion for Kartuzy Municipality to establish information gathering about it.

Table b.7. Hotels located nearby Kartuzy Lakes (https://citkartuzy.pl/baza-noclegow/)

Number	Name of hotel	Adress	Web page
1	Hotel Miłosz Kaszuby	St. 3 Maja 34, Kartuzy	www.hotelkaszuby.pl
2	Hotel Pod Orłem	St. 3 Maja 10, Kartuzy	www.hotel-podorlem.com
3	Image ; Brejka	St. 11 Listopada, Kartuzy	www.image.kartuzy.pl
4	Apartament Alina	St. Reja 3, Kartuzy	www.alinaapartament.pl
5	Pokoje U Gosi	St. Reja 16, Kartuzy	www.pokojekartuzy.pl
6	Gościniec Kaszubski	St. Parkowa 4	www.goscinieckaszubski.pl
7	Stajnia Fiord	Łapalice	www.stajniafiord.pl
8	Gospodarstwo Agroturystyczne Agrojeziorak	St. Marcina 17, Łapalice	www.agrojeziorak.pl
9	Gospodarstwo Agroturystyczne	St. Turystyczna 12, Łapalice	
10	Pokoje gościnne OLEŃKA	St. Zamkowa 90, Łapalice	www.pokojeolenka.pl
11	Apartamenty pod zamkiem	St. Rzemieślnicza 4, Łapalice	www.apartamentypodzamkiem.pl
12	Fenix	St. Świerkowa 2, Grzybno	www.fenix.kartuzy.pl
13	Gospodarstwo Ekologiczne	Kosy 22	
14	Apartament Perła Kartuz	St. Majkowskiego 38, Kartuzy	

In December 2025 the Kartuzy Municipality finalized the beach arrangement on the shore of Klasztorne Duże Lake. The new infrastructure functioning opened the possibility of new work positions. The hiring of 8 persons was announced in local press (*https://expresskaszubski.pl/pl/11_wiadomosci/75303_kartuzy-jest-dofinansowanie-na-miejsca-pracy-min-przy-obsludze-kapieliska.html#goog_rewarded, accessed 18.12.2025)*

1.3.1.11 Sustainable Agriculture

The catchment of Kartuzy Lakes has not agricultural areas (arable lands). The information about catchment use was described in the section 1.2.1.

1.3.1.12 Sustainable transport

Kartuzy Lakes are not used for navigational purposes. The public transport around the city area (city lines) is available for citizens and tourists. Kartuzy city is connected to Tricity by railway too.

1.3.1.13 Sustainable energy

Kartuzy Lakes are not used as source of renewal energy.

1.3.1.14 Sustainable Tourism

Tourism on the area of Kartuzy Lakes catchment was described in the 1.3.1.10 Blue economy section.

1.3.1.15 Water supply & sanitation

Water and Sewage Company in Kartuzy (KPWiK) is responsible for water and sewage management in Kartuzy and nearby villages.

The KPWiK operates 10 water treatment plants with 34 deep wells, the Kartuzy Sewage Treatment Plant, and 42 collective sewage pumping stations in the Kartuzy commune. It supplies water to approximately 31,000 residents spread across 20,528 hectares. The total length of the water supply network is 405 km, and the total length of the sanitary sewer network is 215.5 km. Surface water is not used for water supply (www.kpwik.kartuzy.pl)

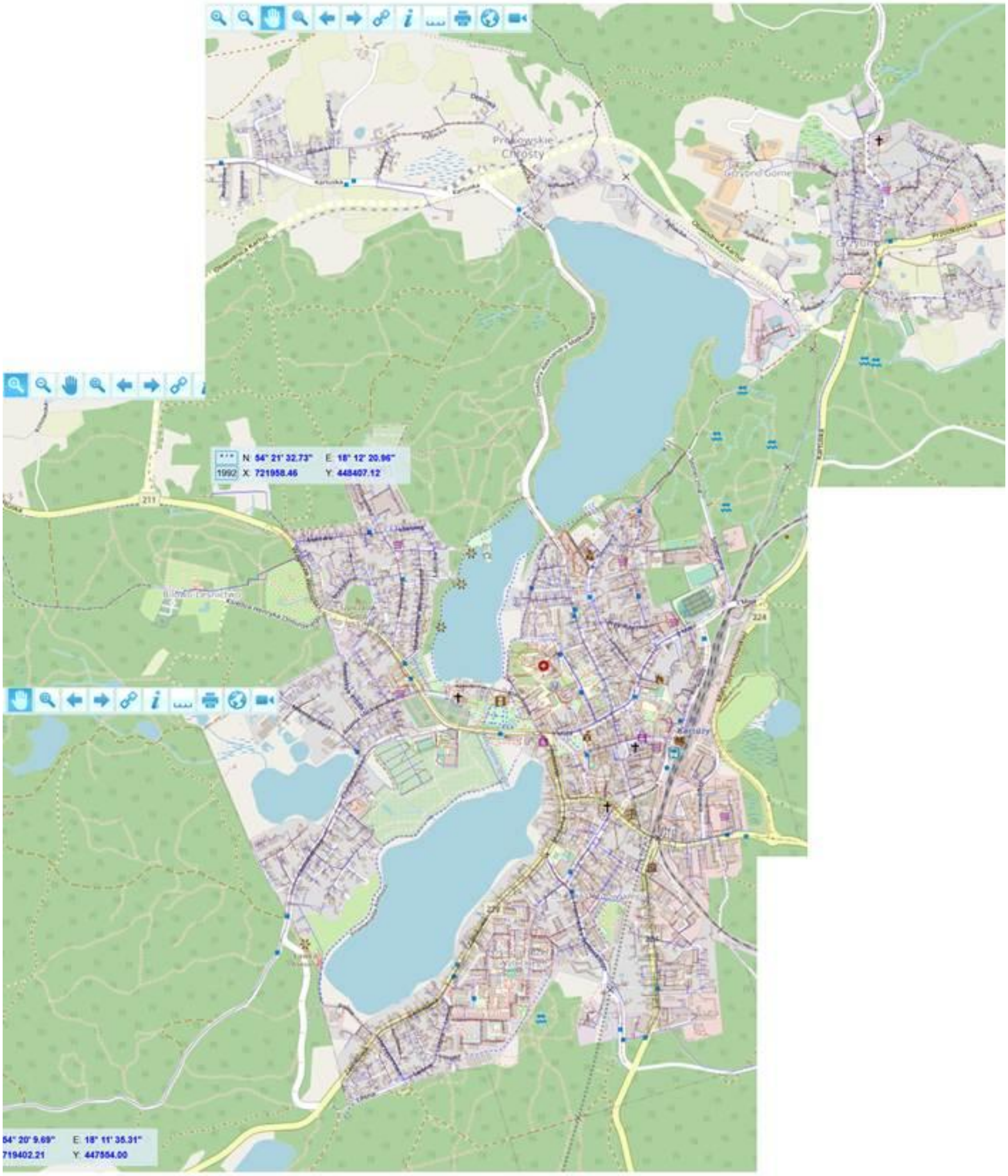

Figure b.31. Scheme of water and sewerage system in Kartuzy (source www.geportal2.gov.pl , mosaic of maps)

2. Unexpected results across criteria, synergies and trade-offs

The Kartuzy Lakes restoration was the biggest lake restoration program in Poland.

The big challenge was implementation of sediment dredging procedure on the whole lake area. Considering logistic it was very demanded procedure. Problems with quality of service delivered by first company resulted in the whole restoration process delay (Grochowska et al. 2023, Grochowska 2024). The Karczemne Lake restoration effects evaluation needs more time – the results of restoration presented in D 4.1 are very short-term and the signs of environmental conditions improvement still are not satisfying (low LMI, PMPL or ESMI indices values).

Together with longer dredging period, climate changes had certain effect on delay in Karczemne Lake restoration results. Modernization of storm sewerage system, which was made before restoration (in mid of 2010's) around Kartuzy Lakes does not ensure the full cutting off storm water from the Karczemne Lake during extremely heavy rains events. This results in an extra nutrient loading entering into lake. That problem is common for many urban sewerage systems in the Polish cities in the last years, and this poses the risk for urban surface water quality.

Figure b.32. The remains of big storm event on the shore of Karczemne Lake (the laid grass area shows the size of flow during heavy rain event, the collector is not active in standard conditions)(© R. Augustyniak-Tunowska).

Monitoring of sediments in Mielenko Lake showed unexpected decrease of organic matter and P contents in the period of 2019/2020, despite of fact of beginning P inactivation procedure (Augustyniak-Tunowska et al. 2024), which should lead to OM and P increase in sediment. During seeking of causes of that unexpected result it was found, that the very warm winter 2019/2020 (first time in record Polish lakes didn't develop ice cover) probably accelerated of sediment OM mineralization in shallow Mielenko Lake (Augustyniak-Tunowska et al. 2024). This observation shows that climate changes can influence on restoration effects, despite of assumptions and expectations.

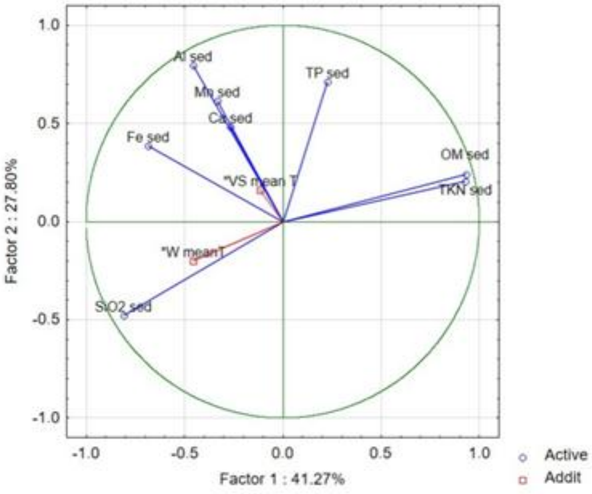

Figure b.33. PCA analysis results for sediment components and mean air temperatures (winter and vegetation seasons) (after Augustyniak-Tunowska et al. 2024).

Another unexpected result was lack of changes in proportion between predatory and Cyprinids in Klasztorne Lakes. We assume, that intensive angling pressure (catching predators rather that Cyprinids) is responsible for unchanged predators share.

3. Summary of effectiveness of restoration programme

The Kartuzy Lakes were one of the most polluted water bodies in Poland because they were transformed into sewage receivers in the mid-1950s. In addition to untreated municipal sewage, industrial sewage, and rainwater were discharged into these reservoirs. The long-term inflow of sewage has caused massive pollution of the Kartuzy Lakes, in whose water and bottom sediment high concentrations of nutrients were recorded. The most loaded were two water bodies of the complex - the polymictic Lake Karczemne and the bradimictic Lake Klasztorne Małe, which, due to the inflow of sewage, became a meromictic reservoir. The external load of the lakes with organic and mineral compounds many times exceeded the limits of the critical load and caused these ecosystems to initiate the process of internal loading and enter the phase of saprotrophy. Saprotrophy is a condition in which a lake is unable to transform excess organic and mineral substances within its structure and the organisms functioning in it, and it suffocates with the products of incomplete decomposition of matter.
A program for the protection of Kartuzy Lakes was developed and implemented, which involved the modernization of the city's sewage system (change of pipes, construction of retention reservoirs for excess rainwater) and allowed for a radical reduction in the external load of nutrients on the water bodies. After the protection measures, a restoration program could be started. All restoration methods used on the Kartuzy Lakes were adapted to the individual characteristics of each water body (chemistry of water and bottom sediments, morphometric conditions).

The applied solutions brought the best results in the Mielenko and Klasztorne Duże lakes, where both water chemical parameters and biological indicators indicate good water quality and moderate or good ecological state. Macrophytes appeared in these lakes, maintaining the improvement in environmental conditions. Monitoring of the structure of ichthyofauna in Mielenko and Klasztorne Duże lakes showed that the biomanipulation carried out, consisting of stocking with pike, zander, and asp, as well as catching white fish, resulted in an improvement in the structure of ichthyofauna, but further stocking with predatory fish is recommended.

In the meromictic Lake Klasztorne Małe, a significant reduction in nutrient content was achieved, particularly in the monimolimnion waters. An assessment of the lake's ecological status, conducted after the restoration was completed, based on the PMPL Phytoplankton Index, showed that Lake Klasztorne Małe is characterized by Class III water quality, meaning it is in moderate ecological condition. Worse results were obtained for the macrophyte index ESMI, which indicated poor ecological condition. This can be explained in two ways. First, the reduction in phosphorus and nitrogen concentrations in the trophogenic zone following the application of coagulants limited primary production processes, which in turn improved light conditions, but the visibility of the Secchi disk did not increase enough for solar radiation to reach greater depths. Second, Lake Klasztorne Małe is a ribbon reservoir with steep banks. A few meters from the shoreline, the lake’s depth exceeds 2 meters. It is worth noting that patches of *Potamogeton perfoliatus* were observed during the past growing season.

During reclamation work, a minor failure occurred in the pipeline transporting bottom sediments extracted from Lake Karczemne to the sewage treatment plant. The pipeline leak caused the excavated material to enter the waters of Lake Klasztorne Małe. The incidental inflow of increased nutrient loads prevented the precipitation of phosphates from the water column using the coagulant doses assumed in the project, which were selected for lower concentrations. It would probably be necessary to use additional doses of coagulants to achieve a deeper improvement in water quality.

The least effective restoration efforts were achieved for Lake Karczemne, from which 240,000 m³ of bottom sediments were extracted. Based on studies of interstitial waters and bottom sediments, it was estimated that by removing the projected amount of bottom sediment, approximately 213 tons of phosphorus and 406 tons of nitrogen were removed from the ecosystem. This confirms the validity of the assumptions behind the adopted restoration method, among which the priority was the removal of bottom sediments outside the Lake Karczemne ecosystem.

Lake Karczemne requires supplemental restoration efforts through the introduction of additional doses of coagulants. Due to deficiencies in the silting work that occurred during the first contractor's work, the assumed coagulant doses were too low to effectively precipitate phosphates from the water column and immobilize phosphorus in the bottom sediments. It is also necessary to further reduce external loading. Existing retention reservoirs for excess stormwater are insufficient to store water during the recent heavy rains.

It should be emphasized that such extensive protective and reclamation activities carried out in the lake complex were successful thanks to the cooperation of many entities.

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c) Lake IJssel complex

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1.1 Lake details

Table C.1. Characteristics that define the surroundings and chemical and hydromorphological status of Lake IJssel and Lake Marken.

			Lake IJssel	**Lake Marken**
Type of characteristics	**Characteristics**	**Unit**	**Value**	**Values**
Geographical characteristics	Latitude	-	5.32683	5.24578
Geographical characteristics	Longitude	-	52.81796	52.55366
	Altitude	mNAP[1]	-0.40 (winter) -0.20 (summer)	-0.40 (winter) -0.20 (summer)
Lake characteristics	Area	km^2	1130.7	675.20
	Maximum depth	m	20.61[2]	30.91[3]
	Mean depth	m	4.58	3.91
	Water volume	bn. m^3	~ 4.7 (in winter)	~2.4 (in winter)
	Depth index (mean depth/maximum depth)	-	0.22	0.13
	Water residence time (τ)	years	0.3	~1
	Residence type	-	Short	Moderate
	Shoreline development index $K = \frac{shoreline\ lenght}{2\sqrt{\pi}\ \cdot lake\ area}$		2.4[4]	3.7

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[1] mNAP = meter Normaal Amsterdams Peil. This term translates to regular Amsterdam water level and is roughly equal to the mean sealevel of the North Sea.

[2] Deepest parts are in navigation channels. Data from 2011.

[3] Deepest parts are in navigation channels. Data from 2011.

[4] Including islands and the Afsluitdijk (= artificial structure, dyke).

	Mixing type		polymictic	polymictic
	Stratification		non-stratified[5]	Non-stratified
Catchment characteristics	Total catchment area	km^2	185 000[6]	
	Direct catchment area	km^2	18770[7]	
	Agricultural areas	% of direct catchment[8]	33.4	
	Urban areas	% of direct catchment	2.7	
	Forests	% of direct catchment	34.2	
	Wetlands	% of direct catchment	2.0	
	Water bodies	% of direct catchment	22.3	
	Other (mainly bare land)	% of direct catchment	4.8	
	Schindler's index (sum of total catchment and lake areas to lake volume ratio)	-	2.90[9]	
Climate characteristics[10] (between 1-jan-1995 and 31-dec-2024)	Mean annual air temperature[11]	°C	10.5	
	Mean annual precipitation	mm/year	897	
	Maximum summer temperature	°C	37.4	

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[5] But can be stratified in certain deep areas.

[6] The lake IJssel is part of the Rhine catchment.

[7] The direct catchment here is defined as the area that supplies water to the Lake IJssel complex.

[8] Original ask was % of total catchment. However, in case of the Lake IJssel complex this would be the full Rhine catchment. Although the whole catchment likely does have an influence on the complex, the direct catchment likely has a larger influence.

[9] ((direct catchment surface area (km^2) + lake complex surface area (km^2)) * (km^2 to m^2 conversion factor)) / lake volume (m^3) = ((18770 + 1805.9) * 1000000) / 7 100 000 000

[10] Source: KNMI station Lelystad

[11] Method: Averaged hour to daily values, then daily – *monthly* – to yearly values, then yearly to 30-yearly avg. See R-script.

	Days number > 15°C per year	n days	167	
	Days with snow per year	n days	19[12]	
Hydrochemistry and trophic type	Alkalinity	meq/L	N.A.	2.13[13]
	Alkalinity type	-	N.A.	High
	Colour category	-	Clear	N.A.[14]
	Colour (HAZEN)	PtCo	5 - 25[15]	N.A.
	Trophic type		Eutrophic	Eutrophic[16]
	Calcium level	Ca/L	40 - 90[17]	50 - 85[18]
	Water hardness		Hard water	Hard water

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[12] 21 year avg instead of 30 year avg due to missing time series.

[13] Noordhuis, R. 2010.

[14] Lake Marken is more turbid than Lake IJssel due to the presence of silt. However, HAZEN measurements are not available for this lake.

[15] Range over the last 15 years.

[16] However, Lake Marken has relatively low total phosphorus concentrations in comparison to its total nitrogen concentrations (2015-2024 summer average 19.5 ugP/l versus 806 ugN/l).

[17] Range for the last 15 years.

[18] Range for the last 15 years.

1.2 Restoration Programme

1.2.1 Background

The Lake IJssel complex (Figure C.1) in its current form was created by the closure of the former Zuiderzee through the construction of the Afsluitdijk (completed in 1932), the subsequent reclamation of the IJsselmeer polders (completed in 1968) and the construction of the Houtribdijk (completed in 1976). After the closure of the Afsluitdijk, the water in the lake became freshwater within a few months, effectively removing the former brackish transition zone to the sea. The salt and brackish organisms that originally inhabited the ecosystem were replaced by a freshwater species over the span of five years.

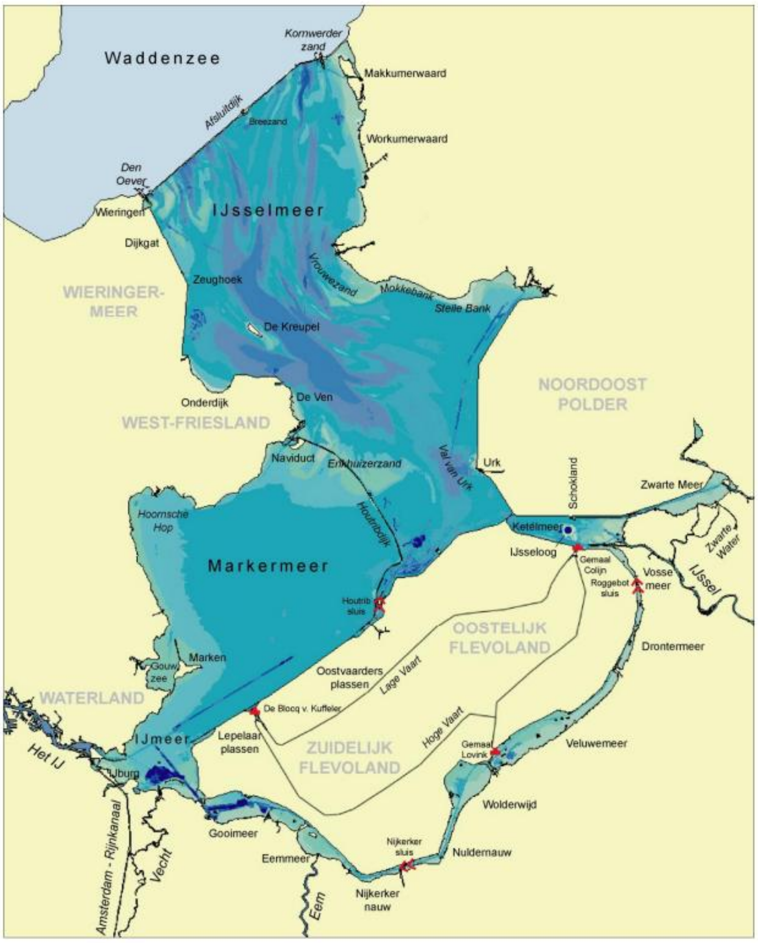


Figure C.1. Map of the Lake IJssel complex and its surrounding area. Markermeer = Lake Marken, IJsselmeer = Lake IJssel. Darker blue colors indicate a greater depth. Source: Noordhuis et al. (2014).

Due to its history as the entry zone of the estuary, Lake IJssel still has channels up to 6.5 meters deep that consist mainly of sandy sediments. Its water transparency is largely determined by algae and is generally relatively high, especially near the mouth of the river IJssel. Most of the water that enters Lake IJssel comes from the river IJssel (a branch of the Rhine river). Although the water level of the lake is now fixed, the large surface area of the lake allows wind to create water level differences of up to one meter between different sides of the lake. At the transition between water and land (in the absence of dykes) and on the low-lying parts of old sandbanks, reed beds can be found, often encroached by willows. On higher ground, shrubland and woodland occur.

Lake Marken formed following the completion of the Houtribdijk between Enkhuizen and Lelystad in 1975. In sheltered and shallow parts of Lake Marken, such as the Gouwzee and the coastal zone near

Muiden, charophyte vegetation has developed. Currently, the southern part of the Gouwzee contains the largest area of charophyte vegetation with *Chara* species in the Netherlands. Lake Marken (including Lake IJ) is an important national and international area for birds, whether they be piscivorous, mussel-feeding, or aquatic plant-feeding.

The Lake IJssel system is a large system that consists of two large lakes and a series of smaller "border lakes" around part of the reclamated areas that are closely connected to each other (Figure C.1). Within FutureLakes we have defined the Lake IJssel complex as the combination of Lake IJssel and Lake Marken (with the latter including Lake IJ). Furthermore, although the lake complex is officially part of the Rhine catchment, due to its relatively small size in comparison to the whole Rhine catchment, we will only discuss the direct catchment of the lake complex as defined by the Dutch government (Figure C.2).

For an overview of the chemical and hydromorphological status of both lakes see Table C.1.

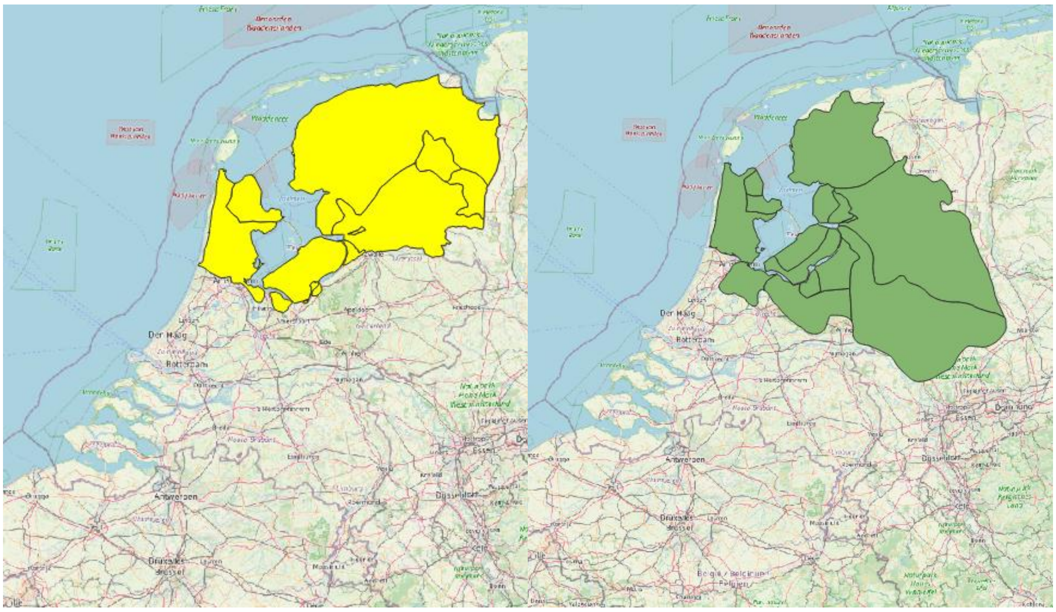


Figure C.2. Direct catchment area of the Lake IJssel complex. Left: the area that receives water from the Lake IJssel complex. Right: the area that (can) supply water to the Lake IJssel complex (i.e., a large part of North Holland will only supply water to Lake IJssel under exceptional circumstances). Source: Rijkswaterstaat (2025).

1.2.2 Restoration measures

Here we list the main developments and restoration measures in the Lake IJssel complex from 1932 until the present. This timeline has been adapted from the timeline from de Haan et al. (2019). A visual overview of the timeline can be found in Figure C.3. A map containing the Nature-based Solution (NbS) and Biodiversity-focused Solution (BfS) locations can be found in Figure C.4. The *implementation* costs of the different NbS and BfS measures, as far as known to us, have been listed in Table C.2. *Operational* costs have not been included due to their limited availability. Other costs, such as the impact of the nutrient reduction measures (regulations implemented in the catchment), the implementation and maintenance of the wastewater treatment plant in Amsterdam and the implementation and impact of the fishing regulations would have been valuable to include too. However, we were unable to find values for these costs. Due to the large number of measures taken for the improvement of the fish in both ecosystems, e.g., the creation of fish passages and the adjustment of sluice management for the benefit of fish, we added this element as a single effort. Finally, the costs of the upgrade of the Markermeer dikes are a combination of costs for improvements for flood protection and nature. We were unable to distinguish between these two elements and thus we included the full (estimated) costs.

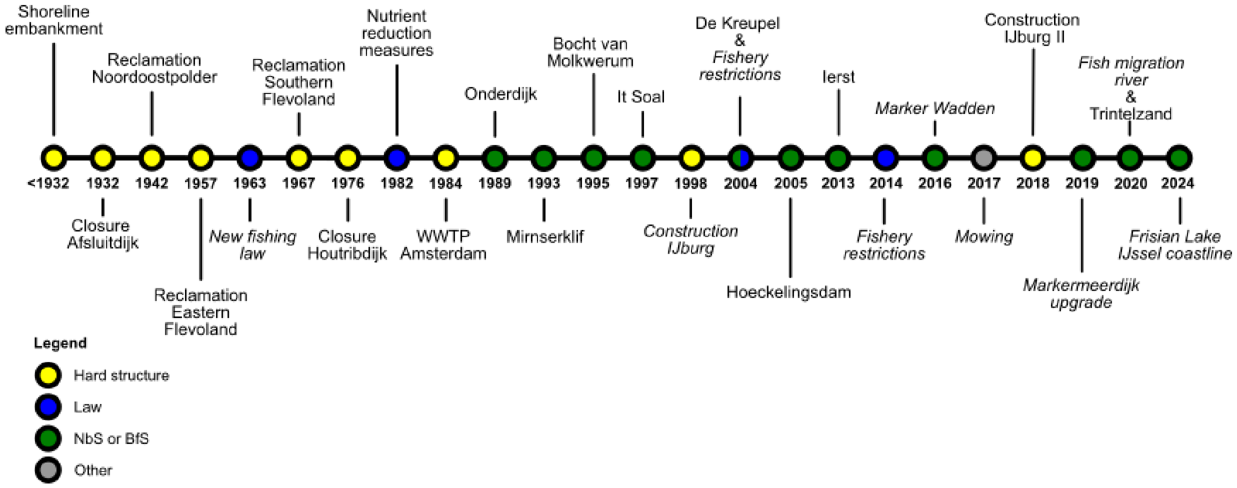


Figure C.3. Timeline of developments and restoration measures in the Lake IJssel complex. Italic text indicates the start of a development or measure, regular text indicates the finalization of a development or measure. This Figure was adapted from Figure 3-1 in Haan et al. (2019).

<1932 The shoreline of the Zuiderzee was embanked to protect coastal villages and meadows from flooding. These embankments, along with the conversion of marshland into agricultural lands, led to the loss of habitats for fish to live, spawn, and grow. The disappearance of land-water transitions not only impacted fish but also caused a decline of macrozoobenthos and zooplankton.

1932 After the closure of the Zuiderzee by the Afsluitdijk, this former salt and brackish water bay became a freshwater lake. The former tidal motion became a (more or less) fixed water level, and fish migration routes vanished. These changes led to the rapid disappearance of marine and estuarine flora and fauna, while phytoplankton, macrophytes, macrofauna, and fish typical of freshwater ecosystems increased in number. However, although the water column and its inhabitants switched from a tidal to a freshwater ecosystem in a matter of years, the sediment would maintain (part of) its marine characteristics for decades.

1942 The Noordoostpolder was the first large polder to be reclaimed from Lake IJssel. This led to the disappearance of a large area of open water and a reduction of shallow water areas. Additionally, two small islands, and their associated habitats, were ‘swallowed’ by the polder.

1957 Eastern Flevoland was reclaimed, further reducing the area of open and shallow water.

1963 The new ‘Fisheries Act’ banned fishing for pike-perch using beam trawls or seines. A few years later, beam trawling was banned entirely and replaced by trap nets and gillnets, mainly to continue eel fishing (however, these techniques also resulted in considerable bycatch).

1967 Southern Flevoland was reclaimed, further reducing the area of open and shallow water.

1976 Completion of the Houtribdijk split the former Lake IJssel in two: Lake IJssel and Lake Marken (together referred to as “The Lake IJssel complex” in this report). The Houtribdijk substantially reduced water exchange between the two lakes. As a result, the amount of silt in the Markermeer increased because it was no longer discharged into Lake IJssel. Fish migration between the lakes also became heavily restricted.

1982 From the 1950s onwards, eutrophication started to become a problem for surface water quality. Due to reduced phosphorus input (e.g., through increased use of phosphate-free detergents), however the concentration of nutrients entering the Lake IJssel complex decreased from the mid 1980s. A large contributor to this reduction were the German efforts to improve the water quality in the River Rhine. Another important factor was the fact that the wastewater treatment plant (WWTP)-East in Amsterdam was taken into use (Waternet, N.D.). This finally stopped the transport of Amsterdam's wastewater into Lake Marken via the large drainage pipe nicknamed 'De Smeerpijp' (roughly translated: 'the filthy pipe'). This wastewater drainage pipe, that was commissioned in 1907, deposited up to 100 000 m^3 of wastewater per day at its peak use (van den Dobbelsteen, 2012).

1989 Development of a foreshore area near the village Onderdijk. These foreshores offer habitat for a.o. birds.

1993 (Mirnserklif) and **1995 (**Bocht van Molkwerum) Additional foreshores are developed on the Frisian coast line of Lake IJssel. These foreshores offer habitat for a.o. birds as well and (will) consist of reed marshes.

1997 The development of a sandbank and a recreational zone (It Soal) on the Frisian coast of Lake IJssel.

1998 Construction of the IJburg residential area in the IJmeer began. To compensate for its impact on nature, Rijkswaterstaat created the Hoeckelingsdam (see 2005) in a shallow bay in the south of Lake Marken.

2004 Due to declining eel and smelt populations over the last decades, measures were taken to reduce the number of traps, eel boxes, gillnets, and fishing permits. Additionally, work on the nature area De Kreupel (an island in Lake IJssel) was finalized.

2005 The Hoeckelingsdam was created as a nature compensation area for IJburg (see 1998). This dam created wind-shelter for a small section of Lake Marken and stimulated the growth of submerged macrophytes via an increase in the transparency of the water. Furthermore, the land was intended to function as a breeding and resting area for birds.

2013 The first (pilot) island "Ierst" for the Marker Wadden is created in Lake Marken.

2014 Further interventions in fisheries were taken: the allowance of high-standing nets was reduced by 85% to halt the decline in scaled fish populations. Low-standing nets were permitted instead, which are used to catch Chinese mitten crabs, among others. Recent studies show that the impact of the fishing interventions have started to result in more and larger adult fish (pers. comm. J.J. de Leeuw; Wageningen University & Research).

2016 The construction of the Marker Wadden began. This group of islands would reduce the area of open water but increase the area of shallow land-water transitions. This new nature reserve was originally intended to stimulate the bird populations in the area, but the gradual transition from land to water around the Marker Wadden also created a suitable habitat for various aquatic plants and fish.

2017 To improve passage for recreational boating, water plants in the Hoornsche Hop began to be mowed.

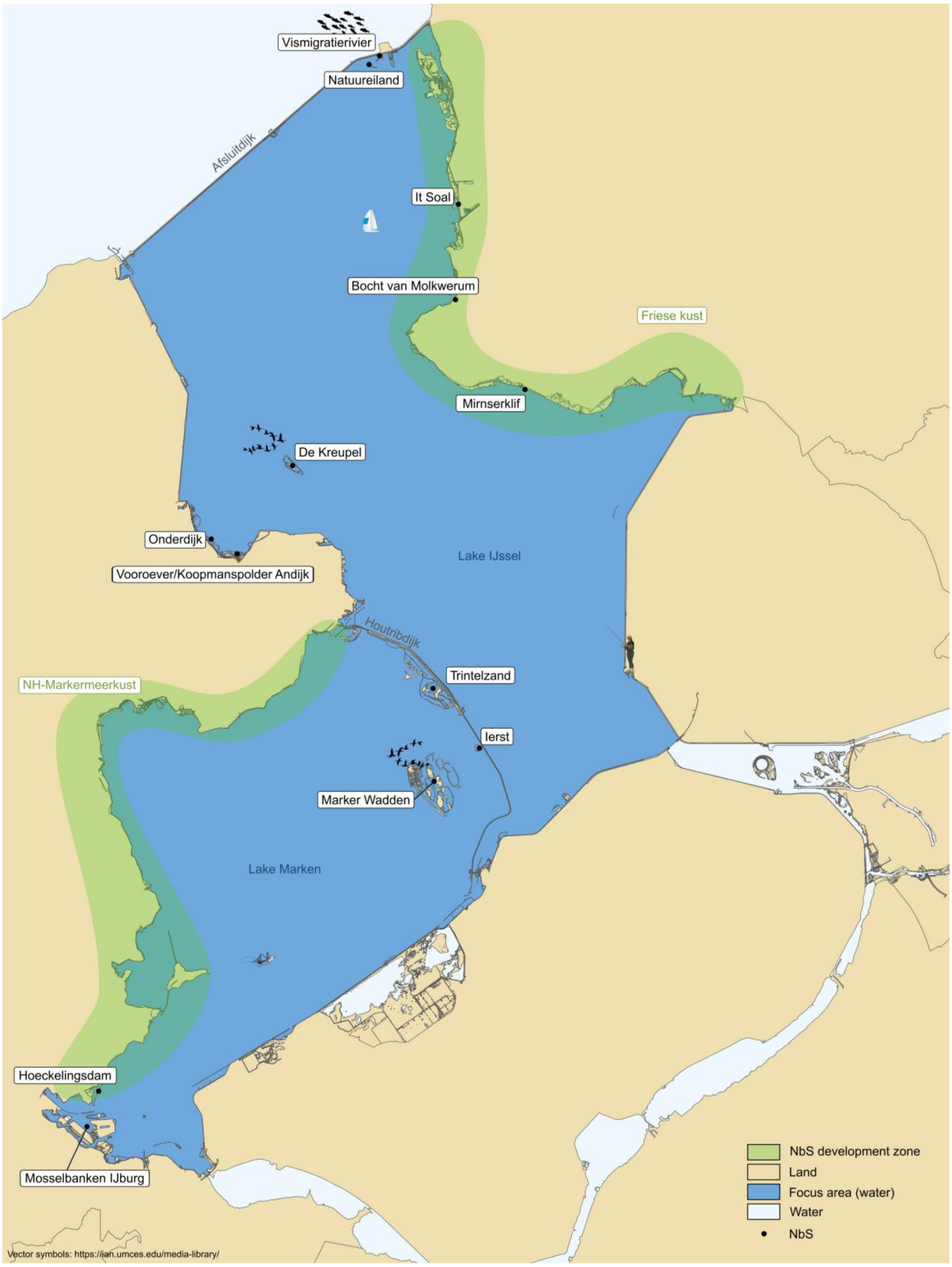
2018 Strengthening of the Houtribdijk between Enkhuizen and Trintelhaven began. This reinforcement reduced open water area but created gradual land-water transitions in some places. Additionally, the construction of IJburg II began.

2019 Strengthening of the Markermeer dikes began. The strengthening of the dike was designed to also increase the area of land-water transitions and thereby restore part of the food web of the lake.

2020 To restore the connection between the Wadden Sea and the Lake IJssel complex, work was started on the fish migratrion river. A large structure in the Afsluitdijk in which the salt water of the Wadden Sea will be mixing with the freshwater from Lake IJssel, thereby allowing migrating fish to travel freely again. The work is estimated to be finished in 2027. Additionally, the work on Trintelzand and the Houtribdijk was finalized in this year. These works have strengthened the function of the dike and created wetland habitat for fish and birds.

2024 Multiple projects started to improve the water safety and ecological quality of the Frisian Lake IJssel coastline.

It should be noted that Lake Marken and Lake IJssel are valuable areas to the Netherlands for flood safety, freshwater provisioning and nature. These elements are closely linked, and sometimes conflict with each other. For example, flood safety measures that have been taken in the past (dykes) impose limits to the type of measures available to restore the water quality and ecology in this area. In specific, the removal of dykes to restore the lack of shallow land-water transitions or the reversal of the seasonal fixed water levels to make them reflect more natural conditions are not possible. At the same time is the (natural) functioning of the ecosystem closely related to the water quality desired for both drinking water purposes and nature restoration. Thus, it can be a challenge to ensure that each element is managed in the most optimal way. However, even though this balancing act remains challenging, the most optimal solutions are most likely to arise from steering these functions in conjunction, rather than as separate silos.



Vector symbols: https://ian.umces.edu/media-library/

Figure C.4. Locations of Nature-based Solutions and Biodiversity-focused Solutions in Lake IJssel and Lake Marken.

Table C.2. Costs of Nature-based Solutions (NbS) or Biodiversity-focused Solutions (BfS) taken in the Lake IJssel complex. Additionally, we mention the costs of the largest infrastructural effort in the area for comparison: the Afsluitdijk and mention the building of Waste Water Treatment Plant - East.

Solution (BfS, NbS, Other)	**Year**	**Area (ha)**	**Implementation costs (M€; est. 2025)**[1]	**Financing**	**Source**
Afsluitdijk *Dyke to close Lake IJssel (Other)*	1932	-	37800	Public	CBP (2012)
Onderdijk *Reed marsh (BfS)*	1989	100	N.A.	Public	Min. van LNV en Min. van VW (2002)
Mirnserklif *4 Sandbars (BfS)*	1993	10	N.A.	Public	Min. van LNV en Min. van VW (2002)
Bocht van Molkwerum *3 Islands for birds (BfS)*	1995	9	N.A.	Public	Min. van LNV en Min. van VW (2002)
It Soal *Sandbar + recreational zone (NbS)*	1997	25	N.A.	Public	Min. van LNV en Min. van VW (2002)
De Kreupel *Island for birds (NbS)*	2004	75	19.2	Public	Min. van LNV en Min. van VW (2002)
Hoeckelingsdam *Dam to dampen wind impact (NbS)*	2005	50	48.4	Public	SBB (2003)
Marker Wadden *Wetland islands (NbS)*	2021	800	96.3	Public / Private	Hüskens et al. (2025)
Trintelzand I *Natural foreshore (NbS)*	2018[2]	N.A.	7.8	Public	Waterrecreatie Nederland (2023)
Trintelzand II *Natural foreshore (NbS)*	2020	155	8.7	Public	Waterforum (2019)
Fish migration river *Structure in Afsluitdijk to stimulate fish migration (BfS)*	2026[2]	90	67	Public	Waterforum (2025)
Markermeerdijken upgrade *Natural foreshores (NbS)*	2026[2]	N.A.	≤ 786.9	Public	NH Nieuws (2019)
Fish friendly environment *> 20 Fish passages and sluice management adjustments (NbS), excluding the fish migration river*	2010 - 2027	-	N.A.[3]	Public	Rijkswaterstaat (2025)

[1)] Corrected for inflation with the inflation calculator at https://www.inflatiecalculator.nl/

[2)] Estimation.

[3] Actual costs unknown. However, the costs of creating a fish passage lies between several tens of thousands (for easy and small passages) to several million euros (for more complex cases) according to Wanningen (2015). Thus, this cost is likely to be at least several hundreds of thousands – several million euros.

1.3 Evaluation of existing restoration programme

In this section we describe the status of Lake IJssel and Lake Marken and the impacts of restoration efforts in these lakes according to criteria that were selected in the FutureLakes project.

1.3.1 WFD

The WFD status of Lake IJssel and Lake Marken has failed to achieve a good status over the last three River Basin cycles and during its last available assessment (2024). An overview of the respective statuses can be found in Table C.3.

Table C.3. WFD status for the quality elements chemistry and ecology per River Basin cycle and in 2024. Colour codes are according to the WFD: red for chemistry = fails to achieve good status, orange for ecology = poor, yellow for ecology = moderate.

Lake name	**Quality element**	**2009**	**2015**	**2021**	**2024**
Lake IJssel	Chemistry	🟥	🟥	🟥	🟥
	Ecology	🟨	🟨	🟨	🟨
Lake Marken	Chemistry	🟥	🟥	🟥	🟥
	Ecology	🟨	🟨	🟧	🟧

The chemical status of both Lake Marken and Lake IJssel continues to fail to achieve good status. This failure to achieve a good status is due to multiple substances surpassing the thresholds, among which are PAC's (polycyclic aromatic hydrocarbons), pesticides and heavy metals (Knoben et al., 2025). Part of these substances are transported into the system from outside the Netherlands (e.g., via the river Rhine) and part of these substances are transported into the system from within the Netherlands (e.g., due to their use on agricultural fields) (Knoben et al., 2025).

The ecological status of both Lake Marken and Lake IJssel also continues to fail to achieve good status. The Biological Quality Elements that underlie the ecological status are at moderate or poor status (see Figure C.5, C.6). The reasons underlying the failure of obtaining a good status for these quality indicators are, amongst others, a lack of migration options for fish (the dykes prevent free access between the two lakes and between the lakes and the Wadden Sea for example), the turbidity caused by wind effects in Lake Marken, the lack of shallow land-water transitions in both lakes, the skewed nutrient ratios, and the still high nutrient levels of nitrogen (Figure C.7) in Lake IJssel.

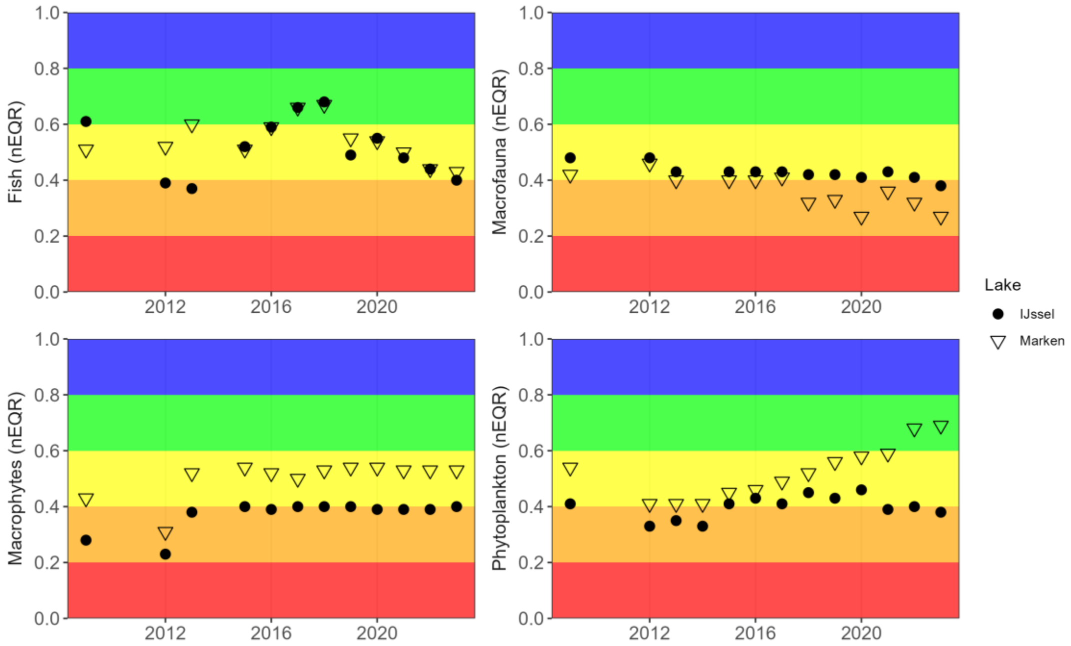


Figure C.5. Biological Quality Elements in Lake IJssel and Lake Marken between 2009 and 2024 expressed in normalized Ecological Quality Ratios.

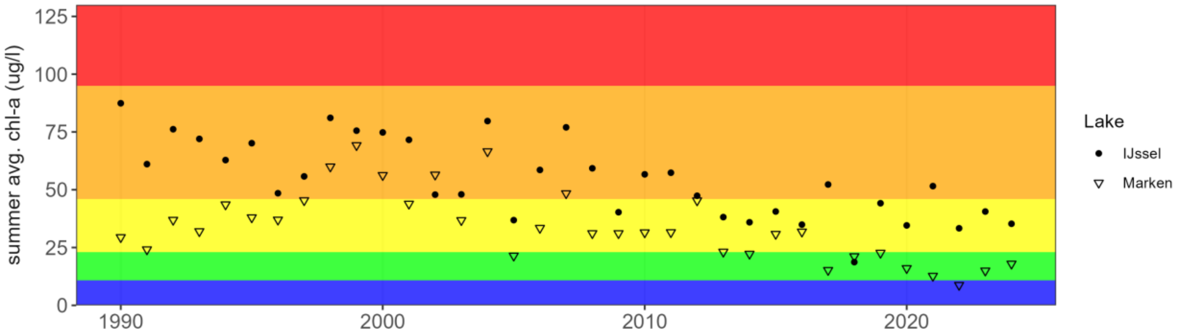


Figure C.6. Summer averaged (1 Apr – 30 Sep) chlorophyll-a concentrations in relation to their WFD status in Lake Marken and Lake IJssel between 1990 and 2024. WFD thresholds are according to current values.

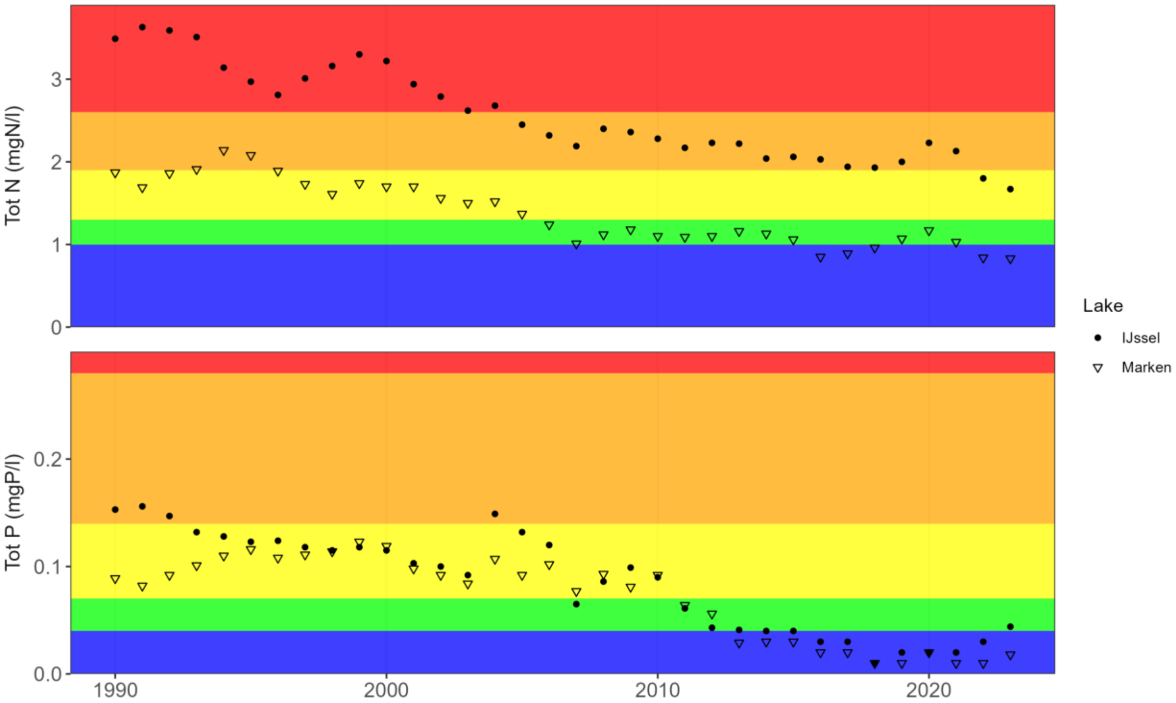


Figure C.7. 3-year summer averaged total nitrogen and total phosphorus concentrations and their respective statuses in Lake Marken and Lake IJssel between 1990 and 2024 according to (current) WFD thresholds. Data source: KRW-NUTrend (https://krw-nutrend.netlify.app/).

Lake IJssel and Lake Marken both use a single monitoring location in the centre of their water body to determine their ecosystem status for nutrients and phytoplankton. However, both lakes can be quite heterogenous in regard to their chlorophyll-a distribution. For example, the Centre - Northern parts of Lake IJssel can become quite phytoplankton-rich over summer, while the Southern parts of the lake can remain quite clear – likely due to mussel grazing in the Southern parts of the lake. Although we did not investigate the impact of having a single monitoring location, we think it likely that having a single monitoring point for both lakes skews the WFD outcomes.

1.3.2 Biodiversity net gain

Lake Marken and Lake IJssel have been designated as a Bird Directive area and partly as a Habitat Directive area under Natura 2000 (Table C.4 and Figure C.8; Ministerie van LVVN, 2025). For Lake Marken conservation objectives have been established for two habitat types (H3140 Hard oligo-mesotrophic waters with benthic vegetation of Chara spp, H3150 Natural eutrophic lakes with Magnopotamion or Hydrocharition-type vegetation), three habitat species (spined loach *Cobitis taenia*, bullhead *Cottus perifretum*, and pond bat *Myotis dasycneme*), and two breeding bird species (great cormorant *Phalacrocorax carbo* and common tern *Sterna hirundo*). Conservation objectives have also been set for 18 non-breeding bird species, including the common goldeneye *Bucephala clangula*, Eurasian wigeon *Mareca penelope*, goosander *Mergus merganser*, and smew *Mergellus albellus*. For Lake IJssel conservation objectives have been established for six habitat types (e.g., H3140 Hard oligo-mesotrophic waters with benthic vegetation of Chara spp and H6430 Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels), four habitat species (pond bat, river bullhead, fen orchid *Liparis loeselii* and an endemic subspecies of the Root Vole *Alexandromys oeconomus*), and 11 breeding bird species, including the cormorant and the Eurasian spoon bill *Platalea leucorodia*. Additionally, conservation objectives have also been set for 31 non-breeding bird species.

Table C.4. Natura 2000 area sizes for Lake Marken and Lake IJssel.

	Lake Marken (incl. IJmeer)	**Lake IJssel**
Bird Directive area (ha)	68463	113341
Habitat Directive area (ha)	1109	2441
Total area (ha)	*68463*	*113341*

For the species protected under Natura 2000, the size and quality of their respective habitats must be maintained or improved to support the carrying capacity of predetermined population sizes. The goals differ per species and per location, however, for most species in the Lake IJssel complex the goal is maintenance. The last known conservation status that has been reported for each (non-bird) species is shown in Table C.5. In the following text, we describe the status of the Root vole and the Pond bat in more detail and give a general overview of the status of birds.

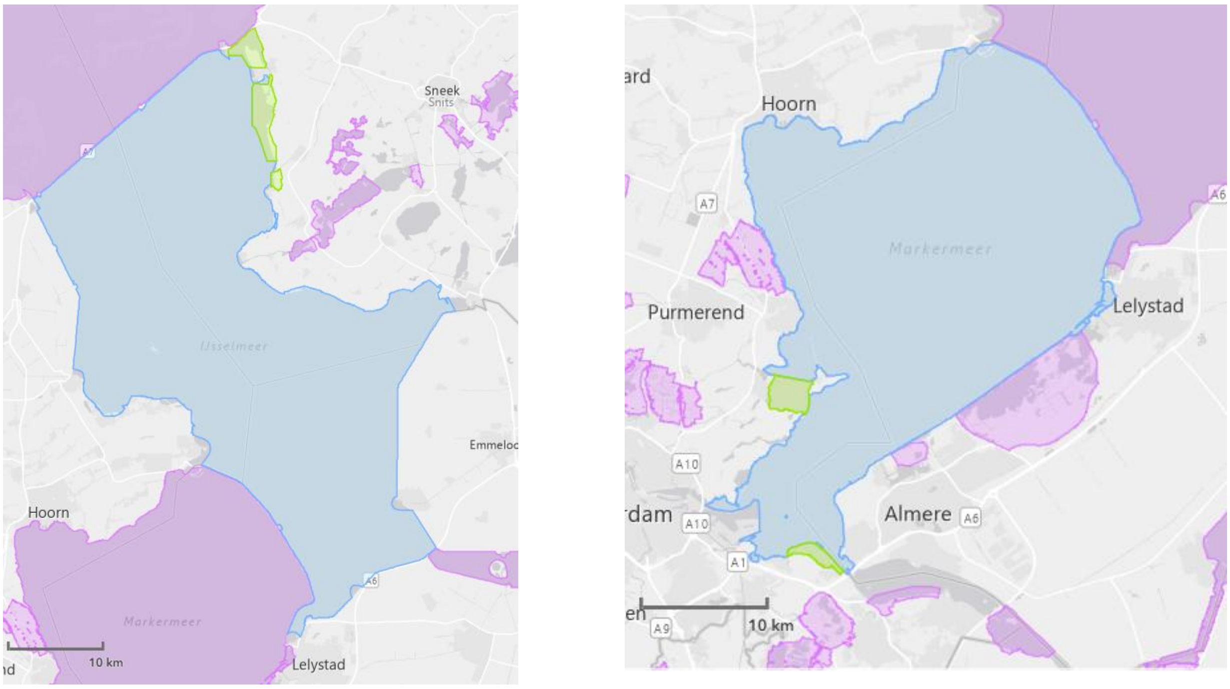


Figure C.8. Natura 2000 areas in Lake IJssel (left) and Lake Marken (right) in blue and green (Blue = Bird Directive areas, green = Bird Directive + Habitat Directive areas). Purple = other Natura2000 areas in the Netherlands.

Table C.5. Conservation status of Natura 2000 non-bird species that occur in the Lake IJssel complex for the Netherlands as a whole (WUR, 2020) and the population and habitat status of the non-bird species in Lake IJssel (RWS, 2025a) and Lake Marken (RWS, 2025b). The colors for population and habitat status indicate red = unfavorable, green = favorable, orange = favorable but requires attention, grey = not enough data available. The signs indicate the goals for each species with = meaning maintenance and > meaning improvement.

Species	**Conservation status in the Netherlands in 2019**	**Lake IJssel**		**Lake Marken**	
		Population	**Habitat (size & quality)**	**Population**	**Habitat (size & quality)**

Pond bat	Highly unfavorable	=	=	=	=
Root vole	Highly unfavorable	>	> & =	Not applicable	Not applicable
Bullhead	Highly unfavorable	=	=	=	=
Spined loach	Stable	Not applicable	Not applicable	=	=
Fen orchid	Stable	=	=	Not applicable	Not applicable

The conservation status of the pond bat in the Netherlands been described as highly unfavorable in 2019 (WUR, 2020). As there is no information available on the population size of the Pond Bat in Lake Marken, its conservation status cannot be assessed (Rijkswaterstaat, 2025b). A large decline in the population is observed in Lake IJssel (from approx. 440 individuals in 2006 to 250 in 2023). Around the Lake IJssel complex, the roosting sites of the bats are under pressure, as older buildings (often containing wall cavities and roof tiles) are replaced. Its foraging area, comprising of gently sloping, nature-friendly banks with dynamic water-levels, is expected to be stable in Lake IJssel, suggesting favourable habitat conditions (Rijkswaterstaat, 2025a). Although no trends in the extent or quality of its habitat are known for Lake Marken, significant parts of the shoreline vegetation are presumed to be too young to provide a high-quality foraging habitat. However, an improvement in habitat quality is expected in the coming years, partly due to the construction of the Marker Wadden. One of the main issues to protect this species is the fact that the majority of breeding areas, flying routes and foraging areas are located outside of the Natura 2000 sites (Haarsma, 2024).

The population and habitat of the northern vole have been assessed as moderately unfavorable in the Netherlands (WUR, 2020), while its distribution range and prospects are considered highly unfavorable. Subpopulations of northern voles are often isolated, which substantially increases the risk of local extinction. Except for the area north of the North Sea Canal in North Holland, the species is declining in all regions due to competition with other vole species. Consequently, the conservation status of the northern vole in the Netherlands has been reported as highly unfavorable. The root vole occurs along the shores of Lake IJssel in wet habitats such as reed beds, marshes, and extensively managed grasslands. The species is well adapted to wet conditions and benefits from dynamic water-level control. Over the past decades, its spatial range has severely reduced. While its conservation objectives were an increase in population and habitat size, both have decreased. A reduction in habitat quality, through reduced water level fluctuations and vegetation management, further increases the competitive advantage for other vole species (Rijkswaterstaat, 2025a).

The conservation status for the spined loach is favourable. Although the observed population size strongly fluctuates over the years, there is no downward trend. This suggests a relatively stable population (Rijkswaterstaat, 2025b). The habitat of the spined loach, comprising shallow, vegetated, low-flow aquatic zones with soft substrates, is also deemed stable. Targets were only set for Lake Marken. The bullhead, on the other hand was not observed since 2015 and only rarely observed before that (Rijkswaterstaat, 2025a, 2025b). Because of this, the conservation objective for the population size of the bullhead is not met. This species shows a preference for hard substrates, such as reinforced banks, stones, and mussel beds. In Lake Marken, their absence is presumably linked to a decline in freshwater mussels and competition with invasive goby species. The sensitivity of the bullhead to water pollution further weakens their position with respect to the more tolerant invasive species. Because of this, their habitat conservation objectives are also not met. While a decline in hard substrates is not observed in Lake IJssel, the current habitat conditions are also deemed unfavorable, due to ongoing competition with invasive goby species.

The fen orchid grows on nutrient-poor, alkaline soils and prefers an open vegetation structure. This species was found on a lime-rich sandbar in the north-eastern corner of Lake IJssel (Makkumer Noordwaard). It was last observed in 2004. Throughout the country, desiccation, acidification, and eutrophication threaten the survival of this orchid. While conservation targets aimed to facilitate the return of this species, its habitat size and quality have only declined further over the past years (Rijkswaterstaat, 2025a).

For many bird species with conservation objectives, numbers have declined sharply since the 1980s, and in recent decades, these objectives have not been met (Noordhuis et al. 2014). Mainly benthivorous birds (benthic-invertebrate-eating birds such as goldeneye, Figure C.9) and piscivorous birds (fish-eating birds such as smew, Figure C.10) have declined substantially in number. Factors that have contributed to this decline of birds in Lake IJssel and Lake Marken are climate change and the improvement of water quality in neighbouring lakes. In specific, climate change has caused mild winters in Northern Europe which has caused wintering birds to stay away (van Roomen et al. 2012) while the improvement of neighbouring lakes has caused birds to stay at these improved lakes (Noordhuis et al. 2014). However, even though a substantial amount of Natura 2000 bird species experiences a decline in number, overall, the Lake IJssel complex remains an area of vital importance to many overwintering and breeding bird species.

For species in the first two categories, conditions deteriorated in the 1990s due to a decline in zebra mussels in the lake and a decline in smelt in both Lake IJssel and Lake Marken. The first process is linked to reduced nutrient availability after the construction of the Houtribdijk combined with high silt loads, while the second process may be climate-related. Despite these declines, the numbers of tufted ducks and smew remain of international and major national importance and the area's significance for large concentrations of moulting waterbirds has not diminished.

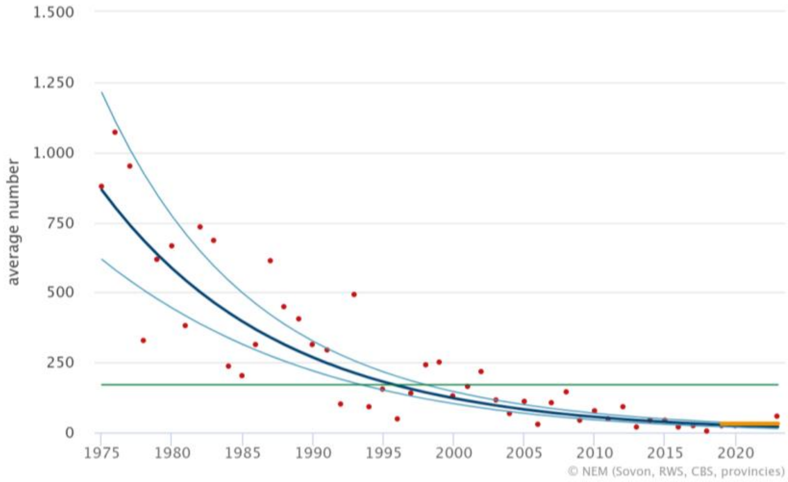


Figure C.9. The average number of Common Goldeneye in Lake Marken (red dots), the trend line (dark blue) and associated standard error (light blue lines) are given. Seasons run from July to June. In green the Natura 2000 goal for the species. The orange line represents the average of the last five seasons. Source: www.sovon.nl.

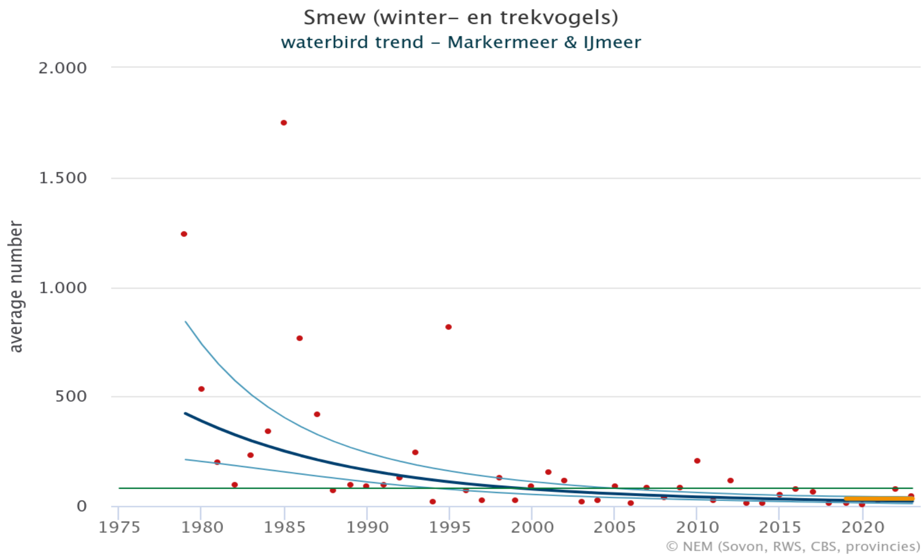


Figure C.10. The average number of Smew in Lake Marken (red dots), the trend line (dark blue) and associated standard error (light blue lines) are given. Seasons run from July to June. In green the Natura 2000 goal for the species. The orange line represents the average of the last five seasons. Source: www.sovon.nl.

1.3.3 Zero pollution

Phytoplankton blooms were a common phenomenon in Lake IJssel until the 2000s (Leeuwangh et al. 1983; Berger and Sweers 1988; Ibelings et al. 2005) (Figure C.11). However, total phosphorus (TP) and total nitrogen (TN) concentrations in Lake IJssel (Figure C.12, A & B) and Lake Marken substantially declined in the 1970s and 1990s due to the implementation of the Dutch Pollution of Surface Water Act, the European dairy produce quota and a ban on P detergents in Germany and the Netherlands (Rozemeijer et al. 2021). This downward trend is also visible in estimated external phosphorus loadings for this time period (Figure C.13, also not the sharp contrast between the nutrient loading between Lake Marken en Lake IJssel). The changes in legislation had a larger impact on the total phosphorus than on total nitrogen, leading to a shift in the NP-ratio in the lakes (Figure C.12, C). Hitherto, Lake IJssel still qualifies as eutrophic, with cyanobacteria as the dominant phytoplankton species (Frenken et al, 2023). It remains unclear if TN or TP or both should be reduced further to obtain better food quality and lower biomass (Frenken et al, 2023).

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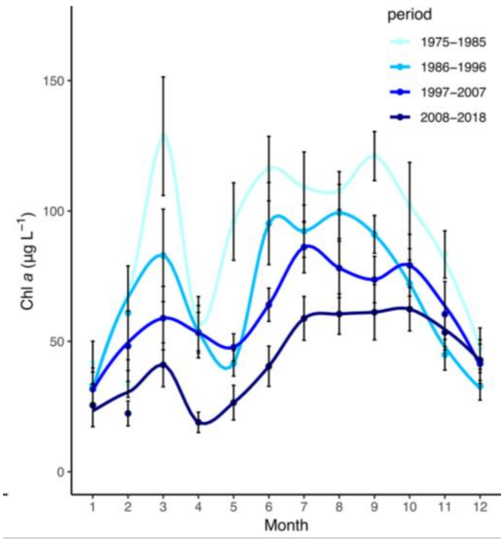

Figure C.11. Seasonal trend of Chl a in Lake IJssel. Trend lines represent loess-smoothed conditional averages. Source: Frenken et al. 2023 (Figure copied with permission).

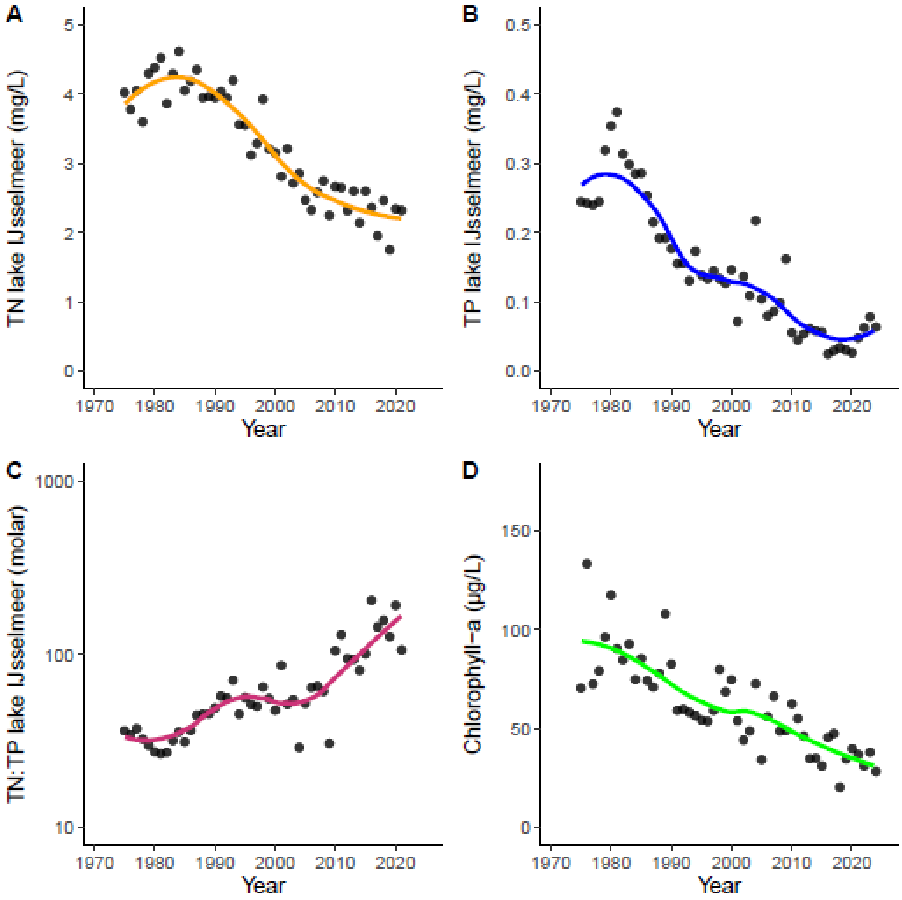

Figure C.12. Concentrations of TN (A) and TP (B), TN:TP ratio (C) and chlorophyll-a concentrations (D) of Lake IJssel surface water. Trend lines represent loess-smoothed conditional averages. Note that (C) is plotted on a logarithmic scale. Source: Frenken et al. 2023 (Figure updated by T. Frenken and used with permission).

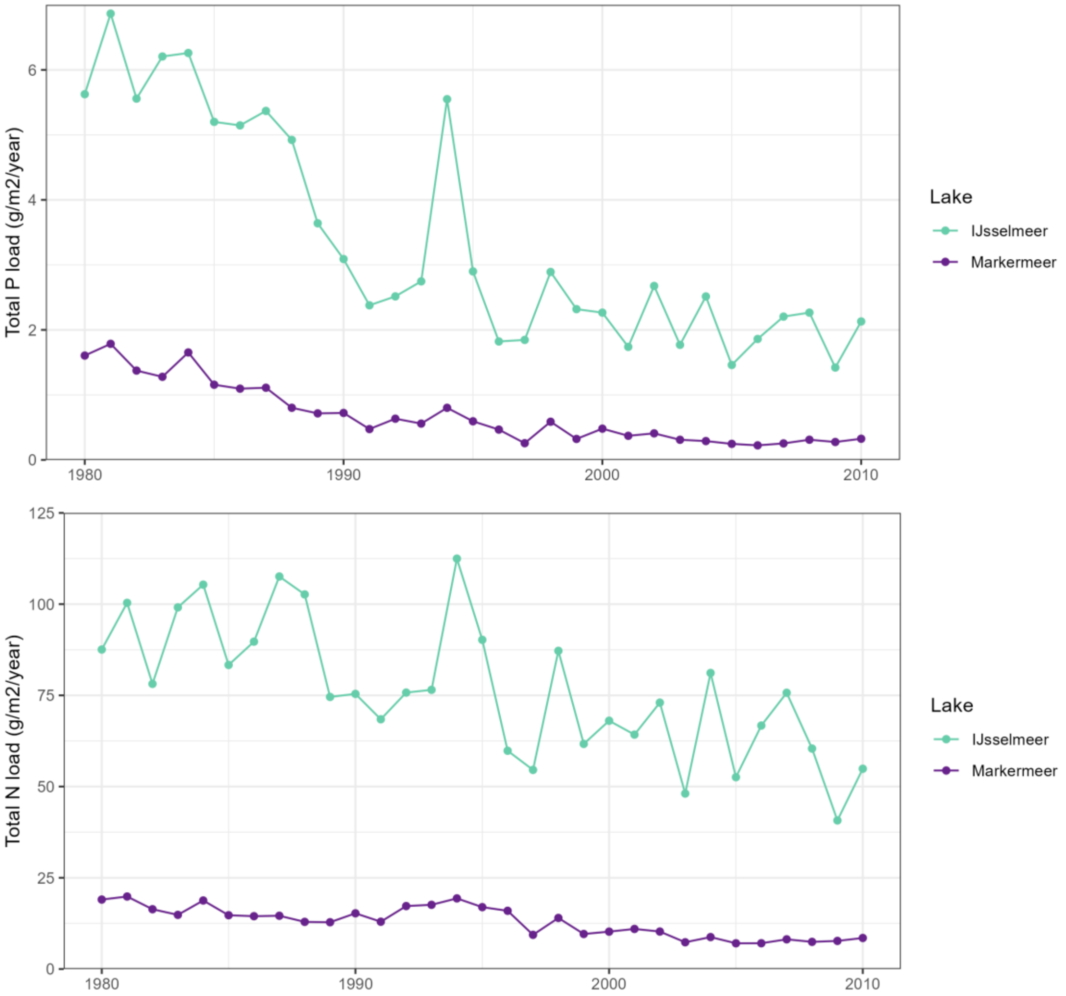

Figure C.13. Estimated water-transported total phosphorus loads (Total P) and nitrogen loads (Total N) for Lake Marken (purple) and Lake IJssel (blue-green) between 1980 and 2010. The figure shows a notable decrease in P loading and a small decrease in N loading over time, reflecting the mitigating effect of policy measures. The numbers are based on unpublished data from the ANT-project (van der Geest, Vonk and Ouboter, 2017) and Noordhuis et al., 2024.

Figure C.14 and C.15 show the available data for an array of water quality parameters between 2015 and 2024. Here we highlight a few elements: from the Biological Oxygen Demand (BOD) data it becomes clear that Lake IJssel has relatively clean water (<2 mg/l defined as clean, and 3-5 mg/l defined as moderately clean) with values fluctuating around 2 mg/l (Figure C.14). Furthermore, we can see that Lake Marken contains more Dissolved Organic Carbon (DOC) than Lake IJssel (Figure C.14). Additionally, Total Nitrogen, Nitrate and Phosphate concentrations are substantially higher in winter in Lake IJssel than in Lake Marken (Figure C.15).

There are no exact numbers for the total amount of plastic pollution in Lake IJssel and Lake Marken. However, based on estimates made by Margriet Schoor, advisor Ecology and Water Quality at Rijkswaterstaat, an average of 60 – 70 million pieces of (macro)plastic likely reached Lake IJssel via the river IJssel in 2023[19] (Schone IJssel, 2023). A large part of these plastics (~ 75%) originates in Germany and Switzerland, however, a substantial amount of plastic is added into the mix in the Netherlands as

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[19] On average 6.5 plastic pieces per 1000 m^3 water in the river IJssel. The river IJssel is the main river that flows into Lake IJssel and contributes on average 72% of the water supply to the lake.

well. Most common plastics that occur in the river come from food packaging and cosmetics (Eikelboom, 2023). Additionally, (macro)plastics can be found in on the shores of the lakes, as demonstrated by a voluntary clean-up effort on Trintelzand in 2025, where volunteers found, amongst others, plastic bottles and food packaging on the shoreline of a protected area. We have not found any data on microplastics in the Lake IJssel complex.

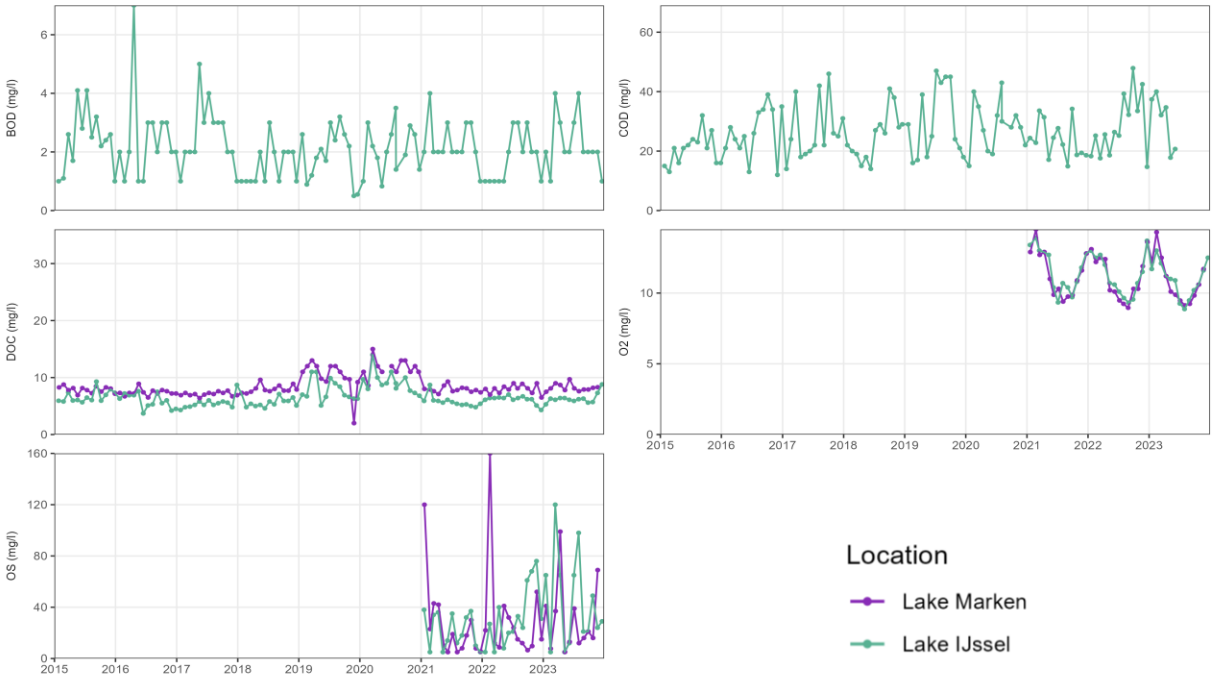

Figure C.14. Chemical measurements in Lake Marken and Lake IJssel between 2015 and 2023. BOD = Biological Oxygen Demand, COD = Chemical Oxygen Demand, DOC = Dissolved Organic Carbon, O_2 = Oxygen, OS = Dissolved substances.

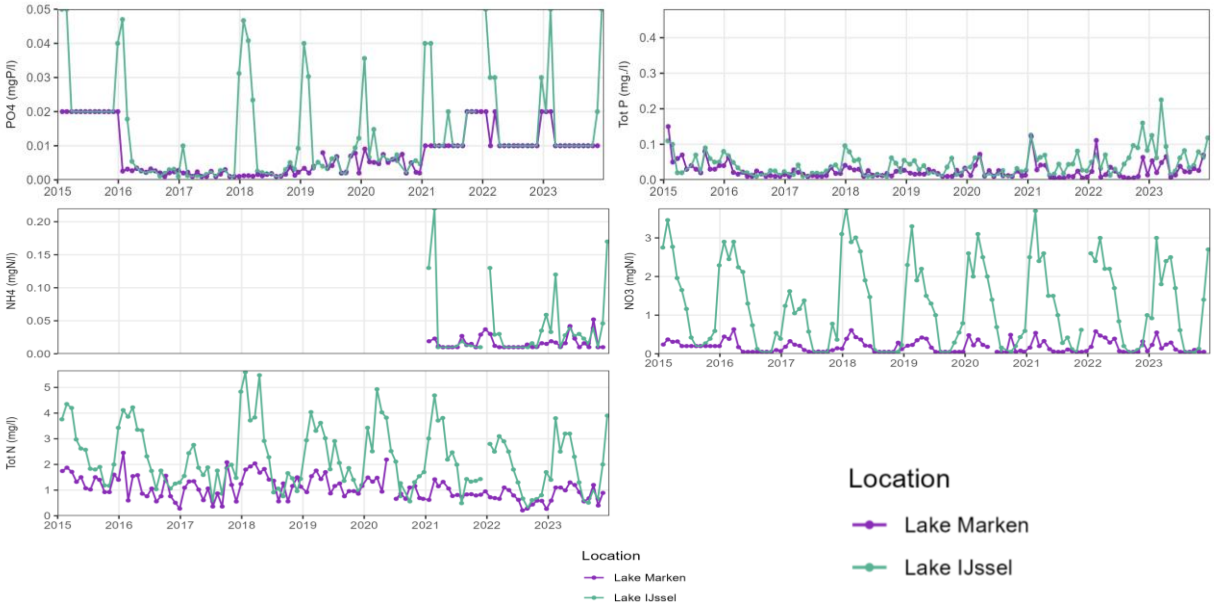

Figure C.15. Nutrient concentrations in Lake Marken and Lake IJssel between 2015 and 2024.

1.3.4 Climate regulation

Climate regulation has been defined as the emission of CO_2 from the lake and/or the carbon sequestration in the lake. Here we describe two approaches to estimate CO_2 emissions from the Lake IJssel complex and one approach to estimate the carbon sequestration in the complex.

The Lake IJssel complex emits 263 661 tonne CO_2-eq/year. This CO_2-equivalent is an estimation based on the IPCC default emission number for reservoirs remaining reservoirs (1.46 tonne CO_2-eq/ha/year; CH_4-emissions only as per IPCC guidelines) multiplied by the total surface area of the Lake IJssel complex (180 590 ha). For more information see Pelsma and Kox (2025) and Net et al. (2024).

The impact of the constructed wetland “Marker Wadden” on the emitted CO_2-equivalents of the Lake IJssel complex is a reduction of 1460 tCO_2-eq/year (roughly 0.5% of the total CO_2-eq emission). This estimate is based on the assumption that no carbon stock changes are considered for (constructed) wetlands (Baren et al., 2025) and that the Marker Wadden covers ~1000 ha of the Lake IJssel complex (1000 ha * -1.46 tonne CO_2 -eq/ha/year = -1460 tonne CO_2 -eq/year).

Please note that the above-mentioned estimates are rough estimates and that at this point in time no measurements are available to verify these estimates. Furthermore, although the Marker Wadden might become CO_2-neutral in the future as indicated by the IPCC guidelines, during their construction the islands likely have produced a substantial amount of CO_2(-eq). Additionally, it is not unlikely that the islands could also sequester CO_2 while in their early succession stages.

Aside from the previously mentioned GHG emission estimates based on IPCC default values, E. Kitson from UK-CEH applied a Bayesian model constructed from a global dataset of ground-based methane measurements and satellite-derived chlorophyl-a data to the yearly average chlorophyll-a values from Lake IJssel and Lake Marken to estimate the methane emissions from these lakes between 2005 and 2024. The model results (Figure C.16) show that the average total methane emission between 2005 – 2023 from Lake IJssel according to this model would be estimated at 26.6 Gg CH_4-C/year and from Lake Marken would be estimated at 60.5 Gg CH_4-C/year (total emission from both lakes at 87.2 Gg CH_4-C/year).

The conversion of CH_4-C to CO_2-eq[20] shows that the Bayesian model from UK-CEH estimates substantially higher methane emissions from the Lake IJssel complex than the estimate based on the IPCC default values:
87.17 Gg CH4-C/year x 29.88 CH_4:CO_2eq x 1.34 Carbon:CH_4 = 3474.09 Gg CO_2-eq/year (range 10 percentile - 90 percentile: 1208.05 to 8010.95 Gg CO_2-eq/year) versus 263 661 tonnes CO_2-eq/year / 1000 = 264 Gg/year.

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[20] CH4-C to CH4 conversion value: CH4 = 16.04 g/mol, C = 12.011 g/mol, thus C to CH4 = 16,04/12,011. CH4 to CO2-equivalent conversion value = 29.88. Source: European Commission. 2025, 8 dec. Methane Emissions. URL: https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/methane-emissions_en#:~:text=In%20fact%2C%20methane%27s%20ability%20to,on%20a%2020-year%20timescale.

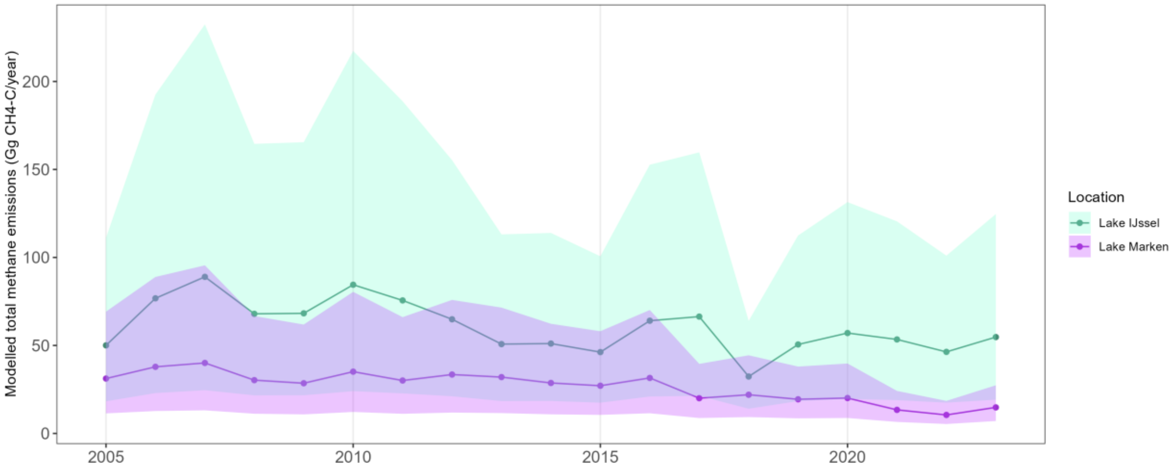

Figure C.16. Total methane estimates (ebullitive and diffusive methane) for Lake IJssel and Lake Marken based on yearly average chlorophyll-a concentrations. The methane estimates were made using a Bayesian model constructed from a global dataset of ground-based methane measurements and satellite-derived chlorophyl-a data. The data used to construct the Bayesian model is available as supplementary information in DelSontro et al. (2018). The Bayesian model was run by E. Kitson, UKCEH.

The nett burial rate (= carbon sequestration) of the Lake IJssel complex is estimated as 40 630 tonne C/year. This estimate is based on the average nett burial rate for Dutch shallow lakes (-22.5 ± 10 gC/m2/year; Mendonça et al. 2017 in Troost et al. 2025) and the surface area of the Lake IJssel complex (180 590 ha).

1.3.5 Climate resilience

The Lake IJssel complex functions as “the rain barrel” of the Netherlands. The water of its lakes is vital as drinking water for citizens (see 1.3.1.15 below), crops and livestock, organisms that naturally occur in the region and for transport. Thus, the water levels of the lakes in the complex are constantly monitored and discussed. For example, the relatively recent decision to widen the bandwidths of allowable water levels in Lake IJssel and Lake Marken was implemented after thorough discussions with multiple stakeholders (Rijkswaterstaat, 2018). This new bandwidth will allow for more flexibility in planning (allowing for more water storage in summer, and less in winter) and (a relatively new development) also partially considers the impact of the change in water levels for organisms (e.g., nesting birds). In case of drought there is a specific water allocation priority list that ensures that the most vital elements of Dutch society will receive the limited available water first (in Dutch known as “de verdringingsreeks”). Conversely, when the threat of too much water arises water will be pumped out of the lake in advance (based on available data from weather reports in combination with computer models of the hydrology of the region) to ensure a minimal risk of flooding. Programs are in place to ensure the availability of water in the future and under different scenarios of climate change (e.g., Deltaprogramma).

Additionally, water boards in the surrounding area of Lake IJssel and Lake Marken also research water retention and flooding prevention to become more climate resilient (e.g, SpongeWorks https://www.spongeworks.eu/).

1.3.6 Health & Well-being

Lake Marken and Lake IJssel are used as recreation areas for many types of recreational use, e.g., fishers, bird watchers, swimmers, sailors (also see section 1.3.1.8). As such this area contributes to physical condition and mental health of people living in and visiting the Netherlands. Here we highlight one element of health and well-being via the proxy of bathing water conditions.

There are roughly 50 official bathing water locations in Lake Marken (21 locations) and Lake IJssel (28 locations). These locations are monitored during the bathing water season (1 May – 1 October) for harmful bacteria such as E. coli and cyanobacteria. The quality of these bathing water locations varies widely; some of these locations have been judged to be in excellent condition, while others have been judged not fit for swimming. A small subset of substances and locations is shown in Figure C.17.

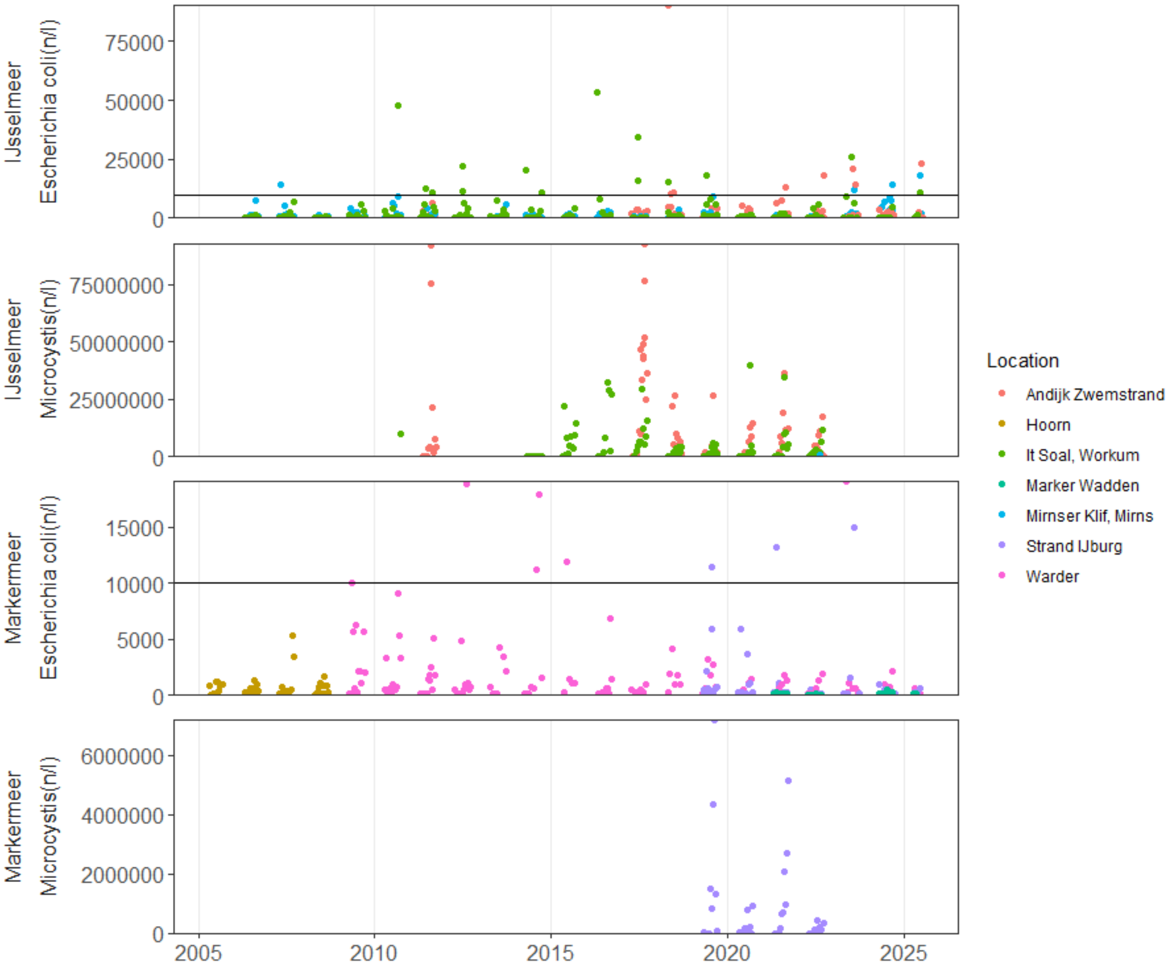

Figure C.17. Selection of bathing water locations and monitored substances in the Lake IJssel complex. The straight black line shows the threshold for good bathing water quality for E. coli.

1.3.7 Inclusivity

There are many stakeholder groups and NGOs active in the Lake IJssel complex to ensure that all voices are heard (see also FutureLakes deliverable 2.1 “Stakeholder mapping”). However, decisions concerning water level regulation or building in the lake (and thus reducing the lake water volume) remain top-down. The function of a freshwater reservoir for drinking water and agriculture (water barrel for now and in the future) continues to dominate these national decisions.

1.3.8 Recreation

There are many recreational and tourist facilities located around the Lake IJssel complex: places to dock yachts (Figure C.18), to stay the night (campsites, bungalow parks, hotels, guesthouses), to eat, to walk or bike, to swim (Figure C.19) or sunbathe, to bird, to hire canoes or SUPs, etc. To highlight the

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abundance of a few of these options: there are about 130 marinas with just under 20,000 berths and roughly 450 traditional ships sail with groups on the lake (charter sailing). There are about 25 holiday accommodation businesses with around 9,000 pitches in the area, along with many large and small attractions. A signposted long-distance walking trail and a long-distance cycling route run around the lakes and nearly half a million sport fishers fish in the lakes at least occasionally, either from the shore or from a small boat.

Foreign tourism is growing again in the Netherlands after the low during the pandemic in 2021. Comprehensive international tourist numbers are not broken down for the Lake IJssel region in specific. In international websites recommended activities are water sports (sailing, and boat rentals) as well as land-based options like cycling, hiking, and visiting charming towns like Makkum and Enkhuizen.

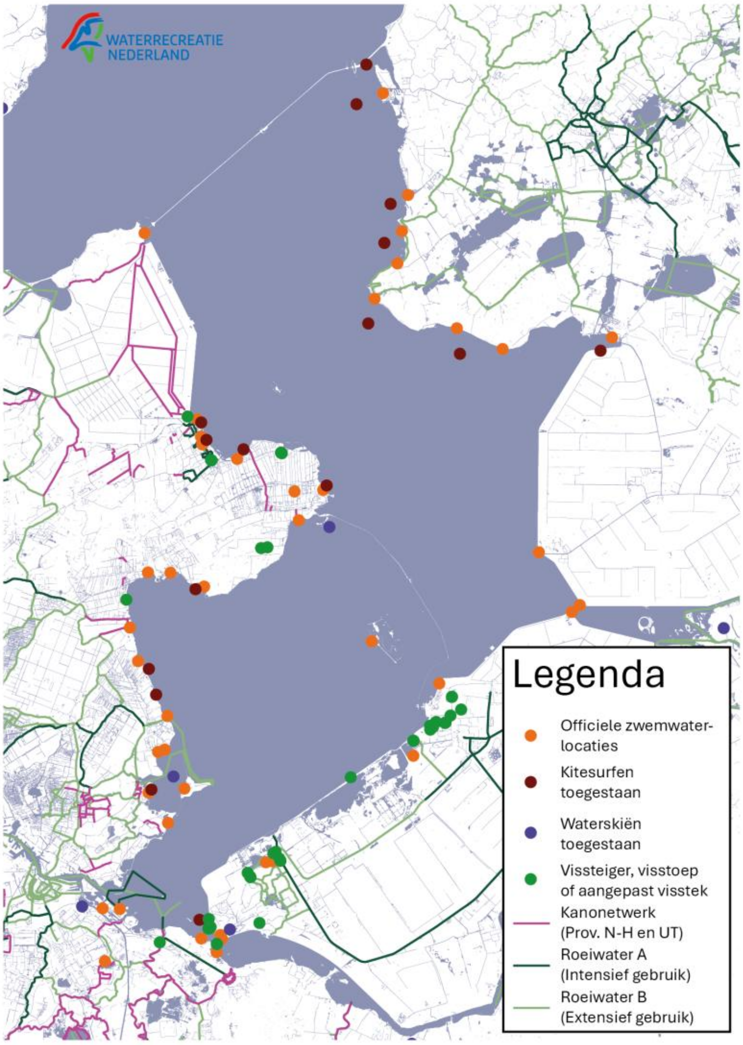

Figure C.18. Overview of recreational locations in and around the Lake IJssel complex.

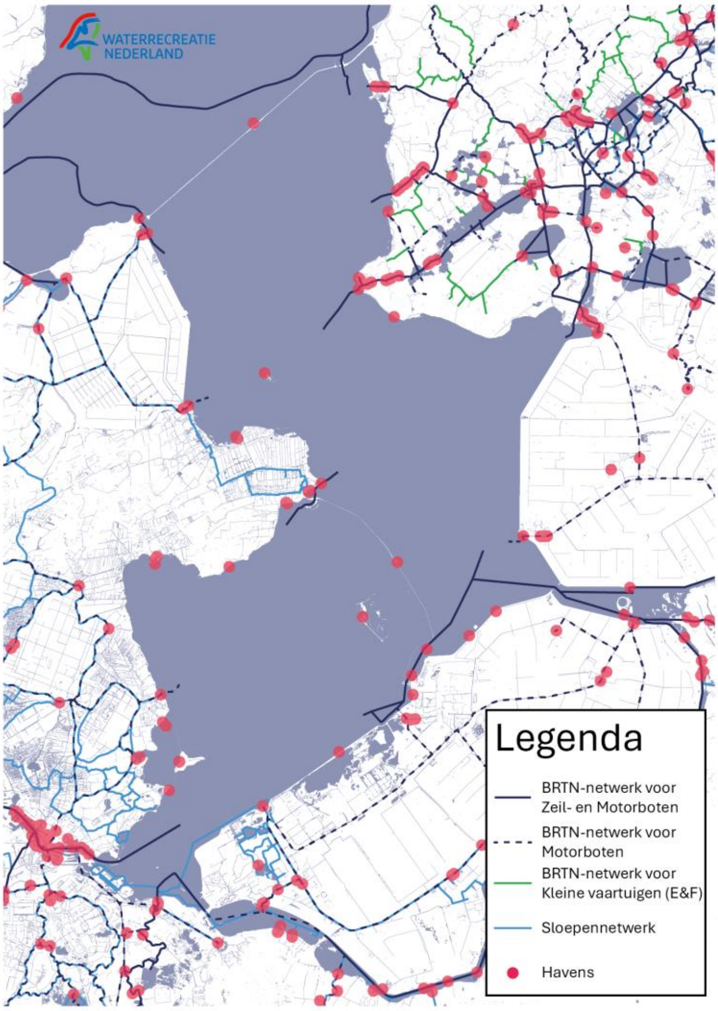

Figure C.19. Overview of harbours (red dots) and navigational channels (coloured lines) in and around the Lake IJssel complex.

1.3.9 Circular economy

The IJsselmeer Regional Agenda 2050 (Ministerie IenW, 2018) mentions circular economy as one of the important themes in addition to water, spatial quality, cultural history, energy transition, recreation and urbanisation. Although the agenda does not elaborate on the principles of a circular economy in detail, it does contribute to the broader goal of the Netherlands to be a circular economy by 2050. The Agenda aims to make the economy in the area more sustainable through renewable raw materials, reuse and avoiding waste. The agenda does not mention any concrete examples.

Potential circular projects are: reducing sand mining, using local sediments for lake restoration measures, harvesting warmer lake water for sustainable techniques (‘aquathermie’; i.e. the use of thermal energy in surface water) for recovery of raw materials from wastewater.

1.3.10 Blue economy

In general, the value of ecosystem services has increased in the Netherlands over time (Figure C.20). An important cause for this rise is the increased prices for recreational nature related activities and the increased prices of agricultural land. A steep increase was seen in 2021 caused by more local activities in nature due to the restrictive COVID measures.

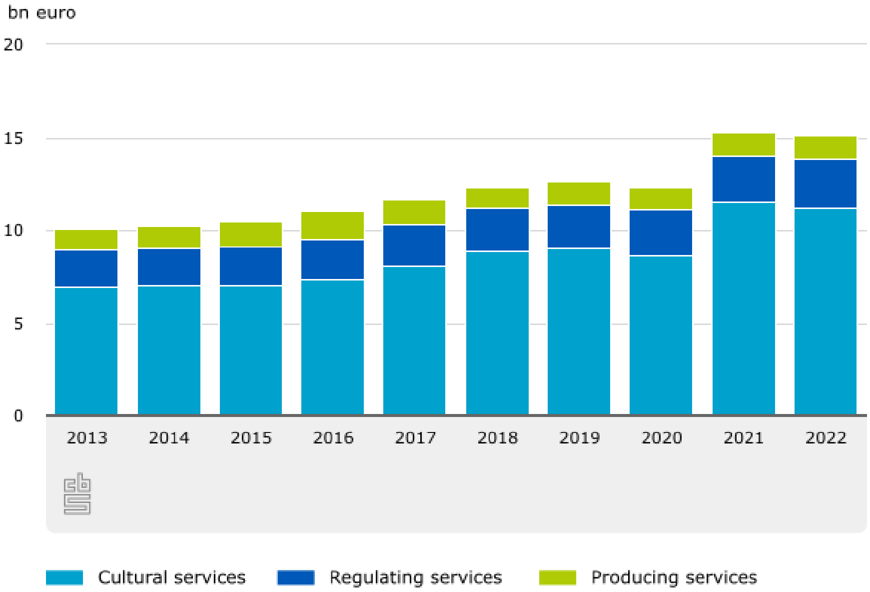

Figure C.20. The socio-economic value of ecosystem services in the Netherlands in billion euros per year (CBS, 2025). This figure has been translated for this report from Dutch to English by L. Kramer.

When we zoom in to the data that is available specific landscapes in the Netherlands (Figure C.21), we can see that the highest values for ecosystem services can be found in forest areas and grasslands. Lake and reservoirs combined represent 0.79 billion euros.

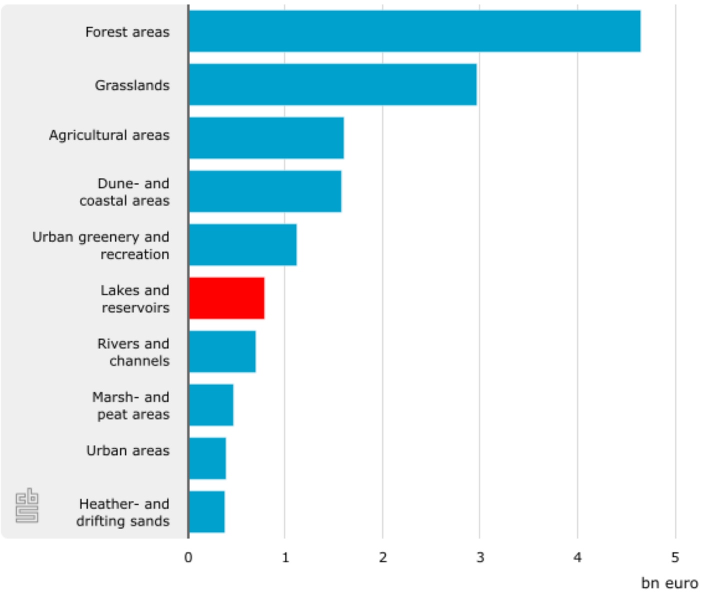

Figure C.21. The value of ecosystem services in 2022 (CBS, 2025). The x-axis shows the value of each group of ecosystem services per billion euros, the y-axis decribes the different ecosystem services. This figure has been translated for this report from Dutch to English by L. Kramer.

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Barely any specific data for the Lake IJssel complex has been found, thus it is impossible to relate the increased services to measures. However, we are aware of jobs that have been created during the construction of the Marker Wadden islands and of jobs that are currently being created in the management and tourism around the area. In specific, Marker Wadden is primarily aimed at nature restoration and has thus also acquired an economic component, with, for example, accommodation options and a recreational island. Additionally, research from Waterrecreatie Nederland (2026) has shown that the estimated value of various water sports in the area is estimated to be around 36,5 million euros per year (Table C.6). This estimate is a minimum estimate, as data from additional sources has indicated that the values for certain types of water sports may be substantially higher (Waterrecreatie Nederland, 2026).

Table C.6. Minimal estimated revenue for different forms of water sport in the Lake IJssel complex (Waterrecreatie Nederland, 2026).

Water sport	**(Minimal) estimated revenue**
Cabin motor boat	€ 4 990 000
Cabin sailboat	€ 6 680 000
Open motor boat	€ 2 180 000
Open sailboat	€ 2 690 000
Sloop	€ 1 140 000
Speedboat / Jet ski	€ 3 570 000
Surfing	€ 2 480 000
Rowing	€ 660 000
Canoeing / Kayaking	€ 530 000
Water skiing / Wakeboarding	€ 360 000
Diving	€ 2 370 000
Standup Paddleboarding	€ 140 000
Fishing	€ 2 340 000
Swimming	€ 6 300 000
Total	*€ 36 440 000*

1.3.11 Sustainable Agriculture

The use of nitrogen and phosphorus for agricultural purposes has been substantially reduced since the 1990s, mainly due to reductions in fertilizer use (Figure C.22 and Figure C.23; Ministerie van LVVN, 2015a and b). In 2023 most of the phosphorus used ended up in animal produce, while most of the nitrogen that was used was lost to the air and soil (although the loss to air and soil has reduced substantially since the 1990s). Large amounts of the 'lost' nitrogen, primarily in the form of ammonium (NH_4^+), are being deposited in natural areas. Consequently, nitrogen in particular still poses significant challenges to achieving the Water Framework Directive (WFD) and Natura 2000 objectives. This is (still) mainly driven by the use of artificial fertilizers and manure in agriculture. Additional sources of nitrogen include emissions from transport and industrial activities.

The amount of dairy cows in the Netherlands has reduced from 5.2 million in 1980 to 3.8 million in 2024 (CLO, 2025a). Main reasons for large changes in the dairy cow numbers are to be found in changes in rules and regulations (e.g., adhering to the EU milk quota and the phosphate production maximum). The amount of chickens in The Netherlands was 81 million in 1980 and 40 million laying hens and 41 million broilers in 2023/2024. Large changes in the amount of chickens in the Netherlands seem to be mainly driven by the bird-flu. The amount of pigs in the Netherlands was 10 million in 1980 and 10.5

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million in 2024. Large changes in the amount of pigs seem to be driven by both disease or changes in regulations (CLO, 2025a).

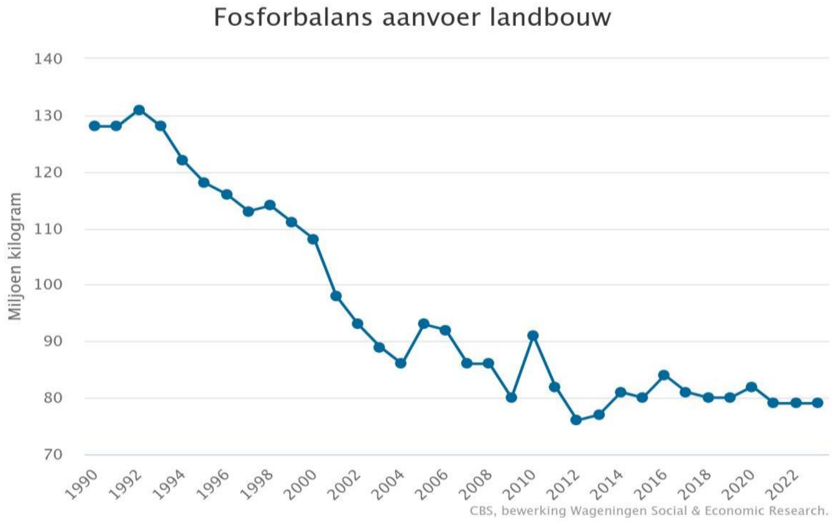


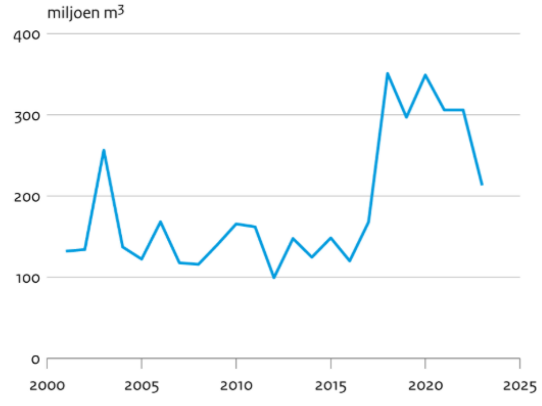
Figure C.22. Phosphorus used in agricultural areas in the Netherlands in million kilograms.

Figure C.23. Nitrogen used in agricultural areas in the Netherlands in million kilograms.

The potential agricultural revenue is (at least) €1,7 - €2.9 billion per year for the direct catchment area of Lake IJssel complex, largely due to freshwater provisioning (Rijkswaterstaat, 2018; data from 2013). Cattle farms use the largest proportion of drinking water in the Netherlands and their drinking water use is relatively constant over the years (CLO, 2025b). Additionally, water use for agricultural and horticultural purposes is highly dependent on the weather (Figure C.24). Dry years cause a substantial increase in water use for irrigation, while wet years keep the water use for irrigation low.

Although the aforementioned numbers apply to the Netherlands as a whole, we can expect a similar trend for the (Dutch part) of the Lake IJssel complex catchment, as this catchment area roughly covers slightly less than 1/3 of the Netherlands.

In Dutch government-managed surface waters, which include Lake IJssel and Lake Marken, there is an increasing trend in both chronic and acute toxic pressure when considering (almost) all substances that are being monitored (519 substances; Figure C.25; van Eck and Pit, 2025). When focusing solely on substances regulated under the Water Framework Directive (WFD), this trend is less pronounced and relatively stable (140 substances). This rise in toxic pressure can lead to a decline in species richness and ecological quality, disrupt food webs, and increase ecosystem vulnerability. Possible drivers behind this trend include the introduction of new substances, improved measurement techniques, and more advanced analytical methods (van Eck and Pit, 2025). Van Eck and Pit also mention that there are indications that mixtures of substances are becoming more toxic. A combination of heavy metals (such as aluminum) and pesticides contributes significantly to the overall pressure.



Bron: Wageningen Economic Research, CBS

Figure C.24. Water use in horticulture and agriculture in the Netherlands in million m^3 between 2000 and 2025.

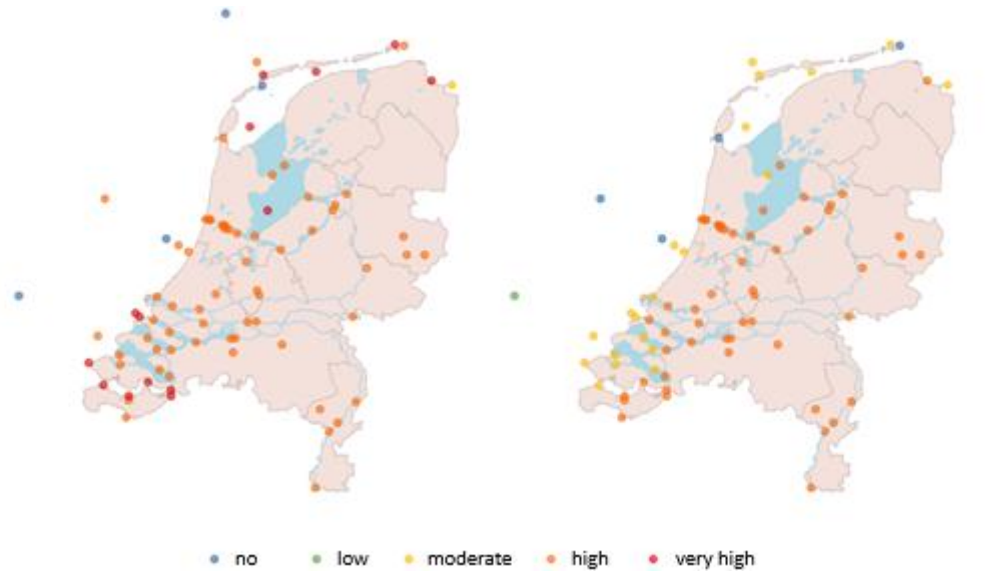


Figure C.25. Toxic pressure per measuring location in the Netherlands concentrations averaged between 2020-2022. The map on the left shows the impacts from all chemical substances, the map on the right shows only the impact from WFD substances. The range varies from blue – no pressure (less than 0.5% of species experiences negative impacts from the chemical substances) to dark red – very high (more than 10% of the species experiences acute impacts from chemical substances). This range has been defined by Postuma et al. (2019), the maps have been produced by van Eck and Pit (2025).

1.3.12 Sustainable transport

Lake Marken and Lake IJssel are used for navigation purposes. In regard to the regulations on the lake: There are no speed limits for boats on Lake IJssel and Lake Marken when one is more than 500 metres away from the shore and outside of specific restricted areas (e.g., areas reserved as bird habitat, reserved for swimming/bathing, specific pilots for nature restoration projects). Furthermore, if a boat is longer than 15 meters or when the boat can go faster than 20 km/h you will need a license to operate the vessel. Rules and regulations are enforced by a special unit of (water) police officers.

We did not find specific information about developments for sustainable transport on Lake IJssel or Lake Marken.

1.3.13 Sustainable energy

Lake IJssel and Lake Marken have several wind farms located within the lakes, that together consist of 161 in-lake wind turbines and produce enough energy to power at least 790 000 households per year (Table C.7). There are many more wind turbines located on the land surrounding the lakes, however, we did not include these in our overview. It should be noted that although wind farms provide sustainable energy to the region, they also have negative consequences for nature. Preliminary monitoring results for the Lake IJssel complex show that wind turbines cause more bird-collisions and disturbance to nature than was assumed initially (pers. comm. M. van den Berg, Rijkswaterstaat).

Table C.7. Lake IJssel complex in-lake wind farm characteristics.

Name wind farm	**Fryslân**[1)]	**Westermeerwind**[2)]	**Windplanblauw**[3)]
Turbines (n)	89	48	24
MW per turbine	4.3	3	5.5
MW total	382.7	144	132
Household equivalents	500 000	160 000	130 000
Operating since	2021	2016	2024

[1)] Windpark Fryslân. 2025, 11 Nov. Het windpark – bouw van windpark Fryslân. https://www.windparkfryslan.nl/het-windpark/

[2)] Westermeerwind. 2025, 11 Nov. Veelgestelde vragen. https://www.westermeerwind.nl/veelgestelde-vragen/

[3)] Vattenval. 2024, 20 Mar. Laatste turbine voor Windplanblauw. https://group.vattenfall.com/nl/newsroom/persbericht/2024/laatste-turbine-voor-windpark-windplanblauw

Additionally, there is an installation on the Afsluitdijk that produces energy on a small scale via osmosis (using the difference in salinity between the saltwater Wadden Sea and the freshwater Lake IJssel). The first pilot phase of this project showed potential; thus, the project is scaling up to enter its next phase (De Afsluitdijk, 2023). There have been suggestions to create floating solar installations in the lake. Although such systems have been installed in other lakes in the Netherlands, until now, permission to build these systems in the Lake IJssel complex has not been granted by the Dutch government.

1.3.14 Sustainable Tourism

The IJsselmeer Regional Agenda 2050, created by key stakeholder of the Lake IJssel complex, states that sustainable tourism is an important part of the future of the area. This means that the development of recreation and tourism must consider environmental, social and economic factors to future-proof the area and balance the needs of visitors, industry, the environment and the local community. The agenda explores different scenarios with stakeholders to discuss this and develop a vision for the long term.

Additionally, the lake restoration project Marker Wadden leaves room for sustainable tourism with as little disturbance for flora and fauna as possible. On the main island there is an off-grid harbour (without drinking water or electricity), a few cabins for overnight stay (of which a part of the earnings flows back to the maintenance of the island), and a low-key restaurant serving lunch and drinks.

More information on tourism can be found in section 1.3.1.8.

1.3.15 Water supply & sanitation

There are 5 drinking water utilities in the Dutch part of the direct catchment area of the Lake IJssel complex (Figure C.26). An overview of drinking water production and consumption for these drinking water utilities can be found in Table C.8.

Regarding sanitation, 99.9% of Dutch households are connected to the sewer system. The number of households that is not connected is roughly 8000 (Beukeboom, 2019). These households are not connected mainly because of their remote location. Instead, these households use septic tanks or other measures to prevent their waste from entering the environment. Additionally, there are no direct storm overflows in Lake IJssel or Lake Marken, however, there are likely several hundred to several thousand storm overflows in the direct catchment. According to the Dutch government (Tweede Kamer der Staten-Generaal, 2024) there were an estimated 13 000 storm overflows in the Netherlands in 2016. There are no specific monitoring schemes to keep track of the emissions of these overflows. However, in some cases the amount of overflow events per year is monitored. This amount can vary between 0 – 10 times a year. The impact of an overflow event is usually local and limited. Furthermore, according to our national emission registration the impact of storm overflows represents 0.4% of the nutrients emitted towards Dutch surface waters.

Table C.8. Production and consuption of drinking water in the Dutch part of the direct catchment of the Lake IJssel complex (Vewin, 2022).

Drinking water utility	**Drinking water produced (million m3)**	**Drinking water consumed (million m3)**	**Water source**
PWN	94	104	Surface water
Waternet	91	66	Surface water
Vitens	368	350	Groundwater
WMD Drinkwater	35	29	Groundwater
Waterbedrijf Groningen	44	45	Groundwater
Totals	*632*	*596*	*Mixed*

Figure C.26 Drinking water utilities in the Dutch part of the direct catchment of the Lake IJssel complex. This map was made with ESRI online resources.

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d) Lake Karla

1.1 Lake details

Table D.1 Summary of Lake Karla details

Lake name: Karla Reservoir		
Type of characteristics	**Characteristics**	**Value**
Geographical characteristics	Geographical coordinators: Longitude Latitude Altitude (m a.s.l.)	**22.80 (22°46’47’’ to 23°51’50’’ E)** **39.50 (39°26’49’’ to 39°32’03’’ N)** **60-80 m**
Lake characteristics	Area [km^2]	**34.925 km^2**
	Maximum depth [m]	**4.91 m**
	Mean depth [m]	**2.2 m**
	Water volume [m]	**85.10^6 m^3 (current)** **[**10y ave <$56x10^6$ m^3, max capacity $200x10^6$ m^3
	Depth index (mean depth to maximum depth ratio)	**0.45**
	Water residence time (τ) [years] Residence type (short < 1 year, moderate >1 year, long > 10 years)	**moderate >1 year (used to be long)**
	Shoreline development index	**1,42**
	Mixing type Bradimictic – short spring and autumn mixing, long stratification, thin epilimnion, steep and thin thermocline Tachymictic – long spring and autumn mixing, shorter stratification, thick epilimnion, not steep thermocline	**Polymictic (Holomictic)**

	Eumictic – between tachy- and bradymixis Polymictic – shallow, all season mixing except ice cover presence period Meromictic	
	Stratification	**non-stratified**
Catchment characteristics	Total catchment area [km^2]	**1663 (37,000 Pinios Basin Included) km^2**
	Direct catchment area [km^2]	**434.15 km^2**
	Land-use (CORINE)	**% of total catchment area**
	Agriculture	**66.66**
	Urban	**3.49**
	Forests	**26.69**
	Wetlands	**0.53**
	Water bodies	**2.3% lake (3.2 including other watercourses and artificial ponds)**
	Schindler's index (sum of total catchment and lake areas to lake volume ratio)	**19.98**
Climate characteristics (30-year average; 1991-2020)	Mean annual air temperature	**14.8±1,5 °C**
	Mean annual precipitation	**547±82 mm/year**
	Maximum summer air temperature	**41.5 °C**
	Days number > 15°C air temperature per year	**Approx. > 200**
	Days with snow per year	**ut0-5**
Hydrochemistry and trophic type (situation in 2025)	Alkalinity (meq/L), Alkalinity type (low - <0.2, medium 0.2-1.0, high - > 1.0)	**high - > 1.0**
	Colour type (colour in HAZEN units – clear < 30, humic 30-90, polyhumic >90)	**humic 30-90**
	Trophic type (oligotrophic, mesotrophic, eutrophic, hypertrophic)	**Eutrophic (used to be hypertrophic)**
	Calcium level (water hardness – softwater <25 mg Ca/L, hardwater ->25 mg Ca/L	**hardwater ->25 mg Ca/L**

1.2 Restoration Programme

The lake is located in a water scarce area and its water management is expected to maximize the efficiency of water provision in agriculture and biodiversity enhancement. The reconstructed Lake Karla serves as a multi-purpose project to combat water scarcity, increasing crop yield production and respective agricultural income in the surrounding area, securing the full coverage of the water supply needs of the closest city of Volos, improving the status of groundwater resources, developing a natural shelter for biodiversity and emerging recreation and touristic opportunities. The main success factors are the positive attitude of decision makers, the full support from stakeholders (mainly farmers) and the positive public perception. The construction and operation costs can be recovered to a high degree through the provision of the abovementioned services and an effective governance plan can ensure the sustainability of the project.

Table D2. Series of successive funding sources and measures implementation

Source	Measures implemented
ERDF -3rd community framework for support (2000-2006)	Reservoir reconstruction and accompanying works regulating water inflows from Pinios River
ERDF (2007-2013)	Lake environment improvement, mountain hydrological works and flood related measures. Creating artificial wetlands, reintroducing native species and improving water quality
ERDF (2014-2020)	1. Study for drinking water supply to Volos city 2. Supplementary infrastructure
Regional Public investment programme	Supporting Studies for Approval by the Karla reservoir Administrative Authority of Thessaly
CAP Reform 2014-2020 - National Programme of Rural Development, Ministry of Rural Development	Construction of Remaining Water Transmission & Distribution Works of Lake Karla Phase I – Public Works Measure RDA
ERDF (2007-2013) - Operational Program for the Environment Sustainable Development	Establishment and operation of the Karla Management Body
ERDF (2014-2020) - Operational Program Transport Infrastructure, Environment and Sustainable Development"	1. Habitat instalment (lakeside tree clusters for bird nesting) 2. Reed beds and wet meadows management for water quality improvement

Greek Green Fund - Natural environment & innovative actions 2017 - Innovative citizen actions	Combination of projects focusing on environmental awareness and active citizenry targeting end users (i.e. farmers) local authorities, young scientists and broad public
Greek Green Fund (2012-2015)	1. Calculation of main ditch flows and volume measurement of all reservoirs in the area using new technologies as well as development of a protocol for monitoring ecological and quality characteristics in real time of Lake Karla. 2. Surface runoff survey routing of the Velestino sub-basin through a technical project and coupling with a groundwater flow model 3. Lake Karla food chain structure assessment 4. Monitoring spatial patterns and ecological processes at the landscape level 5. Hydrological restoration assessment of Iperia Krini spring in Velestino

All restoration measures were public and described in the restoration masterplans

Table D3. Costs as recorded per packages of individual measures (converted to costs in today's 2025 value)

Costs for individual measures		
Individual measure	Cost (2010)	Cost (2025)
Reservoir, collectors and artificial islets construction	74.091.338	202.851.462
Artificial wetland establishment and remaining (peripheral) projects	15.200.000	41.040.000
Water supply (Karla inflow) hydrological connection projects with Pinios river	5.125.467	13.838.761
Karla area mountain hydronomy projects	7.800.000	21.060.000
Drinking water supply projects from Karla to the city of Volos	9.500.000	21.710.000
Environmental promotion and ecotourism works	1.600.000	4.320.000

Environmental information and tourism infrastructure	3.500.000	9.540.000
Water transportation and irrigation projects	25.423.729	68.644.068
Other expenses (Management Body startup, tech assistance, archaeological, dissemination)	18.966.161	51.208.635
Total	**161.206.695**	**434.212.926**

* The initial budget was estimated at 246.296.127 (VAT). The projected total including restoration and maintenance (plus loan interest) reaches 404 m€. So far more than 300 m€ have been invested and still accompanying measures have not been finalized.

** Different annual inflation average: 3% up to 2019, 7% 2020-2025. Raw material up to 11% per year

*** Due to inability to discriminate the area benefited from individual restoration measures the average cost estimation is 2.426 €/ha.
****Drinking water supply is not yet established

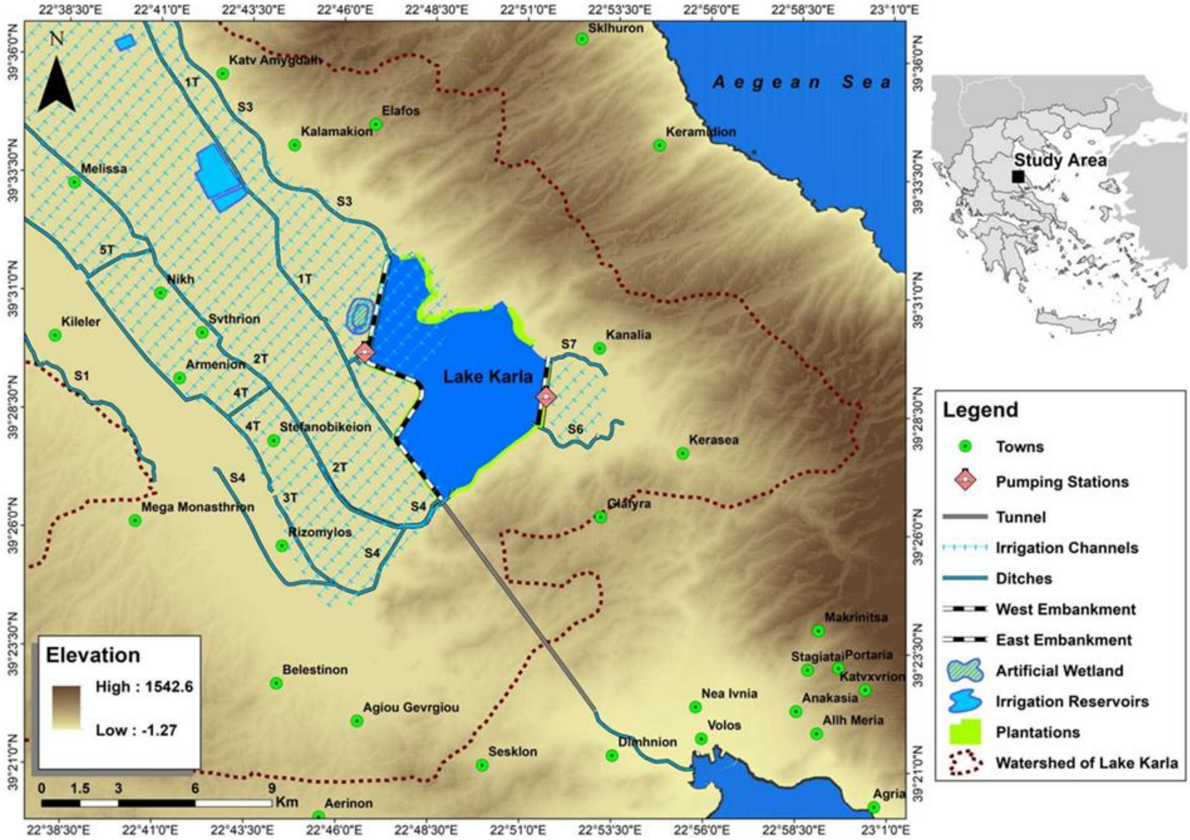


Figure D1. Map of Lake Karla and basin with annotated basic restoration measures

- **Lost earnings**

There is no existing study on lost earnings. Even the nature of Karla basin and the land use profile and the absence of tourism and cultural activities the lost earnings were calculated as: "Cost for land reclamation (48,6 m€ X lost profit from agricultural activities (11%/per year) X inflation factor (overall 2,5 for the 15 year period) " = 200,5 m€ approx.

Table D4. Estimation on financial benefits, according to masterplan, assuming all restoration measures have taken place (without accounting the damages caused by Daniel storm)

Financial benefits of restoration on annual basis after 2026 (€)			
IRRIGATION*	**DRINKING WATER SUPPLY****	**RECREATION*****	**FISHERIES******
2.986.060	2.550.359	117.388	36.684

The total benefit of Karla reestablishment is estimated up to 17,96 m€ (from irrigation and recreation only). The annual estimated profit for 2026 is 5,7 m€.

* A total area of 2000 ha is being irrigated since 2019.
** The infrastructure for drinking water supply and treatment is not yet completed
*** There is significant lack of facilities at the moment to support further touristic growth.
**** Fisheries was banned until 2024. Currently a fisheries master plan is being developed.

Note 1. Benefits are not visible yet as the damages caused by Daniel and Elias storms are estimated at more than 3 b€ for the entire Thessaly region. Regarding Karla basin the 2-year interruption of agriculture activity and infrastructure failure of most accompanying measures and road networks caused further income loss.

Note 2. Financial/economic benefits from groundwater recharge, biodiversity gain and restoration and other regulating and cultural ecosystem services have not been estimated.

1.3 Evaluation of existing restoration programme

Unfortunately for lake Karla there are no timeseries, only sporadically collected data by individual researchers and some regional authorities

Table D5. Series of indicators targeting different restoration subjects (i.e. Biodiversity, water abstractions, groundwater recharge, recreation, job creation, touristic growth and sanitary works)

Indicator No	**Short Indicator Name**	**Specific Indicator**		**Values Before Re-operation**	**Values after restoration**
BD1a	Habitat_condition	<Habitats Directive habitat code>	% area in favourable/good condition (HD)	n/a	1110 – A, 3140 - ? (3,4 ha), 6110 – C, 6220 – C, 91M0 – A, 9260 – A, 9280 - A
BD2a	Species_condition	<Habitats Directive - species latin name>	Species condition (abundance?)		Alosa fallax – DD, Rhodeus amarus – LC, B. sperchiensis – NT, Cobitis

					stephanidisi - CR
BD3a	Bird_condition	<Birds Directive - species latin name>	Bird species condition (bird numbers) (BD)	Historically it was much better (>80 species, >20,000 population)	See biodiv net gain 1.3.1.2
FR1	Increased storage capacity of lake	storage capacity (linked to lake water level which for years was below designated ecol. Limit)		n/a	42,74-28,42 hm^3
FR3	Area of newly designated areas for flooding (ha)	surface	Km^2		No official decision yet (Daniel flood data will be assessed)
DR1	Increased volume of lake				`13.5 (after 2023 Daniel)
DR4	Change of groundwater abstraction by sector over time (e.g. last 20 years) (m3)			Groundwater heads > 50m deep	Groundwater heads ~35 m deep (200hm^{3,} in an area of 578,44.10^6 m^2)
DR5	Change of surface water abstraction over time (e.g. last 20 years)			0	600 ha (21,5 hm^3/y)
In4	Formal public consultation on restoration/management plans	Public consultations on RBMP			7 legal entities
Rec4	Numbers involved in birdwatching			n/a	6 (officially)
Rec6	Length of active travel routes around or connected to the lake (walking/cycling)	Lenght of route& hicing paths	km	n/a	92 (10 routes)
	Nitrogen emissions from agriculture			76500 kg/y (estimat)	69389 kg/y

BE1	Jobs created attributable to restoration activities	Jobs created attributable to restoration activities (jobs created by restoration activities directly implemented by the beneficiary and/or outsourced to contractors)			13 (Management body personnel & TEDRA & accompanying measures operations)
BE2	Jobs created attributable to restoration outcomes	Jobs created attributable to restoration outcomes (e.g. jobs created following improved condition of lake)			8 (KeMeVo & pumping station operation & Rbnb & food truck)
Tour2	Number of overnight stays in an area on an annual basis			-	Est. less than 400
Tour3	Amount of businesses providing tourism and recreation services			n/a	12
Tour6	Infrastructure supporting nature-friendly tourism (eg. paths, visitor centres)	Positive infrastructure alterations		n/a	3 local museums, 1 exposition centre, 1 information centre and 6 designated walking routes
WSS1	Total water consumption in catchment (supplied)		m^3/year	About 200 hm^3	1,168.9hm^3 (broad catchment, <200hm^3 in the direct catchment)
WSS2	Population not connected to sewerage		count	>35,000 (entire municipality)	about 25000 persons (8 villages from 2 municipalities)

WSS3	No. of storm overflows to lake		Number per year	>4	2-3 approx./year

1.3.1 WFD

Table D6. Presentation of basic Biological quality elements for 10 years of monitoring

Year	Chla	Cyano-biomass	Cyano%	Phyto-Biomass (mg/l)	EQR (phyto)
2013	36,46	5,19	73,00	6,76	
2014	128,48	8,48	43,00	18,52	
2015	89,47	3,65	49,00	7,72	
2016	76,37	18,05	51,00	25,77	
2017	90,92	36,08	55,00	47,77	
2018	11,99				
2019	62,48	44,95	96,00	45,99	
2020	33,04	4,63	31,80	7,89	0,49
2021	115,50				0,64
2022	236,16	129,09	99,20	130,08	0,20
2023	94,65	45,32	93,30	47,03	0,46

Table D7. Overall merit regarding hydromorphology, impacts-pressures, and groundwater quantity and quality according to the last RBMP

HYMO	IMPRESS	QUANTITY	GROUNDWATER QUANTITY	GROUNDWATER CHEMICAL WATER QUALITY:
4	**STRONG**	**BAD**	**BAD**	**GOOD**

Table D8. Evolution of ecologic potential, chemical status and overall ecological quality according to the last RBMP

	1ST RBMP			**1ST RBMP AMMENDMENT**			**2ND RBMP AMMENDMENT**		
KARLA	ECOLOGICAL POTENTIAL	CHEMICAL STATUS	OVERALL	ECOLOGICAL POTENTIAL	CHEMICAL STATUS	OVERALL	ECOLOGICAL POTENTIAL	CHEMICAL STATUS	OVERALL
	Unknown	Unknown	Unknown	Bad	Unknown	Unknown	Less than Good	Good	Less than Good

Table D9. Annual average trends of monitored physicochemical data in Karla Reservoir 2013 - 2023

Year	Conductivity	SD (m)	pH	DO	DO%	TSS
2013	3832	0,30	8,48	10,01	109,68	
2014	5091	0,18	8,94	10,88	120,43	
2015	5941	0,09	8,88	10,60	117,74	
2016	4595	0,12	9,05	10,03	120,65	
2017	3749	0,13	9,19	10,55	109,73	89,81
2018	3220	0,40		10,29	114,48	17,32
2019	3094	0,54	9,05	9,95	109,42	14,94
2020	3251	0,45	8,93	10,33	108,13	12,65
2021	4978	0,36	9,12	11,21	110,55	15,93
2022	3790	0,41	9,21	10,37	106,70	25,49
2023	2889	0,55	8,94	9,81	110,43	14,00

No clear trend of amelioration besides SD.

HG boundary for Shallow natural lakes was set at 20 μg/l and GM at 41 (Kagalou et al 2021) but Karla was excluded from dataset as Shallow HMWB with lacking dataset

Chl-a was included as metric in the phytoplankton EQR and could not be correlated

Secchi Depth (unpublished yet) GM boundary is found at 2.7 for shallow NATURAL lakes, Karla was excluded one more time

Hydrological modifications and deficient water balance (long retention time) have been affecting lake since its creation. External nutrient loads (plus Internal) cause a lag in restoration efforts. External loads could not be alleviated due to unfinished peripheral works and supporting infrastructure (ditches, wetlands etc)

EQRs (boundaries) have changed for BQEs since 1st WFD application, monitoring begun in 2013, boundaries are not set!

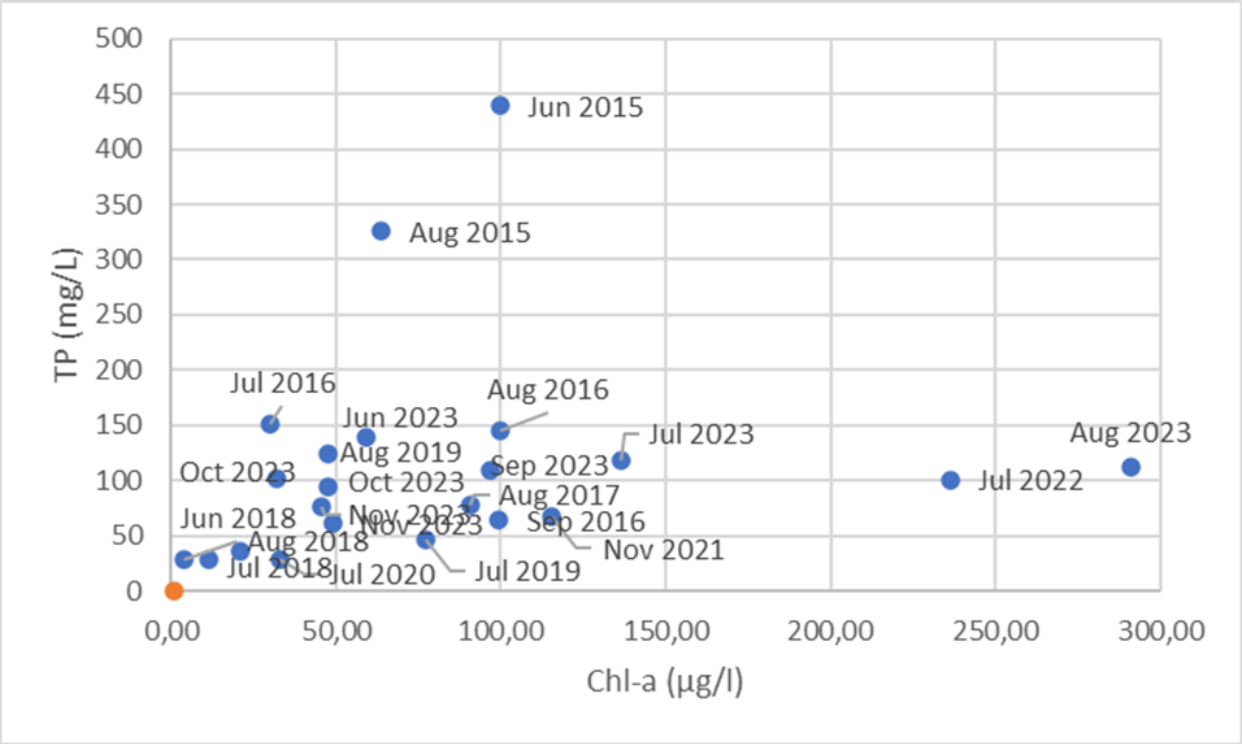


Figure D3. Variation of TP measurements according to the chl-a variant

1.3.2 Biodiversity net gain

Lake Karla is protected under the Habitats Directive as part of the Natura 2000 SAC site "KARLA – MAVROVOUNI – KEFALOVRYSO VELESTINOU – NEOCHORI" (Site code: GR1420004) (47.0 km^2) established in August 1996 and under the Birds Directive as an SPA as part of the Natura 2000 site "PERIOCHI TAMIEFTIRON PROIN LIMNIS KARLAS" (Site code: GR1430007) (16.7 km^2) established in 2010.

Monitoring Programme of Species and Habitats of the Management Unit of Protected Areas of Thessaly (2024 data)

A. KARLA – MAVROVOUNI – KEFALOVRYSO VELESTINOU – NEOCHORI (GR1420004 - SCI)

This site is designated for 12 EU protected habitats (coastal, forests, grasslands and rocky habitats – no lake habitat types) and 5 EU protected species (4 fish species and 1 reptile – green turtle). The 4 fish species all inhabit freshwater. They include the Twaite Shad (*Alosa fallax*) an anadromous fish which migrates into fresh water rivers to spawn. *Cobitis stephanidisi* was last recorded in 2001 at one location in Greece (Chasambali, Pinios drainage) and is associated with low flow freshwater rivers, springs and associated wetlands. Its' distribution appears to include the SE corner of Lake Karla[1]. *Barbus sperchiensis*, is a cyprinid which inhabits streams and rivers and is classed as Near Threatened on the IUCN Red-list [2]. The Vardar spined loach (*Cobitis vardarensis*) is of "Least Concern" on the IUCN red-list[3] and is found in fresh and brackish waters in Greece and North Macedonia.

Table D10. Population size and assessment for GR1420004 - SCI

Species*	**Population size and assessment**		
	Abundance	**Reproducing**	**Isolation**
Alosa fallax (Shad)	P	+	A
Cobitis stephanidisi	P	+	C

Cobitis vardarensis	P	+	C

* Species referred to in Article 4 of Directive 2009/147/EC and listed in Annex II of Directive 92/43/EEC
A – Almost isolated, C - not-isolated withing extended distribution range

Table D11. Other important species of fauna according to Karla Management Unit records for GR1420004 - SCI

Species	**Population size**		
	Permanent (i)	**Reproducing (p)**	**Wintering (i) ****
Egretta garzetta *(B)T*	20	200	20

** 2024 Mid-winter bird counts

Species	**Abundance**
Alburnus thessalicus (F)	P
Chondrostoma vardarense (F)	P
Knipowitschia thessala (F)	P
Pachychilon macedonicum (F)	P
Squalius vardarensis (F)	P

B – Birds, F- Fish

B. PERIOCHI TAMIEFTIRON PROIN LIMNIS KARLAS (GR1430007 - SPA) Protected under the Birds Directive

EU protected bird species: **50 (accrording to natura viewer)**

Table D11. Other important species of fauna according to Karla Management Unit records for GR1430007 - SPA

Species*		**Population size**		
	IUCN status	**Permanent (i)**	**Reproducing (p)**	**Wintering (i) ****
Anas acuta	LC	20	2	4
Anas crecca	LC	200	100	7370
Anas platyrhynchos	LC	150	40	150
Ardea cinerea	LC	20	200	14
Aythya ferina	VU	20	10	660
Aythya fuligula		2	1	0
Buteo buteo		12	6	3
Circus cyaneus	NT	0	0	1
Cygnus olor	LC	8	2	0
Egretta garzetta	LC			
Falco peregrinus		0	1	0
Fulica atra	NT	50	50	150
Himantopus himantopus	LC	0	250	0
Ixobrychus minutus	LC	0	3	0

Merops apiaster	LC	0	16	0
Microcarbo pygmaeus		160	80	200
Nycticorax nycticorax		150	150	0
Podiceps cristatus	LC	40	20	160
Podiceps nigricollis	LC	15	0	0
Spatula clypeata		140	10	140

IUCN status: LC = Least Concern, NT = Near Threatened, VU = Vulnetrable; * Species referred to in Article 4 of Directive 2009/147/EC and listed in Annex II of Directive 92/43/EEC and data

** 2024 Mid-winter bird counts

1.3.3 Zero pollution

Table D12. Annual averages of major nutrients

Year	NO_3	NH_4	TP
2014	0,68	0,31	
2015	0,45		0,28
2016	1,00		0,13
2017			0,14
2018	1,10		0,07
2019	1,60		0,06
2020	2,23		0,04
2021	1,19		0,09
2022	2,85	0,09	0,13
2023	1,07	0,15	0,10

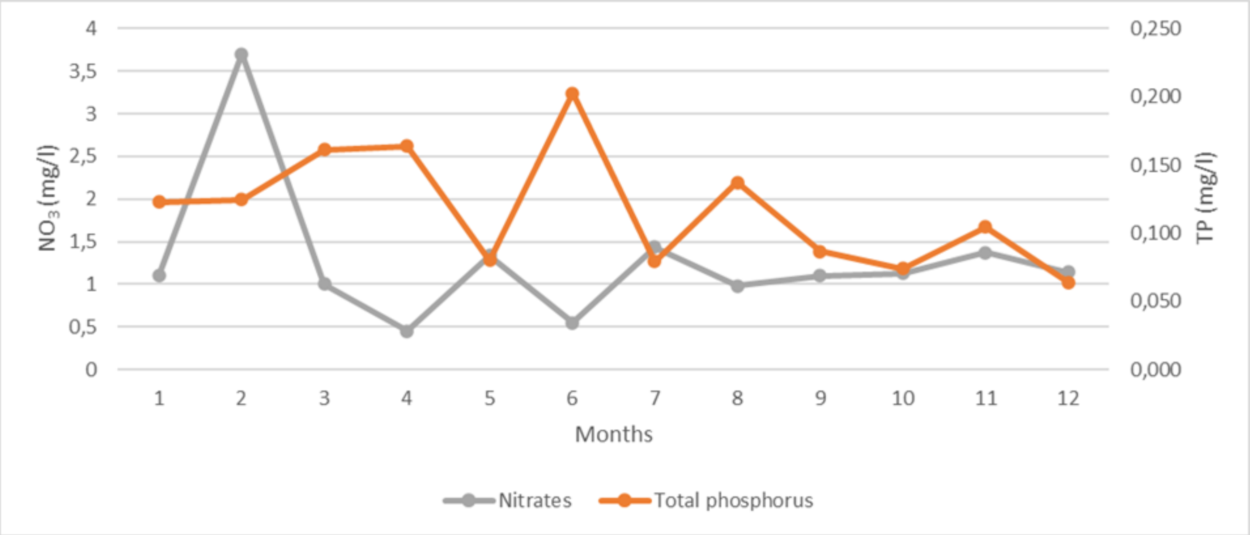


Figure D4. Monthly averages of Nutrient limiting factors showcasing nutrient co-limitation in lake Karla

1.3.4 Climate regulation

Table D13. Modeled Methane Carbon from Chlorophyll-a values

Month	Year	Parameter	Chla	Diffusive_Mean	Ebullitive_Mean	Combined_Mean
5	2013	Chlorophyll_a	15,2	0,232	0,62	0,852
6	2013	Chlorophyll_a	43,4	0,5	1,471	1,971
7	2013	Chlorophyll_a	48,23	0,54	1,609	2,149
10	2013	Chlorophyll_a	38,99	0,463	1,344	1,807
6	2014	Chlorophyll_a	124,85	1,078	3,692	4,77
7	2014	Chlorophyll_a	200,33	1,52	5,669	7,189
9	2014	Chlorophyll_a	60,25	0,635	1,947	2,582
6	2015	Chlorophyll_a	99,84	0,917	3,026	3,943
8	2015	Chlorophyll_a	63,52	0,66	2,038	2,698
9	2015	Chlorophyll_a	105,05	0,951	3,165	4,116
7	2016	Chlorophyll_a	30,11	0,383	1,083	1,466
8	2016	Chlorophyll_a	99,79	0,916	3,024	3,94
9	2016	Chlorophyll_a	99,22	0,912	3,009	3,921
8	2017	Chlorophyll_a	90,92	0,856	2,786	3,642
6	2018	Chlorophyll_a	3,62	0,077	0,204	0,281
7	2018	Chlorophyll_a	11,45	0,188	0,495	0,683
8	2018	Chlorophyll_a	20,89	0,293	0,802	1,095
7	2019	Chlorophyll_a	77,36	0,762	2,418	3,18
8	2019	Chlorophyll_a	47,59	0,535	1,591	2,126
7	2020	Chlorophyll_a	33,04	0,41	1,17	1,58
11	2021	Chlorophyll_a	115,5	1,019	3,444	4,463
7	2022	Chlorophyll_a	236,16	1,714	6,598	8,312
6	2023	Chlorophyll_a	59,2	0,627	1,918	2,545
7	2023	Chlorophyll_a	136,32	1,149	3,995	5,144
8	2023	Chlorophyll_a	291,27	1,997	8,022	10,019
9	2023	Chlorophyll_a	96,58	0,895	2,938	3,833
10	2023	Chlorophyll_a	31,74	0,398	1,132	1,53
10	2023	Chlorophyll_a	47,46	0,534	1,587	2,121
11	2023	Chlorophyll_a	48,99	0,546	1,631	2,177
11	2023	Chlorophyll_a	45,62	0,519	1,535	2,054

For a 10y (2013-2023) period, the average chl-a is about 80µg/l, so, mean diffuse emissions are modelled at about 0.8 Gg CH4-C per year and mean combined (diffuse+ebullative) is above 3000 tons of Carbon

1.3.5 Climate resilience

The area follows the National Strategy on Climate adaptation plan (set up on 2014) and further the initiative LIFE-IP AdaptInGR (Boosting the implementation of adaptation policy across Greece). At Regional level the adoption of the Regional Plan on Climate Adaptation was put in place in March 2025. NBS (wetland re-establishment, riparian restoration, reedbeds, buffer strips) were (are) combined with targeted engineering (embankments, controlled storage) to manage floods and droughts while delivering ecosystem services. **Post-Daniel flood reviews (2023) and expert assessments** call for systemic change: strengthen flood defenses, re-think floodplain use, move dykes, restore river connectivity, restrict new construction on floodplains, and reconsider water-hungry cropping (e.g., cotton). Large-scale proposals (including tripling Karla's area in some scenarios) have been modelled and costed in national consultations. National-level reports highlight fragmented governance and the need to align administrative units with hydrological boundaries to improve resilience and emergency response.

1.3.6 Health & Well-being

Lake Karla has *net positive* impacts on health & well-being in general. Increased temperature during the summer period affects negatively the health & well being especially for the elderly people. Recently, after the storm Daniel (2023) vector-borne disease transmission was increased as it is assessed by mosquito population and West Nile Vector circulation in the whole area (Mourelatos et al. 2023) Cyanotoxins have been detected in lake water and in fish tissues but lower than the WHO threshold (as Total Daily Intake , TDI index).

Restored Lake Karla increases water availability specially in dry periods. This reduces reliance on over-pumping groundwater and associated risks (quality, salinity) and reduces anxiety among farmers about water scarcity.

Ecological restoration has revived wildlife (birds, fish) leading to renewed local pride, cultural identity, and sense of place. Locals report emotional uplift from seeing the lake return.

Sediments in Lake Karla show elevated concentrations of Ni, Cr, Co, Cu, Zn, Pb in places. While some metals derive from natural geology, Pb shows anthropogenic trends. High values of some mineral, ions and metals have been monitored in the aquifers (RBMPs) in some places but without affecting agricultural production or human health.

1.3.7 Inclusivity

There are no barriers but so far there weren't any stakeholder groups, associations, NGOs to gather those voices. Recently things started to change but still the top-down practice in decision making does not allow for much inclusivity except if people are against particular measures.

1.3.8 Recreation

Limited use of the reservoir as a recreation point. Swimming, water sports (canoe kayak, sailing, rowing etc.) and sport fishing are not permitted. Occasional use of the dykes for hiking and biking, Interest for wildlife photography and bird watching is rising every year, supported by an annual photo contest organized by a local environmental group (Karla Biodiversity Observatory - https://www.facebook.com/groups/498716314091735). Events such as running races, bike and horse riding tours take place occasionally but not on a regular basis.

1.3.9 Circular economy

There are opportunities for eco-tourism, trails, nature-based recreation and how cultural & agricultural landscapes around the lake could generate added value BUT NO documented infrastructure built specifically for material recovery or industrial symbiosis tied to the lake's catchment, NO strong evidence of community-level circular business models in place around Karla (e.g. sharing, remanufacturing, zero waste hubs) , NO composting, bioenergy, nutrient recycling from sediments or agricultural / organic waste

1.3.10 Blue economy

This section explains how fisheries, eco-tourism, nature-friendly recreation businesses based around lake, services (café's restaurants) work and support blue economy-based touristic growth. Limited number of cafes, canteens and restaurants (less than 5) are currently active in the nearby village of Kanalia as well as a small number of airbnb houses (2-3). There are occasional visits in the Lake organised by eco-tourism enterprises from Athens or Thessaloniki which are guided in the field by the Management Unit personnel. Fishing is currently prohibited in the reservoir.

Lake Karla is still missing observatories for bird watching, even if there are areas designated for trailer canteen and fairs, the area is still lacking infrastructure (there isn't even a powerline)

1.3.11 Sustainable Agriculture

The entire direct catchment of Karla lake is designated as area vulnerable to agricultural nitrate pollution since 2020. Subsidies were given for measures / restrictions according to N-Directive (fertilizer transport, disposal and application), and only a small percentage falls under organic farming (<5%)

1.3.12 Sustainable transport

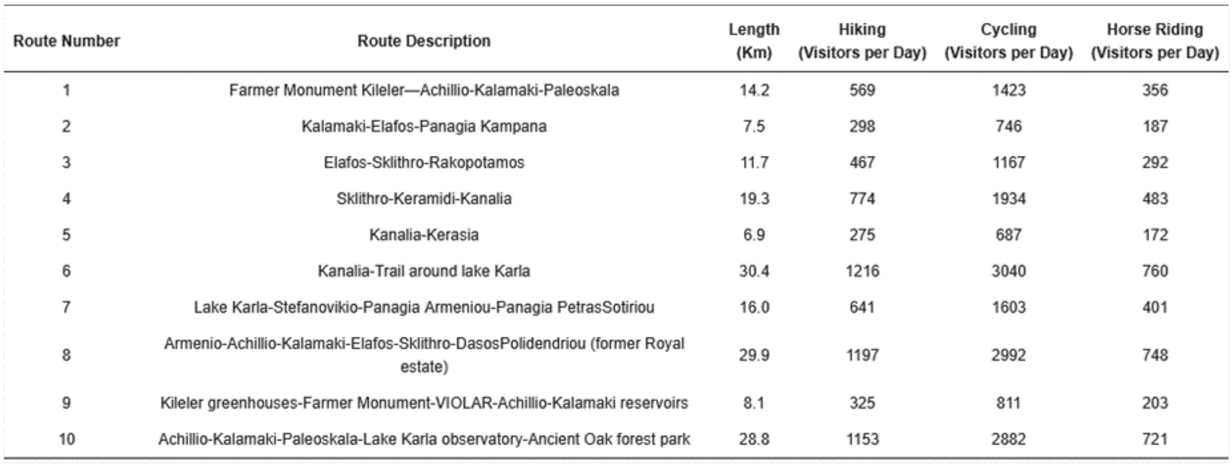
No water transport vessels are active in the lake and a public means of transport network around the lake does not exist.

1.3.13 Sustainable energy

There is no use of renewable energy sources in the infrastructure but photovoltaics (Solar panels) for energy production are existent (rising trend according to the Regulatory authority for Energy waste and water).

1.3.14 Sustainable Tourism

The rates of tourism are so low that only as sustainable could be deemed from an environmentla perspective. But the carrying capacity is high (Trakala et al., 2023) with relatively high Cultural Importance, Ecological Value, Opportunities for Education, Accessibility for Different Uses, i.e., Hiking, Cycling and Horse Riding (in relation to the routes)



Route Number	Route Description	Length (Km)	Hiking (Visitors per Day)	Cycling (Visitors per Day)	Horse Riding (Visitors per Day)
1	Farmer Monument Kileler—Achillio-Kalamaki-Paleoskala	14.2	569	1423	356
2	Kalamaki-Elafos-Panagia Kampana	7.5	298	746	187
3	Elafos-Sklithro-Rakopotamos	11.7	467	1167	292
4	Sklithro-Keramidi-Kanalia	19.3	774	1934	483
5	Kanalia-Kerasia	6.9	275	687	172
6	Kanalia-Trail around lake Karla	30.4	1216	3040	760
7	Lake Karla-Stefanovikio-Panagia Armeniou-Panagia PetrasSotiriou	16.0	641	1603	401
8	Armenio-Achillio-Kalamaki-Elafos-Sklithro-DasosPolidendriou (former Royal estate)	29.9	1197	2992	748
9	Kileler greenhouses-Farmer Monument-VIOLAR-Achillio-Kalamaki reservoirs	8.1	325	811	203
10	Achillio-Kalamaki-Paleoskala-Lake Karla observatory-Ancient Oak forest park	28.8	1153	2882	721

Fig D5. Visitors carrying capacity for three different uses of eco-cultural activities (After Trakala et al., 2023)

1.3.15 Water supply & sanitation

The use of Lake Karla reservoir for water supply in not yet active. Sanitation measures and infrastructure are to be planned in the future. Most villages around the lake do not have a central sanitation system nor wastewater treatment plant. People use septic tanks and water network is pantorhoic.

1.4 Unexpected results across criteria, synergies and trade-offs

The design of the project was in cases problematic, i.e. the ditches/channels targeting to supply water to the lake are also used as agricultural outflow collectors, irrigation water distributors and buffers for flood protection simultaneously. This has led to insuficient water supply to the lake, especially during the 2013-2018 period. The main issue with the hydrological regulation of the lake and the deficient water balance led to a magnification of the effects caused by other drivers like agricultural production.

Still the area around the lake has a high potential supply fro regulating and cultural ecosystem services while the agricultural plain supports mostly provisioning Services

1.5 Summary of effectiveness of restoration programme

Irrigation (Inflow by Pinios, irrigation channels, small irrigation reservoirs, pumping stations, ditches) have partly solved the problem.

Groundwater recharge (mostly due to the re-construction/re-filling of the reservoir) have assisted the depletion problems plus the augmented water storage capacity

Flood resilience (Collectors, pumping stations, drainage networks and the lake itself) have ameliorated several indicators as: cultivated area protected by flooding, land barren area protected by flooding, basin drainage length, non erosive land, soil Erosion by water, Peak flood volume.

Water quality, applying riparian buffer zones (phytoremediation), artificial wetland, planting / forestation, peripheral buffer zone, managed outlet for flushing did not achieve so a better water quality in means of cyanobacteria, blooms and other BQEs (invertebrates)

Actions for Biodiversity preservation and against Habitat degradation (change in protection status, re-creation of the wetland, management policy, creation of fish & bird breeding sites, and the habitat corridors) have partly managed to solve the problem as a rising trend has been recorded regarding species and populations

What challenges still need to be addressed?

Cultural and leisure activities along with green/blue growth (farm to fork strategy, zero mile, green/eco labelling etc) have to be operationally supported and addressed as, besides the establishment of the managing authority nothing more has happened so far

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[3] https://www.iucnredlist.org/species/5040/137242801

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e) Loch Leven

1.1 Lake details

Lake name: Loch Leven		
Type of characteristics	**Characteristics**	**Value**
Geographical characteristics	**Geographical coordinates:**	
	Longitude	3° 30’ W
	Latitude	56° 10’ N
	Altitude (m.a.s.l.)	106
Lake characteristics	Area [km^2]	13.3
	Maximum depth [m]	25.5
	Mean depth [m]	3.9
	Water volume [m^3]	61,708,820
	Depth index (mean depth to maximum depth ratio)	0.15
	Water residence time (τ) [years]	5.2 months
	Residence type	short
	Shoreline development index	1.43
	Mixing type	Polymictic
	Stratification	Non-stratified
Catchment characteristics	Total catchment area [km^2]	158.7
	Direct catchment area [km^2]	145.4
	Land-use (CORINE)	**% of total catchment area**
	Agriculture	62.0
	Urban	5.1
	Forests	23.7
	Wetlands	0.2
	Water bodies	9.0
	Schindler’s index (sum of total catchment and lake areas to lake volume ratio)	2.58

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Climate characteristics (30 year average; 1991-2020 unless otherwise stated)	Mean annual air temperature	9 °C
	Mean annual precipitation	714 mm
	Maximum summer air temperature	21.9 °C
	Days number > 15°C air temperature per year (2001-2020, only)	9.1
	Days with snow per year	Not recorded, but probably <5
Hydrochemistry and trophic type (situation in 2025)	Alkalinity (meq/L), Alkalinity type (low - <0.2, medium 0.2-1.0, high - > 1.0)	1.5; high
	Colour type (colour in HAZEN units – clear < 30, humic 30-90, polyhumic >90)	16.6 mgPt/L; clear
	Trophic type (oligotrophic, mesotrophic, eutrophic, hypertrophic)	eutrophic
	Calcium level (water hardness – softwater <25 mg Ca/L, hardwater ->25 mg Ca/L	25.5 mg Ca/L (on soft/hard water boundary)

1.2 Restoration Programme

1.2.1 Aims

Loch Leven is a shallow lake in south-eastern Scotland, UK. Routine sampling began here in 1968 and, since then, the open water of the loch has been sampled consistently at two main sites – Reed Bower and Sluices (Figure e.1). Water physics, chemistry, biology and hydrology have been monitored at two-weekly intervals since then and there are very few gaps in this 58-year data series.

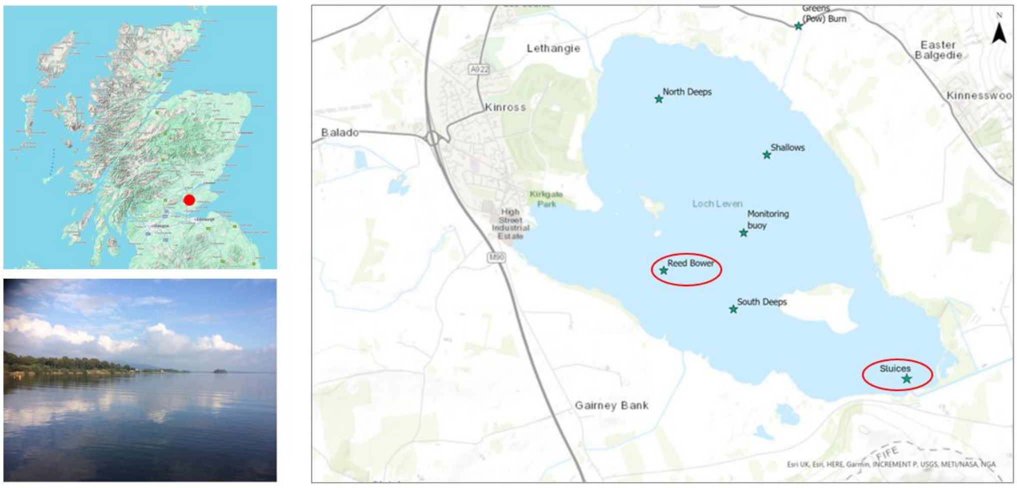

Figure e.1 Location of main sampling sites at Loch Leven, Scotland, UK; the routine monitoring sites are indicated in red.

In the late 1970s to early 1980s, it became clear that potentially toxic cyanobacterial blooms were becoming more common and there were demands for this problem to be resolved. The first step was to examine the existing data to establish the main cause of this decline in water quality. A very close relationship was found between phytoplankton abundance (measured as chlorophyll *a* concentration) and the level of phosphorus in the loch (Figure e.2; May & Spears, 2012a). It was concluded that restoration needed to focus on reducing phosphorus inputs to the loch.

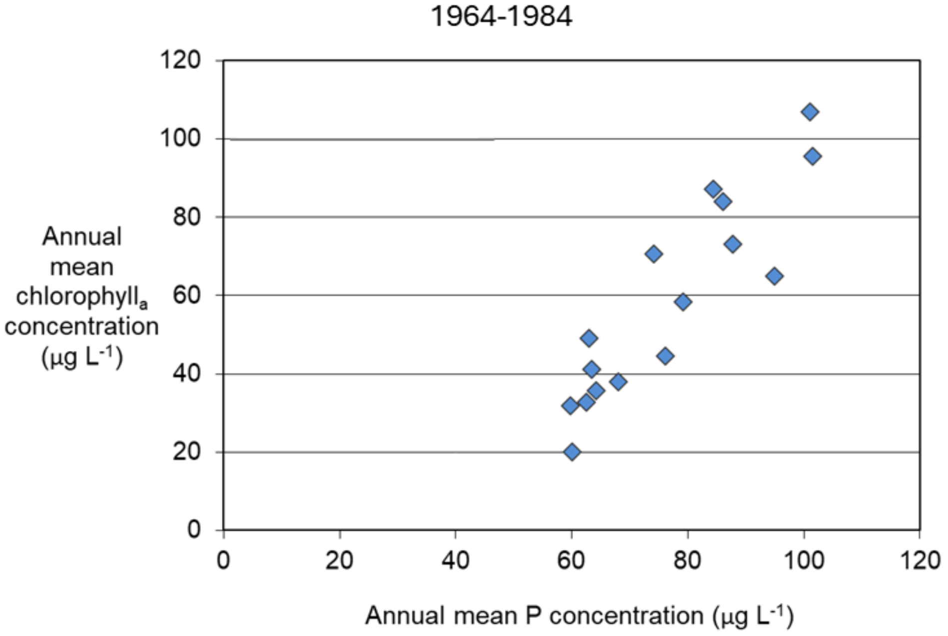

Figure e.2 The relationship between annual mean chlorophyll-a and total phosphorus concentrations in Loch Leven between 1964 and 1984.

A Loch Leven Area Management Advisory Group (LLAMAG) was formed in 1992 after a severe algal bloom was recorded at the loch. This Group, comprising three working groups (Water quality, Planning and Development, and Agriculture and Forestry), developed and published a detailed catchment management plan for the loch (LLAMAG, 1999).

A full nutrient loading study had been carried out in 1985 to determine the main sources of the high levels of phosphorus that were entering the loch (Bailey-Watts & Kirika, 1987) so that the limited resources available for restoration activities could be targeted effectively. It was found that, of the estimated 20 tonnes per year of phosphorus entering the loch from its catchment, the biggest sources were an industrial effluent (6.3 tonnes per year) and runoff from land (8.1 tonnes per year). Discharges from wastewater treatment works contributed an additional 5.3 tonnes of phosphorus per year.

1.2.2 Targets

In 1993, the LLAMAG set water quality standards (WQSs) for the loch. These were:

- Annual mean water clarity of 2.5m, based on Secchi Disc transparency readings
- Annual mean chlorophyll-*a* concentration of 15 µg L^{-1}
- Annual mean total phosphorus concentration of 40 µg L^{-1}

The chlorophyll-*a* and total phosphorus WQSs have been added to the water quality graph for 1964-1984 in Figure e.3. These recommendations were based on various eutrophication models that were variable at the time and were back calculated from the conditions that were expected to allow the recovery and growth of submerged macrophytes to a depth of 4.5 m. They were not considered to be targets *per se*, but instead they were considered to be “the conditions required to sustain the appropriate abundance and diversity of fauna and flora, along with nuisance-free water quality, suitable for all uses” (LLCMP, 1999). It was estimated that these water quality standards would be met if the phosphorus input to the loch was reduced to about 10.5 tonnes per year.

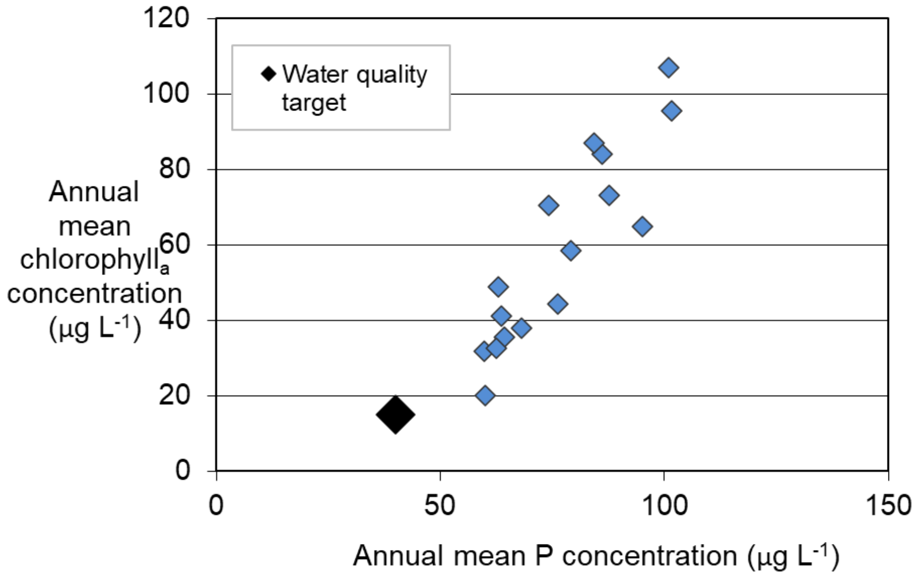

Figure e.3 The relationship between annual mean chlorophyll-a and total phosphorus concentrations in Loch Leven between 1964 and 1984; black diamond indicates the water quality standards set for the loch in 1993.

These were not initially set as water quality targets, as such, differ from the water quality boundary values set for the loch under the Water Framework Directive (Table e.1).

Table e.1 Water quality boundary values set for Loch Leven under the Water Framework Directive; data provided by the Scottish Environment Protection Agency (SEPA)

Parameter	Poor/Bad	Moderate/Poor	Good/Moderate	High/Good
Chlorophyll-*a* (µg/L)	62	19	10	6
Total phosphorus (µg/L)	140	70	35	25
Total nitrogen (mg/L)	3.08	1.54	0.77	0.48

1.2.3 Types of Measures

A number of restoration measures were put in place between 1985 and 1997 (LLAMAG, 1999 – Fig. 4a). These were focused mainly on reducing discharges from point sources, with the industrial effluent from a local woollen mill being reduced by 100 per cent due to a change in its production processes and discharges from waste water treatment works (WWTW) being reduced by about 17 per cent due to the introduction of more effective phosphorus removal processes. Although buffer strips were installed along some of the rivers draining into Loch Leven to reduce contamination by runoff from land, their effectiveness and implementation costs were not quantified (See Section 1.2.4).

1.2.4. Dates

Key dates for phosphorus reduction measures being installed are:

- 1987 Industrial source of phosphorus reduced by 6.29 tonnes per year

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- 1993 & 1997 Phosphorus discharges from Kinross WWTW reduced by 2.1 tonnes per year
- 1995 Phosphorus discharges from Milnathort WWTW reduced by 0.6 tonnes per year
- 1995 Buffer strips installed along some of the rivers that flow into Loch Leven; effect on phosphorus deliver to the loch unknown
- 1997 Phosphorus discharges from Kinnesswood WWTW reduced by 0.6 tonnes per year
- 1997 Phosphorus discharges from Vane Farm WWTW reduced by 0.05 tonnes per year

1.3 Environmental outcomes of restoration programme

The impact of the restoration programme on phosphorus inputs to the loch has been monitored via decadal phosphorus loading surveys that began in 1985. The outputs from these are compared in Figure e.4. The measures put in place between 1985 and 1995 reduced the external input of phosphorus by about 50 percent in the longer term; however, initially, the reduction in phosphorus load due to the restoration programme was estimated to be about 10 per cent higher than this. This anomaly was caused by runoff from land being unusually low in 1995 due to very low summer rainfall.

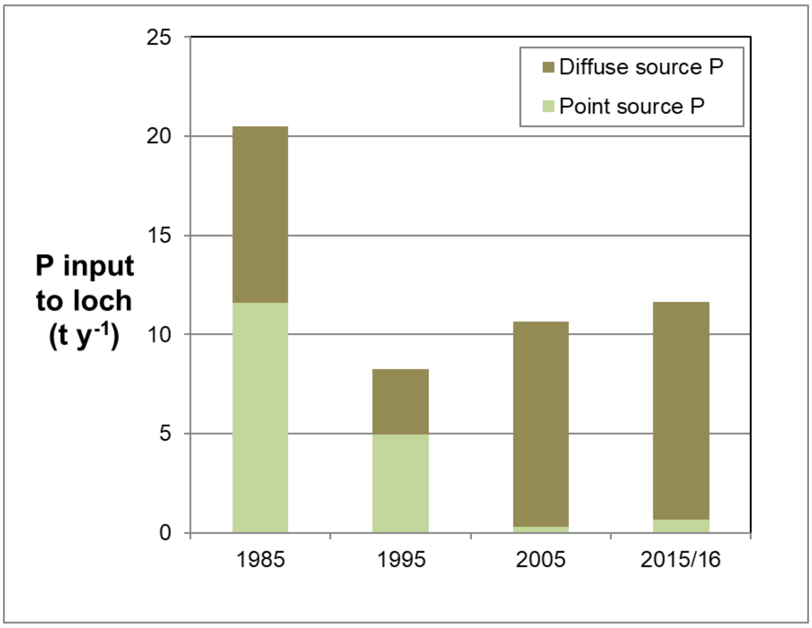

Figure e.4 Phosphorus inputs to the loch estimated from weekly loading surveys undertaken in 1985, 1995, 2005 and 2015.

The impact on loch water quality of the reduction in phosphorus inputs from the catchment in terms of phosphorus and chlorophyll-*a* concentrations is shown in Figure e.5 (May et. al., 2012). Although recovery was slow initially due to the internal recycling of legacy phosphorus from the sediments which continued until 2007 (Spears et al., 2012), the water quality improved over time reaching the phosphorus and chlorophyll-*a* water quality standards that had been set in the early 1990s (Figure e.5).

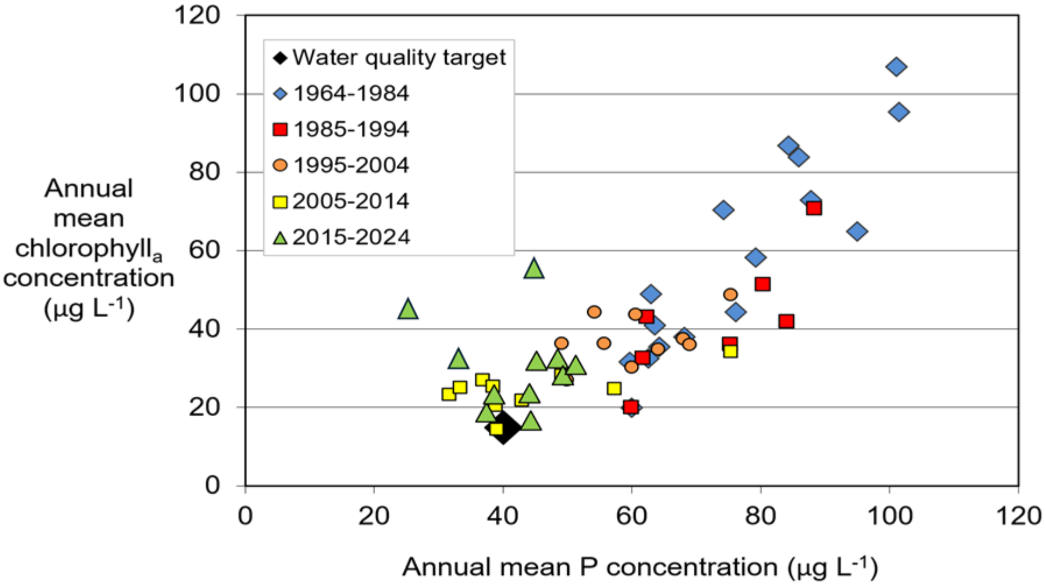

Figure e.5 Recovery graph from Loch Leven showing changes in chlorophyll-a and total phosphorus concentrations over a range of 10-year time intervals.

Since 2018, phosphorus and chlorophyll-*a* levels have started to rise again and algal blooms have returned. There is no evidence that the inputs of phosphorus from the catchment have increased over this period, but recent data suggest that soluble reactive phosphorus (SRP) release from the loch sediments, which was declining over the period of restoration (Spears et al., 2012), is now starting to increase again. This seems to be linked to the water temperature going above 17°C, which was a relatively rare occurrence but is happening more frequently now due to climate change Figure e.6.

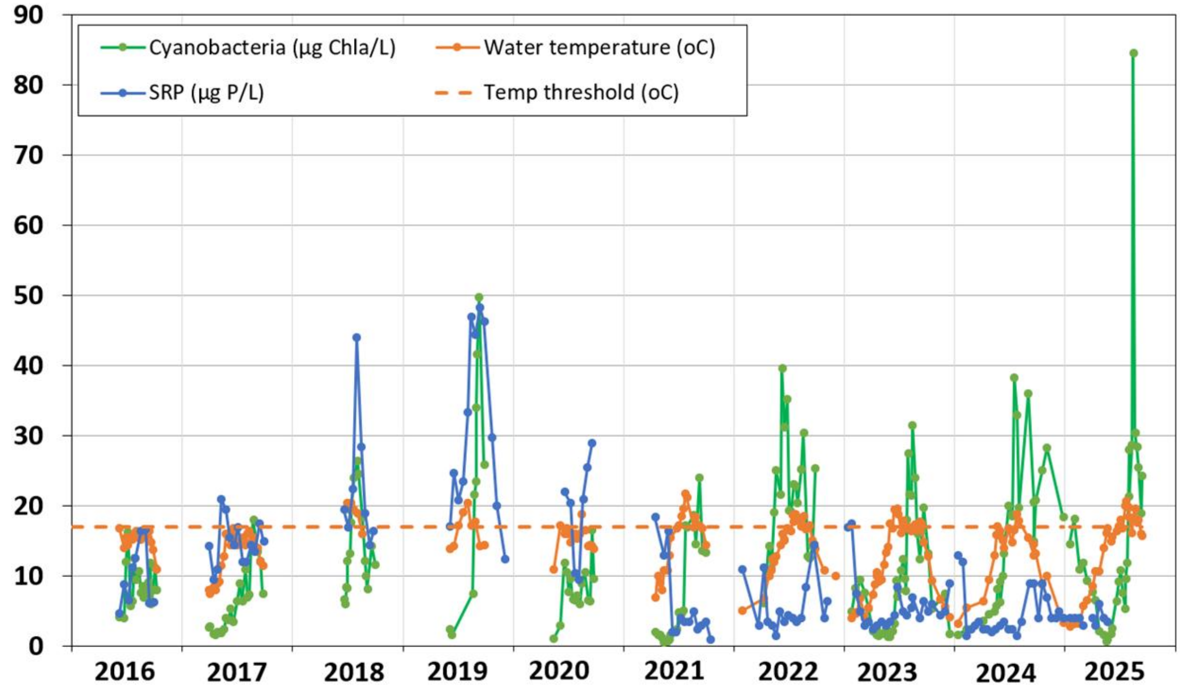

Figure e.6 Cyanobacterial blooms (——) have re-appeared in Loch Leven form 2018 onwards, especially during periods when the water temperature has risen above 17^{o}C (- - -) for several days.

Potamageton praelongus
re-appeared after 100 years

Figure e.7 Maximum growing depth of submerged macrophytes in Loch Leven over the period of restoration.

This strongly suggests that, although initially the loch ‘recovered’ from excess phosphorus pollution, in its current state the loch is not resilient to the effects of climate change and additional measures will need to be put in place to address this issue in the future. The long-term data also suggest that there is an inverse relationship between flushing rate and chlorophyll-*a* levels in the lake.

During the period of recovery, algal blooms reduced and water transparency increased. This enabled submerged macrophytes to re-establish themselves in deeper water (Figure e.7, left panel; May & Carvalho, 2010) with one species (*Potamageton praelongus*) re-appearing after an absence of almost 100 years (Figure e.7; right panel; Dudley et. al., 2012).

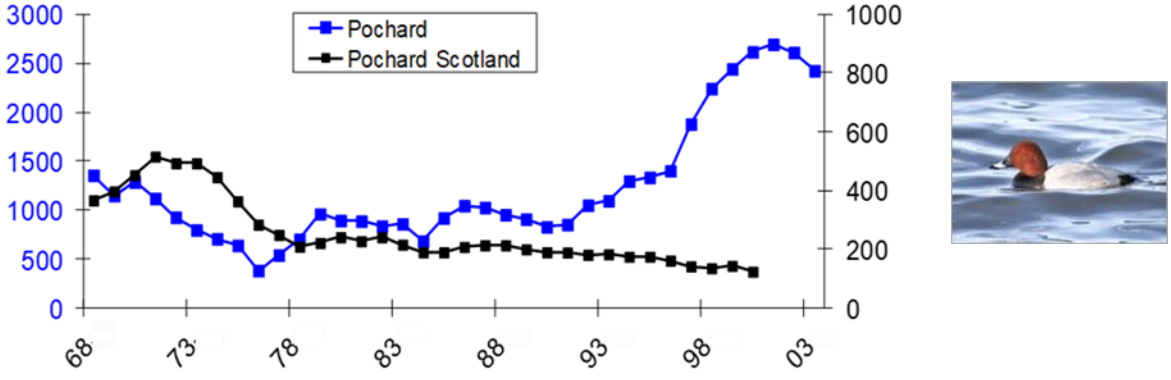

Figure e.8 Changes in the number of pochard at Loch Leven during the period of restoration compared to the numbers of pochard in Scotland as a whole.

When the water clarity increased and the submerged macrophytes moved into deeper water, the populations of aquatic birds that were dependent on the loch for food and habitat began to increase. The most striking example of this, for the pochard, can be seen in Figure e.8 Between 1968 and 1990, the number of pochard at Loch Leven followed the same trend as the number of pochard across

Scotland. However, once water quality began to recover and their food and habitat increased, the pochard at Loch Leven increased markedly while the numbers for Scotland continued to decline (Carss et al., 2012).

Loch Leven was an important recreational fishery until a serious algal bloom occurred in June 1992. This was widely publicised in the media and led to a sudden downturn in the number of fishing boats being hired by anglers (Figure e.9). This caused an estimated loss of income to the fishery of 369,000 Euros per year, based on the higher income generated in 1975 is compared to the lower income generated in 2005. Although the number of boat hires increased again over the period when restoration measures were being put in place (1992 – 1997), they declined again rapidly over the rest of the recovery period. This was due, most likely, to reputational damage over that period. Boat hires began to increase slowly only after 2007, when water quality began to improve.

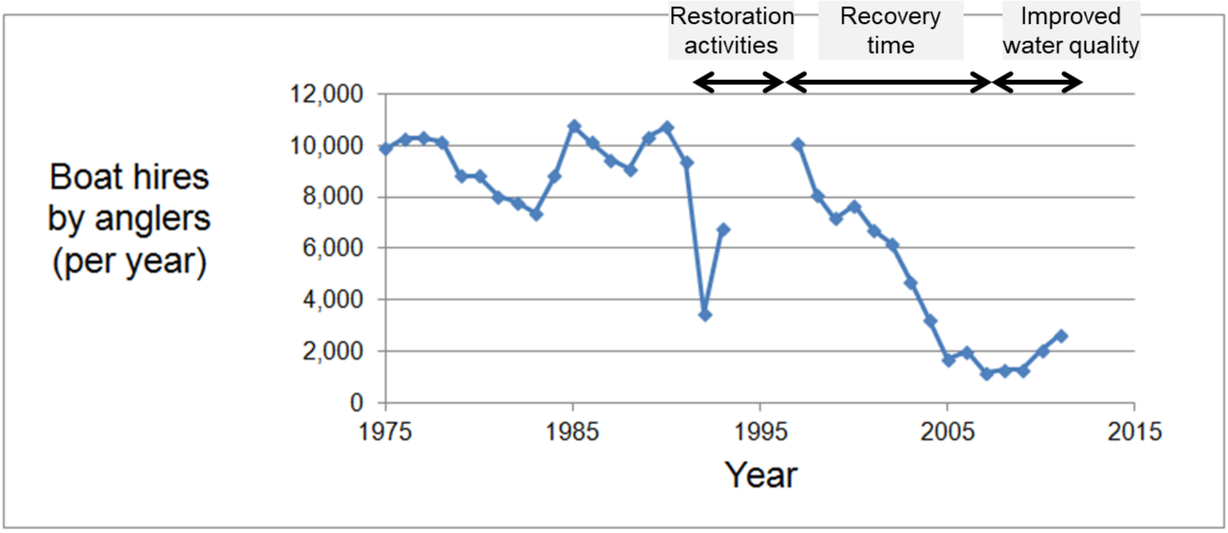

Figure e.9 Annual variation in boat hires over different phases of the restoration and recovery of Loch Leven between 1975 and 2011.

1.3.1 Water Framework Directive

The key water quality targets set for Loch Leven under the Water Framework Directive are shown in Table e.1 The change in loch status estimated from those parameters and additional data are shown in Table e.2. In general, the WFD status of Loch Leven has varied over time showing no obvious trend between 2007 and 2024.

Table e.2 Changes in the WFD status of Loch Leven for selected indicators, 2007-2024. Data: SEPA.

Parameter	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2022	2023	2024
Total phosphorus	🟧		🟧	🟧	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧
Total nitrogen													🟨	🟨	🟨	🟨	🟨
Dissolved Oxygen									🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
Chlorophyll-*a*	🟥		🟥	🟥	🟥	🟧											
Macrophytes	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Macroinvertebrates		🟨	🟨	🟨	🟨	🟨		🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Hydromorphology	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Lake status

🟪	High	🟨	Moderate	🟥	Bad
🟩	Good	🟧	Poor	⬜	No data

In contrast, when the more frequent monitoring data collected by UKCEH are plotted as a time series against the background of the WFD status classes, and over a longer period (Figure e.10), it can be seen that the general trend total phosphorus and chlorophyll-a concentrations has been downward – even though the values have, for the most part, remained within the same WFD status class. This demonstrates that some of the effects of restoration can be lost unless time series data are looked at in detail.

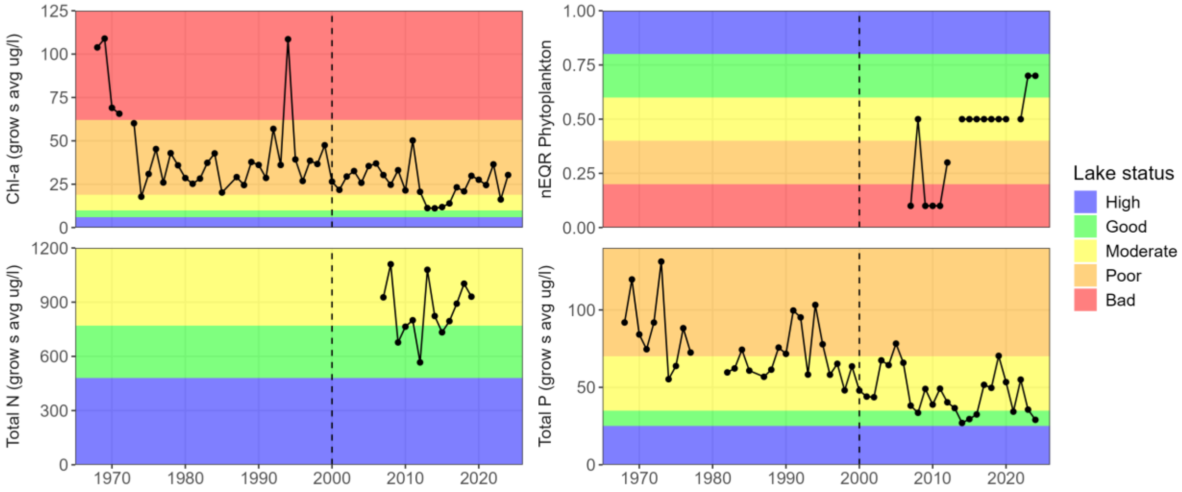

Figure e.10 Plots of key parameters (chlorophyll a (Chl-a); nEQR for phytoplankton; total nitrogen (N); total phosphorus (P)) over time in relation to WFD status class boundaries for Loch Leven.

1.3.2 Biodiversity

Loch Leven is important for its freshwater habitat, which is naturally rich in nutrients (eutrophic), the fen and swamp areas around the loch edges, its breeding and non-breeding wildfowl, and its rare vascular plants and beetles. It supports a wealth of insects, fish and bird species, and the comparatively extensive range of mire and fen types fringing the loch vary from beds of reed and reed grass to sedge-rich areas, wet grassland, fen meadow and willow scrub. Although the diversity of aquatic plants within the loch itself declined during the 20th century because of pollution, there is recent evidence of a recovery.

Loch Leven is a designated National Nature Reserve (NNR) for Scotland, and the NNR overlaps with three other protected areas, all of which cover an area of about 1611 ha: Loch Leven Special Protection Area (SPA), Loch Leven Ramsar Site, Loch Leven Site of Special Scientific Interest (SSSI) and Loch Leven Natura 2000 site. The Loch Leven Ramsar Site designation (RIS, 1976) includes the following qualifying features:

- Naturally eutrophic loch (Ramsar criterion 1)
- Species with peak counts in winter (Ramsar criterion 5)
- Species/populations occurring at levels of international importance (Ramsar criterion 6)

The Loch Leven SSSI designation cover the following notified natural features:

- Freshwater habitats: Eutrophic loch

- Fens: Hydromorphological mire range
- Vascular plants: Vascular plant assemblage

Bird community composition and structure

The large expanse of open water, islands and the abundance of food make the loch very attractive to bird life throughout the year, but especially as a stopover on migration routes in the spring and autumn. Many species of wildfowl and other wetland birds breed around the loch, with St Serf's Island supporting up to 1,000 nesting pairs, especially of tufted ducks; there are also significant numbers of breeding gadwall. In autumn, winter and spring large numbers of cormorant, gadwall, goldeneye, greylag goose, pink-footed goose, pochard, shoveler, teal, tufted duck and whooper swan use the loch for feeding or roosting.

Trends in aquatic bird numbers at the Loch Leven examined trends were examined by comparing 5-year mean species abundances at Loch Leven compared with similar data for Scotland, between 1968 and 2006 (Carss et al., 2012). Five species showed population trends that were similar to those at the Scottish scale (Eurasian Teal, Mute Swan, Great Cormorant, Pink-footed and Greylag geese). These species seem to have been relatively insensitive to the changes in habitat quality provided by the loch management measures. However, the five other species (Mallard, Coot, Great Crested Grebe, Tufted Duck and Pochard) showed distinct differences between local and national trends that are likely to be related to the recovery of macrophyte, invertebrate and fish communities in the loch during and after restoration. However, this requires further evaluation.

Table e.3 List of important bird species at Loch Leven and their level of protection

Bird species	**Level of protection**		
	SPA	**SSI**	**Ramsar**
Cormorant (*Phalacrocorax carbo*)	X	X	X
Gadwall (*Anas strepera*)	X	X	X
Goldeneye (*Bucephala clangula*)	X	X	X
Pink-footed goose (*Anser brachyrhynchus*)	X	X	X
Pochard (*Aythya ferina*)	X	X	X
Eurasian teal (*Anas crecca*)	X	X	X
Tufted duck (*Aythya fuligula*),		X	X
Whooper swan (*Cygnus cygnus*),		X	X
Northern shoveler (*Anas clypeata*)	X	X	X
Mute swan (*Cygnus olor*)			X
Greylag goose *(Anser answer*)		X	X

The most recent condition assessment available (August-September 2009) indicates that all 9 designated bird species were in Favourable condition (maintained) as was the non-breeding waterfowl assemblage.

Important bird species at Loch Leven are protected under the local and international conservation designations show in Table e.3.

Aquatic plant community composition and structure

The Loch Leven SSSI is also designated for its eutrophic freshwater habitat. The site is outstanding for the number of aquatic plant species present, which are representative of a eutrophic water body, including several stonewort species of conservation interest, such as *Chara aspera* and *Tolypella nidifica* var. *glomerata.* The site also contains two vascular plant features, the nationally scarce plants *Limosella aquatica* and *Potamogeton filiformis*. The two species are not specifically mentioned as a feature on the SSSI notification but have been listed as a vascular plant feature at Loch Leven by NatureScot. *Juncus filiformis* and *Hierochloe odorata* are listed as nationally important wetland species on the Ramsar Information Sheet for this site (RIS, 1976).

There have been many surveys of the macrophyte community of the loch going back to 19th century, with the first systematic survey carried out by West in 1907 (West, 1910). In 2012, UKCEH conducted an extensive assessment of changes in the macrophyte community of Loch Leven across the period 1907 – 2008, which indicated a recovery of the macrophyte community towards the state recorded in 1907 (Dudley et al., 2012). The study observed presence of Pota*mogeton praelongus* and *Ranunculus spp.* in 2008, first time since 1907, and an increase in the abundance of *Potamogeton berchtoldii/pusillus* in years 1999 and 2008 compared to 1975 and 1993, when this species was rarely seen. Species richness was highest in 1907 (16 taxa), followed by a decrease in numbers: 7 (1966), 11 (1972 and 1975), 8 (1986), 10 (1993), 9 (1999) and an increase to 13 in 2008. A decline in the maximum growing depth (MGD) of macrophytes observed between 1907 and the early 1970s (from 4.6 m to 1.5 m), was followed by some improvement in the late 1970s and 1980s (2.4 m in 1979) and a dramatic improvement between 1990 and 2008 (1.8 m and 4.3 m, respectively; Dudley et al., 2012). This recent improvement in MGD is likely to be linked to the restoration process, through its positive impact on water clarity.

The current macrophyte community assessment is based on Site Condition Monitoring (SCM) surveys carried out to assess the conditions of the designated features for the Loch Leven SSSI site. The last SCM survey was carried out in August 2020. The results were compared to the August 2004 SCM data, due to the comparability of methods and transects surveyed, to assess trends in the conservation status of the Loch Leven site over a 20-year period. In 2020, the macrophyte flora of Loch Leven were surveyed using two shore wader transects (with associated perimeter searches), whilst, in 2004, the assessment also included a boat transect. In 2020, 13 submerged and floating-leafed species were recorded compared to 16 species observed in 2004. Three additional species, however, were found during a boat survey conducted in 2020 separately from the SCM survey. So, the total number of macrophyte species remained unchanged.

The average abundance frequency of unfavourable species (calculated as the ratio of sampling points in which the species occurred to the total number of sampling points examined; reported as a percentage) in the two wader transects in 2020 was 3%, a decrease compared to 33% frequency recorded in 2004. The number of unfavourable species recorded in 2020 was lower than in 2004 (two and four, respectively) and included *Elodea canadensis* and *Elodea nuttallii*. The latter was not observed in 2004, although the *Enteromorpha intestinalis* and *Chara socotrensis* collected in the surveyed sectors in that year were not recorded during the most recent survey.

Out of two characteristic *Chara* species recorded in 2004 - *Chara aspera* and *Chara virgata* – only *Chara aspera* was observed again in 2020. However, *Chara globularis*, not observed in 2004, was recorded during the latest SCM survey and also during surveys carried out by the Scottish Environment Protection Agency in 2011 and 2017. Four *Potamogeton* species were observed in 2020 compared to three recorded in 2004. These included *P. perfoliatus* and *P. pusillus*, which were also present in the sectors surveyed in 2004. *P. filiformis* was observed in 2004 but not found in 2020. However, two additional species were recorded in the latter year: *P. crispus* and *P. pectinatus. Tolypella nidifica* var. *glomerata* was another feature species observed in both years, whereas *Limosella aquatica* was absent - last recorded at the site in 1973 (JNCC database).

The frequency of characteristic/associated species were 15 % and 80 % in the two wader transects surveyed in 2020, with the characteristic/associated species being only or dominant submerged and floating-leafed species macrophytes, respectively. Although the frequency decreased compared to 2004 when characteristic/associated species were observed in 95% of surveyed points, the relative frequence (calculated as the ratio of a number of times the favourable species were recorded to the total number of records for all submerged and floating-leafed species) remained high at 95%. This suggests that the lake maintained the favourable status.

Macroinvertebrate community composition and structure

Changes in the total number of benthic macroinvertebrate taxa recorded in the littoral area of Loch Leven were evaluated by Gunn et al. (2012). The authors showed that the number of Plecoptera, Ephemeroptera, Coleoptera and Trichoptera species recorded between 1998 and 2006 were much higher than those recorded in earlier surveys (1966–1973), when the loch was more polluted (Gunn et al., 2012). Of particular note is that the later survey data included pollution intolerant Plecoptera and Ephemeroptera species, such as *Diura bicaudate* and *Ecdyonurus dispar*. Loch Leven has also designated as a SSSI for its variety of rare beetles, the rarest of which is *Thanatophilus dispar*, a specialist feeder on carrion such as dead fish or birds.

1.3.3 Zero pollution

Priority pollutants (PFAS), plastic pollution and dissolved inorganic nitrogen (DIN) are not measured at this site, and nitrate (NO_3-N) is measured infrequently. So, it has not been possible to look for trends within the concentrations of these pollutants. However, total oxidisable nitrogen (TON), total phosphorus (TP) and soluble reactive phosphorus (SRP) have been measured at two weekly intervals over the period of restoration and recovery. The results are shown below.

The long-term trend in in-lake TP concentrations are shown in Figure e.11. In general, concentrations fell during the period of restoration and recovery until 2007. Beyond this period, levels began to rise again until 2015, then remained relatively stable. The sudden drop in values in 2007 were due to a reduction in phosphorus release from the sediments, which continued until 2018. Then phosphorus releases from the sediments increased again – probably due to climate change.

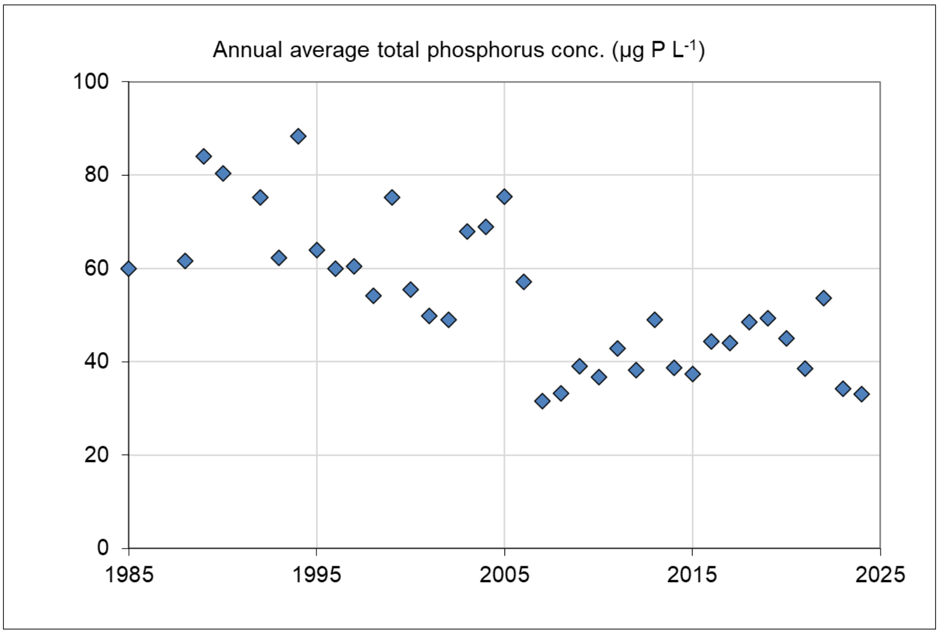

Figure e.11 Changes in the annual average total phosphorus concentrations in Loch Leven between 1985 and 2024

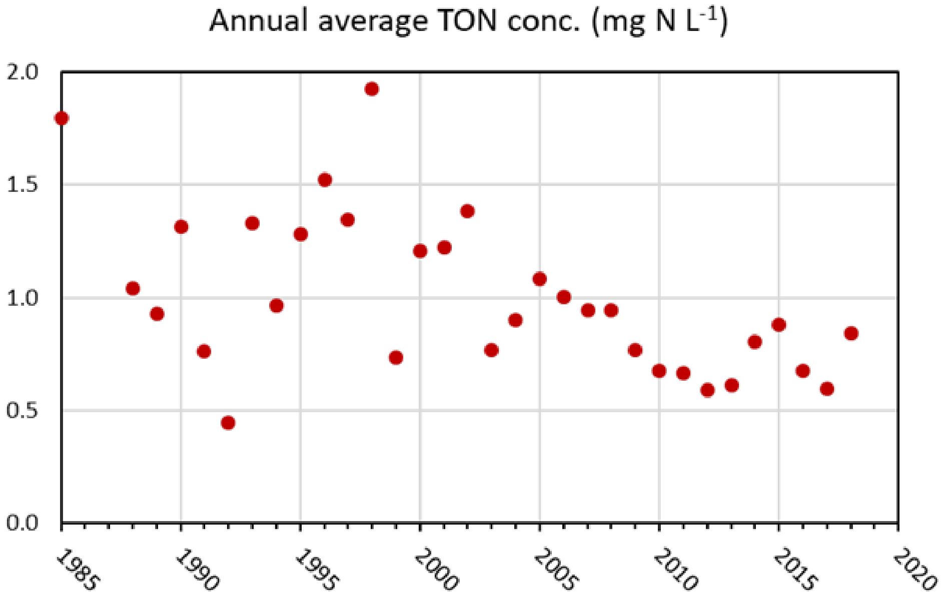

Figure e.12 Annual average total oxidisable nitrogen (TON) concentrations in Loch Leven between 1985 and 2018.

Annual average in-lake concentrations of TON decreased within the loch between 1985 and 2018 (Figure e.12) most likely resulting from a reduction in external inputs. Although these concentrations showed considerable variation from year to year before 2005, from 2007 onwards TON concentrations were consistently at or below 1 mg/L.

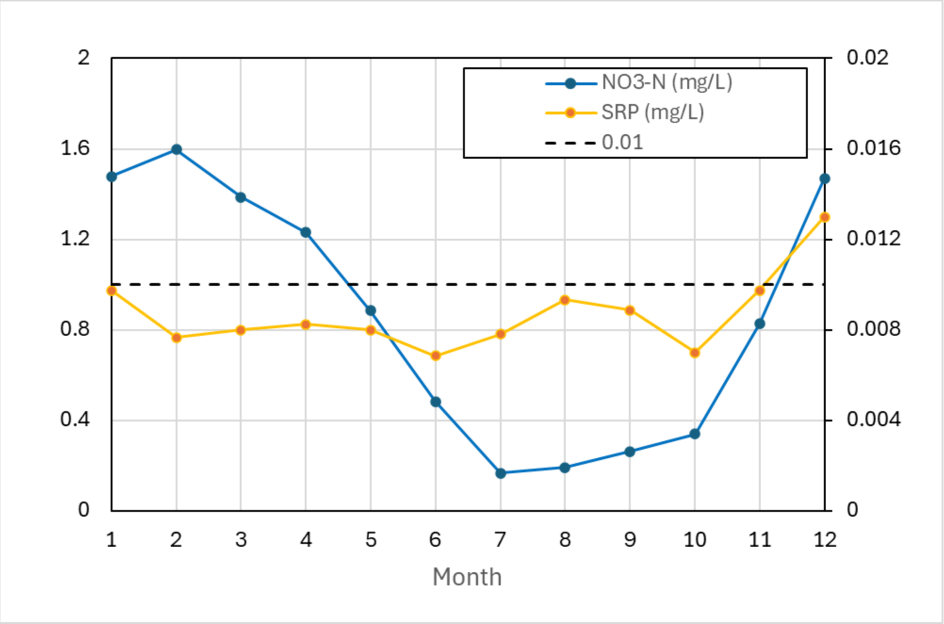

Figure e.13 Monthly changes in dissolved nitrogen (NO_3-N) and phosphorus concentrations (PO_4-P) in Loch Leven based on monthly mean data for 2009-2016

Monthly changes in dissolved nutrient concentrations in Loch Leven between 2000 and 2016 are shown in Figure e.13. The horizontal dashed line indicates potentially limiting concentrations for dissolved N (0.1 mg/L) and dissolved P (0.01 mg/L). The data indicate that, over this period, Loch Leven has generally been P-limited throughout the year, except in December. In contrast, it has been N-limited from May to November over the same period.

1.3.4 Climate outcomes

1.3.4.1 Contribution to climate regulation

Climate regulation, in this context, has been defined as the emission of greenhouse gases (in this case methane; CH_4) from a lake. It has been shown that emissions increase with higher levels of eutrophication and, consequently, higher chlorophyll-*a* concentrations. So, these emissions were estimated for Loch Leven to determine whether reducing chlorophyll-*a* concentrations by restoring the loch is likely to have had the opposite effect, i.e. of reducing CH_4 emissions. These emissions were estimated using a Bayesian model constructed from a global dataset of ground-based methane measurements and satellite-derived chlorophyll-*a* data published by DelSontro et al. (2018). The results have been interpreted in relation to the of the restoration measures implemented. The results are also compared to the level of CH_4 emissions from the loch estimated using IPCC guidance values for reservoirs of 1.46 tonne CO_2-eq/ha/year. It should be noted that, because the IPCC calculation does not take changes in water quality into account, it cannot be used to estimate the potential impacts of the restoration measures implemented at this site.

The annual average methane emissions from Loch Leven, estimated using the Bayesian method, between 1968 and 2024 was 0.676 Gg CH_4-C/year or 26,932 t CO_2-eq/year, although the values varied over time (Figure e.14) Between 1968 and 1984, before the main restoration measures were put in place, the estimated total CH_4 emissions from the loch was 0.87 Gg CH_4-C/year or 34,697 t CO_2-eq/year. Over the main period of restoration (1985-2004), the estimated average CH_4 emissions were 0.67 Gg CH_4-C/year or 26,613 t CO_2-eq/year. In the years that followed (2005-2024), the average estimated CH_4-C emission was 0.489 Gg CH_4-C/year or 19,462 t CO_2-eq/year (a reduction of 57 per cent). This suggests that the loch restoration measures implemented to improve water quality (i.e. reducing catchment phoshorus inputs by about 50 per cent) had also reduced the CH_4 emissions from the lake. In comparison, the CH_4 emissions for the whole period, based on the IPCC guidance values of 1.46 tonne CO_2-eq/ha/year for reservoirs, was estimated to be only 1,942 t CO_2-eq/year.

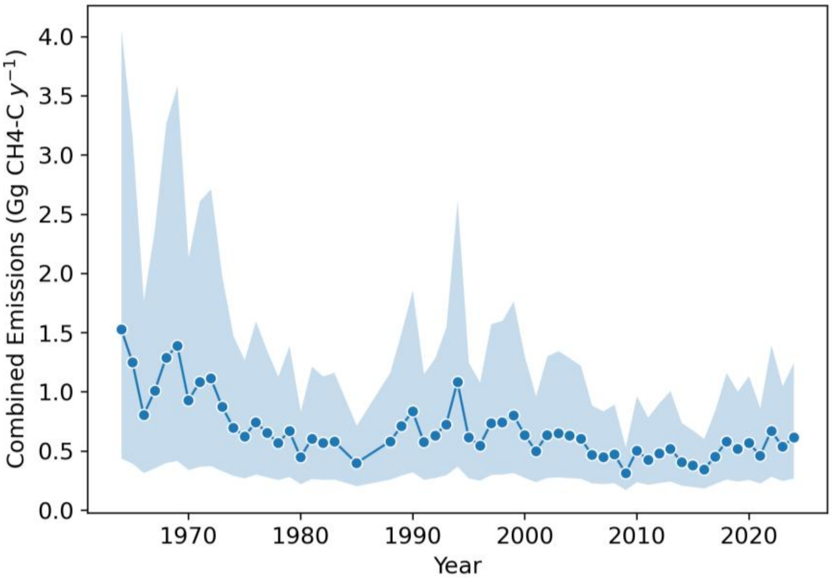

Figure e.14 Combined ebullitive and diffusive methane (CH_4) emissions from Loch Leven based on average annual chlorophyll-a concentrations and estimated using a Bayesian model derived from a global dataset of ground-based methane measurements and satellite-derived chlorophyl-a data published by DelSontro et al. (2018).

When the diffusive and ebullitive emissions of CH_4 were examined separately (Figure e.15) it was found that the estimated diffusive emissions remained relatively constant level of about 0.2 mg CH_4-C/m^2/y over the study period, whereas the ebullitive emissions of CH_4 varied over time (Figure e.15) – closely following the changes in chlorophyll-a concentrations that occurred as a result of the restoration process (Figure e.15).

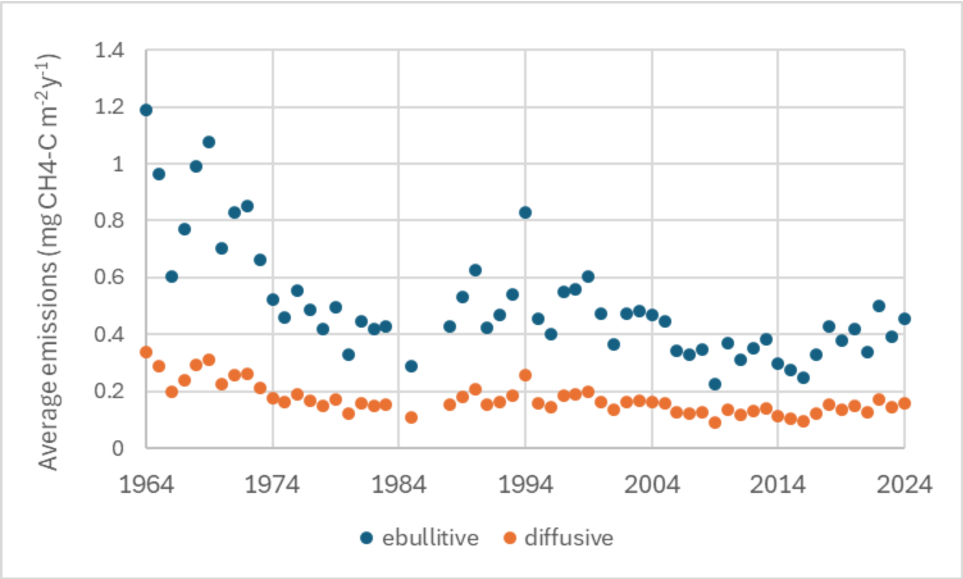

Figure e.15 Diffusive and ebullitive methane (CH_4-C) emissions from Loch Leven based on average annual chlorophyll-a concentrations; values were estimated using a Bayesian model derived from a *global dataset of ground-based methane measurements combined with satellite-derived chlorophyll-a data published by DelSontro et al. (2018).*

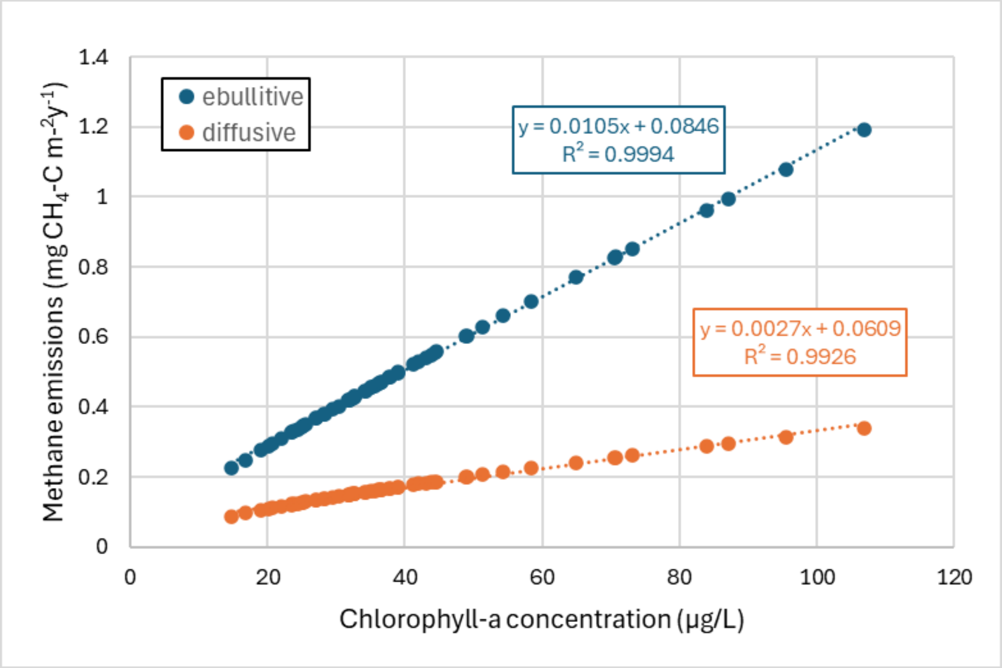

Figure e.16 Relationship between ebullitive and diffuse emissions of methane (CH_4-C) and chlorophyll-a concentration, as estimated by the Bayesian model derived from a global dataset of ground-based methane measurements combined with satellite-derived chlorophyll-a data (DelSontro et al., 2018).

1.3.4.2 Provision of climate change resilience

At Loch Leven, the water level was reduced by 1.4m when sluice gates were installed on the outflow in 1850 (May & Spears, 2012b). The outflow was also straightened to increase the rate of flow. Although these engineering works were put in place to supply a reliable source of water for industrial use downstream, these industries no longer exist and the sluice gates are now managed to maintain pre-agreed water levels within the loch, providing climate change resilience (Binne & Partners, 1965).

1.3.5 Social outcomes

1.3.5.1 Health, Well-being and Water quality

Exposure to nature in the Loch Leven National Nature Reserve provides a range of mental and physical health benefits. The Loch Leven Heritage Trail offers a safe and accessible route for walking, running cycling and use of mobility scooters for all age groups. For example, the scenic shores of Loch Leven have been part of the route for the annual Webster Loch Leven Half Marathon for 40 years. Kayaking, canoeing and angling are also undertaken by loch users, although the use of motorised craft is forbidden on the lake (NatureScot, 2023). These facilities provide opportunities for physical exercise and interactions with nature. In addition to the Heritage Trail, an area of green open space on the north shore of the loch is used regularly for recreation, especially by dog walkers and families with children.

1.3.5.2 Inclusivity in management

There is no information on inclusivity at this site.

1.3.5.3 Recreational Intensity and Tourism Metrics

Loch Leven National Nature Reserve offers a range of recreational opportunities. These include walking and cycling around the loch using the Loch Leven Heritage Trail (described Section 1.3.5.1), kayaking, canoeing, paddleboarding and angling. Wildlife hides that are located within the nature reserve and are accessible from the trail and provide facilities for bird watching. In addition, the Royal Society for the Protection of Birds (RSPB) visitor centre (https://www.rspb.org.uk/days-out/reserves/loch-leven) offers guided walks, such as a bumblebee trail and a bat walk.

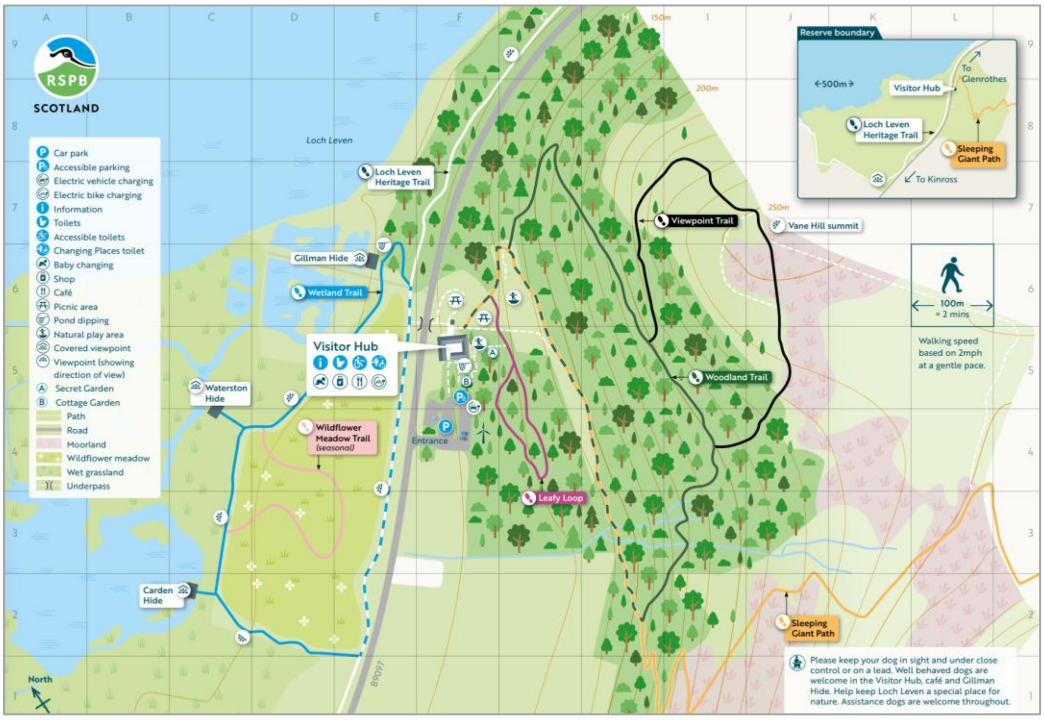

Figure e.18 Walking paths and trails at Loch Leven (Source: RSPB Trail Maps)

There are many other trails in the area including a wetland trail, a woodland hill trail and a 'Leafy Loop' walk (see Family map; Figure e.18); these connect to the Loch Leven Heritage Trail. Families can also hire pond dipping kits from the RSPB from April to October. To improve accessibility, mobility scooters can be hired and a live video link to a red squirrel feeding station can be viewed here.

A 14th century castle, located on one of the loch's islands, is accessible by boat, with tours offered by Historic Environment Scotland (HES) providing a Scottish heritage experience.

1.3.6 Economic outcomes

1.3.6.1 Circular economy

There is no information on the circular economy for Loch Leven.

1.3.6.2 Blue economy

Loch Leven is famous for its brown trout (*Salmo Levensis*) fishery (https://www.fishlochleven.co.uk/). Although stocked with rainbow trout and brown trout during the second half of the 20th century, the loch is now maintained as a wild brown trout fishery only. Fishing is permitted from the fishery's boats, only, and fly fishing is the only permitted method.

The loch attracts more than 300,000 visitors each year (TRACKS, 2023) who use a wide range of services available in the local area. Visitors can stay overnight in motorhomes and campervans in two car parks on the north and south-east shores of the loch, if they have their own on-board toilet facilities. Kayaking, canoeing and paddleboarding are allowed on the loch, but there are localised access restrictions on the use of these in bird sensitive areas. The Loch Leven Heritage Trail, completed in 2014 and established as a part of the National Cycle Network in 2022 – 2023, provides nature-friendly, all ability access to the National Nature Reserve for walkers, cyclists and other members of the public. This benefits local businesses, which have been able to establish or expand their operations around the loch due to the increase in visitors. Loch Leven Lodges, situated on the southern shore of the loch, provides accommodation for tourists. There are two cafes located on the southern side of the loch (RSPB visitor centre; Loch Leven Lodges café); another, Loch Leven's Larder, is situated on the north side of the loch. The RSPB visitor centre and Loch Leven's Larder also have gift shops. In addition to facilities that are immediately adjacent to the lake, visitors have access to a range of cafés, restaurants and local shops that are available in the local town of Kinross, which is within walking distance. The local town of Kinross also offers hotel and guest house accommodation, and a campsite, for tourists who wish to stay overnight.

The biggest impact on the blue economy was the implementation of the Loch Leven Heritage Trail in 2014, at a cost of 4,743,238.82 Euros. This was managed by The Rural Access Committee of Kinross-shire (TRACKS). Surveys carried out by ScotInform, an independent market research company, provide detailed information on the socio-economic impacts of the trail. The studies show an increasing trend in expenditure at businesses around the trail from its initial implementation to its completion in 2014. For example, in 2009, it was estimated that expenditure associated with the trail at five businesses around the loch was about 1,014,130 Euros per annum. Subsequent studies, focusing on seven of the businesses around the loch once the trail had been extended, found that the average expenditure per year had increased from 2,684,223 Euros in 2011 to an estimated 3,380,803 Euros in 2014. Although other factors, such as changes in businesses' own marketing techniques, have contributed to the increasing visitor numbers and associated expenditure, many of the businesses have described how the trail has allowed them to expand their business in different ways. For example, in 2010, one business noted that: "The trail brought customers closer to our business and the ongoing maintenance and upkeep of the trail means this has continued to have a very positive effect" (TRACKS, 2010).

An estimated 208,572 visitors per year used the Loch Leven Heritage Trail in 2014/2015 (Donnell, 2015) with at least 54% of these visitors spending approximately 12 Euros per person at businesses around or associated with the Trail. Similar values were reported for 2023, with 56% of visitors spending approximately 12 Euros each (TRACKS, 2023). These figures apply primarily to businesses immediately adjacent to Loch Leven.

The Loch Leven Heritage Trail is a long-term project that incurs maintenance costs. However, the amount of money the trail brings to the area every year far exceeds these costs. Perth and Kinross Council (PKC) fund the maintenance works, which average around 8,000 - 11,000 Euros per annum. Community engagement in association with NatureScot greatly reduces these costs through a weekly volunteering scheme, where community members contribute about 90 staff days per year towards track maintenance. This simultaneously reduces monetary pressures while promoting community involvement and pride in Loch Leven as a local asset.

1.3.7 Sustainable Agriculture

There are no data available on sustainable agriculture within the Loch Leven catchment.

1.3.8 Sustainable transport

Although Loch Leven is not used for navigation, the Heritage Trail around the loch provides a cycle path that is connected to other cycle paths in the area and supports green transport.

1.3.9 Sustainable energy

Although the loch itself does not provide sustainable energy, the water that flows out of the loch into the River Leven has been used for power generation in the past. More recently, a local community group (https://www.catch-lochleven.org/) has been exploring the possibility of using water source heat pumps to extract heat from the loch to provide community heating to nearby homes.

1.3.10 Sustainable Tourism

Loch Leven offers visitors the opportunity to experience its abundant wildlife, with the loch being an internationally important site for water birds throughout the year. It also has a long and well documented history that includes a 14th century castle located on one of its islands. Visitor numbers have been increasing, with a visitor survey conducted in 2023 estimating the number of visitors to the area to be 314,860 – an increase from 208,572 in 2014/2015 (TRACKS, 2023).

NatureScot, which manages the Loch Leven National Nature Reserve together with partners, provides information about the nature reserve on its websites, together with advice on responsible camping and on good practice when accessing wildlife sensitive areas to minimise disturbance of waterfowl and to protect nature more generally within the reserve (https://www.nature.scot/enjoying-outdoors/visit-our-nature-reserves/loch-leven-nnr/loch-leven-nnr-visiting-reserve). Water sports are discouraged between September and March due to the large number of wintering birds on the loch at that time of year. To enable easy and environmentally-friendly access to Loch Leven, the Loch Leven Heritage Trail was built around the shores of the loch. This 21 km circuit provides safe access to the National Nature Reserve for walkers, cyclists and wheelchair users, with three wildlife hides being accessible to users from the trail. This path avoids areas that provide a refuge for wildlife by following a route that is a short distance away from the loch shore. The trail has become an asset to local businesses that provide services to trail users.

An RSPB visitor centre on the south side of the loch offers access to wildlife hides and woodland trails, as well as providing good views of the loch. Access to the castle is controlled by Historic Environment Scotland, a Scottish government body that provides a passenger ferry to take visitors to the island.

To reduce the level of pollution created by visitors, toilet facilities are provided in several locations around the loch, including Kirgate Park, Boathhouse Pier, Loch Leven's Larder, Loch Leven's Lodges café and the RSPB visitor centre. These connect to septic tanks.

1.3.11 Water supply & sanitation

The water supply to the population living within the Loch Leven catchment is estimated to be about 481,800,000 litres per year, based on an estimated water use of 165 litres per person per day. About 8,000 people within the catchment are connected to a Waste Water Treatment Works (WWTW) owned by Scottish Water. There are two WWTWs within the catchment – at Milnathort and Kinross.

To reduce the amount of phosphorus entering the loch from its catchment at the start of the restoration process, the Kinross WWTW was upgraded to tertiary treatment in 1993 at a cost of Euros 225,000 (2025 value); this included installing phosphorus-stripping, which reduced the amount of phosphorus entering the loch by about 1.7 tonnes per year (Loch Leven Catchment Management Plan, 1999). This was followed by the installation of a new ferric sulphate dosing plant at the Kinross WWTW in 1997, at a cost of 67,000 Euros (2025 value), which reduced phosphorus inputs by another 0.4 tonnes per year (Loch Leven Catchment Management Plan, 1999). In addition, a new WWTW was built at Milnathort, at a cost of 7.7m Euros (2025 value), which reduced the amount of phosphorus entering the loch by another 0.59 tonnes, and effluent from Kinnesswood WWTW was diverted away from the loch at a cost of Euros 3.1m (2025 value) reducing phosphorus inputs to the loch by another 0.6 tonnes per year. Overall, the improvements in WWTWs across the catchment resulted in a reduction of about 3.3 tonnes per year in P entering the loch each year and improvements to waste management and manufacturing processes at a local woollen mill reduced P inputs to the loch by another 6.3 tonnes per year between the 1985 and 1995.

Although some areas of the catchment are sewered, large areas of the catchment are unsewered. There are about 860 properties in this unsewered area, most of which are likely have septic tanks (STs), although new builds, or properties that have been upgraded recently, may be served by individual or communal package treatment plants (PTPs) (May et al., 2017). With increasing demand for rural development in the area, a new rural development policy was put in place to ensure that new houses with private sewage treatment systems did not increase the P input to the loch. In summary, this policy required any new development to mitigate the additional P likely to be discharged from their property by 125% by upgrading other STs within the catchment (Brownlie et al., 2014). In this way, rural development could continue without adding any additional P burden to the loch.

1.4 Unexpected results across criteria, synergies and trade-offs

There were no unexpected results in this restoration programme until algal blooms returned from 2018 onwards; this appears to be due to climate change because the blooms seem to develop when the loch water goes above 17°C for more than a couple of days. This is still under investigation.

1.5 Summary of effectiveness of restoration programme

The reduction in phosphorus load to the loch by about 50% in the 1980s and 1990s had a positive effect on the loch. Phosphorus concentrations fell and algal blooms became less common by 2007. Good water quality continued until 2018, when the restoration trajectory changed and algal blooms re-appeared. This seems to have been an effect of climate change. If so, there will be a need for further mitigation to be put in place to combat this (May et.al., 2024). As inputs of nutrients from point sources is now low, the main challenge that needs to be addressed, now, is how to reduce phosphorus runoff from land to water within the catchment. A number of initiatives are currently underway to address this, for Example the Landscape Enterprise project, which is being coordinated by the Forth Rivers Trust. This aims to make a significant and positive impact on agricultural businesses and natural assets whilst enriching the lives of local wildlife and communities.

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f) Lake Vansjø

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1.1 Lake details

Vansjø is a large and complex lake consisting of several fjords and basins with separate catchments and different influences, environmental conditions and characteristics. The lake is often divided into two main parts/basins, with Storefjorden being the eastern, largest and deepest part, and Vanemfjorden being the western part, as shown in **Figure f.1** and **Figure f.2**. Vanemfjorden, the western part, experienced rapid eutrophication and reoccurring toxic cyanobacterial blooms, especially between 2001 and 2007. Therefore, this basin has been the main focus of the restoration program and mitigation measures. However, Storefjorden, which supplies water to Vanemfjorden, has also been eutrophicated and not reached environmental targets (good status) over the past decades, and this basin and its' catchment is also subject to mitigation measures. Lake Vansjø is a popular and important lake for many purposes. It is the main drinking water source for almost 80 000 people around the lake, it is used for hydropower, agricultural irrigation as well as recreational activities (boating, bathing, ice skating, fishing), and hosts three nature reserves, two water based and one terrestrial.

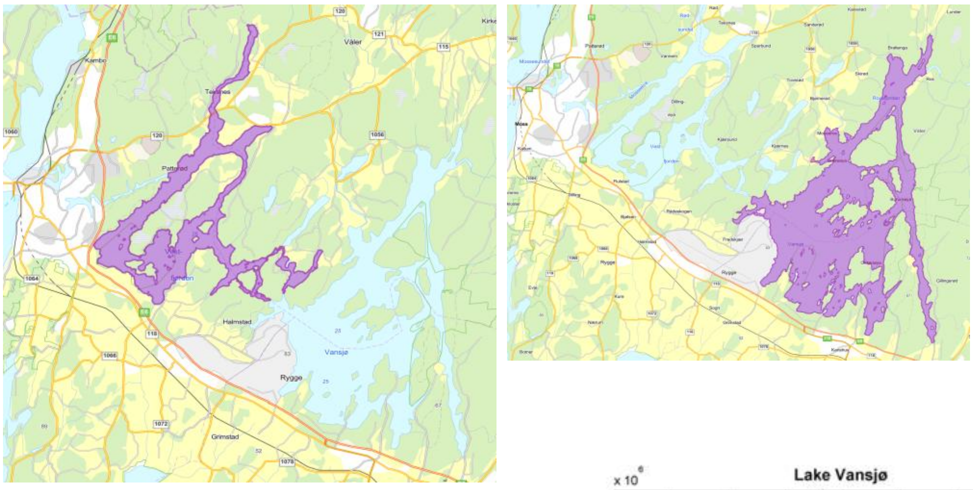

Figure f.1. *Map of Vansjø with the two basins highlighted. Left: Vanemfjorden, the western basin. Right: Storefjorden, the eastern basin. Source: Vann-nett.no*

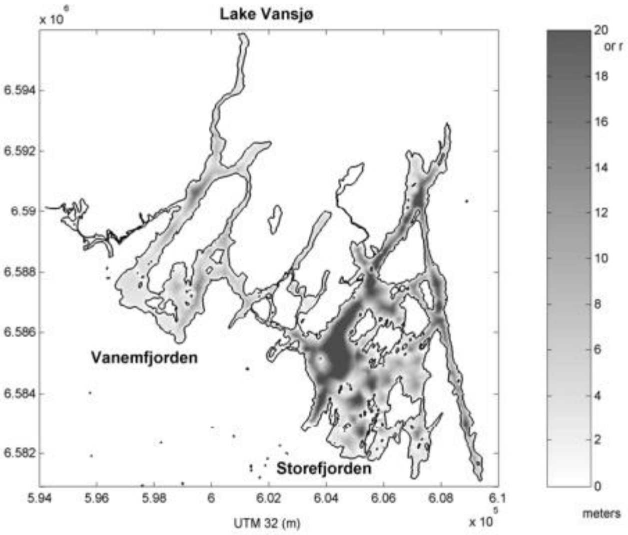

Figure f.2. *Depth chart of Vansjø (Saloranta 2006).*

Lake name: **VANSJØ**			
Type of characteristics	**Characteristics**	**Store-fjorden**	**Vanem-fjorden**
Geographical characteristics	Geographical coordinators (EUREF89):		
	Longitude	10.836507	10.754305
	Latitude	59.393656	59.443629
	Altitude (m a.s.l.)	25 m a.s.l	
Lake characteristics	Area [km^2]	23,8	12
	Maximum depth [m]	41	17
	Mean depth [m]	9,2	3,7
	Water volume [m^2]	73 000 000	
	Depth index (mean depth to maximum depth ratio)	0,22	0,22
	Water residence time (τ) [years] Residence type (short < 1 year, moderate >1 year, long > 10 years)	280 days Storefjorden 0,85 year Vanemfjorden 0,21 year Short	
	Shoreline development index $K = \frac{shoreline\ lenght}{2\sqrt{\pi}\ \cdot lake\ area}$	Shoreline length: 250 km	
	Mixing type	Meromictic	Polymictic/ meromictic
	Stratification	Storefjorden is stratified, other basins mixed	
Catchment characteristics	Total catchment area [km^2]	679,91	
	Direct catchment area [km^2]		
	Land-use (CORINE)	**% of total catchment area**	
	Agriculture	17	
	Urban	5	

	Forests	78	
	Wetlands		
	Water bodies		
	Schindler's index (sum of total catchment and lake areas to lake volume ratio)	9.8	
Climate characteristics (30 year average; 1991-2020)	Mean annual air temperature Mean annual precipitation Maximum summer air temperature Days number > 15°C air temperature per year Days with snow per year	Temp: 7,03°C Prec: 880,6 annual mean Max. temp 33,9°C (27.7.18) Days > 15°C average per year: 64,9 Snow: average 47,7 days per year	
Hydrochemistry and trophic type (situation in 2025)	Alkalinity (meq/L), Alkalinity type (low - <0.2, medium 0.2-1.0, high - > 1.0)	Medium	
		0,218 mekv/L	0,307 mekv/L
	Colour type (colour in HAZEN units – clear < 30, humic 30-90, polyhumic >90)	Humic	
	Trophic type (oligotrophic, mesotrophic, eutrophic, hypertrophic)	Eutrophic	
	Calcium level (water hardness – softwater <25 mg Ca/L, hardwater ->25 mg Ca/L	Softwater	

1.2 Restoration Programme

1.2.1 History and background

Lake Vansjø has experienced high nutrient loading and eutrophication issues since the 1960s, mainly due to pressure from agriculture, sewage from municipalities and scattered dwellings, but also wastewater, urban runoff and floodings, landslides and erosion. Yearly monitoring was initiated in 1976-77, and several committees and action plans have been active since, in order to reduce the pressures on the lake.

The catchment of Vansjø is large, and is separated into several sub-basins with lakes, rivers and streams. The entire catchment and also rivers and streams draining from Vansjø to the Oslofjord are included in the larger catchment area called Morsa, and is shown in **Figure f.3**. For the restoration of Vansjø, it has been necessary and crucial to have a holistic approach and include local, regional and national authorities. As a consequence of the declining conditions of several of the water bodies in the larger catchment, the Morsa project was started as a cooperation initiative in 1999. This allowed authorities to join forces with research organisations in order to develop a knowledge-based mitigation plan aiming to reduce nutrient loading to the lake. The Morsa Project was transferred to the Morsa River Basin District Organization in 2007, under the Glomma River Basin Authority.

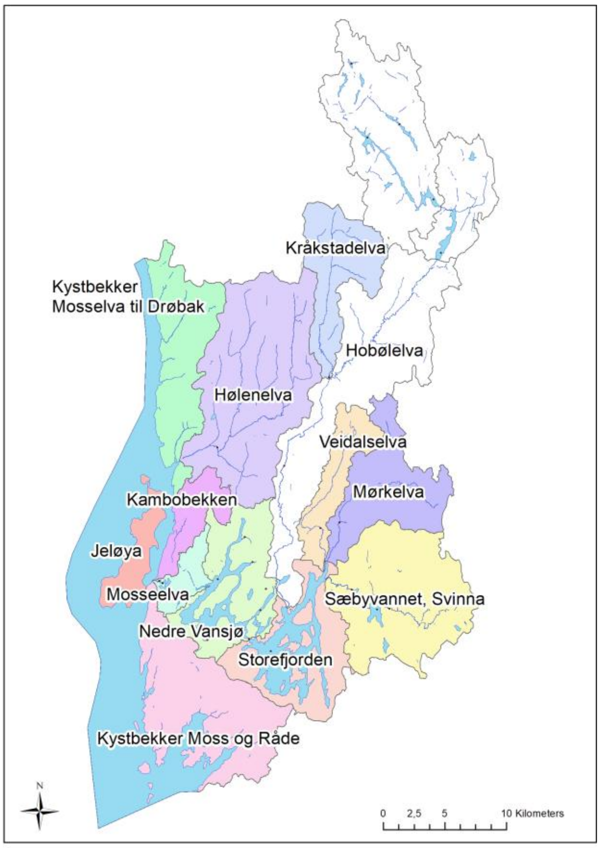

Figure f.3. *Map of the entire catchment comprising the Morsa Water Basin Organization. The lake Vansjø consists in this context of "Nedre Vansjø" and "Storefjorden". Source: Skarbøvik et al. 2025.*

A thorough mitigation analysis was performed in 2001, revealing that agricultural activities contributed about 60 % of the total phosphorus (Tot-P) input to Storefjorden, followed by natural runoff from forest (24 %) wastewater treatment plants (3 %), and scattered dwellings (6 %) as illustrated in **Figure f.4**. Mitigation plans for all relevant pressures and sectors were developed, and individual measures for each source were implemented, as described in the next section. The P-loss analysis was updated in 2006, with new methods and using a new model, which changed the estimated inputs, and also included natural runoff from agricultural areas (**Figure f.4**). Still, the largest source of phosphorus to Storefjorden was agriculture, mainly anthropogenic, but also natural runoff.

In 2000, the area including the Vansjø catchment was exposed to a severe storm event with major flooding. After this, especially between 2001 and 2007, the lake, and especially the western part, experienced even more frequent and heavy blooms of toxin-producing cyanobacteria, leading to bathing bans and a local concern for the health of the lake.

The main environmental objectives of the restoration measures have therefore been to stop eutrophication by reducing nutrient loads, specifically phosphorous, in the entire catchment, and by that to reduce and prevent toxic cyanobacterial blooms. The main focus has been securing the lake as a drinking water source, but also to improve the general health and status of the lake.

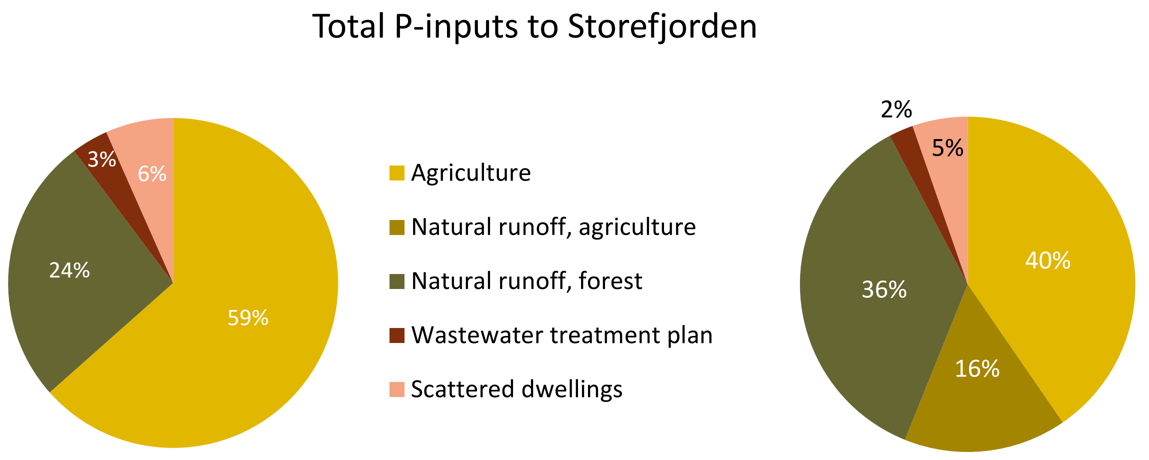

Figure f.4. *The origins of the total phosphorus inputs to Storefjorden, as estimated by an independent analysis in 2001 (left pie, Lyche-Solheim et al. 2001) laying the basis for the implementation of mitigation measures in the Morsa catchment. The calculations were later updated with data from 2006 (right pie, Øygarden et al. 2010).*

History and timeline of major events in the restoration of Vansjø	
1976-77	Reportings of rapid eutrophication since 1970s. Yearly monitoring started.
1979	Vansjø committee is established.
1984	The first action plan for Vansjø is implemented.
1970-80'ies	Sewage control is established, but still there are high P and chlorophyll concentrations in the lake.
1994-1997	New action plan is implemented, and a collaboration is initiated between all municipalities in the catchment.
1999	The Morsa project is onset.
2000	Heavy flood in October leads to worsened conditions lasting for years.
2001	Mitigation analyses is performed, in order to determine the source of the excessive nutrient loadings, and establish a scientific background for measures.

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2002 - now	Intensive mitigation measures are applied in the catchment area of Lake Vansjø with main focus to decrease P loading.
2002-2007	Heavy cyanobacterial blooms occur (also toxic), especially in the Western basin. Swimming bans in several areas.
2007	The Morsa River Basin Organization is established, in accordance with the EU WFD.
2007-2023	Decreasing P concentrations and less cyanobacterial dominance in the lake and Western basin.

1.2.2 Governance

Lake Vansjø has a long history, from the 1970s, of collaboration between municipalities, which has led to several action plans (1984, 1994-1997) addressing the lake's problems and solutions. The "Vansjø river basin organization" was appointed pilot area for the implementation of the Water Framework Directive in Norway, leading to initiation of the Morsa project in 1999, with local, regional and national authorities joining forces with research organizations to develop a knowledge-based mitigation plan to reduce nutrient loading to the lake. Nine municipalities cooperate to implement the necessary measures in order to improve the water quality in Vansjø.

The project is organized into a Water Board, consisting of representatives from the municipalities, county councils, county governors, and national directorates, with the intermunicipal drinking water association, Farmer's Organizations and other NGOs as observers. The organization is illustrated in **Figure f.5**, and also shows the executive committee and the long-standing thematic groups—particularly on agriculture and wastewater—which have fostered a shared understanding and effective cooperation since 1999. These groups meet regularly, exchange knowledge, and jointly apply for project funding, enabling consistent dialogue and mutual learning.

A key strength of the governance model is its flexibility and responsiveness. New challenges, such as climate change, are addressed through adaptive measures, and efforts continue to engage farmers voluntarily, as Norwegian law does not mandate such actions. Knowledge-sharing and motivation are central to success.

Co-creation and ownership is important in the Morsa working group. For example, when developing a stormwater management guide, municipalities were involved throughout the process via workshops and consultations, ensuring relevance and uptake. Dialogue, trust, and informal networks help overcome resource limitations, especially in smaller municipalities. Collaboration across water areas—covering 25 municipalities—has amplified impact, allowing for shared projects, broader networks, and stronger national visibility. This collective approach has facilitated access to higher-level decision-makers and improved policy influence.

The Morsa model demonstrates how locally anchored, knowledge-driven, and participatory governance can lead to meaningful environmental improvements.

Current challenges include balancing environmental goals with agricultural land use, navigating political cycles, and ensuring long-term commitment. The coordinator of the Morsa organization has a role as a neutral facilitator—neither activist nor regulator—something that has proven effective in building trust and driving action.

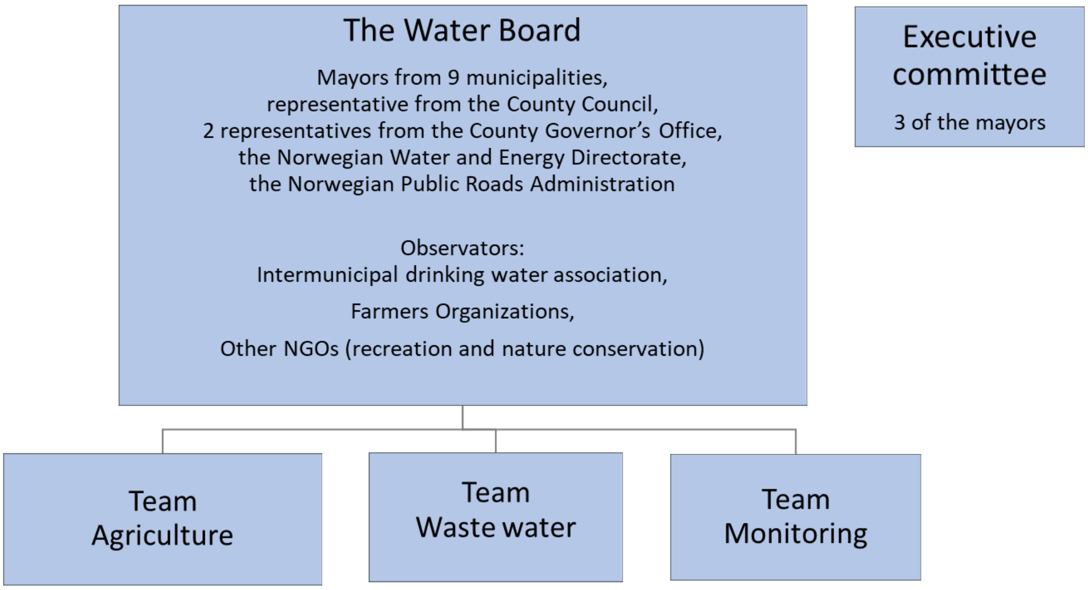


***Figure f.5**. The Morsa river basin organisation.*

1.2.3 Implemented measures in each sector and cost of restoration

The mitigation measures around Vansjø are coordinated, executed and funded through the Morsa River Basin Organization, whom in turn is funded by public sources. Implemented measures are mainly funded by the Ministry of Agriculture, the Ministry of Environment, and the affected municipalities. Most measures were first implemented around or before 1999 and have continued ever since. The measures and costs are described in the following sections, and summarized in **Table 2**.

1.2.3.1 Agricultural

As agriculture was identified as one of the main contributors of nutrients to the lake, new mechanisms was developed to introduce agricultural measures. Starting with education, information campaigns, farmers' meetings, field trips, agricultural advisory for environmental planning on individual farms and farms visits, ending with a system of legal contracts signed with individual farmers combining incentive measures (Skarbøvik & Bechmann, 2010). Since 2005, legislative environmental claims have been in force in various degrees, resulting in various degrees of implementation of measures – the stronger claims the more measures have been implemented. In addition to this, subsidies are important in order to increase implementation of measures.

Overarching environmental contracts

In 2008, farmers in the catchment of the western part of Vansjø (around Vanemfjorden basin) were offered free consultancy on environmental planning and encouraged to sign committing and comprehensive environmental contracts, with financial support given to those who agreed. 75 % signed with the county government. The contracts included: no tilling in autumn, establishment of sedimentation ponds (if recommended), establishment of 10 m buffer zones along open water, establishment of gras-covered waterways where there's risk of erosion, and reduced P-fertilization. Farmers that did not sign this contract still contributed to the environmental measures. The costs of these contracts around Vansjø is estimated to € 106 per hectare, however the costs of the individual measures included in the contract is covered by the respective measure, as listed below.

No tilling in autumn

This is the single measure with greatest effect on reducing phosphorus inputs to Vansjø. It reduces soil erosion and protects the soil from rain and running water, increases organic matter content, increases the stability of the soil aggregates and increases biological activity and structure of the soil layers. In 2024, 90 % of the grain acre in the entire catchment was not tilled in the autumn, which was a large increase from ca 30 % in 1999 and 41 % in 2002. For the separate basins, the increase went from 51 to 96 % in the Storefjorden catchment and from 41 to 100 % in the western part. The cost of this measure is € 149 per hectare, which is funded by the Directorate of Agriculture. The estimated total costs for the Vansjø catchment is € 430 000 per year for implementing no autumn tilling.

Sedimentation ponds

This is another important measure implemented for reducing inputs of phosphorus and soil particles to the water bodies. The Morsa project created their own "sedimentation pond plan" with funding from the Ministry of the Environment and increased the number of ponds around the lake. 110 sedimentation ponds were established between 1994 and 2022 in the entire Morsa catchment. The costs are estimated to €18 064 for establishment of one pond with the size of 0,1 hectare. In addition, the ponds need maintenance (emptying) at appr. € 1063 per year for each pond.

Creating vegetated buffer zones

Wide strips of grass production have been established on agricultural areas (grain acres, fields, medows) adjacent to rivers and streams in order to reduce soil erosion. The costs are estimated to € 1775 per hectare, including establishment and maintenance and € 266 per hectare of lost earnings (lost production of vegetables or grain).

Grass covered water ways

This is a very important measure to reduce soil erosion on the fields. Low areas (small valleys) are sown with grass and thus reduce sediment losses from the land. The costs are estimated to € 3549 per hectare, including establishment, maintenance and € 266 per hectare of lost earnings (lost production of vegetables or grain).

Grass on flood-prone areas

This is another important measure to reduce soil erosion and floods. The costs are estimated to € 266 per hectare in lost earnings (lost production of grain).

Improved/reduced use of fertilisers

This was implemented nationally in 2007, however the western part of Vansjø has its own boundaries and recommendations for soil phosphorus content based on experiments conducted in cooperation with farmers. Between 1999 and 2012 the P-fertilization was reduced with 50 % in general, and 75 % around the western part of Vansjø. The cost of this measure has not been estimated.

Catch crops

This is a recent measure implemented to improve soil health, prevent erosion, and manage nutrients effectively. The cost of this measure is estimated to € 106 per hectare.

1.2.3.2 Sewage treatment

Improvements to municipal sewage treatment plants

This has been implemented to reduce nutrient discharges. Sewage measures in all municipalities in the catchment of € 23 220 000 have been implemented (Morsa 2003). The cost of upgrading municipal sewage treatment plants (e.g. including biological treatment steps) vary with the size and condition of the plants.

Improving local, separate sewage systems

This is implemented in order to separate wastewater from storm runoff and to ensure proper treatment of all sewage. Between 1999 and 2012 2040 residences were attached to public sewage systems, or have separate, modern treatment facilities. The estimated maximum cost per household for installing a mini-treatment or infiltration facility is € 14 876. The cost of connecting separate dwellings to the municipal system is estimated between € 12 220 and 23 377. The cost for the municipality of mapping their separate dwellings is estimated to appr. 132 823 for the municipality.

1.2.3.3 Solutions for erosion/flood management

Establishing and restoring riparian zones

Trees free of charge are provided by the Morsa organization to establish and restore riparian zones. More than 20 000 trees have been planted so far. In addition, bushes and other vegetation is planted. The work is performed by the land owners, farmers and schools, and is largely volunteer work. The costs, provided the use of 4 plants per 10 m, is € 4,13 per meter, or around € 11 per tree.

1.2.3.4 Other measures

Fish manipulation

Outfishing of large pike has been performed certain years, which has increased the number of plankton-eating fish, but also the number of other carnivorous fish.

Changes in water level regulation

Has been tested, especially during summer, and the Morsa organization has applied for permission to alter the regulation regime. The current regime has led to periods of standing water during the summers, which may facilitate the growth of cyanobacteria (Kaabel 2014).

Table f.2. Costs of the different measures implemented in the Morsa catchment between 1999 and 2024. Sources: Kaabel 2014, Morsa 2003, Direktoratsgruppen vannforskriften 2020.

Sector **Measure**	**Source of finance Public/private etc**	**Cost for measure** **2024 value in euros, per hectare**	**Cost for lost earnings (euros per year)**	**Expected effect**	**Cost/effect**
Agriculture					
Environmental contracts	County government	€ 109 / hectare (in addition to costs listed below)		Large	High
No tilling in autumn	Directorate of agriculture	€ 152 / hectare		Large	High
Sedimentation ponds/wetlands establishment	Ministry of Environment	€ 18 485 for one pond of 0,1 hectare		Large	High
Sedimentation ponds/wetlands maintenance	Ministry of Environment	€ 1087 / year for each pond (0,1 hectare)		Large	High
Vegetated buffer zones	Public	€ 1816	272 (included in cost for measure)	Large	High
Grass covered waterways	Public	€ 3632	272 (included in cost for measure)	Large	High
Grass on flood-prone areas	Public		272 (for grain, less for veg.)	Large	High
Reduced use of fertilizers	Public	Not estimated			
Catch crops	Public	€ 109			
Erosion/flood management					
Establishing and restoring riparian zones	Public	€ 132		Medium-large	Medium-high

Sewage treatment					
Improvement of sewage treatment plants in 8 municipalities in 2002-05 and 2006-08	Municipalities	Total costs € 21 692 021		Large	High
Improving local, separate systems (1999-2012)	Municipalities	Total costs € 14 132 898		Large	Medium
Installing treatment facilities	Residents	€ 14 876 (max. cost per household)			
Connecting separate systems to municipal systems	Residents	€ 12 220 - 23 377			

1.3 Evaluation of existing restoration programme

1.3.1 WFD

Vansjø has been monitored since the 1970s with various resolutions. Until 2004, data are mainly based on samples taken from June to September, and often every two weeks. Since 2005, the lake was monitored according to the WFD guidelines, with samples taken from April-October, also fortnightly.

For each figure, normalized ecological quality ratios (nEQR, total and phytoplankton parameters) or concentrations (Tot-P, Chl-a) are given, in addition to the corresponding ecological status classes, where Blue = High, Green = Good, Yellow = Moderate, Orange = Poor and Red = Bad. Storefjorden is evaluated as water type L106 (L-N3, low alkalinity, humic), while Vanemfjorden is evaluated as water type L108 (L-N8, moderately low alkalinity, humic).

1.3.1.1 Evaluation of ecological status class for eutrophication (nEQR)

NEQR values for eutrophication parameters from Storefjorden and Vanemfjorden are given in **Figure f.6**, showing that both basins have mainly been in Moderate status since the 1980s. Earlier data showed that **Storefjorden** was in High status in the 1960s (data not shown). Some exceptional years have occurred, however, with Good status in Storefjorden in 1994 and 1996-97, and Poor status in 2007 and 2020. **Vanemfjorden** was in Poor status between 1994 and 2009 (Moderate in 2003).

The years with Poor status in Storefjorden was mainly due to the ecological status of phytoplankton parameters, especially PTI, but also Tot-P, as shown in the next sections. The period with Poor status in Vanemfjorden was the years where the western part of Vansjø experienced severe blooms of toxin-producing cyanobacteria, which was worsened by the year 2000-storm. Since 2010, the status has been Moderate, mainly determined (worsened) by PTI, while other phytoplankton parameters and Tot-P has improved, as shown in the following sections.

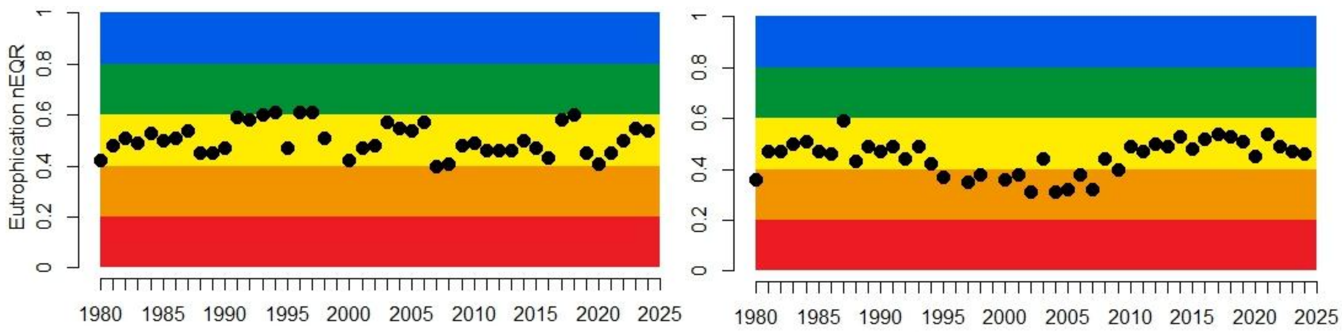


Figure f.6. *total nEQR and corresponding ecological status class for Storefjorden (left) and Vanemfjorden (right) from 1980 to 2024.*

1.3.1.2 Total phosphorous

<u>Storefjorden:</u> Tot-P concentrations in the eastern part of Vansjø has been variable since the 1980s, mainly in Moderate ecological status, but some years of Good status occurred in the 1990s, around 2005, and in 2017-18 (**Figure f.7**). The Tot-P concentration in the eastern part of Vansjø has not directly reflected the implemented measures as much as was expected. The concentration in this basin is partly determined by inputs of erosion particles from the catchment and thereby the amount of precipitation, number of flood events, magnitude of landslides and number of days with snow and cold degrees, and therefore not always directly related to activities in the catchment (Skarbøvik et al. 2025). All these factors are in turn influenced by climate change.

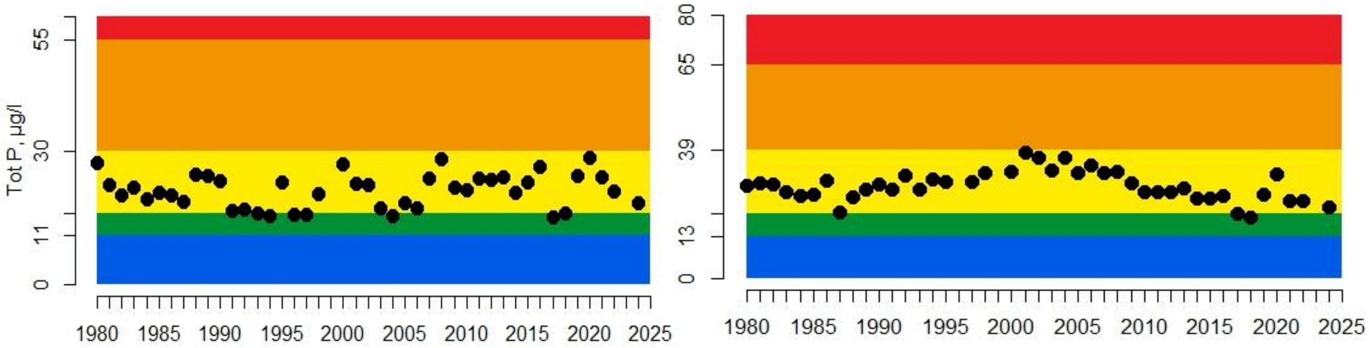
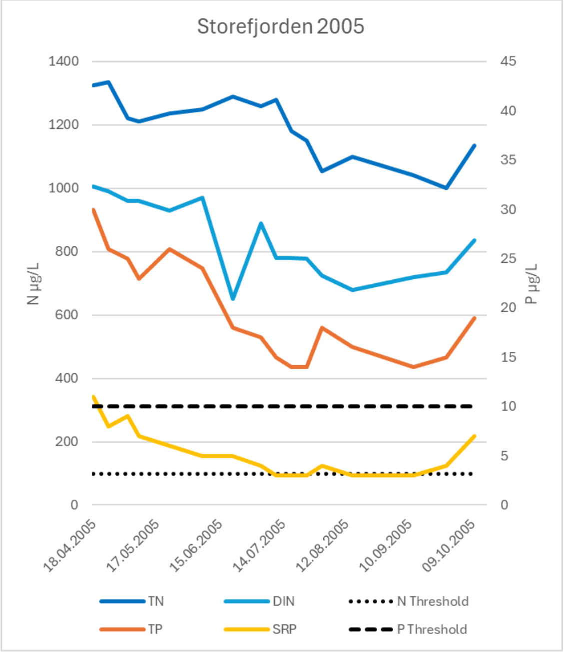


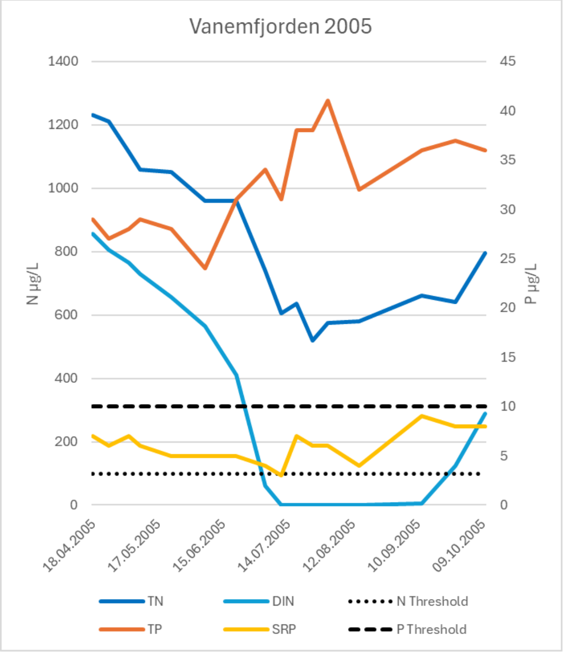
Figure f.7*. Tot-P concentrations in Storefjorden (left) and Vanemfjorden (right) from 1980-2024, with background colors corresponding to ecological status classes.*

<u>Vanemfjorden:</u> Tot-P concentrations have been higher in the western basin, Vanemfjorden, than in the eastern basin Storefjorden since the monitoring started in the 1980s and with less variation over the years (**Figure f.7**). The concentrations correspond mostly to Moderate ecological status, with only a few years in Good status (1987, 2017-18), and with a peak in concentrations at the Moderate/Poor boundary between 2000 and 2005. The flood in 2000 lead to a large increase in Tot-P concentrations in the western basin. Together with the increased occurrence of toxic cyanobacterial blooms (2001-2006) this shows that flood events can have effects on eutrophication that influence the water quality for years after the event, and that counteracts the effect of costly mitigation measures. The P-concentration has declined since 2007, however in 2019-2021 there was a clear increase again as a result of years with much precipitation and high water flow in the catchment rivers (Skarbøvik et al. 2025).

The measures implemented for P-reduction in the Morsa catchment have been counteracted by other factors, such as climate change with increasing precipitation, storm events and warmer winters (more snow melt episodes), but also by reduction in acid precipitation. Less acidic soils and less sulfate has lead to increased humic inputs with following P-content, and a reduction in reactive aluminium, which normally would bind P and contribute to sedimentation of P (forskning.no). Studies have shown that the sediments in Vansjø are not as P-rich as expected, and are therefore not contributing to significant internal P-loading (Andersen et al. 2006). This means that the P-inputs to Vansjø is mainly coming from external sources.

The seasonality of nutrients in the two main basins of Vansjø for selected years are shown in **Figure f.8**. Typically the western basin experiences DIN under detection limit during summer months due to high algal growth. In the years with high cyanobacterial dominance, a change from non-N-fixing cyanobacteria like *Microcystis aeruginosa* to N-fixing cyanobacteria genera like *Dolichospermum* sp. and *Aphanizomenon* sp. were observed. This change in cyanobacterial dominance is not longer prominent in the summer phytoplankton community (Skarbøvik et al. 2025).





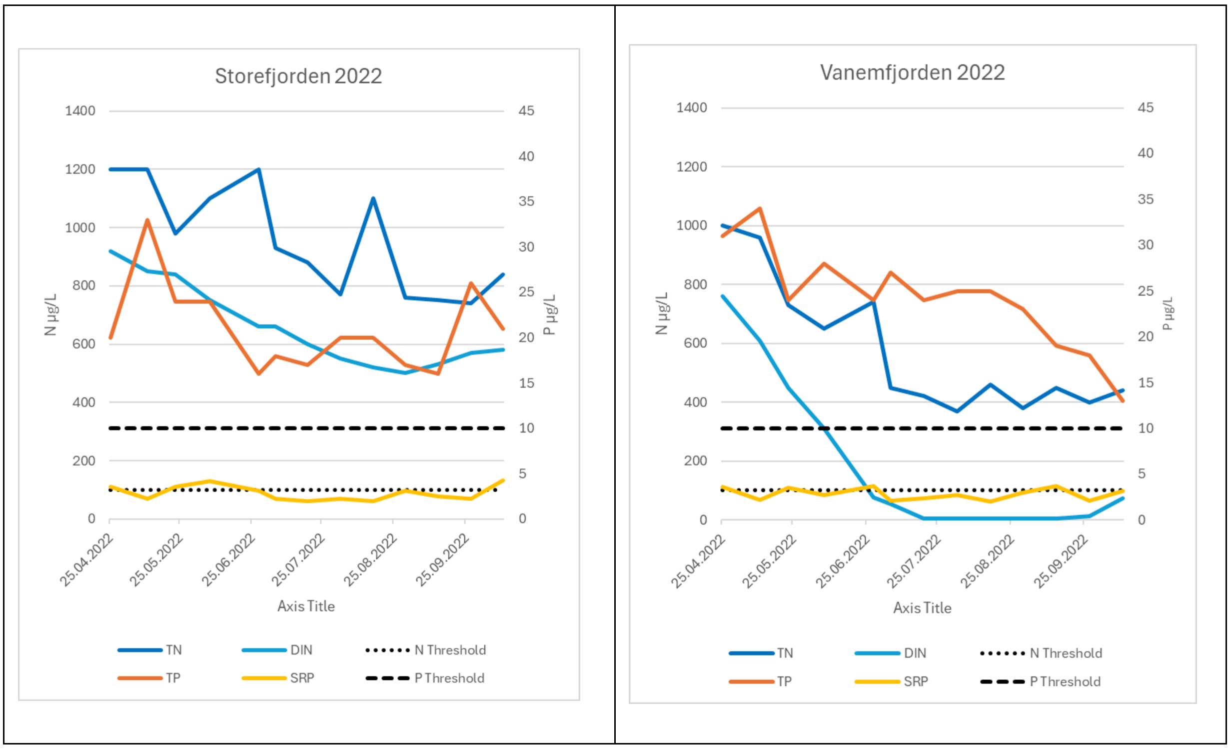


Figure f.8. *Seasonal changes in TN, DIN, TP and SRP in the two basins Storefjorden and Vanemfjorden in Lake Vansjø, represented by year 2005 and 2022.*

1.3.1.3 Chlorophyll *a*

Chlorophyll *a* concentrations from both basins during the monitoring of 1980-2024 are shown in **Figure f.9** with corresponding ecological status class.

In **Storefjorden**, chlorophyll *a* concentrations were variable (Good and High) from the 1980s, but increasing towards 2000, crossing the boundary to Moderate status several years between 1995 and 2003. Since 2004 the status has mainly been Good.

In **Vanemfjorden**, chlorophyll *a* concentrations are much higher than in Storefjorden, and have also been variable since the 1980s, but in Moderate status. The concentrations increased between 1990 and 2006, with mainly Poor status these years. From 2007 the concentrations declined and has been Moderate, with some years even Good status. The continued high levels of chlorophyll *a* can be explained to a certain degree by the presence and often high biomasses of *Gonyostomum semen*, a raphidophyte with high chlorophyll *a* content. This species is known to form extremely large biomass and chlorophyll *a* concentrations at lower phosphorous levels than e.g. cyanobacteria (Cronberg et al., 1988; Hongve et al., 1988).

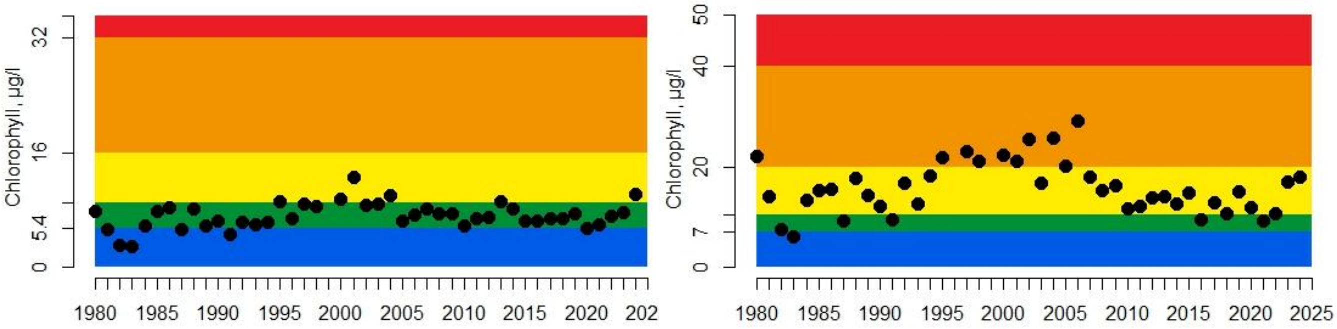


***Figure f.9**. Chl-a concentrations in Storefjorden (left) and Vanemfjorden (right) from 1980 to 2024.*

1.3.1.4 Phytoplankton

Figure f.10 shows the nEQR for phytoplankton parameters in **Storefjorden** from 2005-2024 and total phytoplankton classification from 1980 to 2024. Total phytoplankton status was mainly Good or High until the late 1990s, after when it has been mainly Moderate. The Moderate status is mainly caused by PTI and often biovolume, while chlorophyll a and cyanomax have been more or less Good or High status (**Figure f.19** and **f.10**).

Figure f.11 shows the nEQR for phytoplankton parameters in **Vanemfjorden** from 2005-2024 and total phytoplankton classification from 1980 to 2024. Total phytoplankton status was very variable from 1980 to 1990 (mainly Good-Moderate), and Poor since the mid-1990s until 2008 when it was back to Moderate status. In this basin, the total status is mainly caused by all parameters combined, including chlorophyll *a*, but from 2008 cyanomax was not causing the Moderate status. The data indicate no further problems with cyanobacteria in Vanemfjorden since 2010, however the low PTI nEQR reflects issues with other nuisance algal species such as *Gonyostomum semen*, which is not as closely correlated to Tot-P as cyanobacteria, and which is also increasing as Vansjø has become more humic (Lyche Solheim et al. 2023).

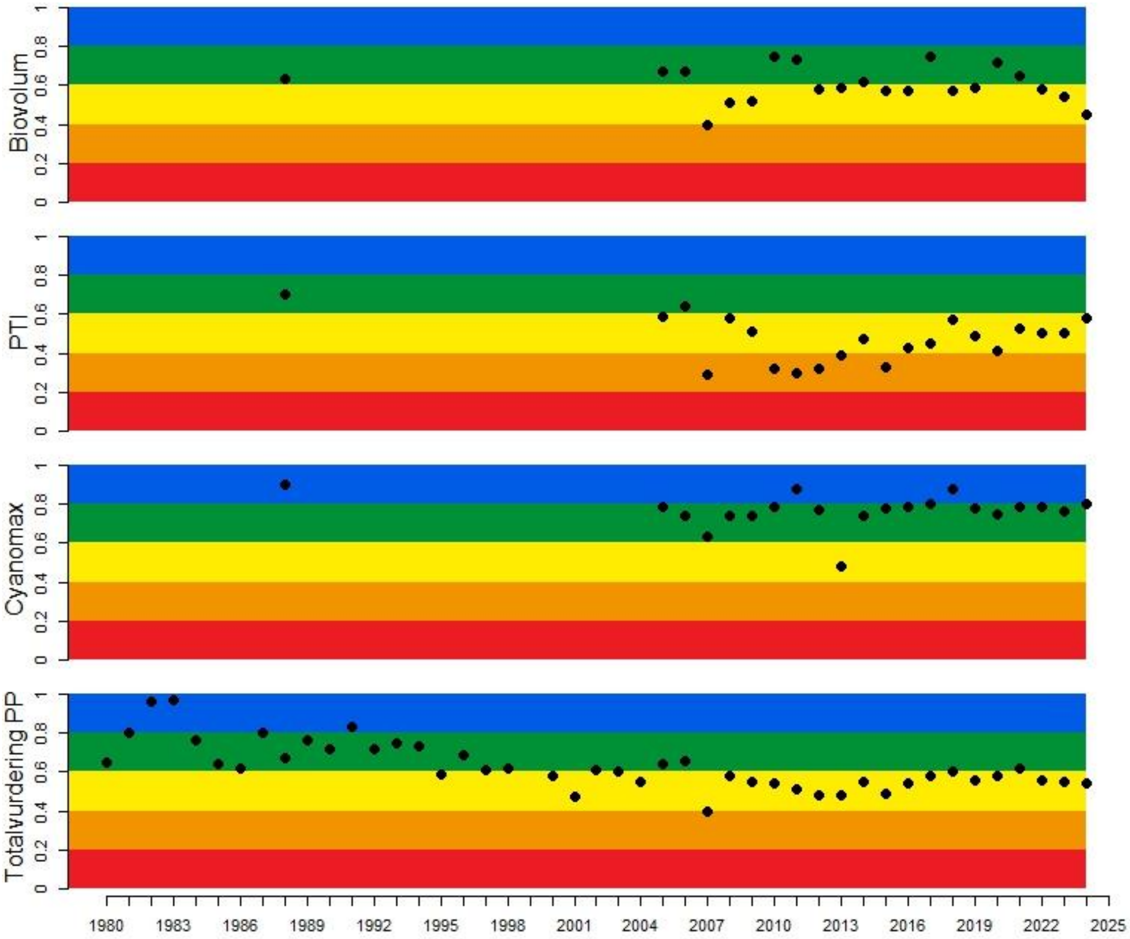


Figure f.10. *nEQR for phytoplankton parameters in Storefjorden from 1980 to 2024.*

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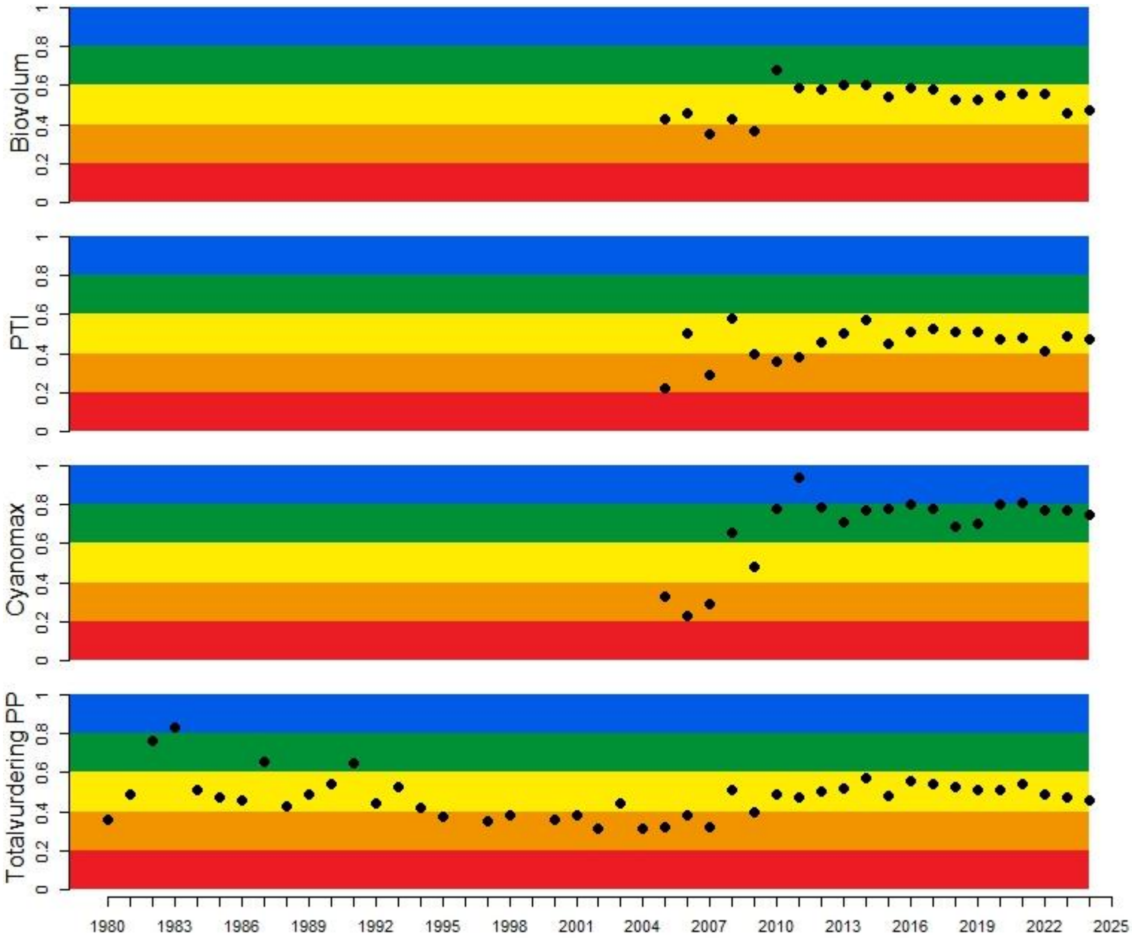

Figure f.11. *nEQR for phytoplankton parameters in Vanemfjorden from 1980 to 2024.*

1.3.2 Biodiversity net gain

1.3.2.1 Macrophytes

A systematic waterplant survey was conducted in Vansjø in 2004 by NIVA (Mjelde et al. 2009). At that time, nymphaeids were the dominant growth form in the water's body, but a total of 29 other submerged and floating water plants were found. The protected shorelines were primarily colonized by helophytes such as *Phragmites australis* and *Schoenoplectus lacustris*. The results from this survey are presented in **Table 3**. The survey was done separately for the two major basins of the lake, Vanemfjorden (western part) and Storefjorden (eastern part).

None of the species found in Vansjø are priority species according to the EU Habitats Directive. However, six of the species found in 2004 are red listed according to the current Norwegian red list. Additionally, there are two other red listed species in the lake, both well documented and recorded after 2004. In 2004 the index for eutrophication level was still under devolvement, but the early calculation gave the lake a score indicating Moderate to Bad ecological condition, based on the water plant assembly (Mjelde et al. 2009).

Table 3. *Aquatic plants recorded in Vansjø in 2004, with plant cover for the two basins and notes on red list category if worse than "least concern" by the latest red list in Norway . The scale indicates plant cover by the sizes: 0 = not present, 1 = rare, … up to 5 = dominant in the euphotic zone. "+" indicates drift material.*

Growth form	**Plant cover**		**Norwegian redlist 2021**
	Vanemfjorden	**Storefjorden**	
Submerged			
Elatine hexandra	0	1	EN
Elatine hydropiper	1	0	EN
Elatine orthosperma	0	1	EN
Elatine triandra	0	1	EN
Eleocharis acicularis	1-2	1	
Isoetes lacustris	0	1-2	
Lythrum portula	1	0	EN
Ranunculus reptans	1	1	
Callitriche palustris	1	0	
Ceratophyllum demersum	4	1	
Juncus bulbosus	2	1	
Myriophyllum alterniflorum	1	3	
Potamogeton crispus	0	+	NT
Potamogeton obtusifolius	2	1	
Potamogeton perfoliatus	2	0	
Ranunculus cf. peltatus	0	1	
Utricularia vulgaris	2-3	2	
Nymphaeids			
Nuphar lutea	4	4-5	
Nuphar pumila	3-4	1	
Nymphaea alba	3	2	
Persicaria amphibia	3	3	
Potamogeton natans	3	3	
Sparganium angustifolium	2	2	
Sparganium emersum	2-3	2	
Sparganium sp.	1	0	
Lemnids			
Lemna minor	1	2	
Spirodela polyrrhiza	1	1-2	
Charophytes			
Nitella opaca	1	1-2	
Bryophytes			
Fontinalis antipyretica	0	1	

In addition to the 2004 survey, numerous volunteers and other professionals have recorded plant life in and around the lake before and after 2004. Below is an overview of other aquatic vascular plants

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found in and close to the lake as registered in the Norwegian Biodiversity Information Centre, Artsdatabanken (Artsobservasjoner.no).

Submerged to partly nymphaeids:

Callitriche cophocarpa, Callitriche hamulata, Callitriche stagnalis, Myriophyllum verticillatum, Nymphaea candida, Potamogeton alpinus, Potamogeton polygonifolius, Ranunculus aquatilis, Sparganium erectum, Sparganium glomeratum, Sparganium natans, Sparganium × splendens, Limosella aquatica, Littorella uniflora, Subularia aquatica, Lobelia dorthmana and *Utricularia australis* (VU), where the *Utricularia australis* have only been found at one locality, lastly in 2025.

Lemnids:
Hydrocharis morsus-ranae (NT), possibly introduced by people to the lake, first recorded in 2014.

Emergent to partly submerged species:

Alisma plantago-aquatica, Calamagrostis canescens, Calla palustris, Caltha palustris, Carex paleacea, Eleocharis mamillata, Eleocharis uniglumis, Glyceria fluitans, Glyceria maxima, Persicaria hydropiper, Ranunculus flammula, Ranunculus sceleratus, Rumex aquaticus, Schoenoplectus tabernaemontani, Sparganium erectum, Sparganium glomeratum, Typha latifolia.

1.3.2.2 Protected areas and birds

In 1992, two nature reserves with a total of 426,5 hectares were established in Vansjø, both with the aim of protecting important wetland areas with vegetation, bird species and other wildlife.

Vestre Vansjø nature reserve is 329,6 hectares and located in the western basin of the lake, Vanemfjorden (**Figure f.12**). 59 wetland species were recorded before the establishment (e.g. Lågbu 1986, Miljødirektoratet Naturbase a).

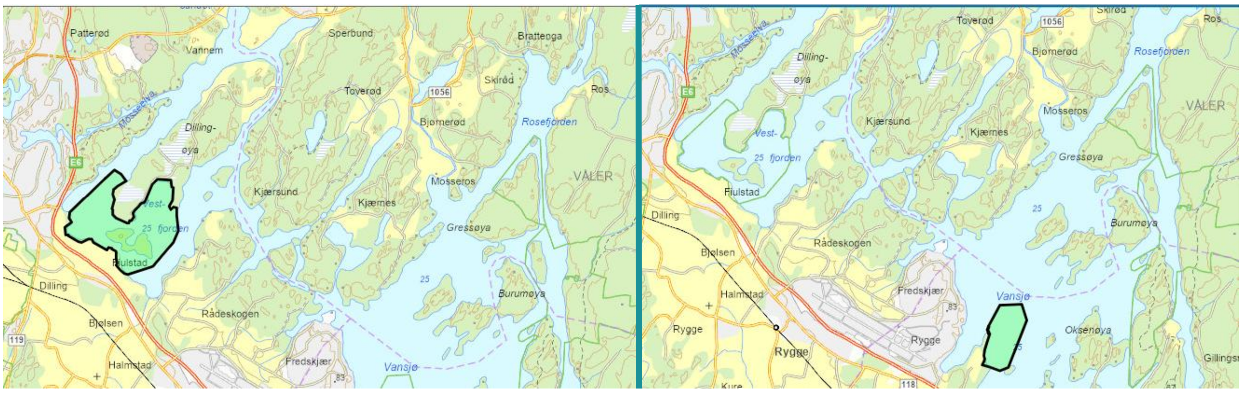


Figure f.12. *Vestre Vansjø nature reserve (left) and Moskjæra nature reserve (right), established in 1992, protecting a total of 426,5 hectares of water, wetland and terrestrial grounds. Source: Miljødirektoratet Naturbase.*

Moskjæra nature reserve is 96,9 hectares and is located in the eastern part of the lake, Storefjorden (**Figure f.12**, Miljødirektoratet Naturbase #2). The area is of great importance as nesting area for wetland birds, with observations of nesting *Podiceps cristatus* (Great Crested Grebe), *Cygnus olor* (Mute Swan), *Acrocephalus scirpaceus* (Common Reed Warbler) *Emberiza schoeniclus* (Common Reed Bunting), in addition to coastal species such as seagulls. Before establishment of the nature reserve (e.g. Lågbu 1986), 33 species of wetland birds were registered in the area, of which 16 were nesting (Miljødirektoratet Naturabase b).

Due to strict regulations on activities in the nature reserves, such as Vestre Vansjø and Moskjæra, scientists have not been able to enter the protected areas in order to make any evaluation of the breeding success for nesting of bird species, and the current productivity in the nature reserves are therefore more or less unknown. Some recent monitoring using drones have, however, indicated that Moskjæra is less attractive to birds than expected, with very few breeding pairs of some previously abundant species. This is likely related to the presence of the invasive Neovison vison (mink), but this is not verified. Also the nature reserve Vestre Vansjø have experienced breeding failures recent years, a reserve previously known for being susceptible to mink predation. Management targeting this invasive species is urgent in order to increase recruitment to populations of several species.

Numerous professional and non-professional volunteers have frequently recorded bird occurrences in and around Vansjø, and these observations are available from the Norwegian Biodiversity Information Centre (Artsdatabanken) and their database Artsobservasjoner.no. A total of 206 species was recorded between 2000 and 2025, of which 58 are red listed according to the Norwegian red list (CR, EN, VU and NT), and three are invasive species *Branta canadensis* (HI), *Phasianus colchicus* (LO) and *Columba livia* (NE).

Several species are found nesting in Vansjø, such as *Podiceps cristatus (Great Crested Grebe), Cygnus olor (Mute Swan), Gallinula chloropus (Common Moorhen), Fulica atra (Eurasian Coot), Acrocephalus scirpaceus (Common Reed Warbler), Pandion haliaetus (Osprey), Ardea cinerea (Grey Heron), Emberiza schoeniclus (Common Reed Bunting) and Pernis apivorus (European Honey Buzzard). Some coastal waterfowl is also found nesting, such as Seagulls, Terns and* Oystercatchers. Some populations are stable (e.g. *Larus marinus* (great black-backed gull)), and some also new to Vansjø (*Larus fuscus* (lesser black-backed gull) and *Larus argentatus* (European herring gull) and have been found nesting only in recent years (Ranke & Krokeide 2025b). However, for *Chroicocephalus ridibundus* (black-headed gull), *Larus canus* (common gull) and *Sterna hirunda* (mackerell tern), populations and nesting activities are believed to have declined the past decades (Ranke & Krokeide 2025b). Nesting of mackerell terns has also been disrupted by recreational activities outside the protected areas (Ranke & Krokeide 2025a).

1.3.2.3 Fish

Vansjø is one of the most species-rich lakes in Norway when it comes to fish, with 21 registered species, of which 11 are native; *Perca fluviatilis, Abramis brama, Lota lota, Esox lucius, Sander lucioperca, Lampetra fluviatilis, Coregonus lavaretus, Rutilus rutilus, Gasterosteus aculeatus, Salmo trutta* and *Anguilla anguilla*, and ten are invasive; *Blicca bjoerkna*, *Cyprinus carpio, Carassius carassius*, *Osmerus eperlanus, Alburnus alburnus, Tinca tinca, Scardinius erythrophthalmus, Lauciscus cephalus, Gymnocephalus cernuss* and *Cottus gobio* (Brabrand & Lien 2004, NJFF 2025). Vansjø is one of the few locations in Norway where *Sander lucioperca* (Pikeperch/Zander) are native.

1.3.2.4 Presence of invasive non-native species

According to the Norwegian Biodiversity Information Centre (Artsdatabanken) where volunteers can register observations, several species on the Norwegian red list were found in and around Vansjø from 2000 to 2025 (Artsobservasjoner.no). Most are terrestrial, but also *Rana arvalis* (moor frog) and *Astacus astacus* (European crayfish) are registered, in addition to the bird and fish species mentioned above.

Several invasive species are also registered in and around Vansjø, mainly terrestrial, but also *Neovison vison* (mink) in addition to the bird and fish species mentioned above.

1.3.3 Zero pollution

1.3.3.1 Chemical status of waterbody (WFD status class), and EQS of specific priority chemicals

The chemical status of Storefjorden is currently Not good due to high levels of mercury (Hg) and perfluorooctane sulfonic acid (PFOS) and its derivates. The PFOS originates from several sources, but the major source is fire extinguishers used at the military airport in Rygge, adjacent to the lake. The use has ceased now, and there are measures implemented to reduce the continued leakage into Vansjø, but these “forever chemicals” will still remain in the lake for years.

In 2014-2016 fish liver (*Perca fluviatilis*) was examined for pollutants and priority substances in **Storefjorden**, and the results were *Bad* for mercury (Hg) and PFOS, while other substances were *Good*. Environmental quality standard (EQS) for Hg in organisms is 20 µg/kg wet weight (w.w.), while the liver concentrations in Storefjorden were 385,8; 317 and 598,4 µg/kg w.w. respectively the three years, far above the EQS. Equally, concentrations of PFOS in Storefjorden was average 173 and 346,2 µg/kg w.w. in 2014 and 2015 respectively, also above the EQS for organisms of 9,1 µg/kg w.w. A larger survey of PFOS in 2020 and 2021 also measured concentrations above EQS in tissue from *Esox lucius*, *Perca fluviatilis*, and *Sander lucioperca* sampled at several locations in Storefjorden, and in liver from *Perca fluviatilis* (Helland 2023).

In 2006, sediments were sampled in the eastern basin, showing concentrations of PFOS averaged at 1,90349 µg/kg dry weight (d.w.), which is above AA-EQS (annual average threshold value) but under MAC-EQS (maximum annual concentration). At the same time and place, muscle tissue from three different species were examined (*Rutilus rutilus, Esox lucius* and *Perca fluviatilis*), all with high concentrations of PFOS; 7,49129; 24,77767 and 57,22508 µg/kg w.w. for the three species respectively, the two latter above EQS for organisms. It must, however, be noted that liver is the preferred matrix for PFOS and not muscle tissue.

In a narrow basin between Storefjorden and Vanemfjorden, sediments were sampled in 2006. Sediment concentrations of PFOS at 1,15268 µg/kg d.w. were above AA-EQS (0,23 µg/kg d.w.), but below MAC-EQS (72 µg/kg d.w.). At the same time, muscle tissue from *Esox lucius* was sampled, showing PFOS concentrations of 44,26 µg/kg w.w., which was also above the EQS, although this was not the preferred matrix.

West in Vanemfjorden, Hg concentrations in *Esox lucius* (muscle tissue) were 730 µg/kg w.w. in 1999. In 2000, Hg concentrations in *Sander lucioperca* were 220 µg/kg w.w., and in *Perca fluviatilis* (both muscle tissue) 440 µg/kg w.w. All were above EQS.

1.3.3.2 Phosphorus emissions from separate dwellings

Due to several sewage measures implemented in the entire Morsa catchment area, the reduction in phosphorus emissions from separate dwellings were 87 and 90 % in the closest catchments of Storefjorden and Vanemfjorden respectively between 2001 and 2021, corresponding to a reduction from 550 to 75 kg P in Storefjorden and from 190 to 20 kg P in the western part of Vansjø (Bechmann et al. 2022).

1.3.3.3 PO4-P (mg/L)

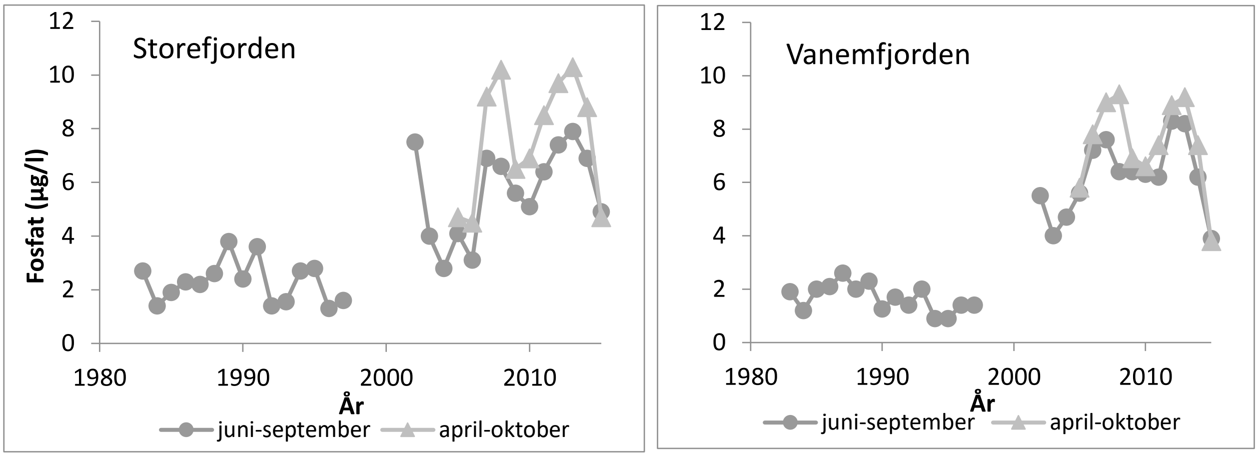
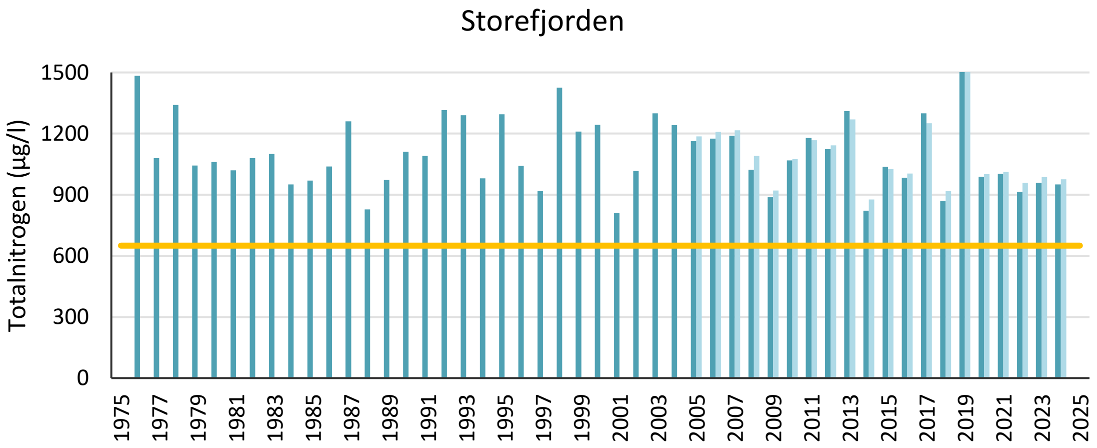


Figure f.13. *Phosphate (PO-4, y-axis) measured in Storefjorden and Vanemfjorden from 1983-2015 (x-axis).*

1.3.3.4 Total nitrogen (mg/L)

Inputs of total nitrogen (Tot-N) from the main river has not changed significantly since 1985, however the inputs of Tot-N to the main outlet river, draining to the Oslofjord, has had a week, but significant declining trend. This is not surprising, as the measures implemented around lake Vansjø has mainly been focusing on reducing phosphorus inputs to the lake, both from agriculture and sewage, and reduction in nitrogen inputs often requires different measures. As seen in **Figure f.14**, Storefjorden – which is receiving water from the main river – had high concentrations of Tot-N since the 1970s, every year above the environmental target for the water type. Vanemfjorden on the other hand, which is the basin draining to the outlet, has lower concentrations of Tot-N since the 1970s, and several years with averages below the environmental target for the water type.



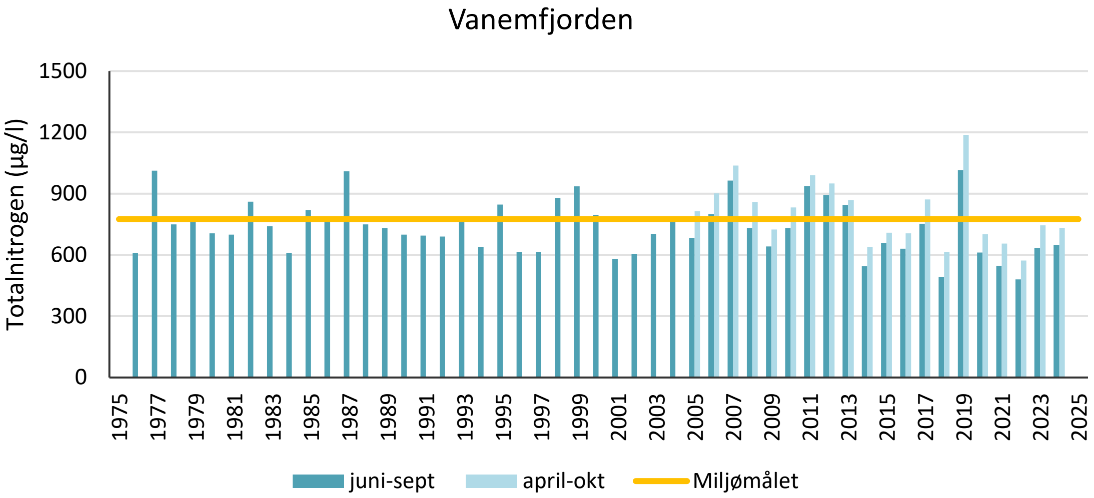


Figure f.14. *Tot-N (µg/L) in Storefjorden and Vanemfjorden from 1976-2024. The yellow lines mark the environmental targets for water types L106 (Storefjorden) and L108 (Vanemfjorden).*

1.3.3.5 Nitrate NO3-N (mg/L)

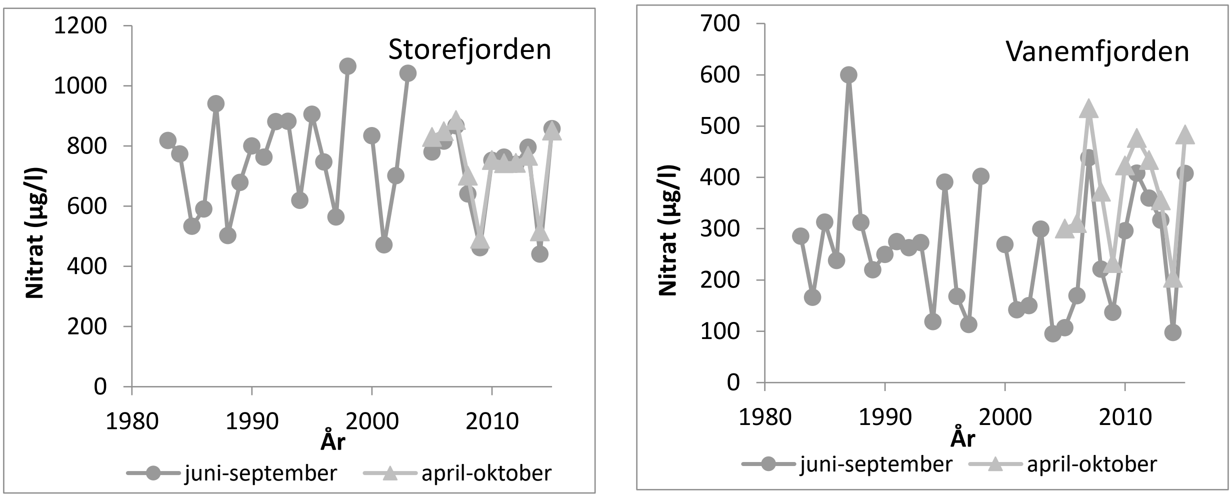


Figure f.15. *Nitrate (NO_3) measured in Storefjorden and Vanemfjorden from 1983-2015.*

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1.3.3.6 Ammonium NH_4-N (mg/L)

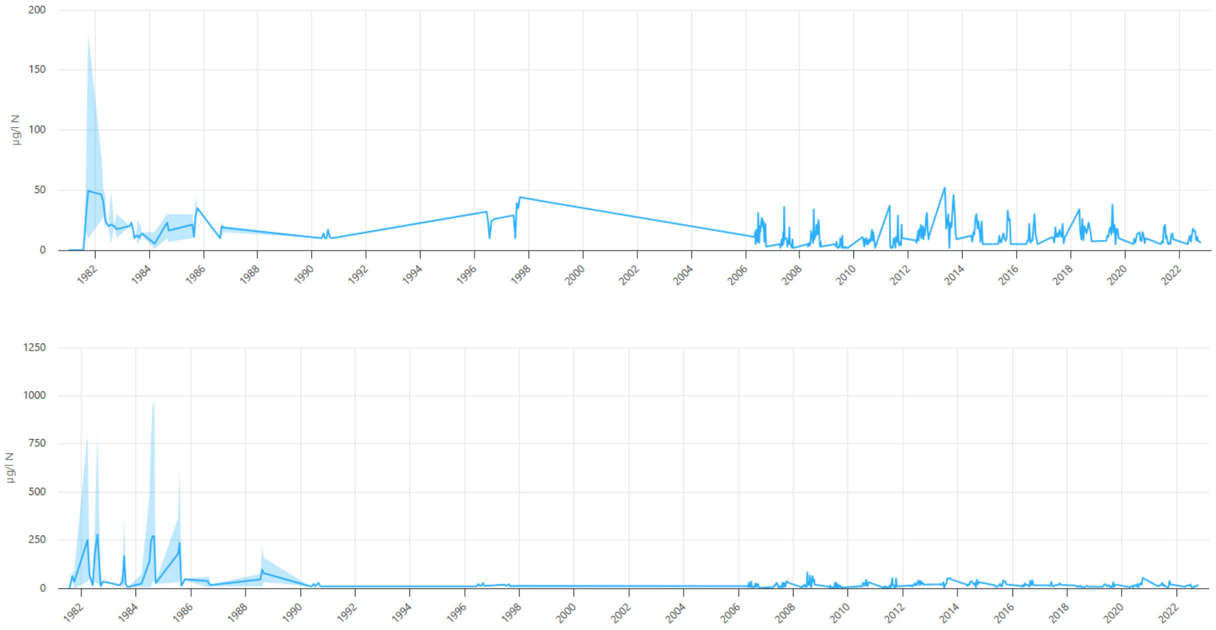

Figure f.16. *Ammonium (NH_4, ug/L) in Storefjorden (top) and Vanemfjorden (bottom) from 1981-2022.*

1.3.3.7 DOC (mg/L) and water color

Vansjø has become increasingly more humic, as seen from both organic matter content (measured as total organic carbon, TOC) and water color, shown in **Figure f.17** and **Figure f.18**.

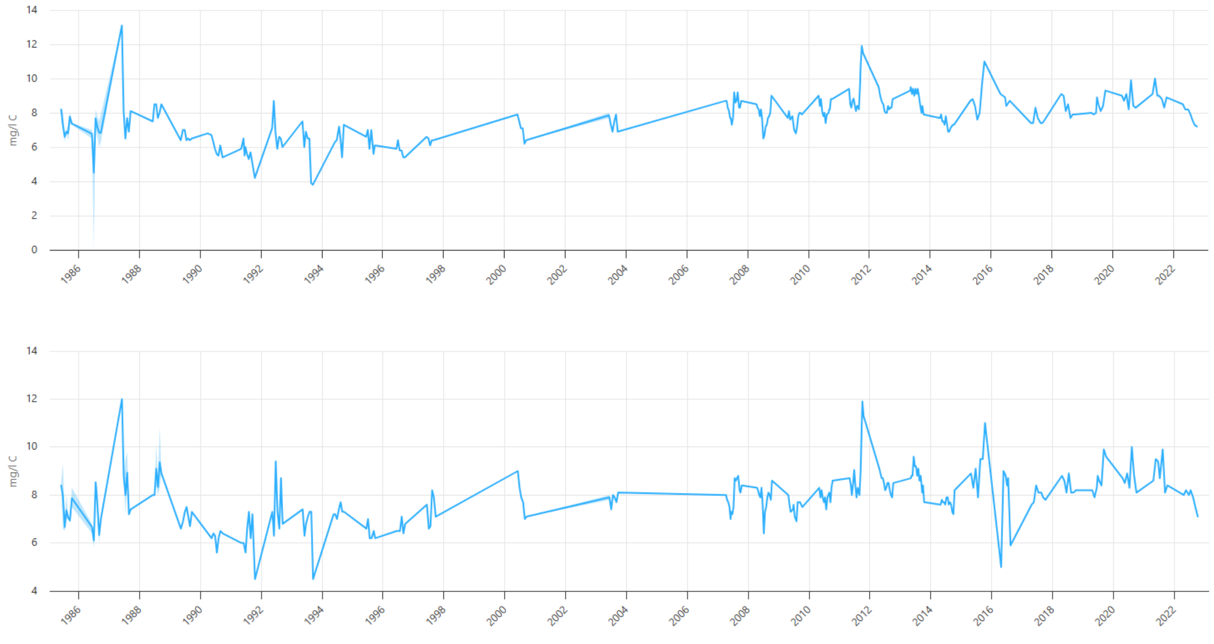

Figure f.17. *TOC (mg C/L) in Storefjorden (top) and Vanemfjorden (bottom) from 1985 to 2022.*

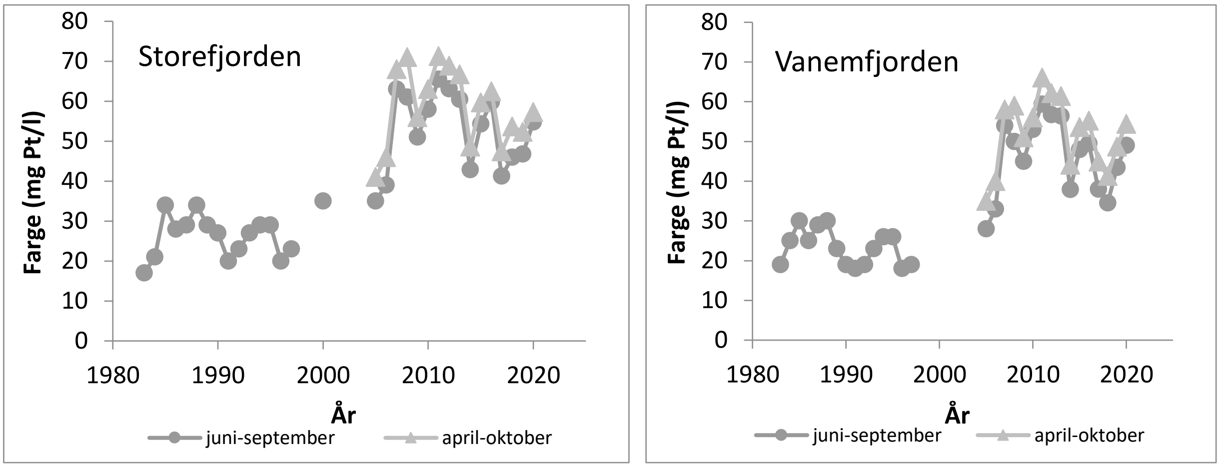

Figure f.18. *Water color measured in Storefjorden and Vanemfjorden from 1983-2022.*

1.3.3.8 E. coli (MPN/100 ml)

Cell numbers of *Escherichia coli (E. coli)* in three streams draining into Vansjø are shown in **Figure f.19 and f.20**. The stream in the eastern basin had low numbers of *E. coli* between 2008 and 2022. Contrary, the cell numbers were higher in the two streams draining into the western basin, however the numbers have declined significantly in both streams after 2011.

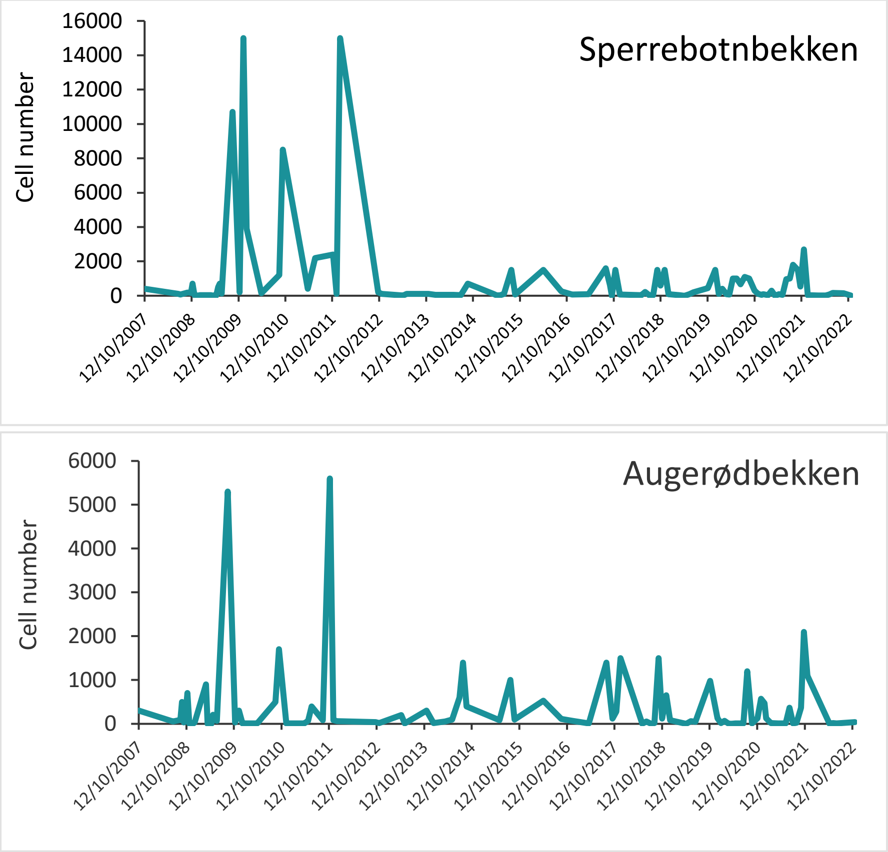

Figure f.19. *E. coli concentrations in two streams draining to Vanemfjorden between 2007 and 2022.*

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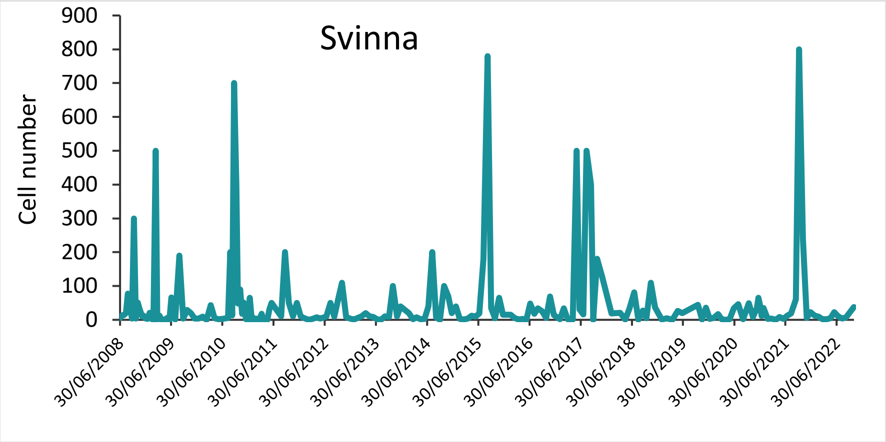

Figure f.20. *E. coli concentrations in a stream draining to Storefjorden between 2007 and 2022.*

1.3.3.9 Microplastics (<5 mm)

In 2018, microplastics (< 5 mm) were investigated in the raw water at Vansjø Waterworks, and after treatment in the drinking water plant. The results showed average 2,3 particles per liter water in Vansjø (raw water), which is a low number and not considered to constitute an issue for the use of the lake as drinking water source.

1.3.4 Climate regulation

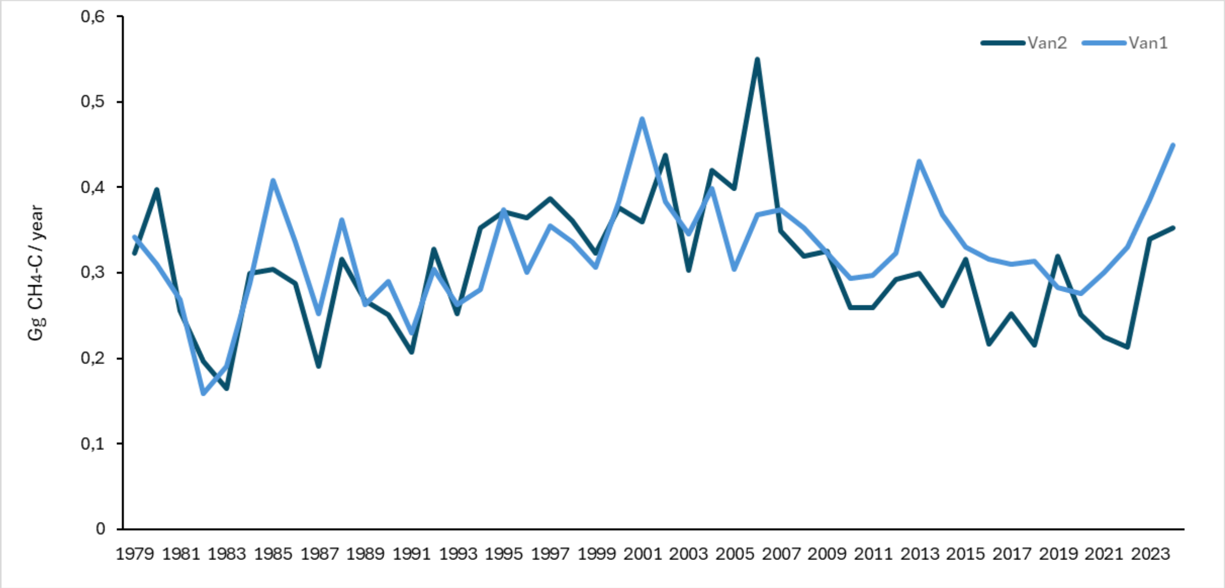

Figure 21. *Predicted sum of ebullative and diffusive methane (CH_4) emissions from the two main basins of Vansjø, based on average annual chlorophyll a concentrations (June-September). Predictions were made using a Bayesian model constructed from a global dataset of ground-based methane measurements and satellite-derived chlorophyl-a data. The data used to construct the Bayesian model is available as supplementary information in DelSontro et al. 2018.*

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1.3.5 Climate resilience

Flooding is a frequent occurrence in Vansjø and its catchment. It has been documented that the implemented mitigation measures would have had an even more significant effect on nutrient loading and water quality if the flood in year 2000 had been prevented. However, still it is suggested that the only permanent measure to reduce flood problems in Vansjø is to increase the outlet capacity, e.g. by a flood tunnel. The estimated costs (per 2011) for this alternative was set to € 8,8 (by The Norwegian Energy Regulatory Authority, NVE) and has not yet been started (Morsa 2011). There is also a great need for securing rivers in the catchment for erosion and flooding, with a estimated cost of € 9.

1.3.6 Health & Well-being

Bathing water quality

Vansjø has experienced several years of cyanobacterial blooms, with consequential bathing bans. The blooms were most frequent between 2000 and 2007, and since then the concentration of cyanobacteria in the western part of Vansjø (Vanemfjorden) has declined significantly. Still, visible blooms occur some years, and there were also recommendations not to swim in the western parts of the lake (Nesparken) in 2019 and 2020 (**Figure f.22**).

Figure f.22. *No swimming in Nesparken in 2019. Photo: Moss Avis, 12.08.2019.*

<u>Cyanobacteria, biomass and toxins</u>

Vansjø experienced heavy cyanobacterial blooms several years, with large, visible green mats occurring several places, especially in the western basin. The blooms were often toxic, but also unappealing to people in and around the lake, causing bathing bans and loss of recreational value. But the visible blooms also motivated stakeholders, farmers and land owners to engage in measures initiated to improve the water quality of the lake, e.g. environmental contracts, even if the costs were high. Since the implementation of mititation measures in the catchment of Vansjø, cyanobacterial biomass have significantly declined in both of the main basins (**Figure f.23**), as have the concentrations of microcystin (**Figure f.24**).

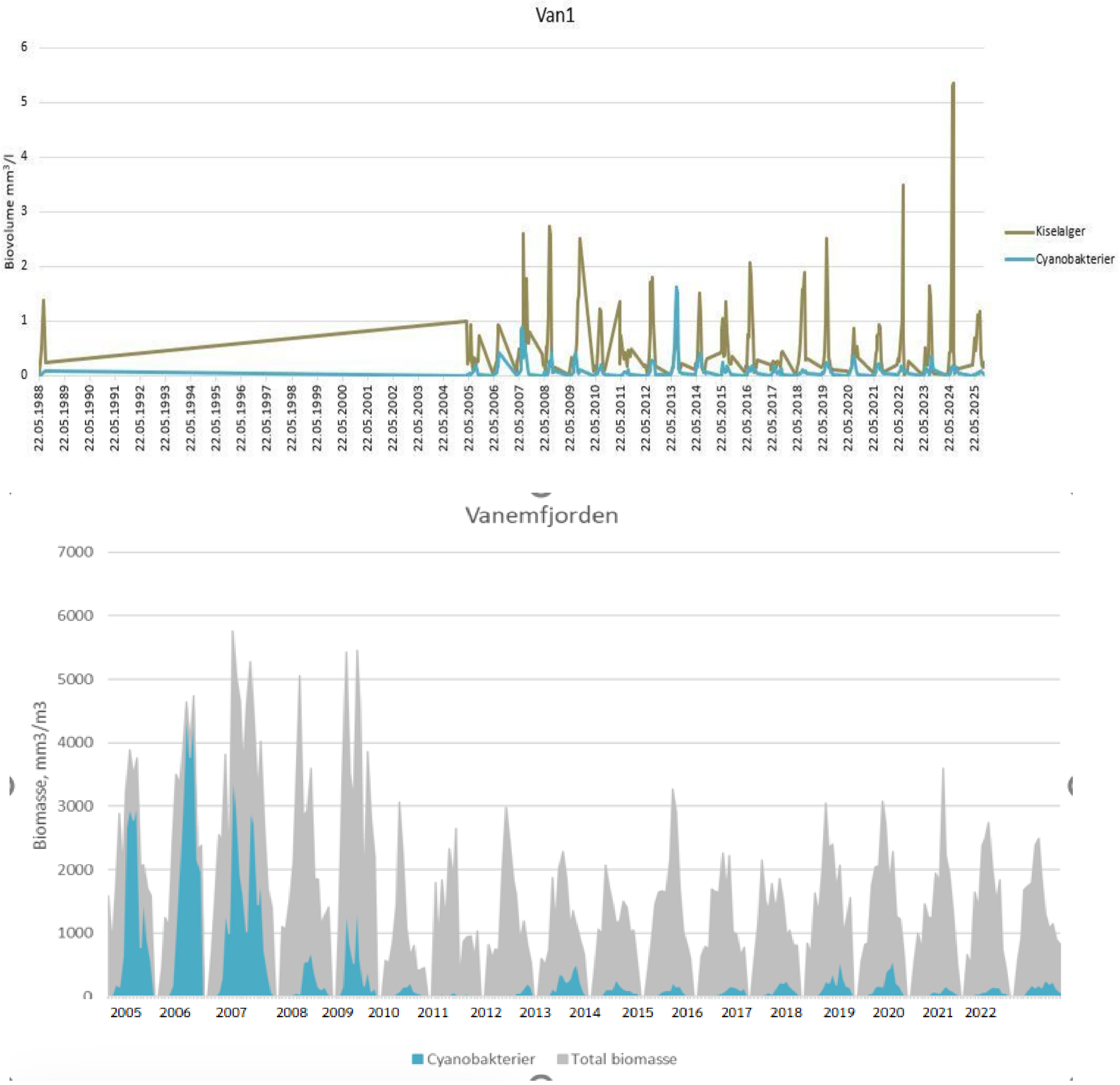

Figure 23. *Cyanobacterial biomass in Storefjorden (above, Van1) from 1988-2025 in relation to diatoms ("kiselalger"), which often are the most dominant group, and in Vanemfjorden (below) from 2005-2025, in relation to total phytoplankton biomass.*

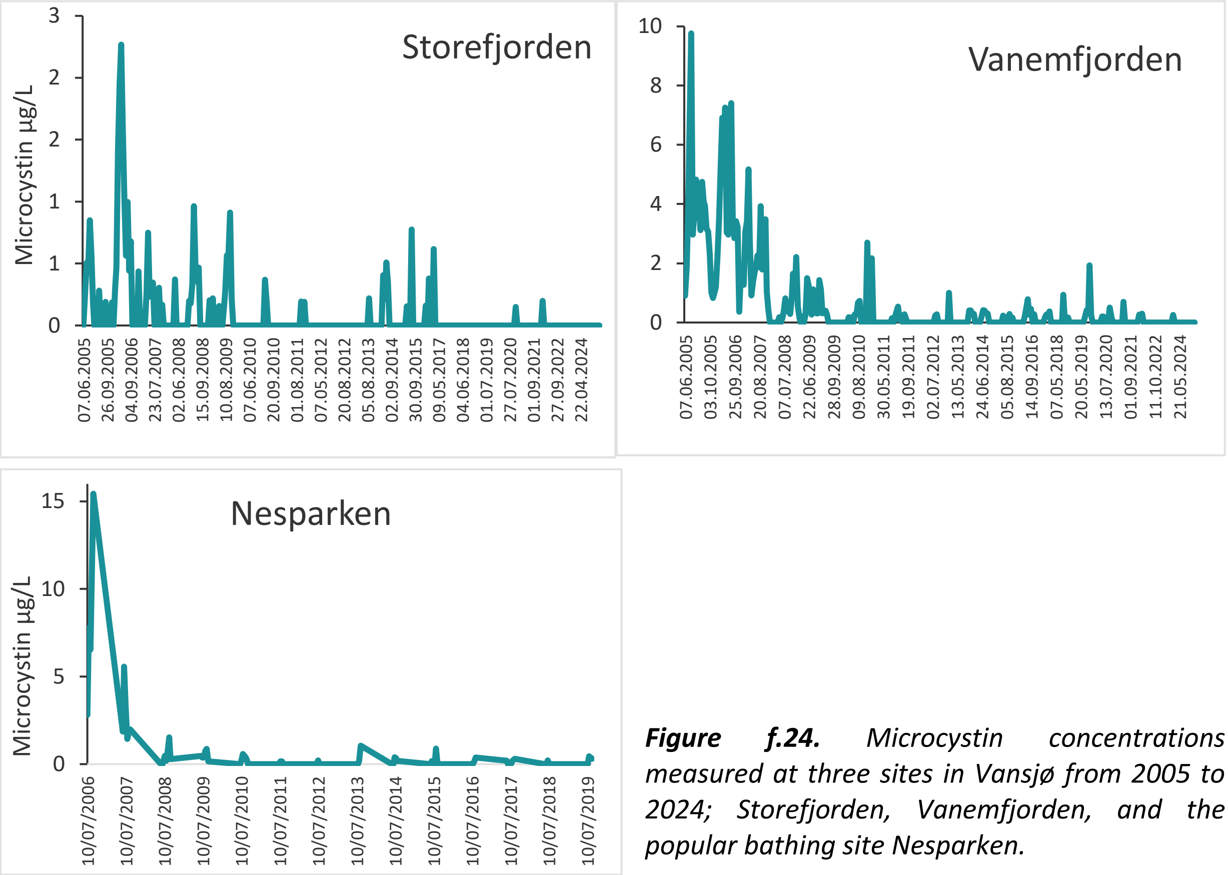

Figure f.24. *Microcystin concentrations measured at three sites in Vansjø from 2005 to 2024; Storefjorden, Vanemfjorden, and the popular bathing site Nesparken.*

E. coli

E. coli numbers have been low between the main basins (station Van5) from 2008-2022, as seen in **Figure f.25**. The numbers have been far beneath the threshold for Good bathing water quality of 1000 cells/100 ml.

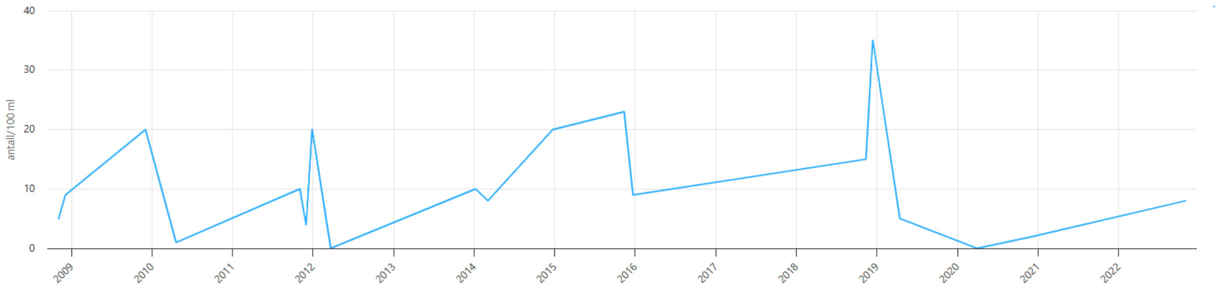

Figure f.25. E. coli *numbers (count per 100 ml, y-axis) measured between Storefjorden and Vanemfjorden (station Van5) from 2008-2022.*

1.3.7 Inclusivity

The entire Morsa project is organized into a Water Board, consisting of representatives from the municipalities, county councils, county governors, and national directorates, with the intermunicipal drinking water association, Farmer's Organizations and other NGOs as observers. Thematic groups (agriculture, sewage, monitoring) meet regularly, exchange knowledge, and jointly apply for project funding, enabling consistent dialogue and mutual learning.

Nine municipalities cooperate to implement the necessary measures in order to improve the water quality and ecological status in Vansjø as well as the entire catchment. Co-creation and ownership is important in the Morsa working group. For example, when developing a stormwater management guide, municipalities were involved throughout the process via workshops and consultations, ensuring relevance and uptake.

Starting with education, information campaigns, farmers' meetings, field trips, agricultural advisory for environmental planning on individual farms, farms visits, ending with a system of legal contracts signed with individual farmers combing incentive measures (Skarbøvik & Bechmann, 2010). There are continuous efforts to engage farmers voluntarily, and they have been offered free consultancy on environmental planning since 2008. 75 % of farmers in the catchment draining to Vanemfjorden have signed comprehensive environmental contracts.

1.3.8 Recreation

The Norwegian Tourist Association (DNT) has its own local group covering the three municipalities around Vansjø, providing activities, maps, routes, cabins etc. in and around the lake (in addition to the rest of the area of these municipalities). The local (county) hunting- and fishing association (JFF) also provides licenses for hunting (ducks and geese) and fishing in Vansjø, and promotes activities connected to the lake. Together with municipalities, the two organizations arrange annual summer camps for kids (10-12 years) in the lake with financial support from the Morsa organization. The camps focus on nature and outdoor activities such as canoeing, fishing, camping etc, and attendance has been increasing each year.

As the lake has free access in all municipalities, the number of people involved in general recreation around the lake is difficult to estimate. The lake is very popular with summer camps, private cabins, beaches, marinas and hiking routes. Some of the hiking paths have been upgraded the past years, and are lit, and facilitated for wheelchairs and strollers. The lake is used all year round. In cold winters, the lake is popular for cross-country skiing and ice-skating, with its own ice-skating group arranging trips and providing information and training.

1.3.9 Sustainable Agriculture

The agricultural practices in the Morsa catchment are dominated by grain production, as seen in **Figure f. 26**. However, due to grants given to farmers and land owners, there was a large increase in grass covered areas between 1990 and 2020, including grass on flood-prone areas, grass covered buffer zones, and grass covered water ways. The increase was largest in the catchment of Vestre Vansjø (Vanemfjorden), and especially visible since 2008. In this area, there was also a reduction in areas with vegetable- and potato-crops, which in combination with increased grass covered areas reduces the risk of erosion and nutrient loss (Bechmann et al. 2022).

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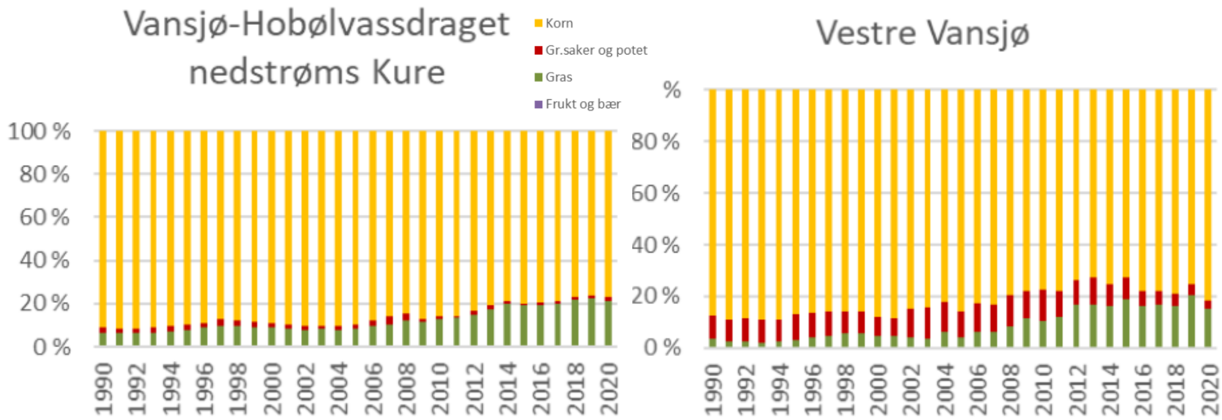


Figure f.26. *Percentage of grain (yellow), vegetables and potato (red), grass (green) and fruits/berries (purple) in the catchments of Storefjorden (left) and Vanemfjorden (right) from 1990-2020 (Bechmann et al. 2022).*

The density of livestock in the Morsa catchment is very low, and not expected to have large influence on the water quality in Vansjø. There are some indications that the density of livestock has declined in the western part of Vansjø between 1999 and 2019, but not in any of the other areas around the lake (Bechmann et al. 2022).

As also described in section 1.2.3.1, there has been a large increase in the grain areas around Vansjø that are not tilled in the autumn, but instead overwintering with stubble. 80-90% of the grain areas around Van1 and Van2 had overwintering stubble around year 2010-11, which is an increase from 20-50 % in 2002. After 2013 the percentage declined again, but it has been stable at appr. 50-70 % since then (Bechmann et al. 2022). The large increase until 2013 was due to environmental agreements (as mentioned in 1.2.3.1) with requirements of 60 % overwintering stubble, a requirement which was removed in 2013.

There has been an increase in the use of catch crops in the Morsa catchment, with the largest increase occurring after 2013 and later. Catch crops reduces the nutrient losses outside the growth/production season, with especially nitrogen being stored in the crops. Loss of phosphorus is also reduced due to the soil not being tilled in the autumn, and because the catch crops covers the soil and protects against erosion. The use of catch crops has increased the recent years due to their positive effects on soil health and increased grants of subsidies (Bechmann et al. 2022).

1.3.10 Sustainable energy

The outlet from Vansjø into the Oslofjord goes through a small hydropower plant, utilizing a water fall of 22,4 m. The plant was established in 1986 and produces 13,00 GWh per year (with effect 3,1 MW, Hafslund 2025).

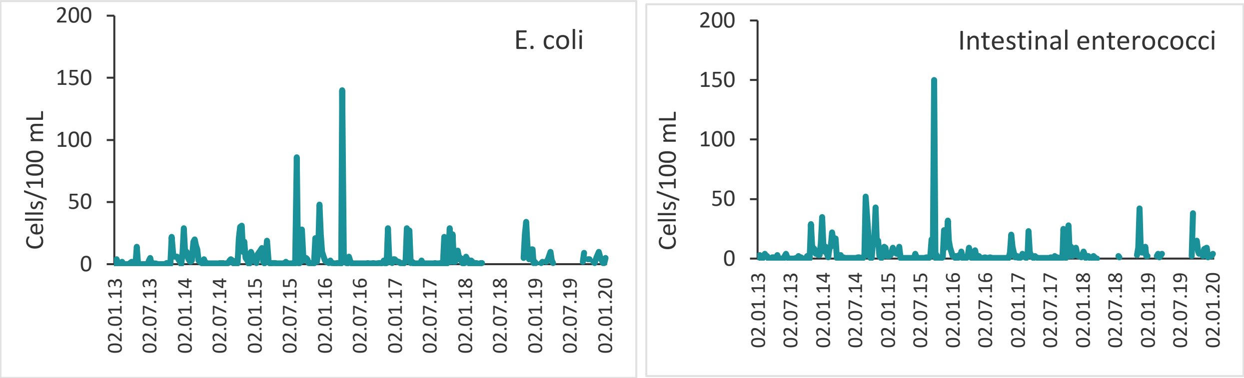
1.3.11 Sustainable Tourism

Vansjø is one of the most used freshwater localities in the county when it comes to sports- net- and commercial fishing. The lake is also used frequently for bathing, paddling and boating. Several venues are located close to the lake, offering accommodation, recreation and activities in and around the lake. The interest for commercial activities along the catchment and Vansjø is increasing (Kaabel 2014).

1.3.12 Water supply & sanitation

Irrigation: Some of the catchments around Vansjø, and especially the lake itself are used for irrigation of e.g. vegetables.

Drinking water: Vansjø Waterworks is one of Norways most comprehensive treatment facilities, with several steps of treatment and disinfection of the raw water, supplying high quality drinking water. Despite the use of Vansjø as drinking water source, there is no restrictions on the use of the lake for protection of the source. The main intake is located in Storefjorden, at 12 and 25 m depth (25 m is mainly used), and is situated in the part of the lake which has the best water quality. Vansjø Waterworks sample weekly for microcystin analysis between from June through September. Microcystin has never been detected in the treated drinking water. Bacterial numbers in the raw water tested by the Waterwork has also been low during 2013-2020, as shown in **Figure f.27**.



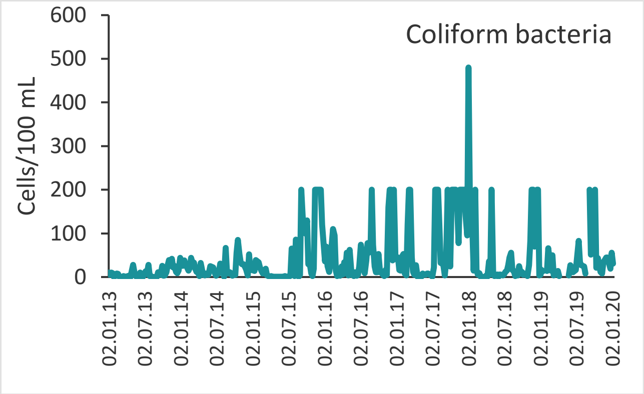


Figure f.27. *Numbers of relevant bacteria analysed in the raw water of Vansjø Waterworks between 2013 and 2020 (movar.no).*

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1.5 Summary of effectiveness of restoration programme

Knowledge-based management was put into practice early in the Morsa cooperation, hence the management and mitigation measures are based on both scientific and local knowledge based on experience. The first party-neutral mitigation analysis was conducted in 2001, and was the scientific foundation for political decision-making and plans of actions and mitigation measures. This analysis was decisive in order to gain accept and agreement on the mitigation measures that were implemented. An action-plan for restoration of Vansjø (western part) was approved by the municipal councils (2007) and therefore locally implemented.

A board (water basin team) was created, consisting of mayors from the catchment municipalities, representatives from the region, as well as professionals from municipalities and the county governor organized into thematic groups, which has been crucial for gaining trust and agreement on demanding and costly actions.

The municipalities have several of the necessary measures needed to e.g. reduce nutrient inputs, with local ownership and proximity to the residents, and are therefore the key actors for the implementation of mitigation measures. However, they do not possess all the necessary means, therefore it’s been crucial for the restoration of lake Vansjø that also the regional and national authorities actively participate. The Morsa group has good cooperation and dialogue with farmers and other users-interests.

The Morsa project has received funding from the Ministry of Agriculture to execute extra-ordinary agricultural environmental measures and to document the effects. Several fertilization experiments were conducted in cooperation with farmers.

Farmers have been offered free environmental consultancy, and they have been encouraged to voluntarily sign extensive and obligating environmental contracts, resulting in about 75 % of farmers in the Vanemfjorden catchment signing such contracts. Information campaigns and subsidies have increased farmers acceptance of legislative environmental claims, and the farmers’ willingness to change their practices, with or without economical gain, is important for the project’s success. Vansjø is also emotionally important for the people living close to the lake, and the fact that the farmers also use the lake and that recreational use (fishing, boating, bathing) had deteriorated due to the algal blooms, was an important driver for their involvement.

Yet, there are limitations in terms of conflicts of interest when it comes to balancing the environmental considerations with the farmers’ livelihood and national need for food production, e.g. with no tilling, which leads to reduced crops and harvest. Although dependent on the farmers’ willingness to participate, the implementation of measures are also been dependent on the establishment of regional or national legislation that promotes the necessary changes in practices.

For sewage treatment the upgrades of the sewerage system were paid for by the residents, either directly in case of private systems, or via their water- and sewage fees for public systems. This may also be creating conflict for the municipalities.

Following the implementation of many phosphorus reduction measures, the TP and chlorophyll-a concentrations declined towards WFD Good/Moderate boundary values and since 2009, the frequent, reoccurring blooms of cyanobacteria stopped. However, the lake has not yet reached Good ecological status after two decades of targeted mitigation measures to reduce nutrient loading, and cyanobacterial blooms still occur some years. Climate change seems to be one major factor counteracting the improvements achieved through mitigation measures. Increased precipitation is leading to even more floods and soil erosion, transporting soil and nutrients into the lake. In addition, Vansjø has become more humic, due to a combination of e.g. climate change, reduction of acid precipitation and changes in forestry. The reduction of sulfate is shown to reduce the concentration of aluminium in the catchment, which is then leading to less P being bound to Al, and also less P being deposited to the sediments and instead staying in the water column (forskning.no). Yet, studies show that without the implemented measures in the Vansjø catchment, the situation for the lake would be even worse than it is, with continued high inputs of nutrients (Vogt artikkel).

Also, reduced acid precipitation increases the pH of the soil, which leads to more leaking of organic (humic) matter containing nutrients into the rivers and lakes. The increase in water colour and organic carbon (browning) occurring in Vansjø over the past decades has led to a change in algal community composition and has also been a cause for the lower presence of cyanobacteria and increased presence of other algal groups and species, e.g. *Gonyostomum semen*. This species is rich in chlorophyll *a*, have large biovolume and often creates large biomasses that are not directly related to P-concentrations, which explains why the PTI values in Vansjø are not responding as positively to the reduction of P as hoped for.

Vansjø is also regulated in the outlet river for hydropower production. The current regulation regime involves high water levels during summer, which is creating stagnant conditions in parts of the lake for large parts of the summer season, increasing the risk for algal blooms (Kaabel 2014)

The current key challenges in terms of eutrophication are therefore climate change, flooding, as well as nutrient loading. Climate change is expected to increase the eutrophication of Vansjø, however land use changes and management practices aimed at improving water quality, could still have an effect (Couture et al. 2013). The study of Couture et al. (2013) also showed that achieving the environmental goals for the western part of Vansjø, even without expected climate change, will be very difficult, but it is important to implement measures to reduce the effects of climate change (Kaabel 2014).

A more recent development is the recognition that Lake Vansjø has been severely affected by pollution of certain per- and polyfluoroalkyl substances (PFAS). The main source of PFAS contamination has been identified as Rygge Airport, where PFOS (perfluorooctanesulfonic acid) was used in fire extinguisher foams. This led to substantial inflow of PFOS into the lake, resulting in concerning levels of the substance in sediments and biota. The Norwegian Food Safety Authority (Mattilsynet) has conducted assessments of PFAS content in fish from Lake Vansjø (2015, 2019) and now advises against consuming fish caught in the lake. The presence of PFAS in the lake ecosystem remains a long-term environmental issue of growing national and international concern that requires ongoing monitoring and management. The effect this has on recreation and fishing in Vansjø is not clear. However, a new working group is being formed to coordinate responses, emphasizing the strength of the organization to show flexibility and responsiveness, allowing the governance system to adapt to emerging challenges.

The way forward will be to develop even more targeted and innovative restoration measures to continue reducing nutrient loading to the lake, while also working on removing the PFOS pollutants.

1.7 Acknowledgements

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