FUTURELAKES

For Nature, Climate and People

Demonstrating Successful Restoration

Lake Vesijärvi Demonstration Site

Deliverable D4.1, DS-Annex a

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Summary

FutureLakes assessed how six major European lake restoration programmes perform—not only on water quality and biodiversity—but also on climate regulation and resilience, societal values and economic returns. The Demonstration Sites are Lake Vesijärvi (FI), Kartuzy Lakes (PL), Lake IJssel complex (NL), Lake Karla (GR), Loch Leven (UK), and Lake Vansjø (NO). The results are documented in a synthesis report by Kramer et al. (2026).

This Annex report documents the broad range of benefits and impacts delivered by the Lake Vesijärvi restoration programme.

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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

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Lake name: Lake Vesijärvi, Finland		
Type of characteristics	**Characteristics**	**Value**
Catchment characteristics	Total catchment area [km^2]	514
	Direct catchment area [km^2]	
	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)

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2 Restoration Programme

2.1 Background

Lake Vesijärvi (lake no. 14.241.1.001) is a 109-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.

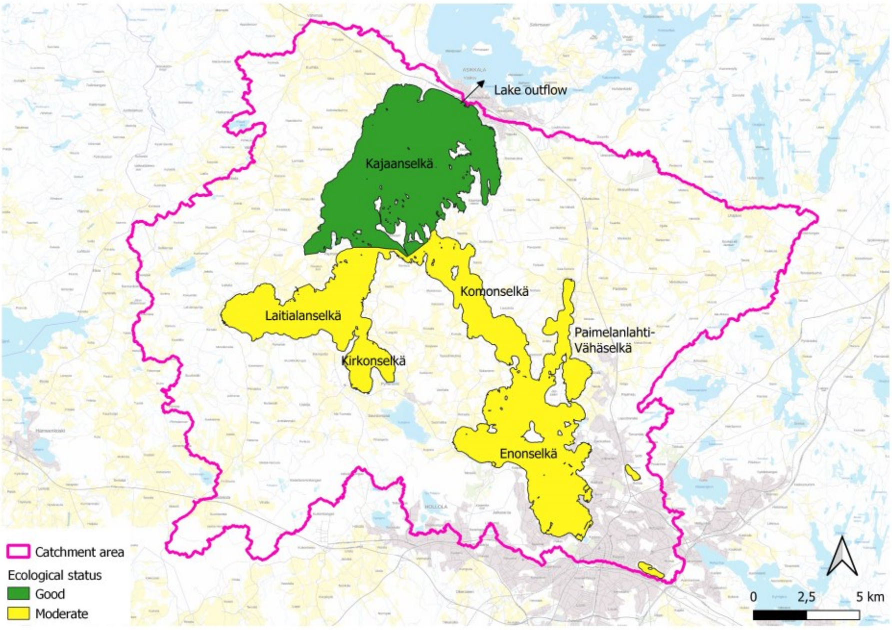

Figure 1. The catchment area of Lake Vesijärvi and the ecological status of the lake's separate basins (water bodies) in the RBMP assessment in 2019: Vesijärvi 1 (Enonselkä, Komonselkä and Paimelanlahti-Vähäselkä); Vesijärvi 2 (Kajaanselkä); and Vesijärvi 3 (Laitialanselkä and Kirkonselkä). Contains 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).

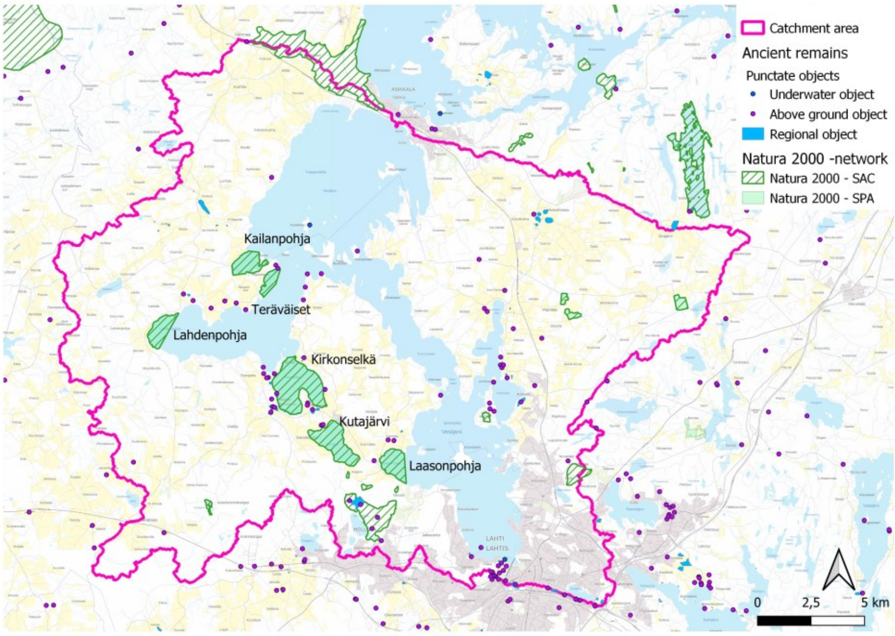

Figure 2. Identified ancient remains and the delimitations of Nature 2000-area at L. Vesijärvi and its catchment area. Contains data from the National Land Survey of Finland, the Finnish Environment Institute and the Finnish Heritage Agency (License CC BY 4.0).

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 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 2.2 and 2.3.

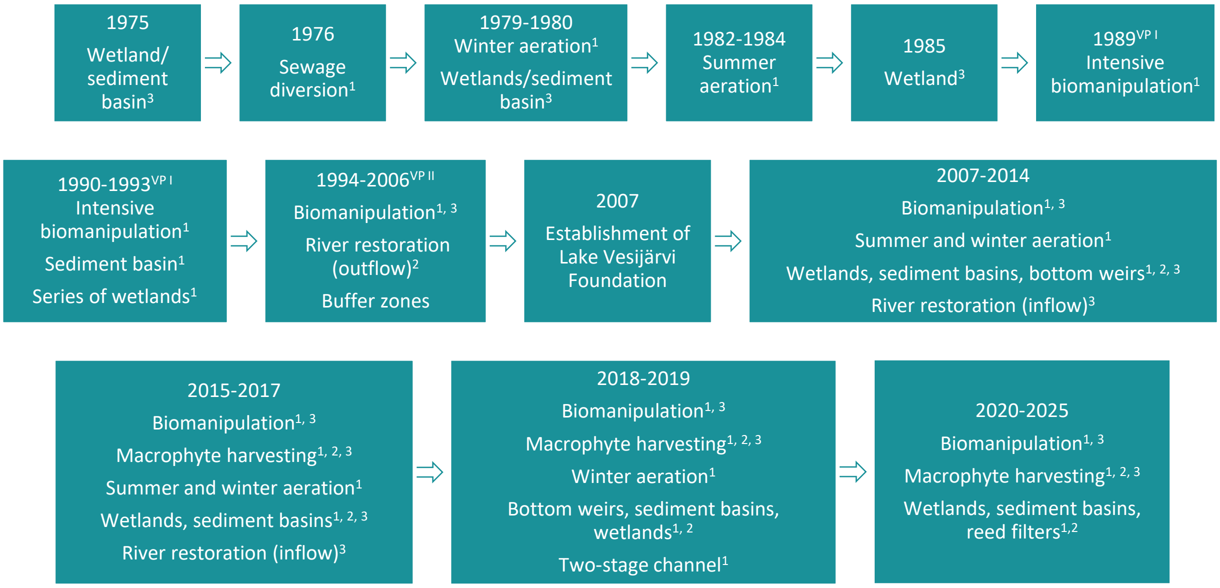

Figure 3. Water protection and restoration measures conducted at Lake Vesijärvi since the establishment of wastewater treatment plant in 1976. Upper indices display the basins to which measures have been targeted (1 = Vesijärvi 1 (basins Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä); 2 = Vesijärvi 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.

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*) (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).

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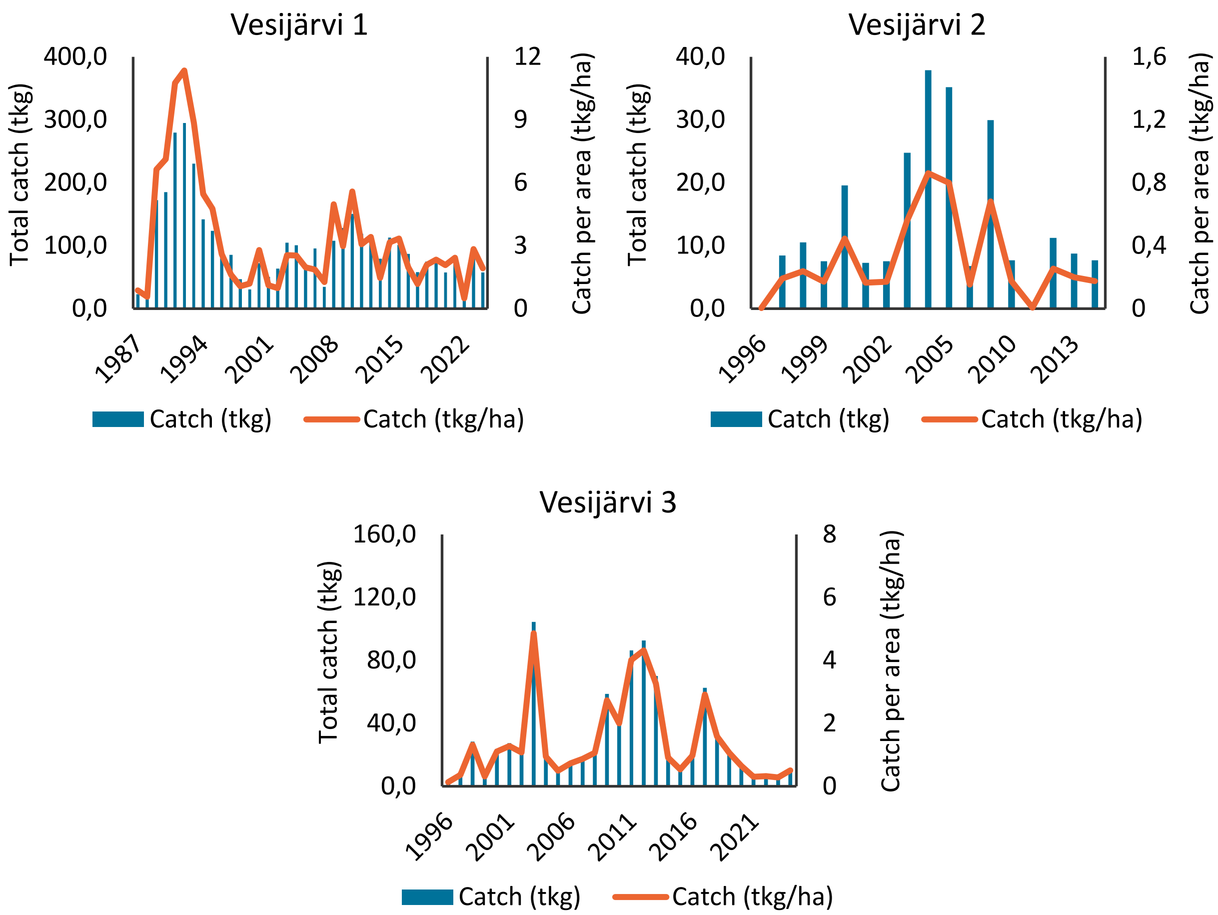

Figure 4. Annual biomanipulation catch of fish at the distinct RBMP water bodies of L. Vesijärvi (Vesijärvi 1 = Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä; Vesijärvi 2 = Kajaanselkä; and Vesijärvi 3 = Laitialanselkä and Kirkonselkä basins). Please refer to Figure 1 for information on the location 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.

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 3.3.1).

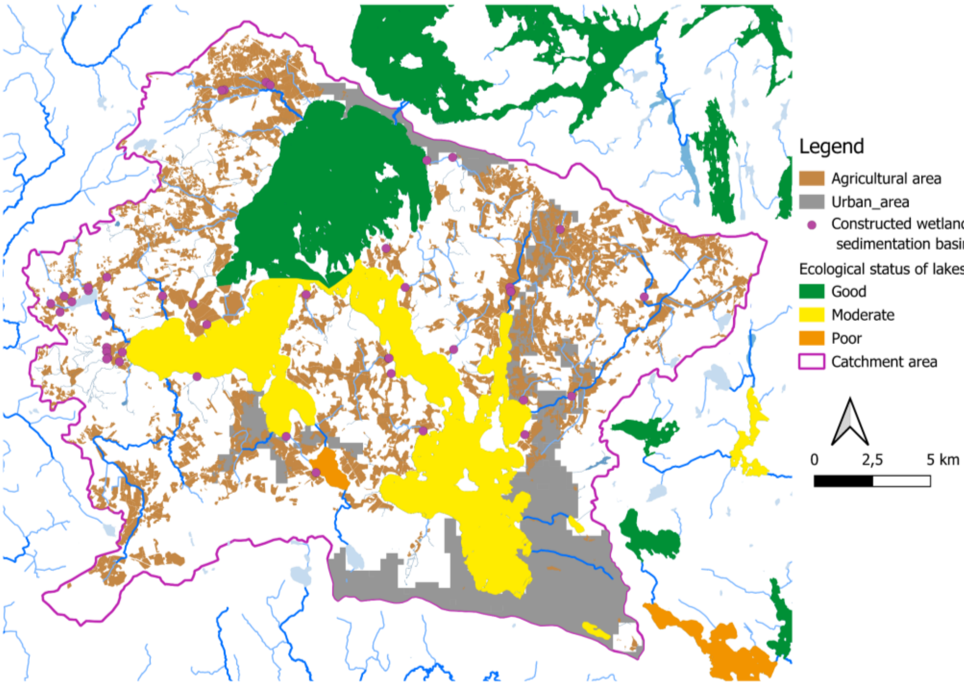

Figure 5. Urban and agricultural areas, and constructed wetlands and sedimentation basins along streams discharging to Lake Vesijärvi. Contains data from the Finnish Environment Institute, The Centre for Economic Development, Transport and the Environment, National Land Survey of Finland, and the Finnish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

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 2010). 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).

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 (value of 2025). Unfortunately, no comprehensive data could be obtained on the costs of fish stocking. In 2008, information is only available for the introduction of eels, when the stocking of 27,500 individuals costed c. €30,000 (€40,575 in the value of 2025). In 2018, introduction of predatory fish (eels (*Anguilla anguilla*), pikeperch and trout (*Salmo trutta*)) to L. Vesijärvi costed €30,000 in (€36,030 in value of 2025) and €40,336 in 2023 (€41,106 in value of 2025).

The annual total costs for aeration in 2007-2009 were €8,000/a (€10,820/a in value of 2025) with one operational pump in use in the Enonselkä basin; €80,000/a in 2010-2015 (€98,200/a in value of 2025) with eight operational pumps at Enonselkä basin; and €35,000/a in 2016-2020 (€41,490/a in value of 2025) 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. €756,230 (value of 2025).

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**	

3 Evaluation of existing restoration programme

3.1 WFD

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 3.1.2).

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).

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 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.

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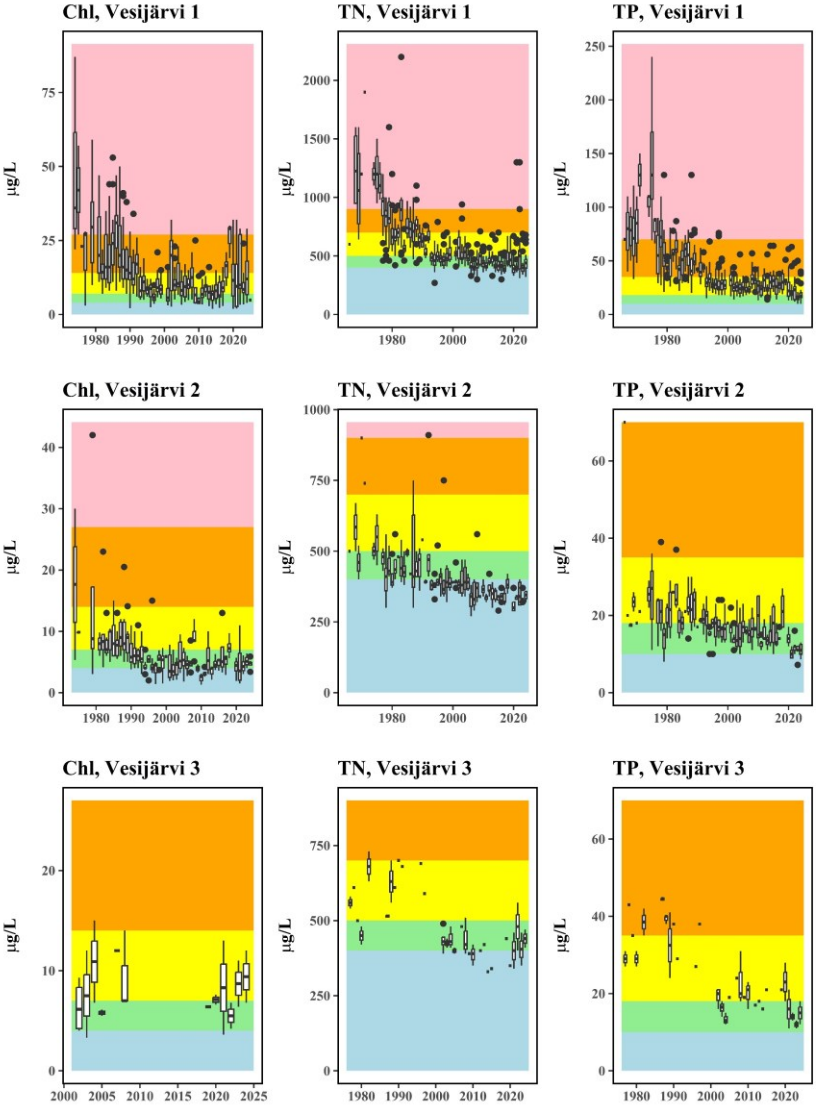

Figure 6. Development of chlorophyll a (Chl a), total nitrogen (TN) and total phosphorus (TP) concentrations in the three RBMP water bodies of L. Vesijärvi since the beginning of monitoring. Vesijärvi 1 refers to basins Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä; Vesijärvi 2 to Kajaanselkä; and 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).

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).

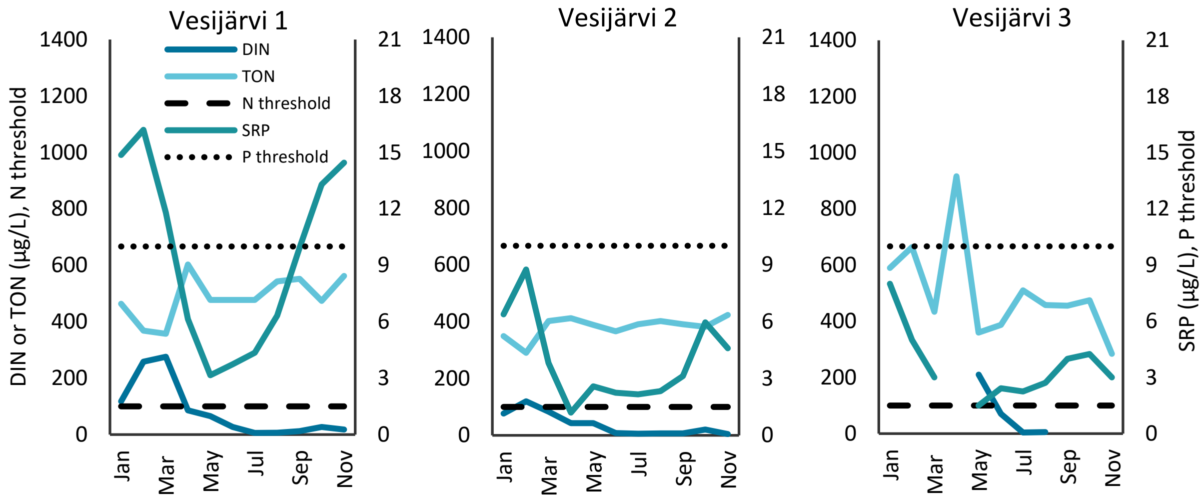

Figure 7. Seasonal changes in surface water (0-4 m) soluble reactive phosphorus (SRP), dissolved inorganic nitrogen (DIN) and total organic nitrogen (TON) average concentrations in L. Vesijärvi subbasins in 1990–2025. The threshold values for P (10 µg/L, dotted line) and N (100 µg/L, dashed line) are 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.

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

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declined and the N_2-fixing cyanobacterium *Dolichospermum* replaced the non-N_2-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 is 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).

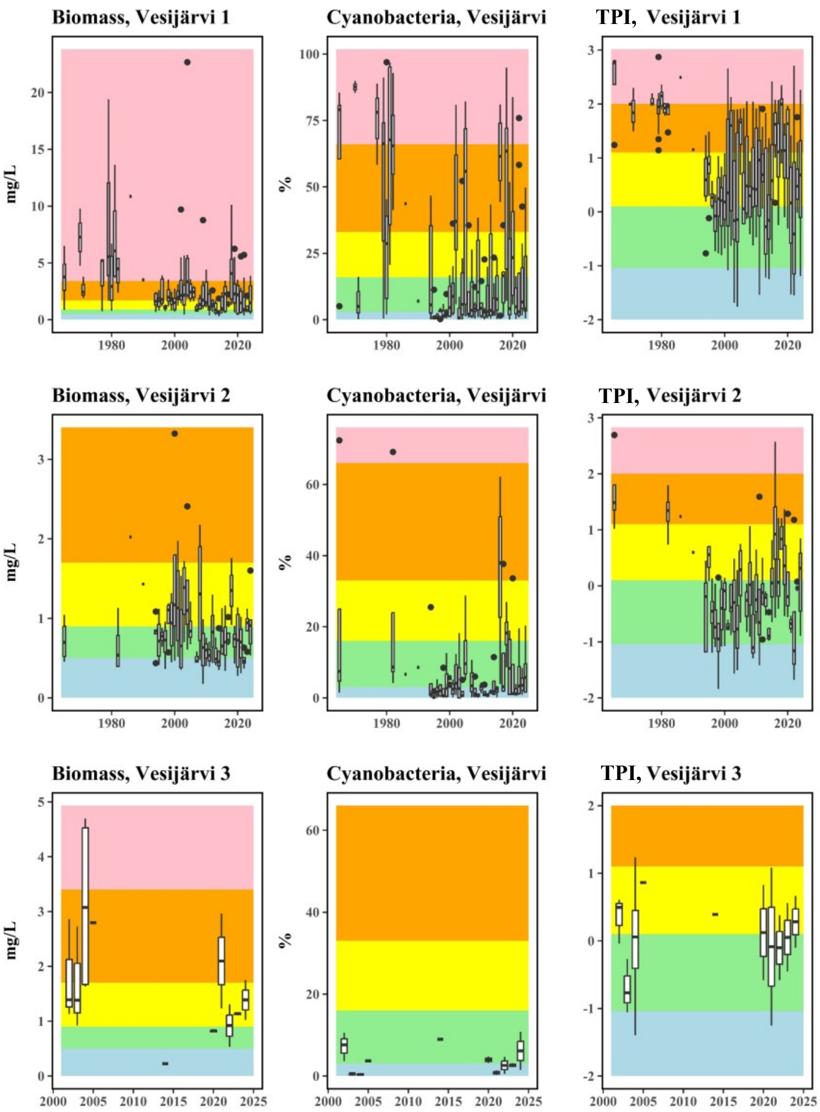

Figure 8. Phytoplankton total biomass, proportion of harmful cyanobacteria of phytoplankton biomass and phytoplankton trophic index (TPI) in the three RBMP water bodies of L. Vesijärvi since the beginning of monitoring. Vesijärvi 1 refers to basins Enonselkä, Paimelanlahti-Vähäselkä and Komonselkä; Vesijärvi 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).

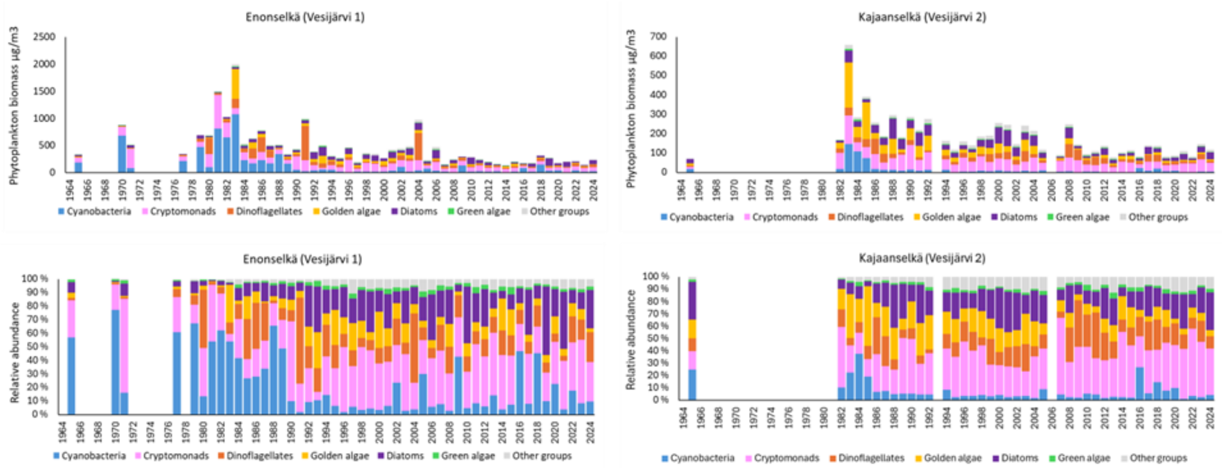

Figure 9. The development of phytoplankton communities at L. Vesijärvi's Enonselkä (Vesijärvi 1) and Kajaanselkä (Vesijärvi 2) basins since the beginning of monitoring in 1965. The data represent average biomasses from June to August. Note the different scales on y-axis.

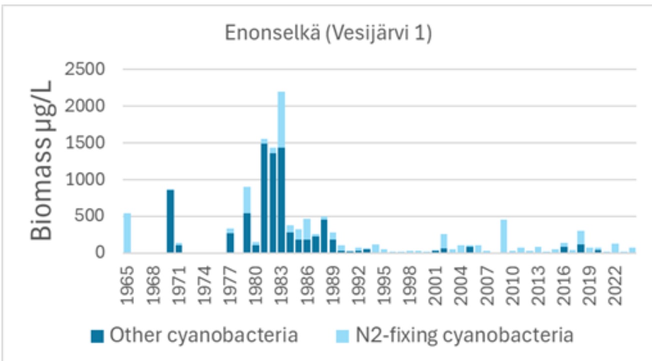

Figure 10. The development of N_2-fixing and non-N_2-fixing cyanobacteria (other cyanobacteria) at Enonselkä basin (Vesijärvi 1) since the beginning of monitoring 1965. Data represent average cyanobacterial biomass from June to August. The data represent average yearly biomasses from June to August.

The phytoplankton quality element (BQE) in Vesijärvi 1 has fluctuated annually and indicated bad to good status, whereas in Vesijärvi 2 it has mostly represented good or high status (Figure 11). From Vesijärvi 3, data are available only from the 2000s, and lake phytoplankton BQE has indicated moderate to good status.

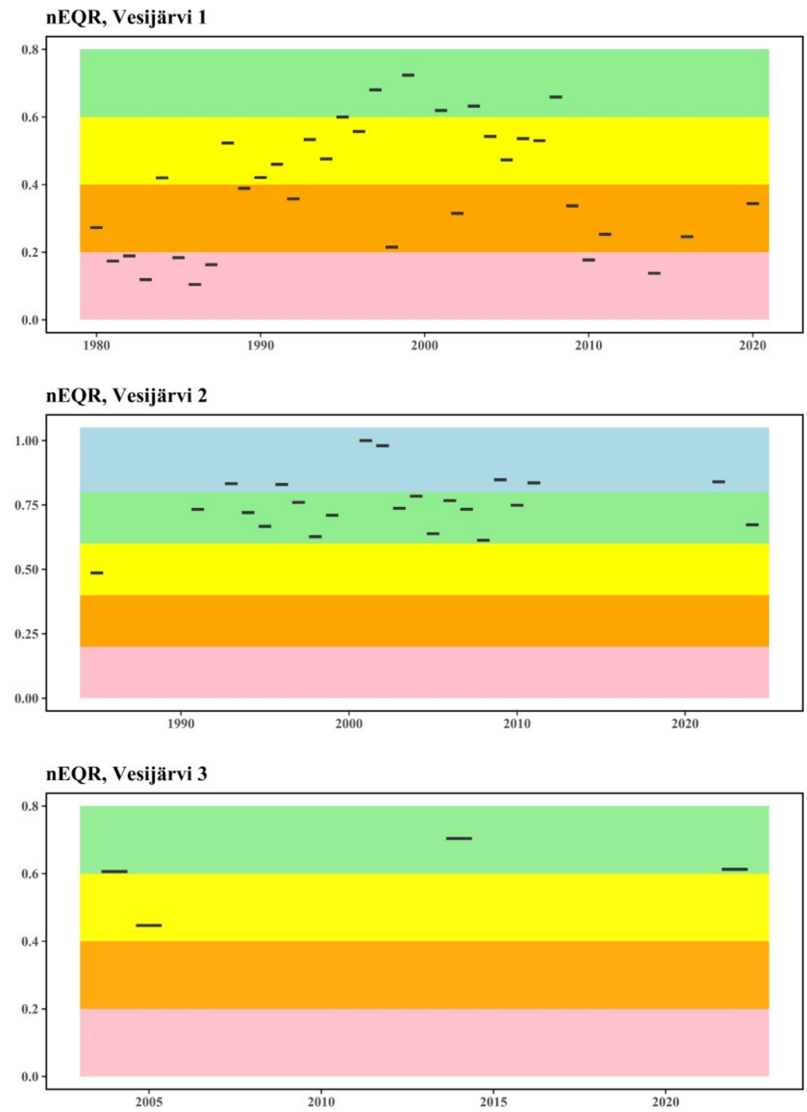

Figure 11. Annual normalised ecological quality ratios (nEQR) of phytoplankton BQE in the three water bodies of L. Vesijärvi since the beginning of monitoring. nEQR's represent the median values calculated from the four normalised lake phytoplankton metrics (Chl a, phytoplankton biomass, proportion of cyanobacteria and TPI). 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 (blue = high; green = good; yellow = moderate; orange = poor; red = bad).

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.

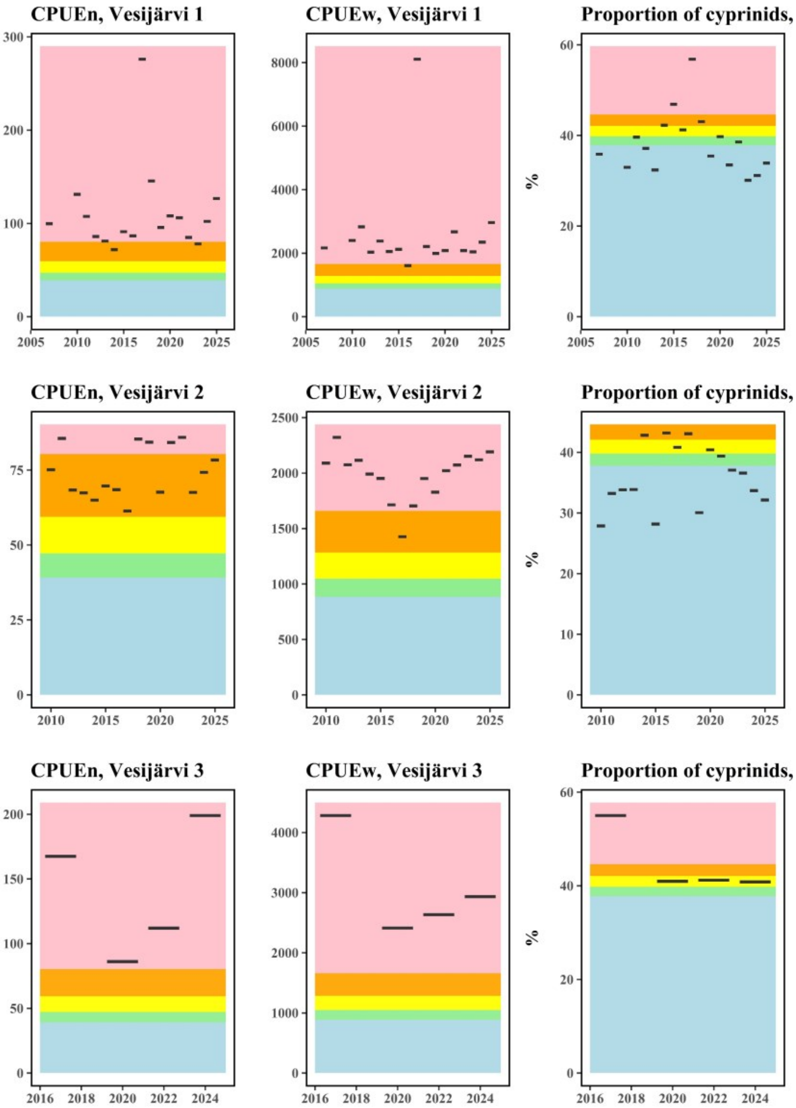

Figure 12. Fish community composition in L. Vesijärvi subbasins based the number of fish per gillnet (CPUEn), biomass (g) of fish per gillnet (CPUEw) and proportion of eutrophication-indicative cyprinids in CPUEw. The colours represent status class boundaries for the respective fish metrics (blue = high; 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 3.1.5). 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.

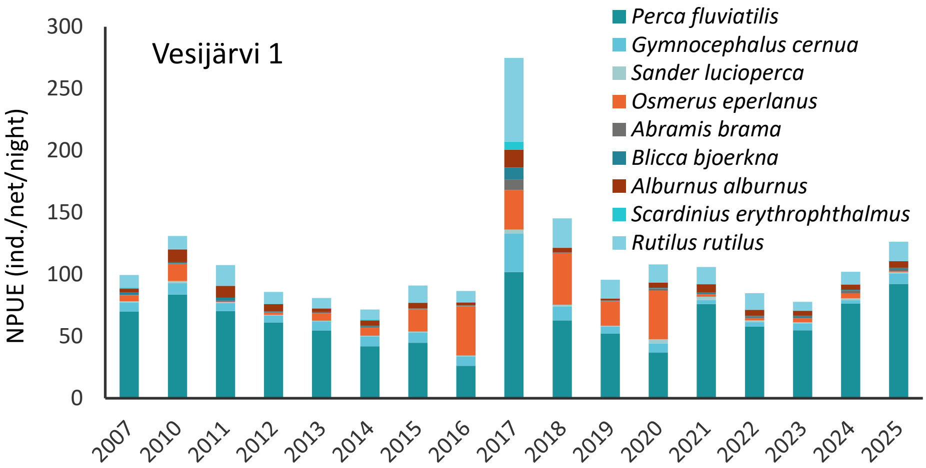

Figure 13. Fish community composition of L Vesijärvi RBMP water body Vesijärvi 1 (Enonselkä, Komonselkä, Paimelanlahti-Vähäselkä basins) based on the number of most abundant fish species per gillnet (NPUE).

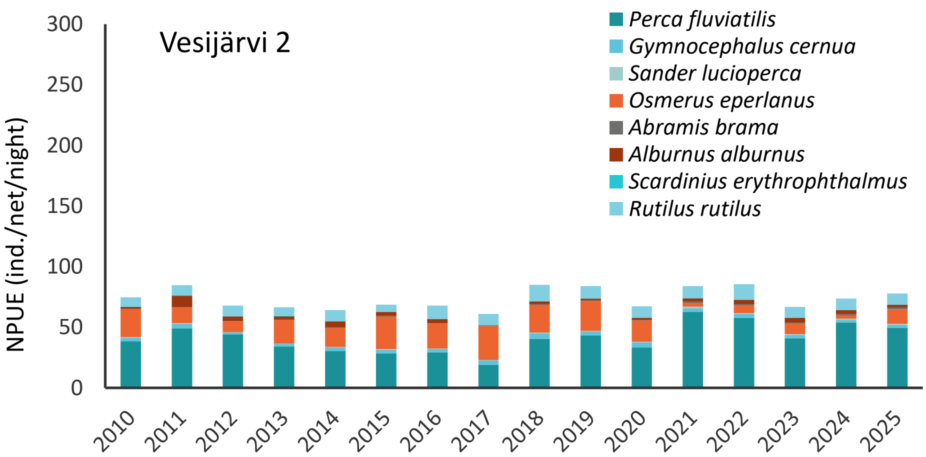

Figure 14. Fish community composition of L. Vesijärvi RBMP water body Vesijärvi 2 (Kajaanselkä basin) based on the number of most abundant fish species per gillnet (NPUE).

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.

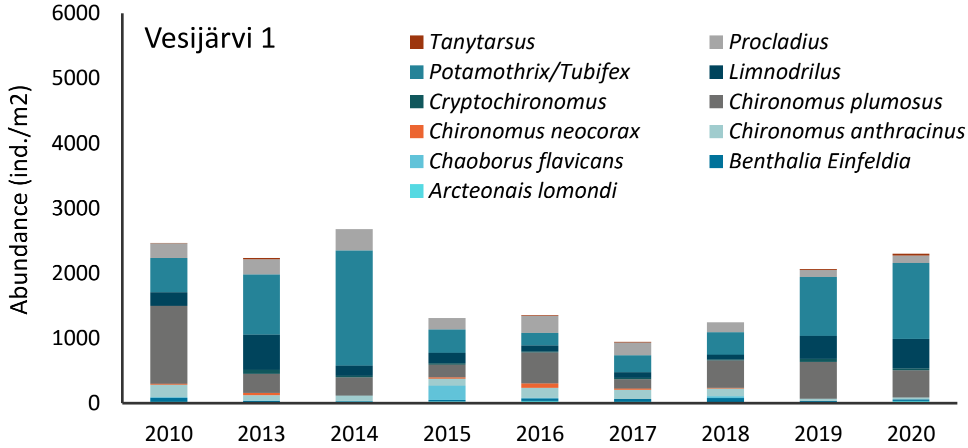

Figure 15. The abundance of selected macroinvertebrate species in 9-32 m depths of L. Vesijärvi Enonselkä basin in between 2010-2020. Only the species that have occurred almost during all the years of sampling are presented. Aeration of Enonselkä both during the winter and summer took place in 2010-2017,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

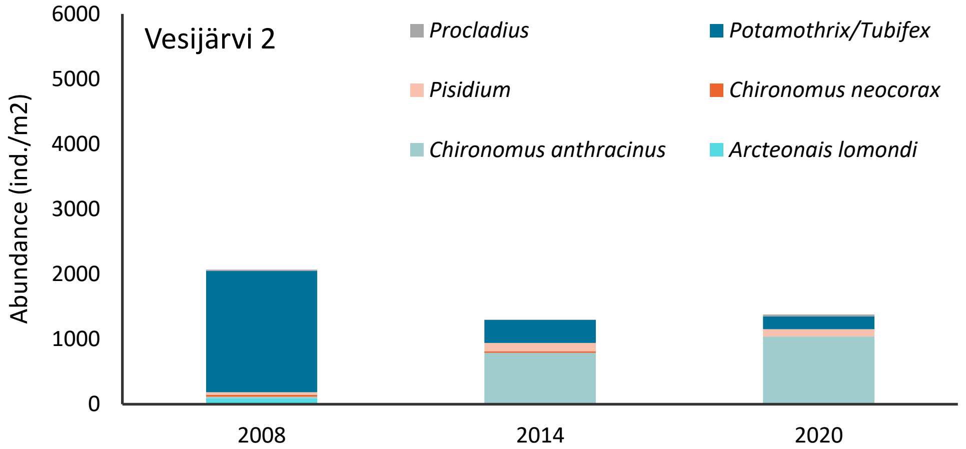

Figure 16. The abundance of selected macroinvertebrate species in 35-37 m depths of L. Vesijärvi Kajaanselkä basin in between 2008-2020. Only the species that have occurred almost during all the years of sampling are presented.

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.

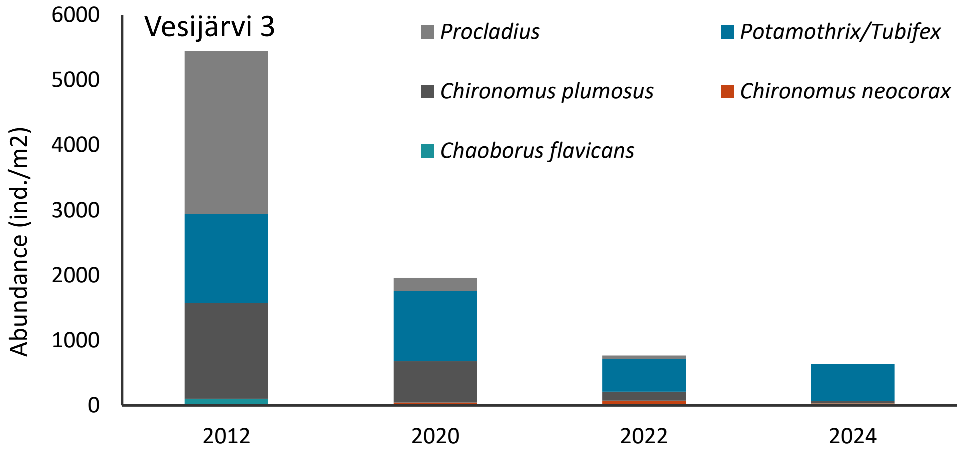

Figure 17. The abundance of selected macroinvertebrate species in 16-18 m depths of L. Vesijärvi Laitialanselkä basin in between 2012-2024. Only the species that have occurred almost during all the years of sampling are presented.

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./m^2, whereas in 2011 it had increased to c. 2900 ind./m^2. In the deepest parts of the basin, the total abundance in 2009 was c. 1500 ind./m^2 and increased to c. 5000 ind./m^2 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.

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). However, zooplankton of the Enonselkä basin (Vesijärvi 1) has been monitored since the 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 18). *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).

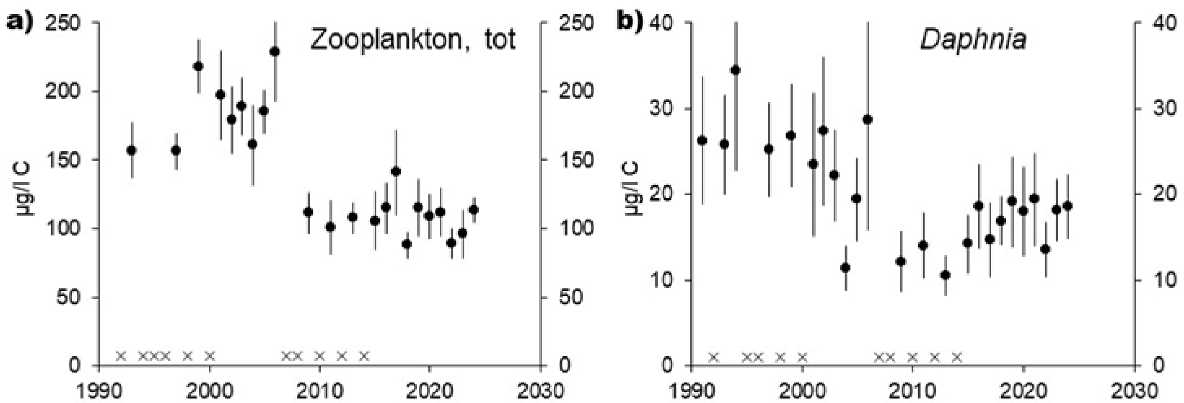

Figure 18. The volume-weighted average (±SE) annual carbon biomass of a) total zooplankton (cladocerans, copepods and rotifers) and b) all Daphnia species in samples collected from Enonselkä basin (Vesijärvi 1) from the depth of 0-30 m between years 1991–2024. The years when samples have not been analysed are marked with an x.

3.2 Biodiversity net gain

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).

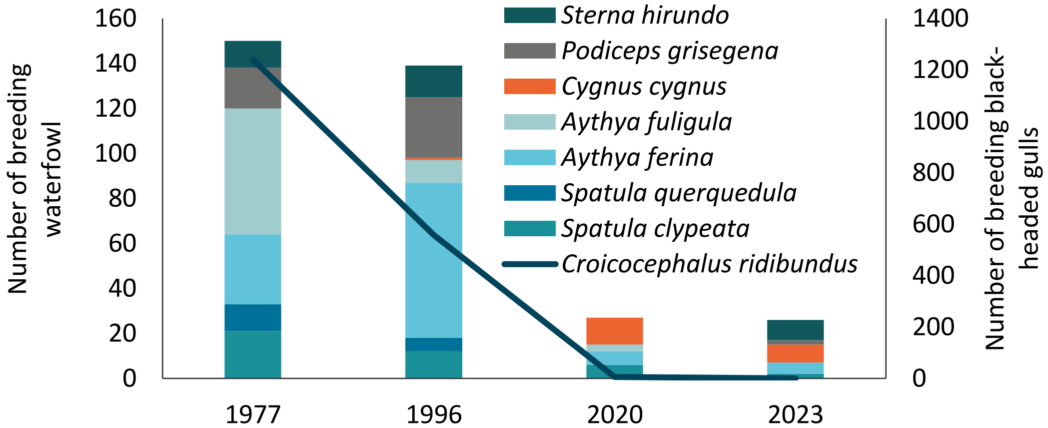

Figure 19. The numbers of selected breeding waterfowl and black-headed gulls (Croicocephalus ridibundus) that are behind the protection of Natura 2000-area FI0306006 ("Kutajärven alue") since the beginning of monitoring in 1977.

3.2.2 HD Annex IV species

The dragonflies in Kutajärvi 2000-area have been mapped in 2007 (Mäkinen 2007). Then 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. 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 Finland (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 Finland, the species is most abundant in the southern and central parts of the country. 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).

3.2.3 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 eutrohication were most severe (Keto et al. 2010). Another species that begun to spread along with increasing eutrophication was *Phragmites australis*. *P. rutilus*, in turn, 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).

3.3 Zero pollution

3.3.1 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 2.3) and changes in agricultural practices (see Section 3.11). 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).

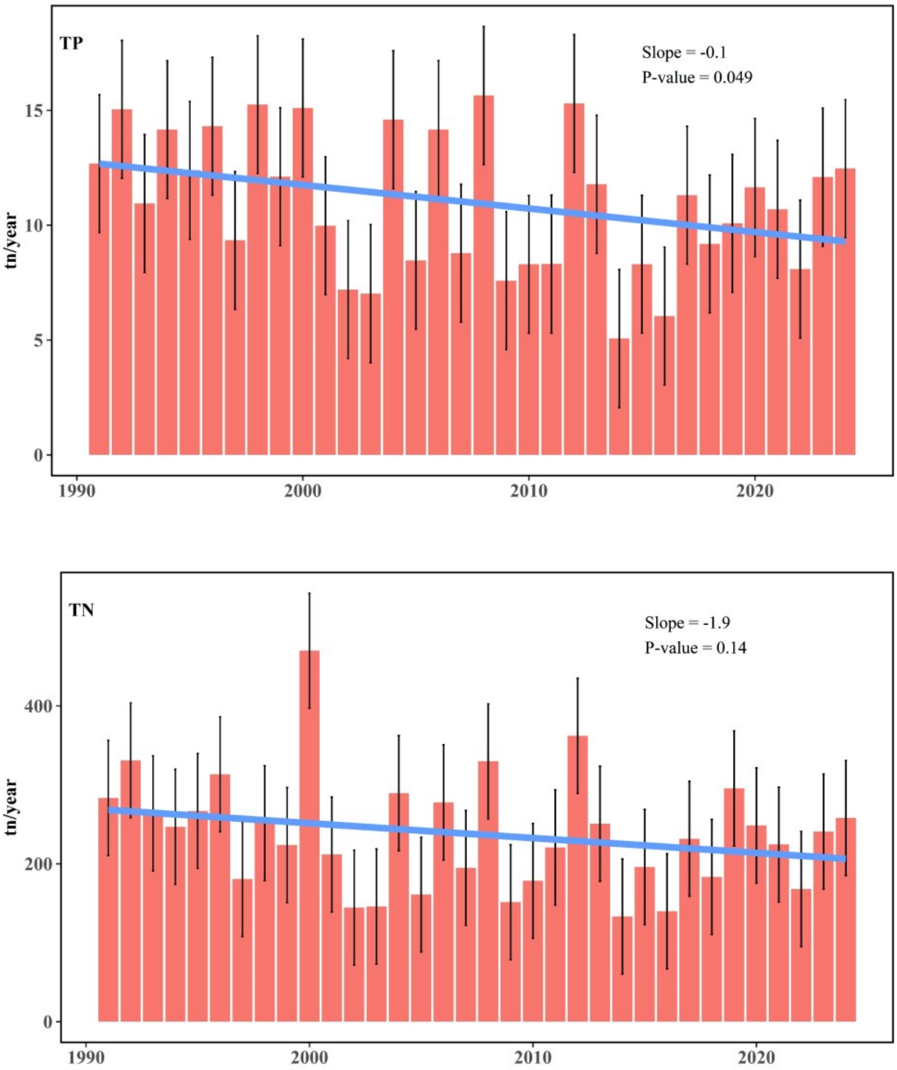

Figure 20. Changes in external TP and TN loading to Lake Vesijärvi from 1991 to 2024 based on the Water quality and nutrient load model system for Finnish watersheds WSFS-Vemala (Huttunen et al. 2016).

3.3.1.1 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 m^3/a in 2021-2024.

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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.

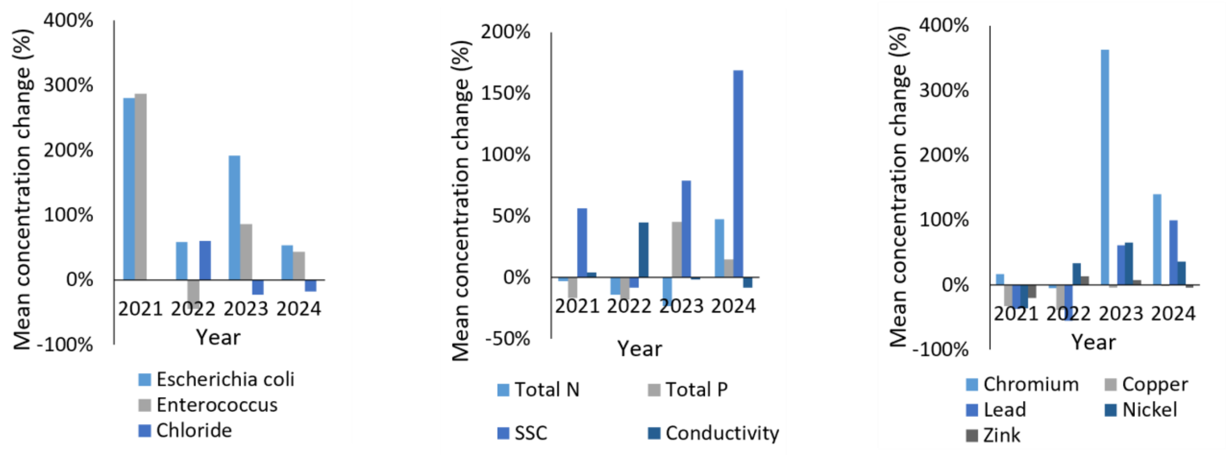

Figure 21. Average concentration changes between the outlet and inlet of the Hennala stormwater treatment system (negative values indicate reductions). Data from the City of Lahti.

3.3.2 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]).

3.4 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 CH_4 emissions are predicted to originate from Vesijärvi 1 that contains the Enonselkä basin that was most subjected to wastewater loading during the 20th century.

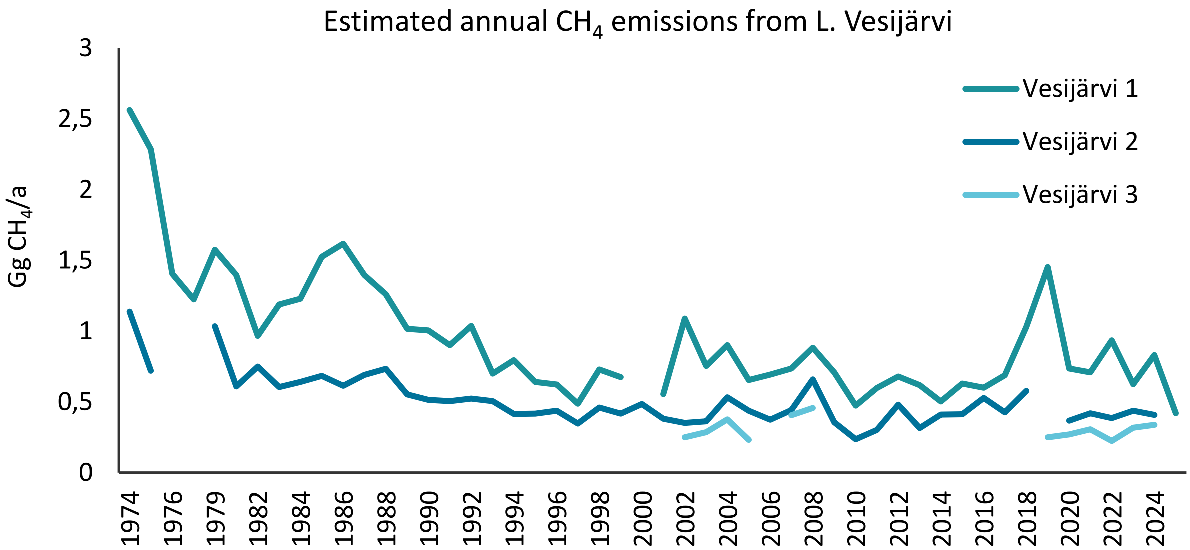

Figure 22. Predicted sum of ebullitive and diffusive methane (CH_4) emissions from the three subbasins of L. Vesijärvi based on average annual growing season (June-August) chlorophyll a concentration. The diffusive and ebullitive methane predictions were made using a Bayesian model constructed from a 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/m^2 and 0.04 mol/m^2, 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

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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/m^2, 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/m^2/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 CH4 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).

3.5 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 2.3) and change in agriculture (Section 3.11) 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 Mm^3. 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 3.3.1).

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 programmes guiding their climate and sustainability work in the upcoming years.

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3.6 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.

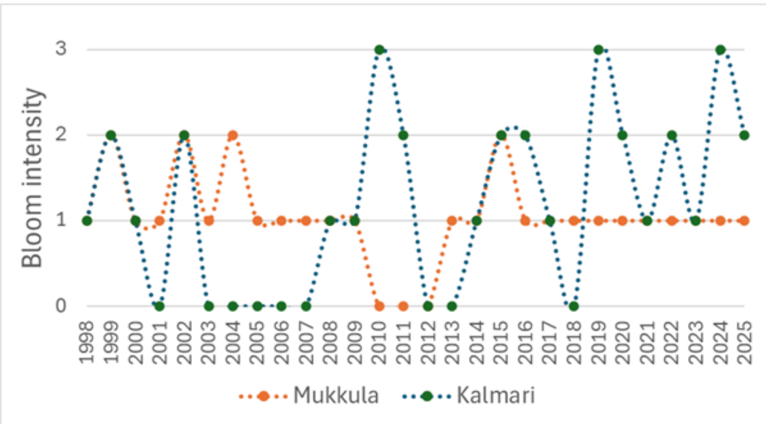

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Figure 23. Annual maximum cyanobacterial bloom intensities on the public beaches of Mukkula (Enonselkä basin) and Kalmari (Kajaanselkä basin). 0 = no cyanobacteria, 1 = some cyanobacteria, 2 = abundant bloom, and 3 = very abundant bloom.

3.7 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.

3.8 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 3.6) 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 3.10, also Section 3.12).

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 3.10).

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]).

3.9 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 3.10). 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).

3.10 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/m^2 (value of 2004) 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 (value of 2020; M€5.5/a converted to the value of 2025) for the Lahti region in the form of purchasing boats and fishing equipment locally (Haro 2020). Commercial biomanipulation (see also Section 3.9) 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.

3.11 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.

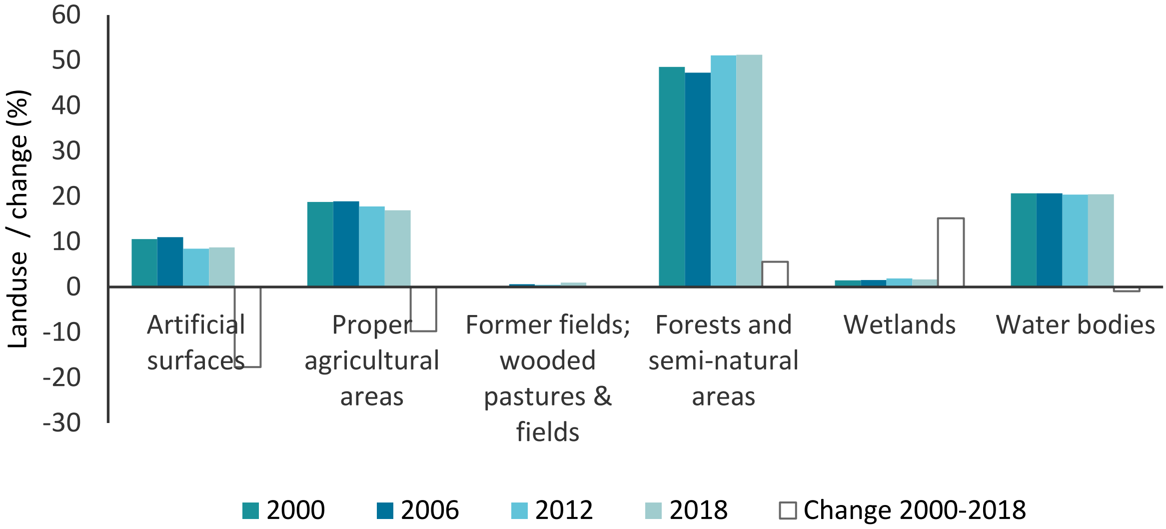

Figure 25. Changes in catchment land use between 2000 and 2018 based on Corine classification. Data from Finnish Environment Institute, Natural Resourses Institute Finland, Finnish Food Authority, LIVI, DVV, EU, MML Maastotietokanta 01/2017).

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.

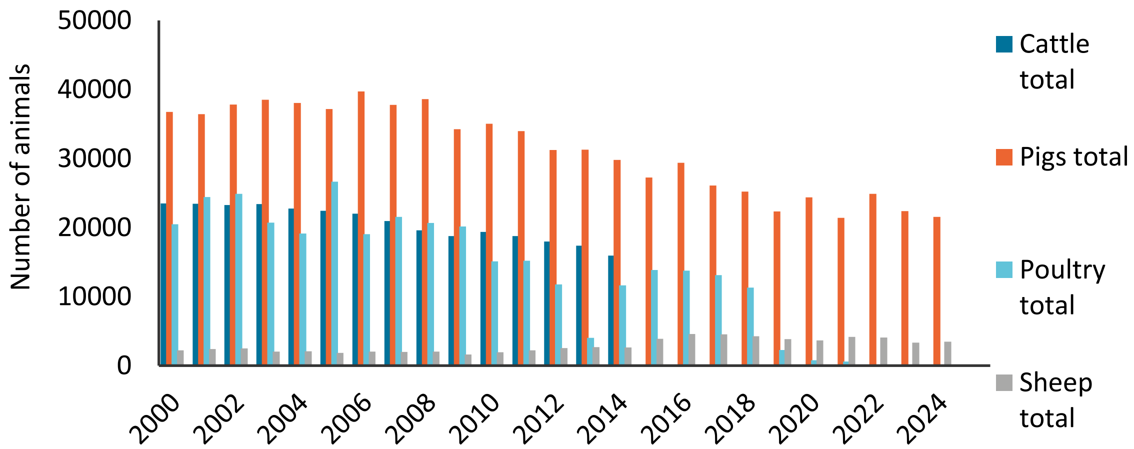

Figure 26. Regional changes in number of livestock. Statistics from Natural Resources Institute Finland.

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 2010-2023 regionally, which are expected to decrease erosion and thus the leaching of particularly particulate P.

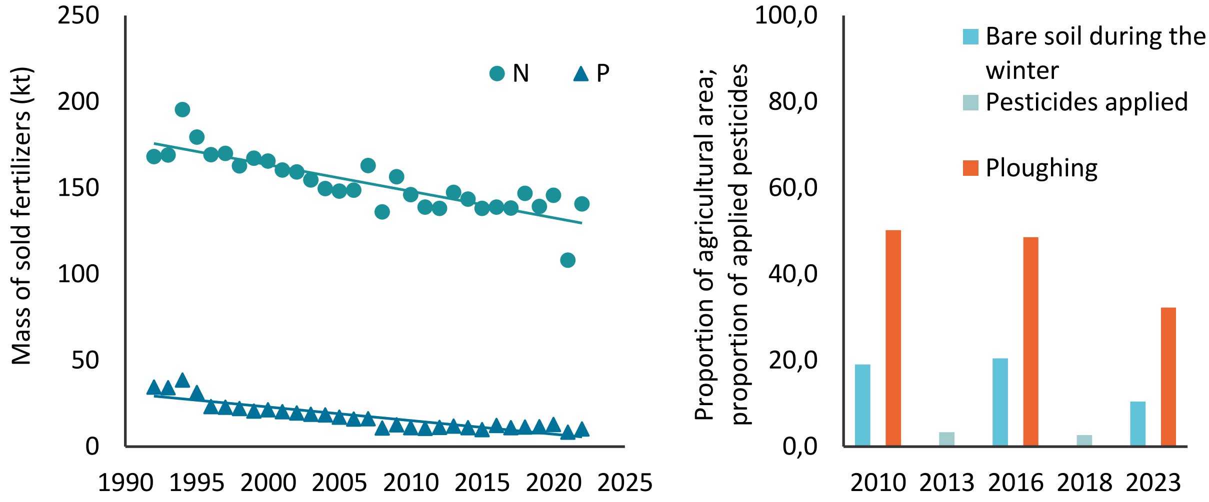

Figure 27. Masses of nitrogen (N) and phosphorus (P) fertilizers sold to farms (national figures), and the proportion of fields with environmentally harmful agricultural practices (bare soil during the winter, ploughing; regional figures) and of applied pesticides (national figures; only available for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

3.12 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.

3.13 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 Mm^3 of cooling and process water was taken from L. Vesijärvi, and 15.2 Mm^3 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 m^3/s. In 2024, maximum discharge was 1.41 m^3/s and the mean discharge 0.48 m^3/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.

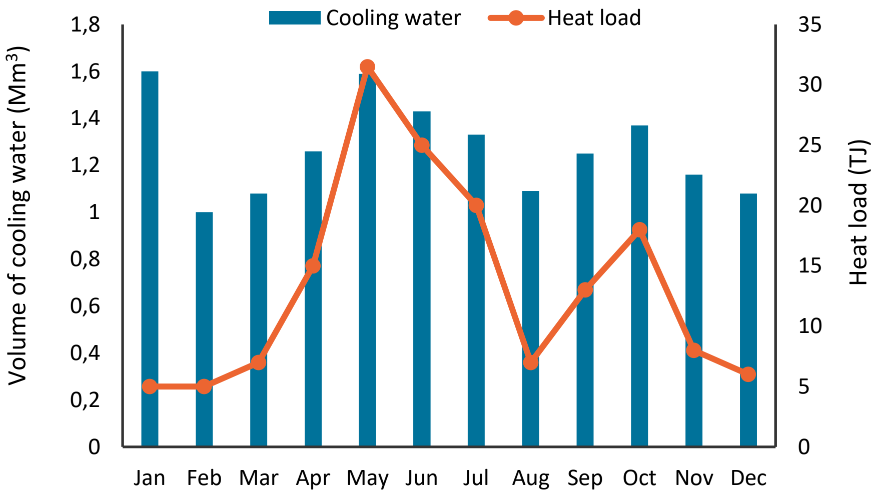

Figure 28. Monthly volume and heat load of cooling water directed to River Joutjoki from Kymijärvi power plants in January-December 2024. Modified from: KVVY Tutkimus Oy (2025).

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	Energy conducted to Vesijärvi	Increase of temperature in Enonselkä basin	Increase of temperature in L. Vesijärvi
	million m^3	TJ	˚C	˚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

3.14 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.

3.15 Water supply & sanitation

3.15.1 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 Mm^3/d of groundwater. In between 2015-2024, the reported groundwater abstraction has been on average 1.0 Mm^3/d with some of the intakes having zero abstraction.

3.15.2 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).

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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.

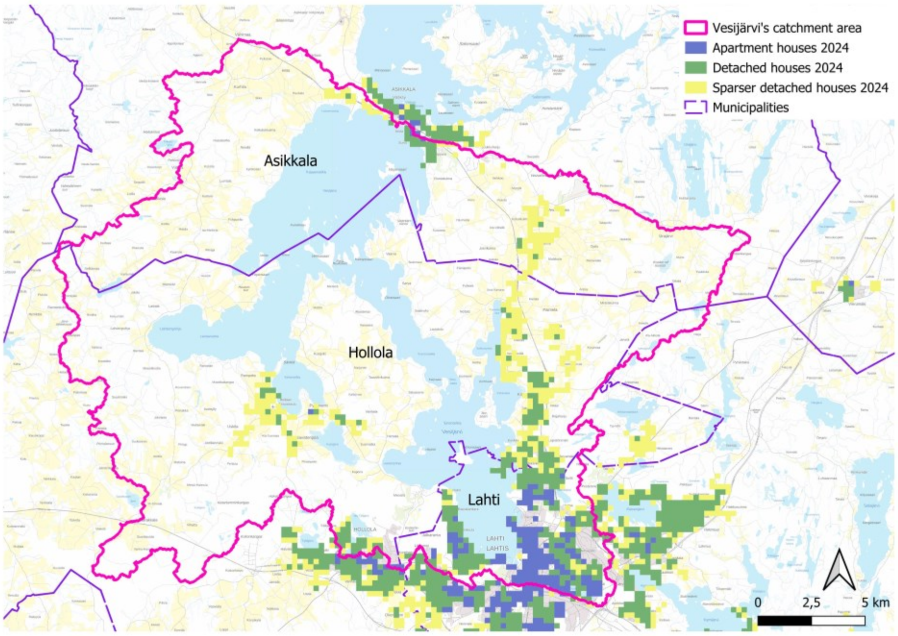

Figure 29. The neighbourhoods of the City of Lahti and the municipalities of Asikkala and Hollola in L. Vesijärvi catchment area during 2024. These areas are mostly within the water supply areas and are presumably connected to the sewage.

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 3.2.3). 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 3.2.1).

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).

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).

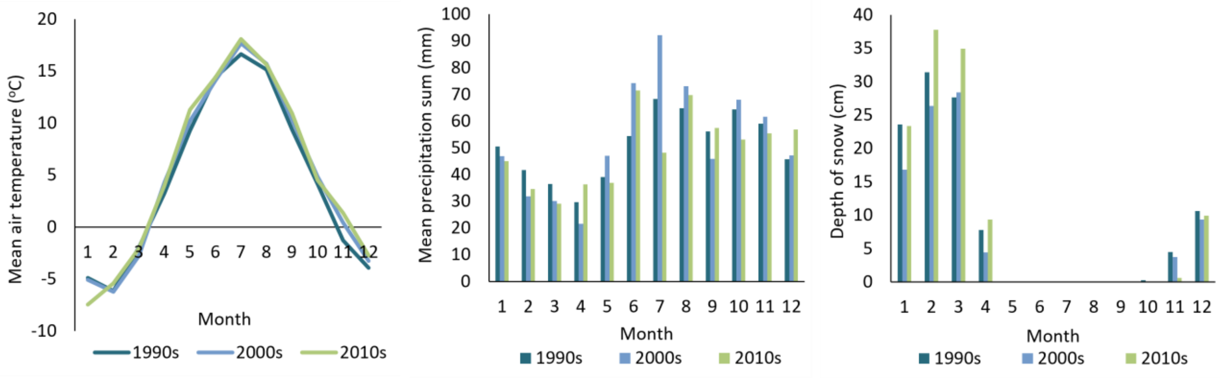

Figure 30. Mean monthly air temperature, precipitation sum and depth of snow in Lahti region (Lahti Laune monitoring station) in 1990-2024. Contains data from the Finnish Meteorological Institute, Licence CC BY 4.0.

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).

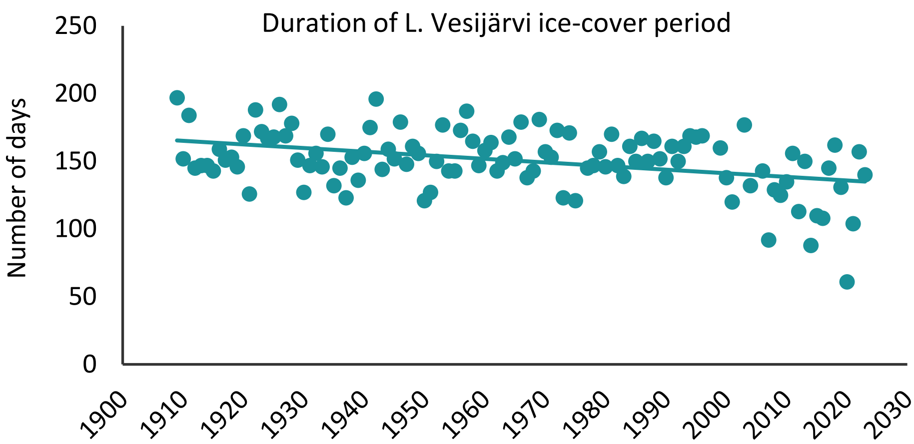

Figure 31. The duration of ice-cover period in L. Vesijärvi Enonselkä basin since the beginning of the 20th century expressed as days between the formation and disappearance of permanent ice cover in the horizon.

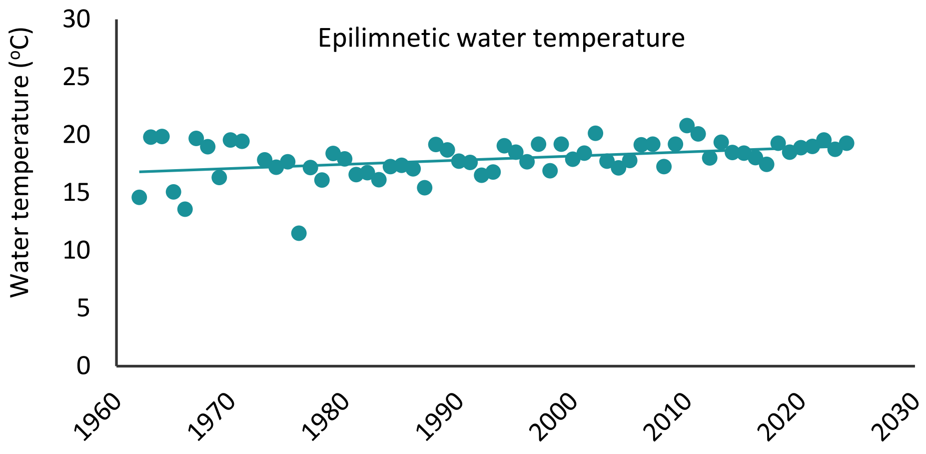

Figure 32. Mean epilimnetic (0-4 m) water temperature during the growing season (June-September) in L. Vesijärvi since the beginning of 1960s.

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. The durability 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 programmes over decades; and widespread local awareness of the social and economic benefits of restoration.

6 Acknowledgements

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

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