

Pumping of epilimnetic water into hypolimnion improves oxygen but not necessarily nutrient conditions in a lake recovering from eutrophication

Pauliina Salmi,^{1,3*} Ismo Malin,² and Kalevi Salonen^{1,3}

¹ Lammi Biological Station, University of Helsinki, Lammi, Finland

² Lahti Region Environmental Services, Lahti, Finland

³ Department of Biological and Environmental Science, University of Jyväskylä, Jyväskylä, Finland

* Corresponding author: pauliina.u.m.salmi@jyu.fi

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Abstract

To mitigate deep water oxygen depletion and its consequences, epilimnetic water was pumped into deep water of a eutrophic, 26 km² subbasin of Lake Vesijärvi, Finland. In winter, the mechanical mixing largely eliminated vertical differences in temperature, oxygen, and nutrients. Although ice cover prevented oxygen flux from the atmosphere, the high proportion of shallows in the basin with high oxygen concentration facilitated the avoidance of hypoxia by mixing. Despite the disappearance of anoxia in deep water, the volume-weighted mean concentrations of nutrients were not affected. In summer, the introduction of epilimnetic water into the hypolimnion improved oxygen conditions, but anoxia or hypoxia continued to develop. This condition favored the coexistence of nitrification and denitrification and, similar to winter, more than halved total and ammonium-nitrogen (NH₄-N) concentrations in deep water. Despite the presence of nitrate or low concentration of oxygen, phosphorus concentrations continued to be high, and therefore deep water anoxia cannot have been the primary driver maintaining the basin in its eutrophic state. Consequently, in the management of Lake Vesijärvi, a major emphasis should be on external nutrient load and the leakage of nutrients from shallow sediments. A longer time series and attention to biological parameters is needed to determine the final outcome of pumping epilimnetic water into the hypolimnion.

Key words: eutrophic lake, mixing, nutrients, oxygen, temperature

Introduction

Eutrophication in lakes is a common problem connected to anthropogenic activities. High productivity increases sedimentation of organic matter, which can lead to oxygen depletion in deep water. Einsele (1936) and Mortimer (1941) suggested that after the development of anoxia, phosphate is released from sediment by the reduction of an iron–phosphate complex. Phosphate may then accumulate in the deepest water and eventually arrive in the euphotic zone to fuel primary production. Since the formulation of the iron–phosphorus coupling hypothesis, however, evidence has accumulated for alternative or parallel mechanisms of phosphorus (P) release from the

sediment (Golterman 2001, Hupfer and Lewandowski 2008), which should also be considered when interpreting lake P dynamics.

Various techniques have been applied to avoid hypolimnetic oxygen depletion and to accelerate the recovery of lakes from eutrophication (Beutel and Horne 1999, Singleton and Little 2006). Because each lake is unique, however, experiences have been variable (Singleton and Little 2006, Hupfer and Lewandowski 2008, Liboriussen et al. 2009). Due to the short time span and lack of replications, the results of most studies also often suffer from stochastic interannual variations that may override the effects of management efforts. Thus, the interpretation of results is not straightforward.

Management based on simple mechanical mixing, in which oxic epilimnetic water is pumped into deeper water layers, has been attempted in a number of lakes (e.g., Sandman et al. 1990, Matinvesi 1996, Singleton and Little 2006). Compared to many aeration and particularly oxygenation methods, pumping more profoundly affects the stratification of the water column (Singleton and Little 2006). Hence, the associated increase in hypolimnetic temperature from pumping may limit or destroy the habitat of cold-water fish (Beutel and Horne 1999) and enhance respiration, which may counteract the positive effects of mixing.

Mechanical mixing by pumping in winter has been tested in the eutrophic southern basin of Lake Vesijärvi, Southern Finland, but because improved oxygen conditions (Keto 1982) were followed by massive cyanobacteria blooms in summer (Keto and Tallberg 2000), the mixing was discontinued. Cyanobacteria in the less eutrophic and rather isolated (Fig. 1) northern basin of Lake Vesijärvi increased at the same time without any management efforts (Keto and Tallberg 2000); therefore, more regional factors than the mixing at one deep site of another basin was likely involved. Because mechanical mixing was not considered too risky, further experiments were started by local authorities and a foundation committed to long-term operations to improve water quality of the lake.

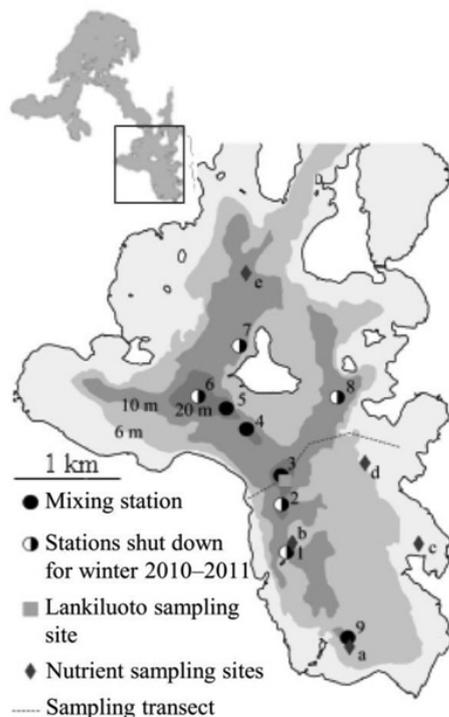


Fig. 1. The Enonselkä basin of Lake Vesijärvi with locations of sampling sites and mixing stations. Sampling depths for nutrient sampling sites were (a) 1, 10, and 12.5–14 m; (b) 0, 10, and 22 m; (c–d) 1 and 3–4 m; and (e) 1, 10, and 17 m.

In this study, we investigated the effects of large-scale mechanical mixing in 2010–2013 in the eutrophic southern basin of Vesijärvi. The mixing approach was originally meant to immediately improve water quality, first by eliminating harmful cyanobacteria blooms. We hypothesized that improvement of deep water oxygen conditions by mixing, both in winter and in summer, would reduce the release of P from the sediment and, consequently, reduce problems with frequent algal blooms.

Materials and methods

Lake Vesijärvi is located in Southern Finland between 2 glaciofluvial eskers (the Salpausselkä ridges), and its basic limnological characteristics are impacted by groundwater seepage. The lake's southern Enonselkä basin (area 26 km², volume 176 × 10⁶ m³, mean depth 6.8 m, maximum depth 33 m, and relative depth 0.57% [$Z_r = 50 \cdot \max. \text{depth} \cdot \sqrt{(\pi / \text{area})}$]; Fig. 1) is connected to the rest of Vesijärvi by rather narrow straits that prevent significant upstream exchange of water with the other basins. For decades, Enonselkä was heavily loaded with untreated sewage waters from the city of Lahti. After the sewage diversion in 1976, water quality improved (Keto 1982), and thereafter various management attempts were implemented to strengthen the recovery of the lake. In addition to the reduction of external load, since 1989 Vesijärvi has been manipulated by removal of cyprinid fish (Keto and Sammalkorpi 1988, Kairesalo et al. 1999). To increase zooplankton grazing on phytoplankton, during 2000–2012 (2007–2008 data missing) 38–94 tons of fish (equivalent to ~0.23–0.57 tons of P), mainly cyprinids, were annually removed from the Enonselkä basin. Nevertheless, the deepest water has often been depleted of oxygen, and algal blooms have persisted.

In November 2009, an extensive attempt was initiated to relieve the oxygen deficit during ice cover and summer stratification periods. Pumping of oxygen-rich surface water into deep water was deemed the most cost-effective strategy, and it was implemented using 8 Mixox MC-1100 mixing stations (2.5 kW) and one Mixox MC-750 station (1.5 kW; Water-Eco Ltd, Kuopio, Finland) located at the deepest sites of the Enonselkä basin (Fig. 1). Water from about 3 m depth was pumped down through a 1 m diameter canvas tube at a speed of about 1 m s⁻¹ (Fig. 2). The functional principles have been explained in more detail by Lappalainen (1994) and Bendtsen et al. (2013). To limit re-suspension of the sediment, the lower ends of the tubes were 8–10 m above the bottom. The stations were generally operated continuously, excluding spring and autumn overturn periods and short operational malfunctions. In winter 2010/2011 only 4 stations were powered (Fig. 1). In summer 2013, mixing stations were activated on 12 July, which was 36–39 days later than in other mixing summers.

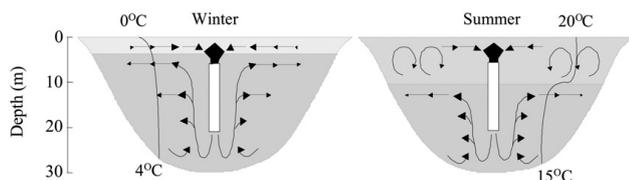


Fig. 2. Flow patterns created by the mixing stations in winter and summer visualized according to temperature and oxygen results of this study. Vertical curves illustrate distributions of temperature with approximately representative values at the surface and at the bottom. Vertical positions of the pumps (3 m depth) and the bottom of the tubes (8–10 m above the bottom) are in scale.

Vertical profiles of dissolved oxygen, nutrient, and iron concentrations were determined in the laboratory from samples collected with a Limnos tube sampler (with inside thermometer) at the 31 m deep site off Lankiluoto islet (Fig. 1), located ~50 m from the mixing station. During ice cover, samples were collected once in January–February and once in March–April. In June–August, samples were collected at roughly monthly intervals. In March–April and in August, samples were also collected from 5 other sampling stations (Fig. 1a–e) for total phosphorus (TP) and total nitrogen (TN). Volume-weighted TP and TN concentrations for the Enonselkä basin were calculated from the depth-integrated product of the mean concentrations in 2.5, 3.5, or 5 m thick water layers and their respective volumes (assuming geometric form of a frustum). Oxygen concentrations were determined by Winkler titration, and nutrient concentrations were determined spectrophotometrically using molybdate-antimony for TP and phosphate-phosphorus ($\text{PO}_4\text{-P}$), peroxydisulfate or peroxydisulfate-sulfanilamide-aromatic amine for TN, and hypochlorite-phenol for ammonium-nitrogen ($\text{NH}_4\text{-N}$) methods. Nitrate-nitrogen ($\text{NO}_3\text{-N}$) was determined by ion chromatography with conductivity detection. Iron (Fe) concentration was determined by mass spectrophotometry. Epilimnetic pH at the Lankiluoto sampling site was measured from samples taken from 1 m depth with laboratory meters in January–February, March–April, and at 1–5 week intervals during May–August. Chlorophyll *a* (Chl-*a*) concentration was determined spectrophotometrically using 75 °C ethanol extraction at 1–5 week intervals during May–August 2000–2012 from integrated samples taken from 0–6 m depth, which was twice the measured Secchi depth. Absorptions were measured at 665 and 750 nm wavelengths by a spectrophotometer, and Chl-*a* concentration was calculated using an absorption coefficient of 119.

In winter, when oxygen was present throughout the water column, oxygen consumption was calculated from the volume-weighted decrease in oxygen from baseline concentrations measured in January and March at the Lankiluoto sampling site. In summer, oxygen consumption was calculated as described above, but only for the

hypolimnion (depths of 12.5–31 m) and June–July data when some oxygen remained, and extrapolated until the end of August by assuming Q_{10} of 2.7 (Bergström et al. 2010). A conservative estimate of the amount of oxygen pumped into the deep water was made by multiplying pumped water volume by the difference between oxygen concentrations at the inlet depth of the pumps and those at the upper part (12.5–17.5 m) of the hypolimnion. We assumed that water pumped into the hypolimnion spread evenly on a horizontal plane.

Since summer 2008 (excluding summer 2009), more detailed temperature observations have been made at the Lankiluoto sampling site every half hour using temperature recorders (Star-Oddi, Iceland, accuracy ± 0.05 °C) attached to a rope at 2 m depth intervals. Water column Schmidt-Idso stabilities (Idso 1973) were calculated from the results of the temperature recorders as:

$$S = \frac{g}{A_0} \int_0^{Z_{\max}} A(z_g - z)(\rho_1 - \rho) dz, \quad (1)$$

where A_0 = lake surface area, A (e.g., km^2) = lake area at depth z (m), ρ (kg m^{-3}) = water density, ρ_1 (kg m^{-3}) = water density when completely mixed, g = gravitational acceleration ($9.81 \text{ kg m}^{-1} \text{ s}^{-2}$), and z_g (m) = the depth of the geometric center of gravity of the lake. Heat contents (Θ ; Johnson et al. 1978) were calculated as:

$$\Theta = \frac{1}{A_0} \int_0^{Z_{\max}} c_p A T dz, \quad (2)$$

where A_0 = lake surface area, c ($\text{J g}^{-1} \text{ °C}^{-1}$) = the specific heat capacity of water, ρ (kg m^{-3}) = density of the water layer, A (e.g., km^2) = lake area at depth z (m), and T = temperature (°C).

Oxygen samples for titration were collected from the Lankiluoto site at 5 m depth intervals. In winters 2010–2012, additional profiles of dissolved oxygen were measured as a transect across the basin (Fig. 1) with an optical sensor (ProODO, Yellow Springs Instruments, USA, accuracy $\pm 0.1 \text{ g m}^{-3}$ or $\pm 1\%$ of the reading) calibrated by Winkler titration. Snow depth and ice thickness were measured with a scaled rod. In summers 2008–2013, temperature and oxygen concentrations were also measured hourly at a measurement float with Marvet sensors (Elke Sensor LLC, Estonia, accuracy 0.1 °C and $0.1 \text{ g m}^{-3} \text{ O}_2$) installed at 10, 20, and 30 m depths.

To minimize the effects of possible directional trends in the time series due to climate change (IPCC 2007) or the reduction of nutrient load in the 1970s (Keto and Tallberg 2000), only the last 10 years before the mixing experiment were used as reference. Confidence limits for the medians of the results of the reference years are given according to tables by Van der Parren (1970). Statistical analyses were conducted with SPSS Statistics version 21 (IBM, USA).

Results

To evaluate the effects of mechanical mixing, we present the results of profoundly different seasons: winter and summer. We took advantage of this contrast, in combination with a mechanical mixing experiment, to evaluate the role of anoxia in the release of nutrients from the sediment.

Winter

During winter of the reference years 2000–2009, deep water temperature under the ice of the Enonselkä basin increased at 29 m with increasing duration of ice cover ($r^2 = 0.68$, data not shown). In winter 2008/2009 without mixing, this increase was high, 3.7 °C at 30 m between freezing in December and sampling in March. Compared to the reference years, mechanical mixing in the following years kept temperature in the deepest water ~ 1 °C cooler (Fig. 3), and although the number of observations was too low for statistical testing, the slope of the regression with ice duration seemed similar to the reference years. Mixing largely disrupted the vertical temperature gradient below the depth of the mixing pumps, and the temperature gradient (0.4–0.7 °C) between 5 and 29–30 m depths was greatly reduced compared to the reference years (1.3–2.2 °C). The ascending return flow of pumped water from the deepest layers, however, stayed below 3–5 m depth (Fig. 3), and the thermal stabilities were similar to reference winter 2009 (Table 1). In the period between lake freezing and the end of March, heat content increased 24–32 MJ m⁻²; thus, mixing probably did not enhance heat loss to ice but rather enhanced heat gain from the sediment. Vertical distributions of temperature, minimal differences in ice thickness over the Enonselkä basin, no detectable delay in freezing, and negligible advance in melting above the pumps beyond a few meters distance also indicated that mixing did not markedly affect the ice cover in the neighborhood of the mixing station.

In late winter of the reference years, Enonselkä frequently suffered from oxygen depletion in the deepest water (Fig. 4), but interannual variation was high due to variable water temperature and duration of ice cover. In the mixing winters, deep water oxygen concentration remained high, mainly due to the dilution effect by mixing; there may also have been a decreasing trend in oxygen consumption of the whole water column (Fig. 5). Because oxygen concentration is more sensitive than temperature for indicating horizontal spread of water from the neighborhood of the mixing stations, even distributions at each depth over the basin (Fig. 6) suggest that the results obtained at ~ 50 m distance from the mixing station satisfactorily represented the whole basin. Horizontal

mixing, however, was limited only to depths shallower than the shoulders between the isolated deep sites; thus, in winter 2010/2011, anoxic conditions developed in sites where the mixing stations were not powered.

At 1 m depth, the concentrations of TP and PO₄-P were similar in March–April, both in the reference and mixing years (Fig. 3). In the deepest water in the reference years, oxygen depletion was regularly accompanied by up to 2 orders of magnitude higher, but interannually variable, concentrations of TP and PO₄-P (Fig. 3 and 4). Mixing reduced vertical differences, and deep water concentrations were 50–80% of the median and much lower than the highest concentrations of the reference years. Fe possibly also decreased, but it was at the lower range of the reference years. TN behaved similarly to TP. NH₄-N, which was abundant only in deep water of the reference years, was dramatically decreased by mixing. In contrast, the concentrations of NO₃-N roughly doubled in relation to the median value (Fig. 3 and 4). The concentrations of TP and TN at different depths of the water column remained relatively stable during January–March, both in the reference and mixing winters (Fig. 7). At 29 m the variation of the results was higher than at shallower

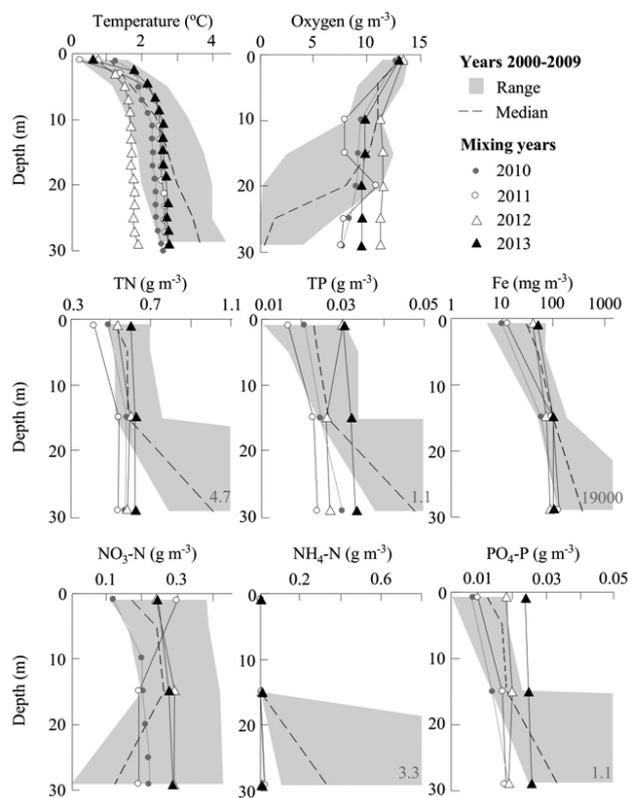


Fig. 3. Vertical distributions of temperature, dissolved oxygen, and nutrient as well as iron concentrations during March–April of the reference and mixing winters. In the graphs of NO₃-N and NH₄-N, the y-axis begins at the detection limit of 0.01 g m⁻³, and in the PO₄-P graph at 0.002 g m⁻³.

depths, probably due to differences in the distance from the bottom following variation in the precise location of sampling around the deepest point. The small contribution of deep water to the total volume of the basin, however, led to no differences in volume-weighted TP and TN concentrations in March between the reference and mixing years (Fig. 8).

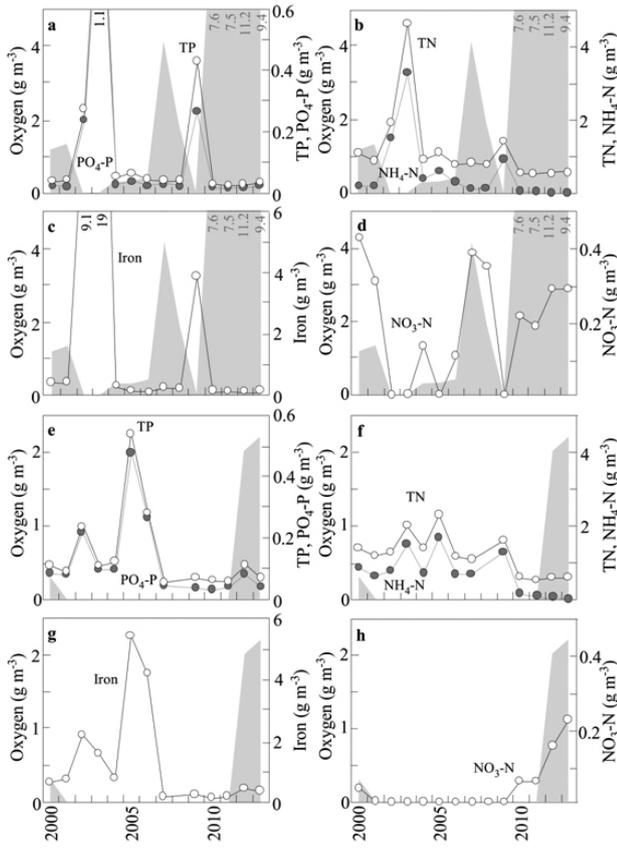


Fig. 4. Deep water (29 m) concentrations of dissolved oxygen, nutrients, and iron during (a–d) March–April and (e–h) August of the reference and mixing years. In the graphs of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$, the y-axes begin at the detection limit of 0.01 g m^{-3} . Grey area represents oxygen concentration. Results from August 2008 were excluded due to early beginning of autumn convection.

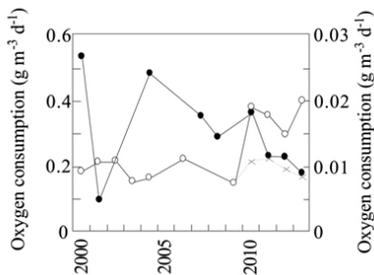


Fig. 5. Oxygen consumption in January–March in the whole water column (dots, right scale) and in June–August in the 12.5–31 m hypolimnion (circles, left scale). The crosses show results where oxygen pumped into deep water have not been taken into account.

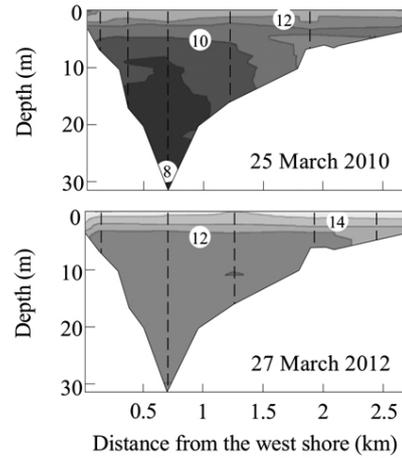


Fig. 6. The extremes of horizontal distributions of dissolved oxygen concentration in March of the mixing winters 2010–2012 through a sampling transect shown in Fig. 1.

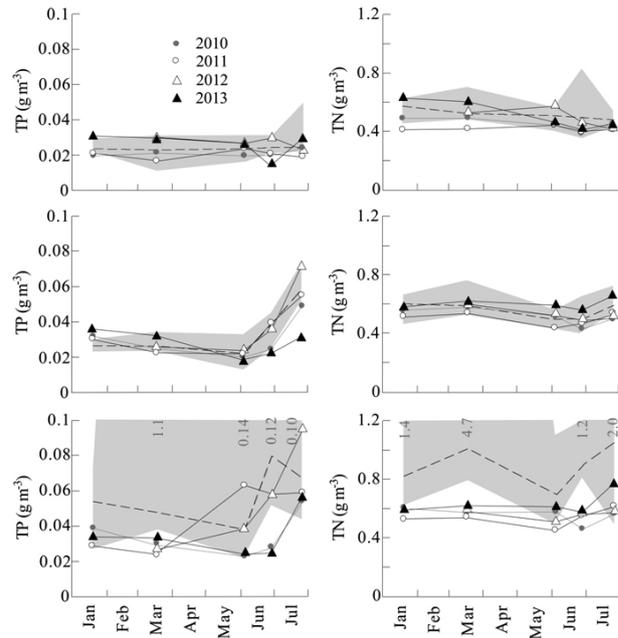


Fig. 7. Seasonal development of the concentrations of TP and TN at 1 m (upper panels), 15 m (middle panels), and 29 m (lower panels). Grey area = range 2000–2009; dashed line = median 2000–2009.

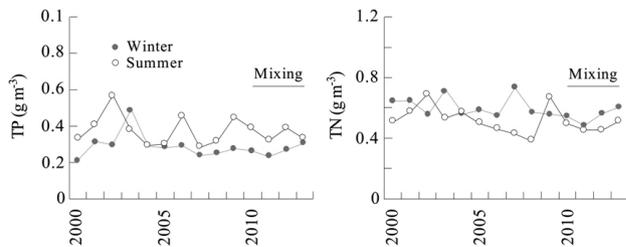


Fig. 8. Volume-weighted TP (left panel) and TN (right panel) in winter (Mar–Apr) and summer (Aug) calculated for the whole Enonselkä basin.

Table 1. Maximum stabilities and heat contents of the water column at 12:00 h in winter and summer in the reference (2008-2009) and mixing (2010-2013) years.

	Year	Stability (J m ⁻²)	Heat content (MJ m ⁻²)
Freezing - March	2009	8	37
	2010	6	54
	2011	10	47
	2012	5	46
	2013	9	56
June - August	2008	94	559
	2010	212	627
	2011	203	608
	2012	103	562
	2013	226	530

Summer

In August of the reference years, the depth of the epilimnion was generally ~10 m, and below the metalimnion, temperature slowly decreased to 10.8–13.4 °C at 29 m (Fig. 9). Detailed temperature recorder data from July–August 2008 showed little fluctuation or increase of deep water temperatures (Fig. 10), which suggests stable stratification. Mixing in the summers 2010–2012 elevated the deepest water temperature to 17–17.5 °C, and the temperature difference between the 5–6.4 m and 29–30 m depths in August was only 0.9–3.9 °C compared to 4.5–9.9 °C in the reference summers. In summer 2013, when mixing began 36–39 days later than in the other years, deep water temperature remained closer to the reference years, and the temperature difference between 5 and 30 m was 6.2 °C (Fig. 9). Mixing led to a sharp metalimnion (Fig. 9 and 10), which moved upward during the summer stratification; thus, warm epilimnetic water pumped into the hypolimnion was mixed so effectively with cooler deep water that the ascending return flow stopped in the metalimnion 4–8 m below the depth of the pumps. Consequently, the volume of deep water affected by mechanical mixing was much smaller than in winter.

Although mixing theoretically decreases thermal stability of the water column, it was masked by interannual variation in weather conditions. In the mixing summers 2010 and 2011, air temperature (Finnish Meteorological Institute, data not shown), and thus the surface water, were unusually warm and explain the higher thermal stabilities compared to summer 2008 without mixing (Table 1); however, heat contents of water in summers 2010 and 2011 were only slightly higher. The higher stability in 2013 than in the other mixing summers may be explained by the late start of mixing.

In August of the reference summers, anoxia regularly occurred below 10–20 m (Fig. 4 and 9). Only in 2000 was a low concentration of oxygen (0.3 g m⁻³) found at 29 m. The results of the oxygen sensor installed at 30 m depth showed that, compared to summer 2009, mixing reduced the duration of anoxia from 97 days to 35, 60, and 10 days in 2010, 2011, and 2012, respectively, and to about 1 day in 2013; however, mixing generated hypoxic conditions in a much larger water volume, especially in summers 2010 and 2011 compared to previous years (Fig. 9). In the reference summers, the volume-weighted median oxygen consumption in the 12.5–31 m depth layer in June–August was 0.18 g m⁻³ d⁻¹ (95% confidence limits 0.15–0.22 g m⁻³ d⁻¹; Fig. 5), while in the mixing summers, when the pumped water was taken into account, it was almost twice as high (range 0.30–0.40 g m⁻³ d⁻¹). Due to totally different stratifications in winter and summer, their oxygen consumptions in the reference years could be compared only at 29 m depth. The median oxygen consumption rate was 0.28 g m⁻³ d⁻¹ (range 0.03–0.45 g m⁻³ d⁻¹) in summer, which is one order of magnitude higher than in winter, 0.06 g m⁻³ d⁻¹ (range 0.0–0.14 g m⁻³ d⁻¹).

In the mixing summers, TP and PO₄-P at 29 m were 51–100% and 32–87%, respectively, of the reference years' median (Fig. 4 and 9). In contrast to winter, no significant relationship between anoxia and TP or PO₄-P in the hypolimnion could be found, but respective relationships of Fe with TP or PO₄-P were obvious (Fig. 4). When the mixing years were excluded, there was no linear correlation ($r^2 = 0.1$) between TP concentration and oxygen consumption at 29 m in June–August (Fig. 5). Mixing reduced concentration of TN in deep water, and at 29 m it was only about 50% of the minimum of the reference summers. Mixing even more strikingly reduced NH₄-N, so that its concentration in the deepest water decreased from up to 0.17 g m⁻³ to below detection. At the same time, mixing increased NO₃-N concentration at 29 m depth, from undetectable concentrations to 0.07–0.23 g m⁻³ (Fig. 4).

During summer in the reference years, TP concentration at 1 m depth was stable (Fig. 7). At 15 m and 29 m the concentration increased on average by 76% and 190%, respectively, (paired t-test, $p < 0.05$) in June–July, and the mixing years followed the same trend (up to 200% increase; Fig. 7). TN showed smaller average increases (24% and 71% at 15 m and 29 m depths, respectively, t-test, $p < 0.05$). Compared to the reference years, only at 29 m depth were TN concentrations in the mixing years different (10–50% lower) from the respective median values (Fig. 7). Due to the small volume of deep water, volume-weighted TP and TN concentrations in late summer were not notably affected by the mixing (Fig. 8).

Volume-weighted TP and TN concentrations calculated from samples taken from the 6 sites were on average 1% and 3% lower, respectively, than concentrations calculated only from the samples taken from the Lankiluoto sampling site. In winter, respective concentrations were 7% and 3% higher. Excluding winter TN concentrations (paired t-test, $p = 0.02$), these differences were not significant (paired t-test, $p > 0.05$), indicating that the results obtained from the Lankiluoto sampling site alone well represent the whole basin.

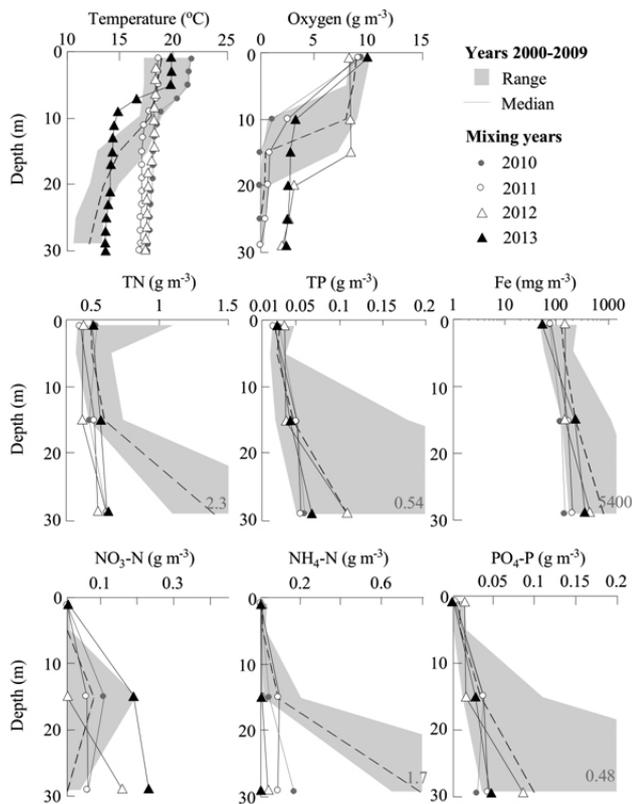


Fig. 9. Vertical distributions of temperature and dissolved oxygen and nutrient and iron concentrations in August of the reference and the mixing summers. In the $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ graphs, the y-axes start at the detection limit of 0.01 g m^{-3} (0.002 g m^{-3} for PO_4). Results from August 2008 were excluded due to early beginning of autumn convection.

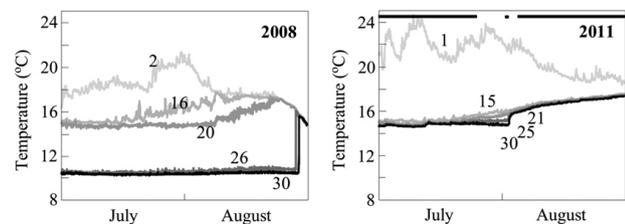


Fig. 10. Temperature at fixed depths (m) in July–August with mixing (right panel) and without mixing (left panel). Shutdowns of mixing station 3 are shown by interruptions in the black horizontal bar on the top of the right panel.

The seasonal development of Chl-*a* concentration in the epilimnion was inter- and intra-annually variable (Fig. 11), but the results of mixing years (summer average 11.0 mg m^{-3} , $\text{SD} = 8.7$) closely corresponded to those of reference years (summer average 10.0 mg m^{-3} , $\text{SD} = 5.2$; Fig. 11). Similarly in both cases, epilimnetic pH typically reached high values (>8) in May during the spring maximum of phytoplankton but decreased in June–July to 7.5–8, and in some years increased again in late summer (Fig. 11).

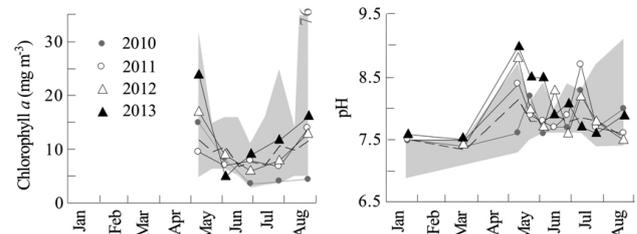


Fig. 11. Seasonal development of chlorophyll *a* at 0–6 m depth (left panel) and pH at 1 m depth (right panel). Grey area = range of 2000–2009; dashed line = median 2000–2009.

Discussion

Technically, the mechanical mixing worked as expected both in winter and summer. In line with earlier studies (e.g., Grochowska and Gawrońska 2004), mixing profoundly affected hypolimnetic temperature and stratification. Due to the dependence of water density on temperature and slightly steeper vertical temperature gradient in summer, density differences between 5 m and 30 m depths were an order of magnitude lower in winter ($\sim 0.02 \text{ kg m}^{-3}$) than in summer ($\sim 0.6 \text{ kg m}^{-3}$), which greatly facilitated mixing in winter. Despite higher oxygen consumption in the mixing years, the high oxygen binding capacity of cold water and the proportionally very high volume of shallow water maintained the high deep water oxygen concentration. In summer, the power of the mixing stations was not sufficient to avoid hypoxic or anoxic conditions. As indicated by relatively high hypolimnetic temperatures in the reference years, the Enonselkä basin is sensitive to wind and has a tendency to destratify in early autumn (Fig. 10); therefore, at the coolest range of summers, the development of polymictic conditions might be possible, and an increase in mixing power might not be a good alternative. In winter, small changes in temperature due to mixing probably have marginal ecosystem effects, while in summer, a several degrees increase in hypolimnetic temperature affects both organisms and their metabolism. Perhaps the most dramatic ecosystem effect was the destruction of the cool oxygenated metalimnion, an important habitat for cool-water fish.

In the Enonselkä basin, the stability of deep water temperatures before the late summer cooling of the epilimnion in 2008 (Fig. 10) suggests low exchange of water between anoxic and oxic water layers. In addition to temperature, salts (as indicated by 28% higher median conductivity at 29 m compared to 15 m, data not shown) leaching from the sediment significantly contributed to the resistance of the deepest water against mixing. Thus, in the midsummer period of reference years, thermal and chemical stratification together formed a strong barrier against nutrient flux from the anoxic water layers. Despite no difference in thermal stabilities between the reference and mixing years, the conditions within the hypolimnion were different. Small vertical temperature differences throughout the hypolimnion in the mixing summers, compared to those in the reference summers with continuous temperature gradient down to the bottom, should have favored nutrient transport from the hypolimnion to the epilimnion; however, epilimnetic total nutrient concentrations of the mixing summers were not different from 2000 to 2009 (Fig. 7). Because Chl-*a* concentration was not affected (Fig. 11) in relation to the median of the reference years, mechanical mixing did not seem to increase nutrient fluxes from the hypolimnion.

In the mixing summers of the Enonselkä basin, the importance of temperature on respiration was emphasized by the heat flux caused by pumping warmer water into the hypolimnion. Increased oxygen supply and turbulence probably also enhanced the mineralization of organic matter during its sedimentation, but their role could not be quantified. Similarly, Gantzer et al. (2009) found increased hypolimnetic oxygen consumption in 2 drinking water reservoirs in Virginia that were oxygenated in summer by bubble-plume diffusers. Because mixing did not affect epilimnetic Chl-*a* concentration in the Enonselkä basin, phytoplankton biomass likely remained unaffected; therefore, increased temperature and turbulence, and perhaps also availability of oxygen, were mainly responsible for increased hypolimnetic oxygen consumption. Based on Q_{10} of 2.7 (Bergström et al. 2010), the observed 5 °C elevation of hypolimnetic water temperature in late summers 2010–2012 (Fig. 9) by mixing could have increased oxygen consumption by 85%, which agrees with the estimated 62–120% increase in the 12.5–31 m deep water. Consequently, in the Enonselkä basin the observed increase would mean a quantitatively important reduction in the proportion of organic matter accumulating in the sediment, which should lead to a gradual decrease in oxygen consumption by the sediment. In agreement with that, our results suggested the reduction of under-ice oxygen consumption in winter when respiration in the sediment relies on sedimentation in earlier summers; however, due to the low

number of observations this trend is still tentative. The reduction of hypolimnetic oxygen consumption during several years was also observed by Gantzer et al. (2009).

During summer, epilimnetic TP concentration may be decreased by sedimentation and inflow. Kamarainen et al. (2009) found consistently decreasing TP during the summer months in Lake Mendota where epilimnetic concentrations of TP and Chl-*a* are similar to the Enonselkä basin. A gradual increase in epilimnetic TP during summer has been observed in many eutrophic lakes (Jeppesen et al. 1997, Søndergaard et al. 1999, Spears et al. 2008, Solim and Wanganeo 2009), however, possibly due to lower dilution of external load, although it has often also been attributed to leaching from anoxic sediments. Evidence is growing that anoxia is the consequence rather than the cause of elevated nutrient concentrations (Gächter and Wehrli 1998, Hupfer and Lewandowski 2008). This conception is corroborated by our mixing experiment with the contrasting sedimentation conditions between winter and summer.

In the Enonselkä basin, P release from sediment to water was closely coupled with release of Fe (Fig. 4), thus supporting the traditional coupling between Fe and P. Because epilimnetic TP concentration remained stable throughout the summer, external load of P as well as its flux from shallow sediments or deeper water layers were in balance with sedimentation and other losses. Mechanical mixing obviously maintained redox levels so high that nitrate, and in 2012 and 2013 also some oxygen, were left in the hypolimnion at the end of the summer stratification (Fig. 4), conditions that should not favor the release of P from the sediment (Andersen 1982). Because mixing year concentrations of TP at 15 m were similar and at 29 m (Fig. 7) were between the median and the lower range of the reference years, and because the relationship between TP and oxygen concentrations at 29 m depth in late summer (Fig. 4) was negligible, factor(s) other than anoxia must have been more important for the increased hypolimnetic TP concentrations in the Enonselkä basin, as suggested also by Niemistö et al. (2012). Although direct information of P-flux from the sediment is lacking, the improved oxygen conditions, and even absence of anoxia in the water column in mixing summers, provide strong evidence that the reason for the observed increase in deep water TP was high nutrient load rather than oxygen depletion.

When oxygen is depleted in water or sediment, a number of facultatively aerobic microorganisms shift to use $\text{NO}_3\text{-N}$ (Knowles 1982), which is why $\text{NO}_3\text{-N}$ was generally depleted in the deep water of the reference years. The presence of $\text{NO}_3\text{-N}$ in the hypolimnion of the mixing years in the Enonselkä basin down to the sediment surface shows that increased redox potential enabled nitri-

fication, which can occur at rather low oxygen concentrations ($>0.3 \text{ g m}^{-3}$; Stenstrom and Poduska 1980). Because of the spatial variability inherent in mixing, virtual coexistence of nitrification and denitrification is possible within a certain range of oxygen concentrations. In winter, such conditions occurred in the sediment, and in summer in hypolimnetic water. The enhancement of nitrification–denitrification due to mixing was clearly observed in deep water, where TN concentration was reduced to half of the reference years' minimum (Fig. 9). This is in agreement with the finding that mixing doubled denitrification rates (S. Hietanen, unpubl. data) from sediment samples taken from 17 m depth at 70 m distance from the mixing station.

Under high pH, P leaching from oxic sediments in the epilimnion may be accelerated (e.g., MacPherson et al. 1958, Christophoridis and Fytianos 2006). During summer stratification, pH values in the epilimnion of the Enonselkä basin were often >8 , as also found by Keto and Tallberg (2000). Because pH fluctuates according to the diurnal cycle of primary production, however, our results should be considered only directional. The experiments of Tallberg (2000) and Koski-Vähälä et al. (2001) with sediments taken from 9 m depth in the Enonselkä basin have shown that between pH 7 and 9.5, P mobilization from the sediment is further enhanced by an increase in silicon (Si) concentration. They hypothesized that the sedimentation of diatoms after the spring maximum could increase the concentration of reactive Si so that P mobilization would be amplified. Because the strength and species composition of the high phytoplankton spring maximum may vary (Liukkonen et al. 1997), it would be interesting to relate existing phytoplankton data with deep water TP and $\text{PO}_4\text{-P}$.

Lake management by mechanical mixing has generally been based on the idea that the consequences of bottom deposits accumulated over the long term need to be controlled, but only a small fraction of organic matter settling out of the epilimnion can be left until next growing season. Matzinger et al. (2010) found that in 2 small (areas 2% and 12% of that of the Enonselkä basin), stratified Swiss lakes, where about half of the water volume was deeper than 10 m, $\sim 80\%$ of oxygen consumption in the hypolimnion was due to the present lake productivity rather than to old organic matter in the sediment. Although management methods other than the reduction of external load might have only limited success, the results of the Enonselkä basin suggest that the mixing approach may still provide small improvements that might be stretched by careful optimization of mechanical mixing practices.

The 4-year mixing experiment of the Enonselkä basin suggested both favorable and unfavorable effects, some of which may only be realized later. In winter, the

improvement of oxygen conditions by mixing is indisputable, and due to low water temperature and primary production, improvement was easily attained. Mixing was able to largely homogenize under-ice nutrient concentrations, but as indicated by reduced respiration, it probably also contributed to a slight decrease in nutrient concentrations of water that regulate the important spring phytoplankton maximum. In summer, redox conditions were also clearly improved, particularly indicated by the presence of $\text{NO}_3\text{-N}$ in the hypolimnion, but while the concentrations of N were reduced, those of P were affected only slightly. Although no remarkable reduction in volume-weighted TN was observed (Fig. 8), mixing clearly enhanced the coexistence of nitrification and denitrification. Continued experimentation is needed to evaluate the final importance of the effects of the mixing on the Enonselkä basin and whether they justify its running cost (€97 000 in 2011). It is also too early to judge how mechanical mixing compares with the other management practices of the Enonselkä basin. The mixing approach has an outstanding advantage in that it can be varied, modified, and repeated. Vesijärvi, with its mixing stations, various automatic measurements, and associated monitoring and research activities, provides promising possibilities to test various scientific and management hypotheses with a time span and scale rarely available.

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