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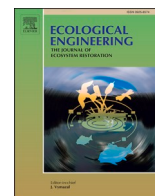
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Different responses to artificial ventilation in two stratified coastal basins

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ABSTRACT

We studied the effects of pumping surface water down through the pycnocline (i.e. artificial ventilation) on hydrodynamics, oxygen concentrations, hydrogen sulfide, and nutrients in two anoxic coastal basins (Lännerstasundet and Sandöfjärden). In addition, in a corresponding laboratory aquarium experiment, pumping of less saline surface water entrained dense bottom water with a mixing ratio of 6.8 and illustrated dispersal below the pycnocline. Oxygen saturation increased from 0 to 20%; oxygen penetrated poorly into the sediment of the aquarium. In the salinity-stratified Lännerstasundet basin, ventilation also oxidized the anoxic bottom water. The ventilation removed hydrogen sulfide and decreased the sub-pycnocline water pools of phosphorus and ammonium, which was not observed in a neighboring reference basin. The summertime ventilation warmed and made the sub-pycnocline water less saline. In the autumn, the inflows of cooled water from the surroundings with equal or higher salinity promoted its sinking in the relatively warm ventilated basin. The inflows maintained oxygen concentrations between 4 and 8 mg L⁻¹ for months after the ventilation ended. In contrast to Lännerstasundet, ventilation did not prevent formation of anoxia and release of nutrients in the temperature-stratified Sandöfjärden. Here, the ventilation capacity was less than that in Lännerstasundet and ventilation expanded the sub-thermocline bottom area, warmed the bottom sediments, and probably displaced oxic water from the experimental area. The ventilation did not promote density conditions for inflows and no marked inflow-induced oxidation was observed after midsummer. We conclude that a significant amount of anoxic water was entrained into the ascending plume which reduced the oxygen content below the pycnocline ventilation in aquarium experiment. Additionally, summertime ventilation may improve the status of the salinity-stratified basins for further oxidation. The improvement occurs due to autumn cooling and favorable basin topography, which promote inflows of oxic water with larger density and thereby, renewal of bottom water in the pumped basin. The semi-enclosed and temperature-stratified basin cannot form such favorable density conditions for inflows and thus ventilation is less efficient.

1. Introduction

Oxygen deficiency is increasing in coastal seas due to eutrophication and temperature increase (Breitburg et al., 2018). Oxygen deficit has been a serious problem in the open Baltic Sea (Bendtsen and Hansen, 2013; Carstensen et al., 2014; Conley et al., 2009; Hansen and Bendtsen, 2013; Meier et al., 2012) and in many coastal basins that suffer from semi-permanent hypoxia (Conley et al., 2011). Although nutrient loading is low in many of these coastal basins, shallow sills above the

pycnocline restrict horizontal exchange of oxygen-rich bottom water with the adjacent sea. Additionally, such basins often accumulate organic matter, and the enhanced oxygen consumption may lead to hypoxic conditions.

Several solutions to counteract oxygen deficiency have been suggested and tested in lacustrine and marine systems (Cooke et al., 2005; Holdren et al., 2001). One technique is pumping oxygen-rich surface water into denser near-bottom water, which results in oxidizing the anoxic water (artificial ventilation). This oxygenation technique has

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been widely used for restoration of lakes in Finland (Lappalainen, 1994; Lappalainen and Lakso, 2005). A similar pumping technique has been proposed as a solution to expedite recovery of the Baltic Proper (Stigebrandt and Gustafsson, 2007). Stigebrandt et al. (2015) tested artificial ventilation in a stratified anoxic coastal bay at the Swedish west coast of Skagerrak. Pumping of oxygen-rich and low-saline surface water into the deeper high saline layers (salinity >30) promoted horizontal inflow across the sill. Oxygen and nutrient conditions were improved both directly due to pumping of oxic water and due to increased frequency of horizontal inflows.

Here, we studied how pumping of oxic surface water into sub-pycnocline depths affects hydrodynamics, oxygen conditions, and water quality in an aquarium and in two semi-enclosed coastal Baltic Sea basins. The experimental basins differed in their stratification properties. One basin is located in the Stockholm Archipelago, Sweden, and is stratified with salinities of 0.8 to 4.5 in the surface and 3.7 to 4.8 in the bottom water. The Sandöfjärden basin on the Finnish southern coast is seasonally stratified by temperature in summer only with missing or only occasional salinity stratification. Based on results from both aquarium and field experiments, we discuss the buoyant plume formation, density changes, and the distribution of oxygen and nutrients in connection with artificial ventilation.

2. Material and methods

2.1. Experimental areas

Sandöfjärden is a semi-enclosed basin in the coastal Gulf of Finland (Fig. A1, Table A1, see also Lehtoranta and Lännergren, 2012) that suffers regularly from late summer oxygen depletion with high bottom release of phosphorus. Anoxia is partly related to the restricted sub-pycnocline water exchange of the basin after formation of the summer thermocline. The bottom sediment is soft mud and sediment accumulation areas are found at water depths >15 m. The locations of the pumps and sampling station are presented in Fig. A1b.

Lännerstasundet consists of two sub-basins in the inner Stockholm archipelago (Fig. A2, Table A1, Lehtoranta and Lännergren, 2012). The surface water is influenced by outflow from Lake Mälaren and by drainage water and discharge from sewage treatment plants. Both sub-basins suffer from anoxia because mixing and exchange of water are restricted by a semi-permanent halocline. Stagnant periods may prevail from 1 and up to 4 years, while periods with oxic conditions in the near-bottom water are relatively short (Lännergren and Eriksson, 2009). There is a steep chemocline between the oxic and anoxic water layers and accumulation of hydrogen sulfide into sub-pycnocline water is common.

In addition to the regularly monitored western basin A, two stations B and C were established (Fig. A2). Station B was situated at the deepest point in the middlemost sub-basin. Station C was situated in the pumped basin approximately 100 m northeast from the oxygenation device (Fig. A2). The B and C sub-basins have comparable geomorphological and hydrographical characteristics. Sulfidic mud sediments are found from water depths >9 m. The eastern basin C was chosen for oxygenation because the water exchange is limited by two shallow sills at its entrances (8.6 m and 3 m).

2.2. Ventilation method and dimensioning of ventilation

The oxygenation system pumps oxic water from the surface layer through a canvas pipe into the sub-pycnocline near-bottom water. The technique requires less energy than aeration with atmospheric oxygen and has higher oxygenation efficiency (10–12 kg O₂ kWh⁻¹) compared to that achieved by pumping atmospheric oxygen (0.5–1.5 kg O₂ kWh⁻¹) (Lakso, 1988). A Mixox MC 1100 oxygenator (2.5 kW, diameter 1100 mm) pumps water at a flow rate of approximately 1 m³ s⁻¹ (see details Saarijärvi et al., 2012). The oxygen-transport capacity of the pump

depends on the concentration at the inlet of the pump (e.g., the capacity at 9 mg O₂ L⁻¹ is approximately 780 kg O₂ d⁻¹). The ventilation periods and capacities in Sandöfjärden (six Mixox pumps) and Lännerstasundet (one Mixox pump) are presented in Fig. A3a and b.

The dimensioning for the ventilation was based on estimated oxygen consumption rates in water (mg L⁻¹ d⁻¹) and estimates on sediment oxygen demand (g O₂ m⁻² d⁻¹). On the basis of oxygen decrease in the sub-pycnocline water of Sandöfjärden (thermocline) and Lännerstasundet (halocline), the oxygen consumption was estimated to be 2600–6000 kg O₂ d⁻¹ and 180–250 kg O₂ d⁻¹, respectively. On the basis on a sediment oxygen demand of 1 g O₂ m⁻² d⁻¹ found in eutrophic lakes (Liikanen et al., 2002), the estimated sediment oxygen consumption rates were 4750 kg O₂ d⁻¹ in Sandöfjärden and 265 kg O₂ d⁻¹ in Lännerstasundet (bottom areas 4.75 km² and 0.26 km², respectively; Table A1). In Sandöfjärden, the capacity of pumps was approximately 4400 and approximately 5300 kg O₂ d⁻¹ for the years 2010 and 2011, respectively. This was close to the estimated sediment oxygen consumption rate but less than the maximum estimate of 6000 kg O₂ d⁻¹. In Lännerstasundet, the capacity of the pump (780 kg O₂ d⁻¹) exceeded the calculated estimates and was 2.9 times the estimated sediment oxygen demand of 265 kg O₂ d⁻¹.

2.3. Monitoring and chemical and statistical analyses

An extensive monitoring program was performed in both Sandöfjärden and Lännerstasundet. The acoustic profiling devices RCM9 RDCP and ADCP with oxygen optodes and temperature and salinity loggers moored at the bottom were used to measure currents, oxygen concentrations, temperature, and salinity. Temperature was also monitored with TidbiT loggers mounted approximately 10 cm above and below the sediment-water interface.

Water for chemical analyses was sampled with Limnos samplers. Concentrations of total nitrogen and phosphorus, sum of nitrite and nitrate, ammonium, phosphate, and iron (Table A2) were analyzed according to Koroleff (1983) at the Tvärminne Zoological Station, University of Helsinki. In Sandöfjärden, dissolved iron was filtered through Whatman Nucleopore Track-Etch Membrane (pore size 0.47 μm). Chemical analyses for Lännerstasundet were performed by Eurofins laboratory Sweden according to standard methods (see Appendices for description).

The effect of ventilation on nutrient pools in Sandöfjärden (calculated on the basis of vertical concentrations and water volumes) was analyzed by comparing the mean values of nutrient pools with *t*-test (2-tailed, equal variances not assumed). The comparisons were realized for pools in the bottom volume of the basin (≥10 m) between the reference year 2009 (minor testing of pumps) and the large-scale ventilation years 2010 and 2011 (pumping volumes in Fig. S1a). The statistical analyses covered oxygen-depleted summer periods lasting 41–43 days in July–September during the 3 years. The analyses were performed with SPSS Statistics Version 23.

For Lännerstasundet we used Before-After Control-Impact (BACI) analysis to study the differences in the nutrient pools of the non-ventilated reference basin (A + B) and the impacted ventilated basin C before (2009) and after pumping (2010–2011). Nutrient pools were calculated for the sub-pycnocline water volumes (≥10 m) of the basins. Our BACI analysis was based on a two-way fixed effect ANOVA model (see details in Appendices). Since the assumptions of normality and equal variances are not met, we applied a bootstrap procedure of ANOVA and Tukey's test. Bootstrap was based on resampling with replacement a single dataset to create many simulated samples that allows the calculation of standard errors, confidence intervals, and hypothesis testing (Kulesa et al. 2015). As ANOVA was here used in BACI context, particular attention was paid to the significance of the interaction term and pairwise differences. *The steps to define the significance of parameter estimates and pairwise differences are described in the Appendices.* The procedure was performed using R version 4.0.2 (R Core Team,

2020).

A time series of temperature, salinity, and oxygen showed that bottom water in Lännerstasundet was significantly influenced by inflow from the neighboring basin. The inflow was estimated from a simple model of oxygen conditions in the bottom water during a period without ventilation in autumn 2010 (3 October–29 November). During this period, oxygen changed rapidly several times in less than a day and these jumps could be explained by major inflows over the shallow sill from the neighboring basin.

It was assumed that the observed variability in oxygen concentration was due to replacement of the entire sub-pycnocline water layer of the eastern basin (with volume $V = 2.18 \cdot 10^6 \text{ m}^3$) and that in-flowing water had an initial oxygen concentration ($O_2(i)$) of 10 mg l^{-1} , corresponding to values observed in the beginning of October 2011. During this period without pumping, the bottom water was replaced by oxygen-rich inflowing water at a varying rate (Q) and oxygen also decreased due to remineralization of organic matter (OM) with a constant remineralization rate (λ) and a constant oxygen to organic matter remineralization ratio ($\eta_{O_2:OM}$).

The conservation equation for oxygen in the bottom layer can therefore be described as:

$$V \frac{\partial O_2}{\partial t} = Q(O_2(i) - O_2) - \lambda VOM \eta_{O_2:OM} \quad (1)$$

Thus, the temporal change (t) of oxygen is a combined effect caused by the inflowing oxygen-rich water and the local oxygen consumption due to bacterial remineralization of organic matter. The pool of labile organic matter was assumed to be large and was approximated as a constant during the period.

The influence from remineralization of organic matter was calculated during a stagnant period where the inflow could be assumed to be zero and the oxygen change could then be calculated as:

$$\frac{\partial O_2}{\partial t} = -\lambda' \quad (2)$$

where $\lambda' = \lambda \text{ OM } \eta_{O_2:OM}$ in Eq. (1). A relatively stable period was observed during a 3-day period from 6 to 9 October, where bottom temperature and salinity at 18-m depth were nearly constant (temperature and salinity varied between 11.94 and $11.95 \text{ }^\circ\text{C}$ and 4.17 – 4.18 , respectively, i.e., within the uncertainty of the sensors). In general, short-term fluctuations characterized the oxygen measurements, likely due to advection of bottom water within the basin and local gradients in oxygen sinks. Therefore, oxygen was filtered with a running 12-h low-pass filter to represent the average conditions in the basin. During this period, the low-pass filtered oxygen decreased from 5.5 to $2.8 \text{ mg O}_2 \text{ L}^{-1}$ and this resulted in $\lambda' = 0.871 \text{ mg O}_2 \text{ d}^{-1} \text{ L}^{-1}$. The corresponding specific remineralisation rate in this range corresponds to 0.16 – 0.3 d^{-1} and can be compared with coastal remineralisation rates. Hansen and Bendtsen (2013) found carbon specific remineralisation rates of 0.05 d^{-1} in Kattegat during the summer month and this indicates higher lability of organic matter in Lännerstasundet, as would be expected for a near-shore enclosed system. The remineralisation rate was calculated during an oxic period and this was characteristic for the timeseries where the concentration was above 1 mg L^{-1} and 0.1 mg L^{-1} in 94% and 99% of the time, respectively. Therefore, the potential effect from low oxygen or anoxic periods on the remineralisation was not considered to be important for the estimated exchange during the two-month period. However, the sensitivity of the inflow estimates (Q) to oxygen consumption, i.e. the value of λ' , was considered in the model analysis by varying the value by $\pm 50\%$. The sensitivity of the inflow estimates (Q) to oxygen consumption (i.e. the value of λ') was considered in the model analysis. The inflow (Q) was calculated from the finite difference form of Eq. (1), using λ' and the low-pass filtered time series of oxygen. The simple model neglects turbulent vertical mixing of oxygen across the pycnocline. This assumption was justified by comparing the potential

oxygen transport from vertical mixing (using a typical turbulent diffusion coefficient in the pycnocline of the order $10^{-5} \text{ m}^2 \text{ s}^{-1}$ e.g., Ledwell et al. 2004), which was found to be two orders of magnitude less than the inflow from the neighboring basin calculated from Eq. (1).

The nutrient retention induced by the ventilation alone was estimated based on the nutrient pools in the experimental basin. There was one period when no marked inflows occurred from the adjacent area (the period 2–9 June 2010; Table 3). The calculations were made by assuming that the outflow from the basin equaled the pumping rate ($1 \text{ m}^3 \text{ s}^{-1}$) and that there was a corresponding and compensating inflow of surface water from the adjacent basin. The concentrations used in the calculations for nutrients flowing in and out were taken from a surface depth of 3 m and from the sill depth (8 to 10 m), respectively, using data from the sampling date 9 June 2010.

2.4. Aquarium pumping experiment with sediment and saline water

Pumping of oxic surface water into anoxic bottom water causes mixing, spreading and oxidation of the water. Wind-driven currents and mixing cause turbulence in water which can be avoided in aquarium conditions. To simulate the pumping effects without natural disturbance we pumped surface water with constant flow rate into a still-water system where salinity stratification and bottom topography were controlled. We followed and measured the spreading of plumes and oxygen in the simulation. The experimental setup was constructed in a 300-cm long, 33-cm high, and 4.65-cm wide aquarium (see details Lindstrom and Sandberg-Kilpi, 2008) at constant temperature of $6 \text{ }^\circ\text{C}$. Sediment from Sandöfjärden covered the bottom of the aquarium and a two-layer system with a halocline was established above the sediment (water height was 26 cm). A peristaltic pump created a constant flow of less saline oxic water (salinity 5.5) colored with rhodamine through the pycnocline and into the more saline hypoxic water (N_2 bubbled, oxygen saturation approximately 5%, salinity 10.5). The flow rate was adjusted to 9 ml min^{-1} . Altogether, 443 ml of oxygen-rich surface water with rhodamine (2 mg l^{-1}) was pumped within 49 min into a more saline sub-pycnocline water layer 5 cm above the sediment surface (Fig. 1a and A4). In the experiment, we followed the horizontal and vertical spreading of the plume and measured oxygen profiles at different distances from the pump and water depths. Oxygen concentrations were measured with a Unisense OX100 microelectrode from the top of the sill and from a site nearby the pump outlet in the aquarium (Fig. 1). The horizontal and vertical dimensions of the colored area were measured with a ruler and used together with the width of the aquarium to calculate the colored volume of water.

3. Results

3.1. Spreading of plume and oxygen in the aquarium experiment

The pumping of less dense water down through the pycnocline in the aquarium experiment created an expanding colored plume below the pycnocline (Fig. 1). The plume occupied a volume of 3010 cm^3 (i.e., ml) after pumping of 440 ml of less saline water with dissolved rhodamine, corresponding to a mixing ratio 6.8. Resuspension of the surface sediment occurred only in an area of 10 to 20 cm^2 directly below the outlet. After reaching the sediment sill, the plume spread out at the height of the sill from the pumped basin and formed a separate colored layer in the adjacent basin (section on the right in Fig. 1). The pumping oxygenated the near-bottom water up to a saturation of 20% and to 5% close to the sediment surface (Fig. 1). No oxygen was found at the sediment surface in the deep section of the aquarium (N.B. oxygen was not measured below the pump outlet, because moving the pump outlet was likely to cause disturbance). However, oxygen was found in the area where the plume reached the height of the artificial sediment sill (Fig. 1).

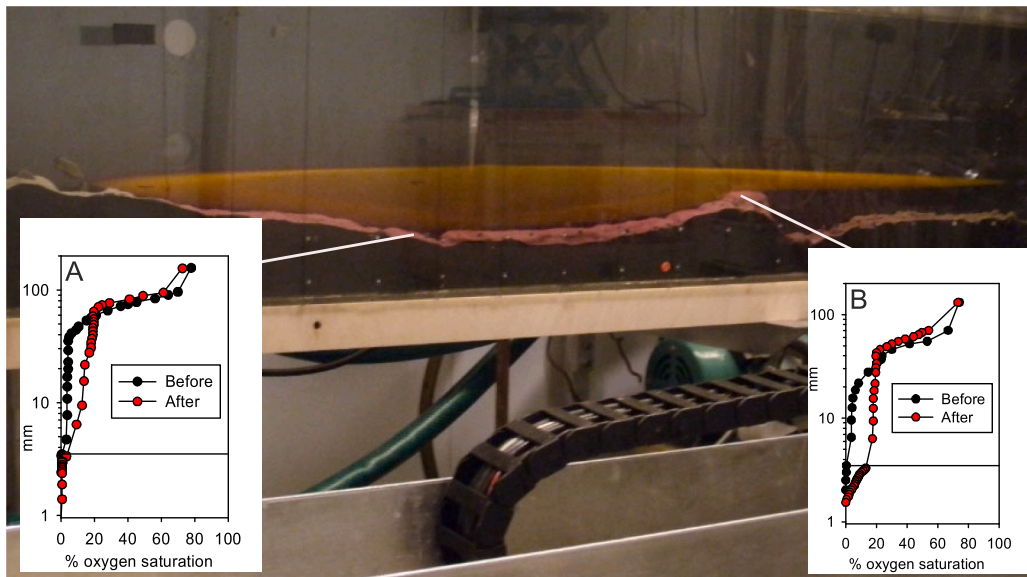


Fig. 1. Spreading of pumped rhodamine in the aquarium and vertical oxygen profiles before and 2–3 h after pumping of oxyc water in close vicinity of the outlet (A) and at a depth of an artificial sediment sill built on the bottom of the aquarium (B). The sediment-water interface is marked with a horizontal line.

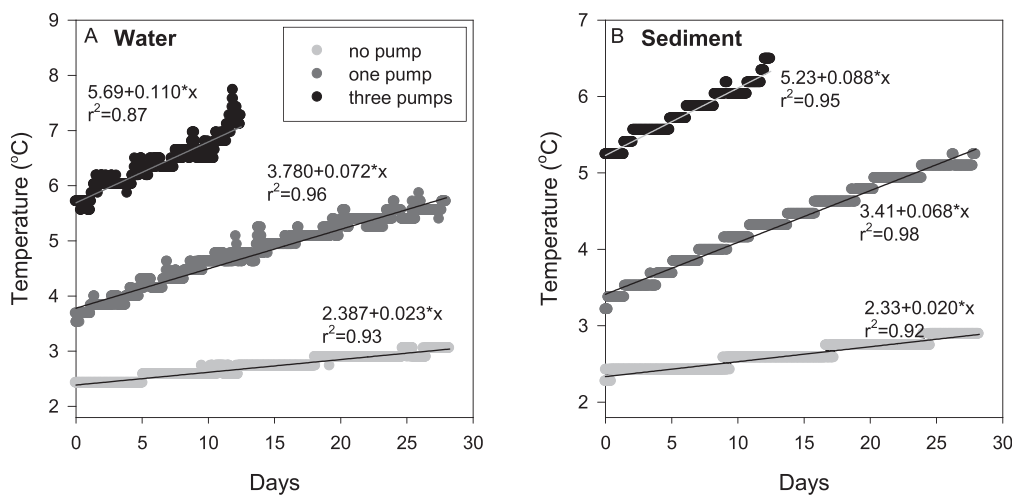


Fig. 2. A and B. Warming of A) water 10 cm above the sediment and B) sediment at 10 cm depth with different numbers of operating pumps in Sandöfjärden station. Measuring periods: no pump 14 July to 11 August 2009; one pump 18 August to 14 September 2009; three pumps 16 September to 28 September 2009. Surface water temperature close to the inlet depth of the pump for the periods above varied between 13–19, 15–18, and 13–15 °C, respectively.

3.2. Ventilation and warming of near-bottom water and sediment in Sandöfjärden

The ventilation was started in August 2009 when a relatively strong summer thermocline and a minor vertical difference in salinity prevailed. The ventilation raised the thermocline by 4 to 5 m in the close surroundings of the pumps and the ventilation also created a well-mixed bottom layer below the pycnocline. The ventilation warmed the near-bottom water and the sediment at a distance of about 250 m from the pumps within a few days (data not shown). The upper 10 cm of sediment responded rapidly to the warming of near-bottom water (Fig. 2a and b).

In the near-bottom water and surface sediment, the rate of warming was approximately 0.02 °C d^{-1} without ventilation. The switching on of one pump increased the warming close to 0.07 °C d^{-1} . Assuming that the change was caused by the pump, this suggested an enhanced warming of 0.05 °C d^{-1} of both water and sediment (Fig. 2a and b). The switching on of additional pumps enhanced the warming, as three pumps, estimated correspondingly, warmed the near-bottom water at a rate of 0.09 °C d^{-1}

and the sediment at a rate of 0.07 °C d^{-1} .

3.3. Effects of ventilation on oxygen and nutrients in Sandöfjärden

The oxygen concentration started to decrease when temperature stratification developed. However, the mixing and the occasional inflows into the basin induced marked variation in the oxygen concentration in the near-bottom water (data not shown). The oxygen concentrations below the thermocline were low and even anoxia in near-bottom water was observed every summer in 2009–2011 despite the ventilation. Thus, oxygen conditions in the basin did not differ markedly from the previous reference years since 2000 (see Fig. A5a).

According to the decrease in the sub-pycnocline water oxygen pool, the estimated consumption rate was calculated as $2972 \text{ kg O}_2 \text{ d}^{-1}$ without ventilation in 2009 (Fig. A5b and c). During the ventilation campaigns in 2010, the estimated consumption rate was $2995 \text{ kg O}_2 \text{ d}^{-1}$, which also included the oxygen content of the pumped water. Thus, the rate was comparable to that observed in 2009 even though the

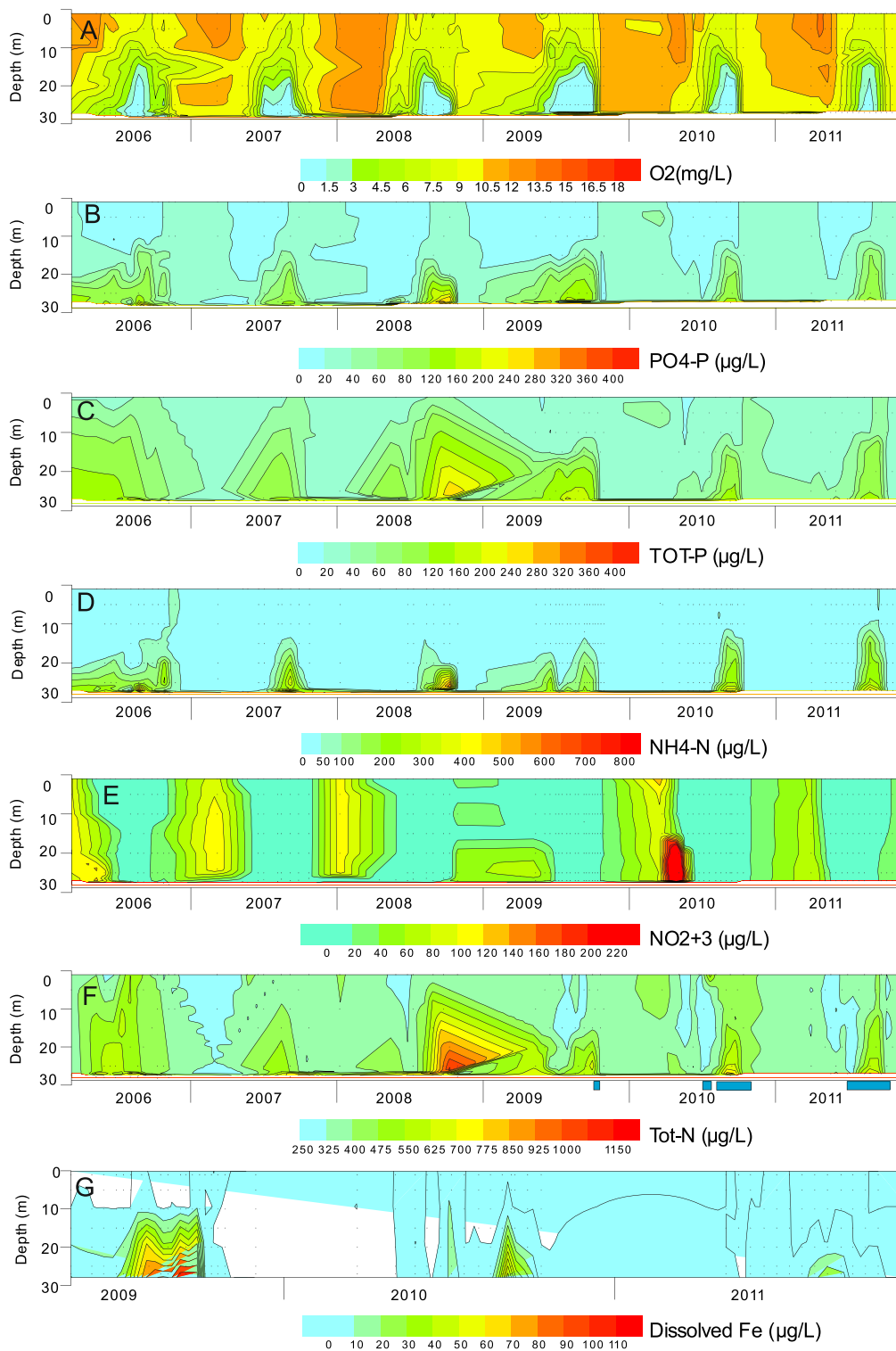


Fig. 3. Concentrations of A) oxygen (O₂), B) phosphate (PO₄-P, C) total phosphorus (Tot-P), D) ammonium (NH₄-N) E) NO_x (NO₂ + 3), and F) total nitrogen (Tot-N), and G) dissolved iron (Fe) in Sandöfjärden station. Note the different time scale for iron (Fe). Blue bars on time scale of Tot-N denote ventilation periods. Kriging was used as gridding method to produce the contours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ventilation transferred 4400 kg d⁻¹ oxygen into the near-bottom waters during the same period. In 2011, the estimated consumption rate of 3457 kg O₂ d⁻¹ was markedly higher than in previous summers even though ventilation was further increased to 5300 kg O₂ d⁻¹. The values above are based on the assumption of a stagnant bottom water layer and may underestimate the actual oxygen consumption. It was also notable

that temperature and the change in the sub-pycnocline water pool of oxygen were not well related (Fig. A6).

In general, the ventilation did not result in detectable concentrations of nitrate and nitrite (NO_x) in the anoxic water of Sandöfjärden. However, in 2010 there was a marked increase in the concentration of NO_x, which may have been induced by ventilation before the formation of

Table 1

Mean values of sub-pycnocline water nutrient pools (kg/kg) and DIN:DIP ratios (w:w) in the Sandöfjärden-ventilated basin for the years 2009/2010 and 2010/2011. Insignificant pool changes between the years are indicated as “ns” (i.e. $p > 0.05$) and significant increases are marked with “+” ($p < 0.05$).

	Sandö Pump	Sandö Pump
Nutrient	2009 / 2010	2010 / 2011
PO4-P	2185 / 1983 ^{ns}	1983 / 2392 ^{ns}
Tot-P	2769 / 2541 ^{ns}	2541 / 2847 ^{ns}
NH ₄	2184 / 3976 ^{ns}	3976 / 5057 ^{ns}
NOx	78 / 99 ^{ns}	99 / 51 ^{ns}
Tot-N	10,597 / 14,381 ⁺	14,381 / 14139 ^{ns}
DIN	2262 / 4074 ^{ns}	4074 / 5107 ^{ns}
DIN:DIP	1.0 / 2.0 ⁺	2.0 / 2.1 ^{ns}

anoxia (Fig. 3a and c). The concentrations of ammonium, in turn, increased in the near-bottom water and even exceeded concentrations measured in previous years (Fig. 3b). This increase occurred after depletion of oxygen and was positively correlated with warming of the sediment (data not shown). As the basin became anoxic, phosphate also started to accumulate in near-bottom waters (Fig. 3b and d). In contrast to phosphate, anoxia did not lead to iron release (Fig. 3f), which resulted in a low iron to phosphate ratio. In summary, no marked changes were observed in the concentrations of NOx, total phosphorus, and phosphate compared to the previous non-pumped years 2006–2008 (Fig. 3).

The *t*-tests also supported the finding that the sub-pycnocline water nutrient pools in 2009, when the ventilation capacity was relatively low, did not differ significantly from those accumulated during the efficient ventilation campaigns in 2010 and 2011 (Table 1). Even a marked increase in the mean bottom water pool of ammonium from approximately 2200 kg to approximately 4000 kg was only indicatively significant ($p < 0.10$). Furthermore, changes in the nutrient pools were insignificant when the sub-pycnocline water pools in 2009 were compared to those in 2011 (Fig. 4a–h).

3.4. Effects of ventilation on inflows and oxygen in Lännerstasundet

The ventilation warmed sub-pycnocline waters in Lännerstasundet, whereas the sub-pycnocline waters remained unchanged in the reference basin (Fig. 5). Furthermore, ventilation removed hydrogen sulfide and oxidized the near-bottom water within a few days, and further ventilation kept the pumped basin oxic (Fig. 6). No hydrogen sulfide was detected in the pumped basin during the campaigns in 2010 and 2011. In contrast, oxygen decreased in the non-pumped reference basin during the same period and hydrogen sulfide concentrations increased to high values of $>30 \text{ mg l}^{-1}$.

It was notable that pump use Pumping in early June 2010 improved the oxygen conditions similarly to the pumping in early winter 2009 when the basin was oxidized within a few days. However, even though the pump was not running after Midsummer 2010, the near-bottom water remained oxic for several months. In late August 2010, the oxygen concentration approached zero. However, oxygen conditions improved again in autumn 2010. The near-bottom water then remained oxic until end of April 2011. Thus, 3 weeks of ventilation in June 2010 resulted in improved oxic conditions for a period of several months. The ventilation was started again in early summer 2011. After stopping the pump on 25 October 2011, the sub-pycnocline water remained oxic and oxygen consumption did not result in anoxia before the end of November 2011.

The continuous time series from the mooring emphasized the episodic character of inflows affecting oxygen concentrations during non-pumped periods (Fig. 7). The oxygen measurements in the bottom water (depth 18 m) showed day-to-week variation due to inflow events from the neighboring basin and their influence was simulated with simple oxygen model. Significant short-term variability was also observed and this may be explained by internal movements of bottom

water in the basin where gradients in oxygen sinks or gradual mixing of inflowing water created local oxygen gradients. Therefore, the low-pass filtered oxygen concentration is assumed represent the average conditions in the near-bottom water, and this timeserie was applied in the model calculations.

The accumulated transport during the 57-day period corresponded to approximately 12 times the bottom volume or $26.8 \cdot 10^6 \text{ m}^3$ and corresponded to total oxygen transport of 2680 tons O₂. The largest inflows from early October to 29 November 2010 peaked at $11 \cdot 10^6 \text{ m}^3 \text{ d}^{-1}$ during short periods of only a few hours. This corresponds to a transport of $114 \text{ m}^3 \text{ s}^{-1}$ or a current speed of 16 cm s^{-1} across the shallow sill (cross section of 780 m^2). The average transport across the sill during the entire period corresponded to an inflow rate of $5.4 \text{ m}^3 \text{ s}^{-1}$ or a current speed of 0.7 cm s^{-1} . The sensitivity of the accumulated estimate to the oxygen concentration in the inflowing water was analyzed. For example, a value of 9.5 mg l^{-1} instead of 10 mg l^{-1} would increase the accumulated transport to approximately 15 times the bottom volume. The sensitivity of the accumulated transports to the value of the oxygen consumption rate (λ') was estimated by varying its value by $\pm 50\%$ and this resulted in an accumulated transport between 10 and 14 times the sub-pycnocline water volume. Thus, the estimate of an accumulated exchange of approximately 12 times the volume of the sub-pycnocline water layer varied within 25% and was therefore considered as representative for the exchange with the neighboring basin during the period.

To test whether the inflows from the adjacent basin would occur as in the previous summer, the pump was not in operation from 5 to 22 July 2011. However, only insignificant inflows occurred, and the absence of ventilation led to a rapid depletion of oxygen. However, restart of the ventilation oxidized the water again even though the temperature had risen considerably in the sub-pycnocline water due to earlier ventilation. No parallel changes in the reference basin were detected.

3.5. Effects of ventilation on nutrients in Lännerstasundet

In short-term experimental ventilation, the bottom water concentrations of total phosphorus and phosphate decreased after oxygenation (Fig. 6). In addition, the ammonium concentration decreased whereas that of NOx increased (Fig. 6). The stop of ventilation in summer 2011 led to anoxia and increased ammonium and phosphate concentrations. As in Sandöfjärden, the phosphate concentration in near-bottom water surpassed that of dissolved iron under hypoxic and anoxic conditions.

The sub-pycnocline water pools of total phosphorus, phosphate, total nitrogen, ammonium, and dissolved inorganic nitrogen (DIN) were significantly smaller after ventilation (Table 2, Fig. A7). Thus, the ventilation decreased the pools of nutrients (Fig. 8), except for NOx; the NOx pool increased markedly, but not significantly (Table 2). The DIN pool declined significantly after ventilation and this was explained largely by the removal of ammonium. The ventilation diminished the phosphate pool relatively more than that of DIN. Accordingly, the DIN:DIP ratio increased significantly after ventilation (Table 2, Fig. 8h). In the early autumn during the last period of ventilation in 2011, the DIN:DIP ratio increased from approximately 5 (no ventilation) to nearly 20.

Contrasting results for the nutrient pools were observed in the reference basin when compared to the experimental basin. The sub-pycnocline water pools of total phosphorus, phosphate, ammonium, and DIN increased significantly from the year 2009 to the period of 2010–2011 (Table 2). The decrease in the pool of NOx was not significant. Thus, the nutrient conditions worsened during the period of ventilation in the reference basin.

The nutrient removal was estimated based on the in-basin changes of the pools and fluxes of nutrients transported in and out of the basin during the ventilation period in early June 2010. A short-term ventilation decreased the pool of total phosphorus by 70 kg and that of phosphate by 134 kg (Table 3). Additionally, the proportion of phosphate from the total phosphorus pool decreased from 71% to 43%. In Lännerstasundet, the amount of NOx decreased by 11 kg and removal of

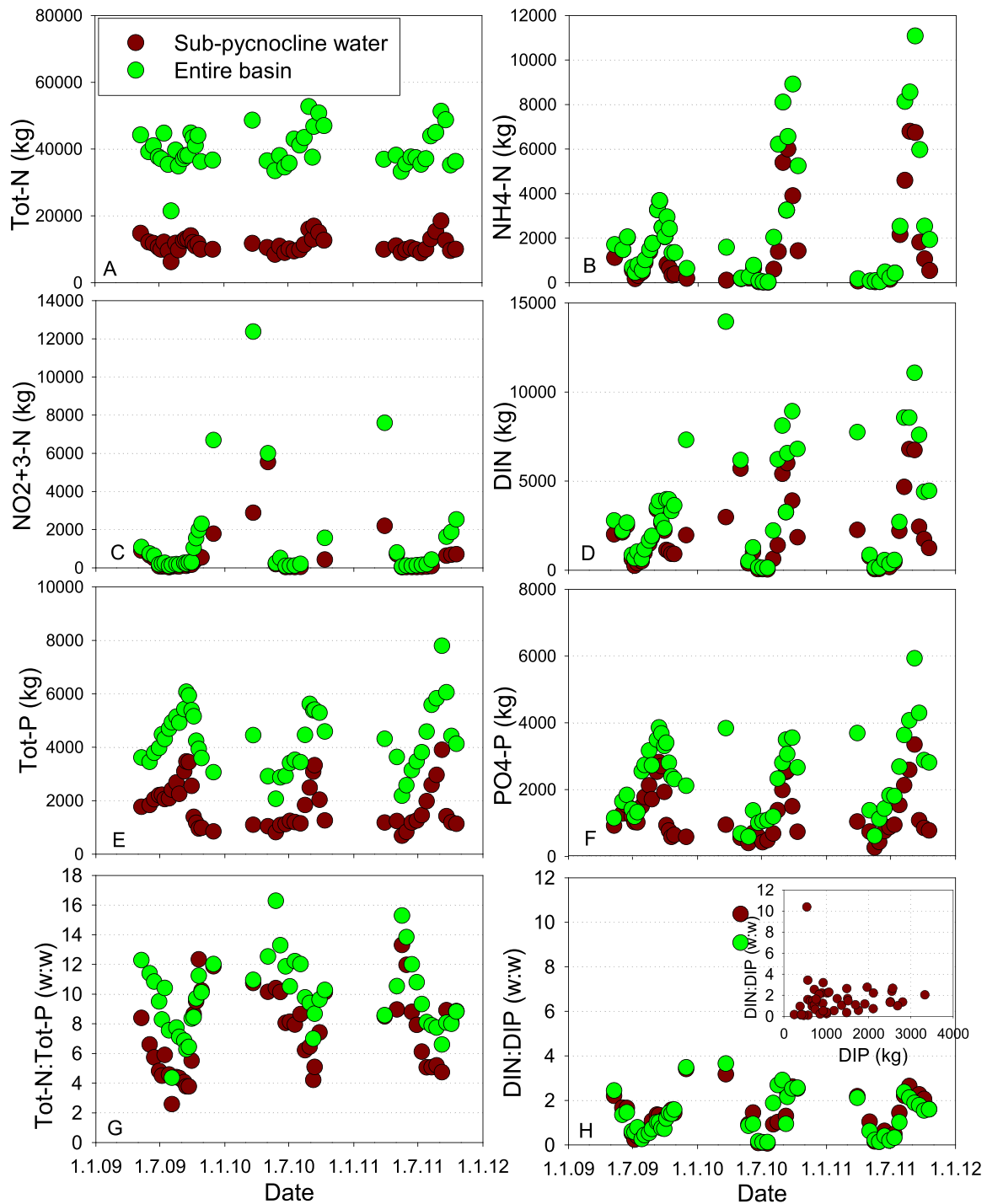


Fig. 4. Variation in the pools of A) total nitrogen (Tot-N), B) ammonium (NH₄), C) NO_x (NO₂ + NO₃), D) inorganic nitrogen (DIN), E) total phosphorus (Tot-P), F) phosphate (PO₄-P), G) Tot-N:Tot-P ratio, and H) inorganic nitrogen:phosphate ratio (DIN:DIP) in Sandöfjärden sub-pycnocline water (below sill depth 12 m) and entire basin in 2009–2011. The relationship between the pool of DIP and DIN:DIP ratio below sill depth is shown in the right upper corner of panel H.

ammonium was calculated to be 256 kg.

4. Discussion

4.1. Buoyant plume and oxygen concentrations in the aquarium experiment

The aquarium simulations revealed that pumping did not break down the halocline above the outlet of the pipe or elsewhere. Furthermore, the pumped surface water was mixed with the water below the

halocline and caused the outflowing water to ascend as a buoyant plume below the halocline alongside the outlet set. This finding was consistent with the convective vertical and horizontal motion around the Mixox pump, as previously observed in a tracer experiment where the buoyant plume ascended upward near the pipe and spread out at its neutral level below the pycnocline (Bendtsen et al., 2013). The movement of the plume, which did not reach the surface water layers in the aquarium or in the field-scale experiment, indicated that pumping does not transfer substances markedly from deeper layers to surface waters. This may explain the undetectable direct effect of pumping on surface algal

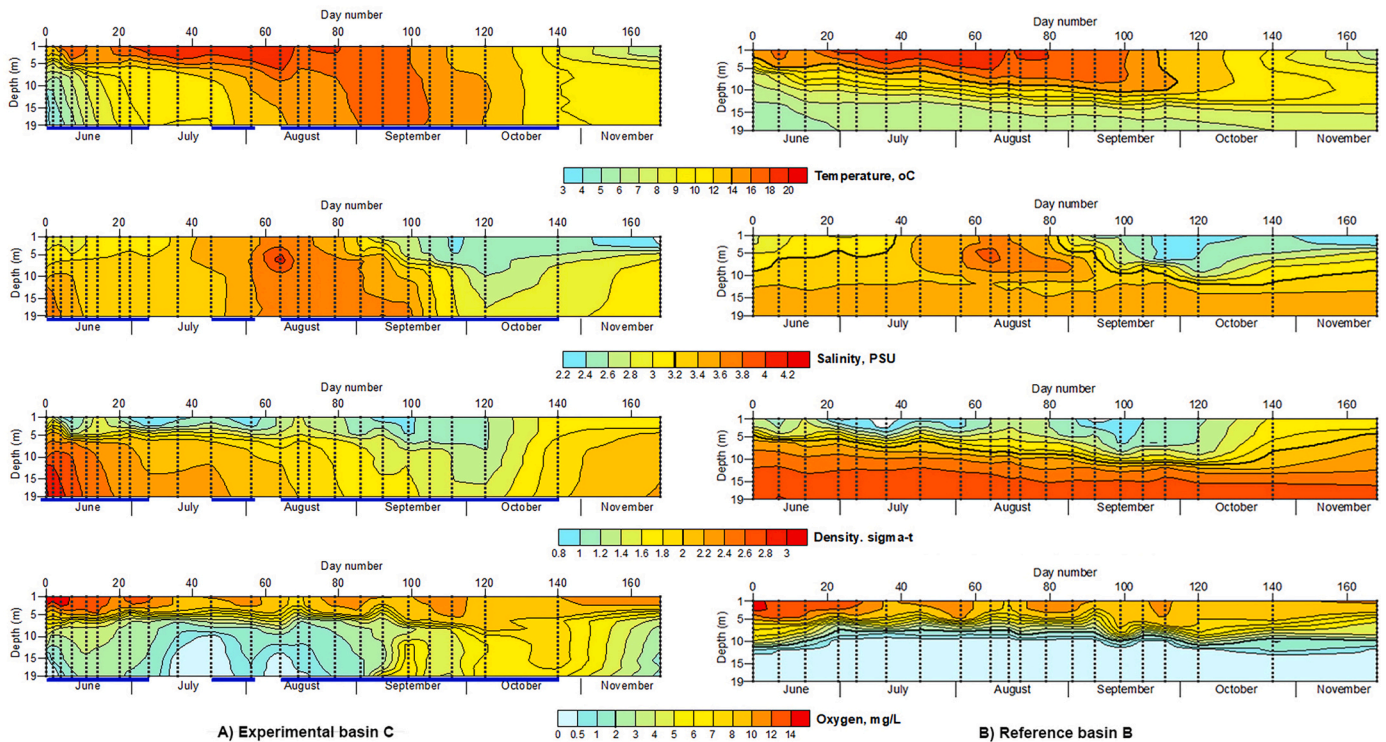


Fig. 5. Effect of ventilation on temperature, salinity, density, and oxygen concentration in Lännerstasundet A) experimental basin C and B) neighboring reference basin B in June to November 2011. The pumping periods are marked with a blue line below the x-axis. Triangulation with linear interpolation was used to produce the contours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

communities (Lehtoranta et al., 2012).

The aquarium experiment revealed a significant entrainment of saline water into the plume with an increased outflow by a factor of 6.8. The value was very close 7, which was observed in the Sandöfjärden tracer experiment (Bendtsen et al., 2013). Thus, in addition to the primary circulation induced by the pumping, the large volume of colored water at the end of the experiment indicated that a significant secondary circulation was established for compensating for entrained water; thus the near-pump circulation was enhanced.

Although the pumping oxidized the water, entrainment of anoxic water maintained a low saturation level in the spreading plume water. This indicated that pumping of fully saturated surface water has only a weak ability to oxidize anoxic sub-halocline waters above saturation of 20%. The plume water was lighter than the water above the bottom and was unable to oxidize the sediment directly. However, oxygen was found at the height of the artificial sill, which suggested that sediment oxygenation may occur in the shallower areas where the water from the expanding plume is in contact with the sediment surface.

4.2. Warming effect of ventilation and oxygen conditions in the experimental basins

The summertime ventilation of warm surface water weakened stratification but did not break it down entirely in Sandöfjärden. The warming effect of ventilation in the near-bottom water and in the sediment was detectable and significant. The warming was not directly proportional to ventilation capacity, as initiation of one pump increased the warming rate by a factor of 3.5 and engagement of two more pumps increased the rate by a factor of 4.5 compared to the non-pumped period. Warming may enhance oxygen consumption and anaerobic mineralization processes, such as dissimilatory sulfate respiration (Jørgensen 1977).

In Sandöfjärden, the basin oxygen concentration of sub-pycnocline water started to decrease right after the formation of temperature

stratification during the study period, as observed in the non-pumped years. Inflows from the surrounding areas brought oxic water into the sub-thermocline water layers of the pumped basin in early summer, but inflows were largely blocked after midsummer both in 2010 and 2011. The inflows stopped because summer warming deepened the thermocline below the sill depth, which prevented the inflows of cold and dense water. After midsummer, the pumping capacity of 4400 and 5300 kg O₂ d⁻¹ in 2010 and 2011, respectively, did not markedly affect the overall oxygen content in the basin and did not postpone the formation of anoxia compared to conditions during non-pumped summers. Based on pumping capacity and the existing pool of oxygen, the entire oxygen consumption in the basin can be estimated as high as 10,000 kg d⁻¹ in 2011. This would result in a consumption rate of 2.1 g O₂ m⁻² d⁻¹ when calculated for the bottom area below 12 m depth (i.e. 4.75 km²). This rate is considerably higher than the rates of 0.5–1 g O₂ m⁻² d⁻¹ estimated for the inner archipelago of Stockholm (Walve et al., 2018).

Possible explanations for the high consumption rate and inadequate oxidation in Sandöfjärden include the following: ventilation lifted the thermocline upwards 2 m, which expanded the oxygen-consuming area and volume of sub-thermocline water about 0.8 km² and 9.5 milj. m³, respectively; a significant part of the pumped oxic surface water was entrained with the sub-thermocline water and outflowed below the pycnocline and over the sills to the adjacent areas (see the plume spreading over the sill in the aquarium experiment, Fig. 1); ventilation induced warming and, thereby, stimulated aerobic and anaerobic respiration below the pycnocline; and ventilation enhanced oxygen consumption by mixing of water and movement of particles below the pycnocline.

The relationship between the sub-thermocline water temperature and oxygen consumption was rather weak in Sandöfjärden (Fig. A6). Therefore, explanations other than ventilation-induced warming must be considered for the poor success in oxygenation. Aeration in lakes increases turbulence and sedimentation of particulate matter, which have enhanced oxygen consumption significantly below the pycnocline

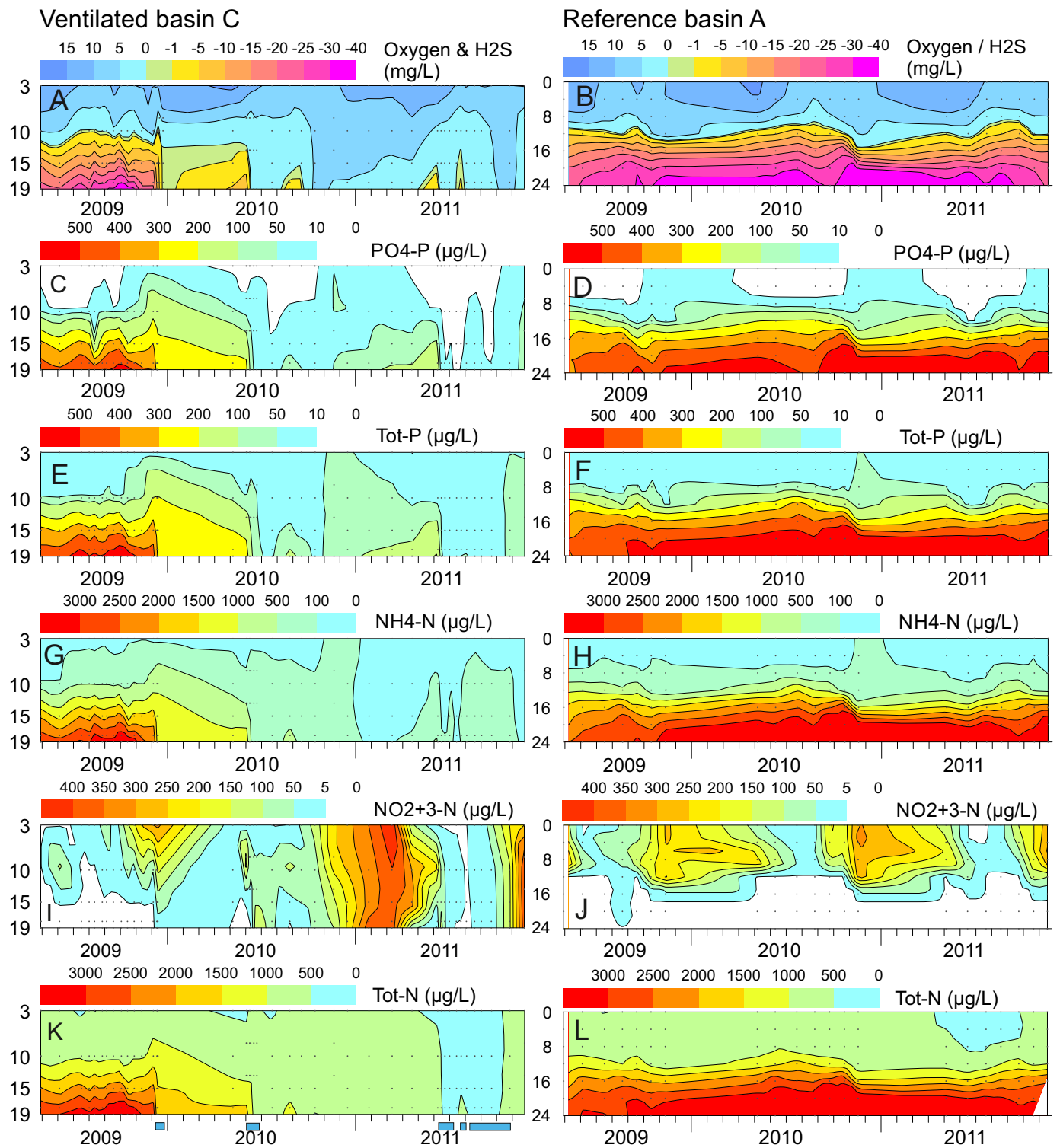


Fig. 6. Concentrations of A-B) oxygen and hydrogen sulfide (H₂S), C-D) phosphate (PO₄-P), E-F) total phosphorus (Tot-P) G-H), ammonium (NH₄-N), I-J) NO_x (sum of NO₂ + 3-N), and K-L) total nitrogen (Tot-N) in the ventilated basin in Lännerstasundet (left) and in the reference basin A (right) during 2009–2011. Blue bars below the time scale of Tot-N indicate ventilation periods. Triangulation with linear interpolation was used to produce the contours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Gantzer et al., 2009; Niemisto et al., 2016). As a result of the possible explanations above, the ventilation could not maintain oxic conditions and the Sandöfjärden basin became anoxic as in previous, non-pumped summers.

In Lännerstasundet it was found that, 11 days of ventilation in early winter warmed and lowered the salinity in the anoxic sub-pycnocline

water. The ventilation removed hydrogen sulfide and the basin became oxic without breaking the halocline. Also the summertime ventilation campaigns in 2010 and 2011 reduced the sub-pycnocline density by warming and decreasing the salinity. In early October 2010, the surface water in the surrounding areas cooled below the temperature in the sub-pycnocline water of the pumped basin. The

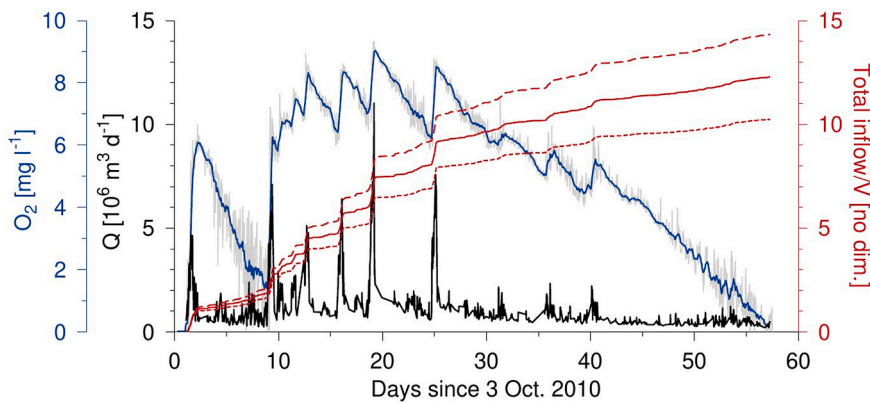


Fig. 7. Time series of oxygen at the mooring (18-m depth, 30-min interval, light gray), the 12-h low-pass filtered oxygen (blue), and the estimated inflow rate (Q) from the adjacent basin to the eastern pumped basin (black). The accumulated total inflow scaled with the volume (V) of the bottom layer below the pycnocline (red, right axis) and the sensitivity experiments with a $\pm 50\%$ variation of the oxygen sink due to remineralization of organic matter (λ') (red dashed lines) are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Bootstrap Tukey's test results for pair "reference basin before and after" and pair "ventilated basin before and after" pumping. 2.5th and 97.5th percentiles of ANOVA parameter estimates for sub-pycnocline nutrient pools are presented. Positive values show an increase and negative values a decrease in the pool size in units of kilograms. * denotes significance at the 95% confidence level.

Basin	Variable	2.5th percentile	97.5th percentile	Significance
Reference	PO4-P	111	599	*
Ventilated	PO4-P	-364	-229	*
Reference	Tot-P	10	456	*
Ventilated	Tot-P	-379	-228	*
Reference	NH4-N	465	3067	*
Ventilated	NH4-N	-2182	-1617	*
Reference	NO2 + 3-N	-357	84	
Ventilated	NO2 + 3-N	-5	194	
Reference	Tot-N	-531	2612	
Ventilated	Tot-N	-2134	-1563	*
Reference	DIN	449	2843	*
Ventilated	DIN	-2077	-1558	*
Reference	DIN:DIP	0.3	-1.4	
Ventilated	DIN:DIP	4.5	19.6	*

cooled oxic water with the same or slightly higher salinity flowed first into the western reference basin and streamed above the sub-pycnocline waters to the experimental basin. The inflowed water would have eddied through the experimental basin, but the implemented pumping had decreased the density stratification of the basin. Therefore, the inflowed water was able to sink into the bottom layer of the pumped basin. This suggested that pumping enabled the sinking of inflowing water and oxidation events. Such inflows occurred several times and kept the sub-halocline conditions relatively well oxidized for months after the ventilation period of only a few weeks.

The model estimates for oxygenation events highlighted that the inflow events occurred within hours and that the entering volumes of water was very large compared with the volume below the pycnocline of the experimental basin. The secondary oxidation effect was comparable to the results obtained from a similar ventilation experiment performed in more saline water on the Swedish western coast (Stigebrandt et al., 2015). However, the oxygenation efficiency of inflows in basins such as Lännerstasundet is dependent on the volume and oxygen concentration in the incoming water that can replace and mix with the ventilation affected bottom water.

4.3. Effects of ventilation on nutrients

Generally, the oxygen conditions were linked to changes in nutrient concentrations with a recognizable pattern. For example, in Sandöfjärden the concentrations of ammonium and phosphate were low in near-bottom water when oxygen was present. Once ventilation was unable to keep the sub-pycnocline water oxic, the accumulation of ammonium and

phosphate started. The accumulation of ammonium to levels above those from summers without ventilation was likely explained by warming, which enhanced mineralization below the pycnocline. The phosphate accumulation after the formation of anoxia indicated the key role of oxygen in phosphorus retention, which also has been observed in the main basins of the open Baltic Sea (Viktorsson et al., 2012). The oxygen is linked to phosphorus cycling through redox reactions of iron and microorganisms taking up phosphorus under oxic conditions (Deinema et al., 1985; Hupfer and Gachter, 1995; Viktorsson et al., 2012). The introduction of oxygen into the system enhances nitrification and phosphorus binding to iron. The artificial ventilation is expected to form nitrate and decrease the release of phosphorus and therefore increase the DIN:DIP ratio. However, the poor success of ventilation kept the sub-pycnocline water DIN:DIP ratio low (0.1–3.9) in Sandöfjärden.

This was not the case in Lännerstasundet, where ventilation increased the DIN:DIP ratio. An increased ratio was also observed in the ventilation experiment realized in the By Fjord (De Brabandere et al., 2015; Stigebrandt et al., 2015). In Lännerstasundet, the concentration of NOx increased markedly from the surface towards the near-bottom layers after ventilation. However, there was an 11-kg decrease in NOx (Table 3), which corresponded to a removal rate of $6.0 \text{ mg N m}^{-2} \text{ d}^{-1}$. This value is comparable to denitrification rates between 1.4 and $9.5 \text{ mg N m}^{-2} \text{ d}^{-1}$ measured after artificial sub-pycnocline water ventilation in the By Fjord (De Brabandere et al., 2015). In both cases, the oxidation was likely to favor NOx formation and nitrogen removal through the coupled nitrification-denitrification, which is the key process in nitrogen removal in the Baltic Sea (Hietanen and Kuparinen, 2008; Tuominen et al., 1998).

The ammonium pool decreased without a corresponding increase in the NOx pool in Lännerstasundet (Table 3). In the By Fjord, ventilation also decreased the efflux of ammonium from the sediments, but a considerable discrepancy between the denitrification rate and large removal of DIN was observed (De Brabandere et al., 2015). It is possible that a part of the DIN removal was explained by sediment microbes, such as Beggiatoa, accumulating nitrate intracellularly (McHatton et al., 1996) or by adsorption of ammonium on particles (Rozic et al., 2000) in the By Fjord and Lännerstasundet. Additionally, a part of the ammonium may have been exported out from the pumped basin in Lännerstasundet.

In Lännerstasundet, even a short-term ventilation decreased the pool of total phosphorus and phosphate, resulting in a removal of 0.26 and 0.52 g P m^{-2} of phosphorus and phosphate, respectively. The significant removal and retention of phosphate in the water column could be explained with dilution and further outflow and with binding of phosphorus by iron oxides and microorganisms taking up phosphorus under oxic conditions (Deinema et al., 1985; Hupfer and Gachter, 1995; Viktorsson et al., 2012). The increase in the pool of total nitrogen suggested resuspension of organic and nitrogen-rich matter caused by the downward flow of water induced by the pump. The increase in total nitrogen

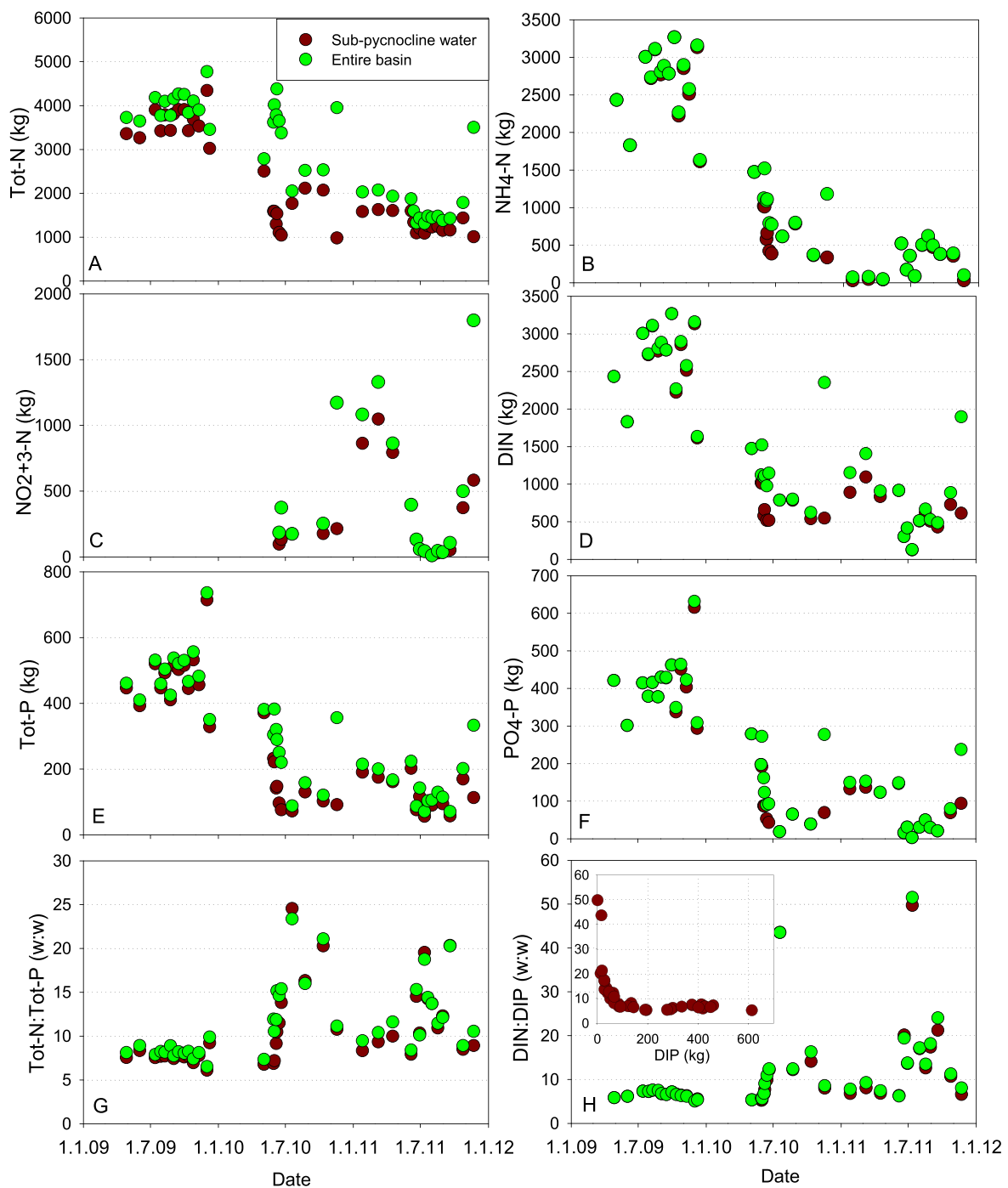


Fig. 8. Changes in the pools for A) total nitrogen (Tot-N), B) ammonium (NH₄-N), C) nitrite+nitrate (NO₂ + 3-N), D) inorganic nitrogen (DIN), E) total phosphorus (Tot-P), F) phosphate (PO₄-P), G) Tot-N:Tot-P ratio, and H) inorganic nitrogen:inorganic phosphate (DIN:DIP) ratio in the sub-pycnocline water volume below the sill depth of 8 m (brown) and the volume of the entire experimental basin of Lännerstasundet (green). The relationship between the pool of DIP and DIN:DIP ratio below the sill depth is shown in the left upper corner of panel H.

and the lower removal efficiency for total phosphorus than phosphate can be partly explained by the resuspension of particulate matter (see Niemisto et al., 2016).

The termination of ventilation in Lännerstasundet led to anoxia and an increase in the concentrations of ammonium and phosphate. Iron concentrations did not increase in either of our experimental basins, which is typical for marine systems (Blomqvist et al., 2004; Roden and Edmonds, 1997). In both basins, the phosphate concentration surpassed that of dissolved total iron, which indicated that the formation of iron sulfides inhibited the release of iron but enabled the benthic release of

phosphate to the sub-pycnocline water. The behavior of iron and phosphorus in the basins is comparable to the findings of laboratory and near-bottom water studies from eutrophic sub-basins of the Baltic Sea (Blomqvist et al., 2004; Lehtoranta and Heiskanen, 2003). Regarding oxygenation techniques, the formation of iron sulfides decreases iron ability to scavenge phosphate from the water even if it would be oxidized in brackish systems.

Table 3

Estimated nutrient removal for an area below the sill depth of 8.6 m (area 0.26 km²) in the Lännerstasundet experimental basin based on changes in nutrient pools during the ventilation campaign in 2010.

Date	Tot-P (kg)	PO4-P (kg)	Tot-N (kg)	NH4-N (kg)	NOx (kg)	DIN (kg)
2 June 10	382	272	4011	1517	259	1776
9 June 10	289	123	4375	1106	234	1340
Outflow for 7 days	36	15	520	163	37	200
Inflow for 7 days	13	0	375	8	23	31
Removal	-70	-134	509	-256	-11	-267

5. Conclusions

The aquarium simulations showed that the depth of pycnocline controls the upper limit of the spreading plume and the topography of the basin regulates the areas which the plume can reach. Ventilation of surface water into sub-pycnocline water layers weakens density stratification, and summertime pumping of surface water into sub-pycnocline waters warms the sub-pycnocline water and surface sediment. Warming may accelerate biogeochemical processes and the release of ammonium. In salinity-stratified basins, summertime ventilation is likely to promote horizontal inflows of oxic water from adjacent basins after cooling of surface water in autumn. Such inflows may oxidize the bottom layer of a pumped basin and extend the oxic period significantly. Ventilation may keep phosphate levels low if near-bottom water remains oxic and even remove phosphorus, as indicated by the results from Lännerstasundet. Thus, at least in coastal basins where salinity is the main factor causing density stratification, the ventilation and inflows of oxic water from adjacent areas may be an option to improve the status of the coastal basins suffering from anoxia.

In temperature-stratified basins, such as Sandöfjärden, the oxidation through inflows is not promoted similarly as in salinity-stratified basins. Furthermore, the ventilation may expand the oxygen-consuming bottom area below the pycnocline and a significant proportion of the pumped oxygen can be transported away from the area within the expanding plume below the pycnocline. Warming may also promote oxygen consumption via increased remineralisation rates of organic matter. Taking this into consideration, a successful oxygen delivery rate must significantly exceed the oxygen consumption rate estimated for the natural conditions. However, the pumping capacity needed to reach such a delivery rate may accelerate the decay of the seasonal pycnocline and cause an early overturn.

After the ventilation ceases, previous conditions with stratification, anoxia, and bottom release of ammonium and phosphate are re-established. The effect of ventilation on aerobic and anaerobic respiration pathways, redox reactions, and sequestering mechanisms for nutrients remains unclear. Thus, there is a further need to study how the ventilation-induced changes in hydrodynamics, temperature, and oxygen conditions affect the cycles of carbon, nitrogen, phosphorus, iron, and sulfur and the derived influence on the biota in oxygenated areas.

CRedit authorship contribution statement

Jouni Lehtoranta: Conceptualization, Investigation. **Jørgen Bendtsen:** Conceptualization. **Christer Lännergren:** Methodology, Investigation. **Erkki Saarijärvi:** Conceptualization, Investigation. **Magnus Lindström:** Methodology, Investigation. **Heikki Pitkänen:** Conceptualization, Investigation.

Declaration of Competing Interest

One of the authors Erkki Saarijärvi works in VesiEko company which delivered the pumping devices. He participated in planning and

calculations of the study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoleng.2022.106611>.

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