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RESEARCH PAPER

Closed-circuit hypolimnetic withdrawal and treatment: impact of effluent discharge on epilimnetic P and N concentrations

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Abstract

Closed-circuit hypolimnetic withdrawal and treatment systems (HWTS) represent a novel lake restoration technique in which nutrient-rich near-bottom water is pumped through a treatment system and returned to the same lake. However, the design of such systems is not yet standardized and routing of effluent waters must be planned carefully to minimize the risk of adverse water quality impacts. Here we assessed the risk of HWTS effluent to elevate epilimnetic nutrient concentrations under a range of withdrawal and effluent discharge scenarios (4.5–45 L/s, sand filtration only and sand filtration combined with wetland) at Lake Kymijärvi, Finland. The filter of the HWTS removed most of the phosphorus (67%), but only a small fraction of nitrogen (14%). For both nutrients, filter effluent concentrations were elevated with respect to the lake epilimnion. However, the results of our calculations suggest only minor increases (0–12%) in epilimnetic phosphorus concentrations in all withdrawal and discharge scenarios. For nitrogen, somewhat higher increases (1–17%) are expected unless the filter effluent is first discharged into a wetland as part of the HWTS circuit. We conclude that the impacts of the filter effluent on the epilimnion do not mask the benefits gained in the treated lake by the closed-circuit HWTS, but use of a buffering system such as a wetland decreases the risks further.

Keywords Lake · Eutrophication · Management · Restoration · Phosphorus · Nitrogen

Introduction

Hypolimnetic withdrawal is a well-established lake restoration method based on removing phosphorus (P) and other nutrients from stratifying eutrophic lakes. By extracting nutrient-rich near-bottom water from the lake, this technique can lead to long-term improvements in water quality (Dunalska et al. 2007; Nürnberg 1987). The technique is traditionally carried out by simply diverting the withdrawn water downstream of the treated lake. However, the possibility to purify the water to avoid polluting the downstream systems has lately been studied by investigating the suitability of different P-sorbing filter materials through which the water can be led (Hussain et al. 2014; Łożyńska et al. 2020, 2021).

Closed-circuit hypolimnetic withdrawal and treatment systems (HWTS) are a recent modification of hypolimnetic withdrawal and purification. In this application, water is returned to the same lake after nutrient removal instead of being discharged downstream. The advantage of the HWTS approach is that the withdrawal does not risk lowering the lake water level, hence use of the technique is not dependent on the lake outflow rates. A few cases of closed-circuit

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HWTS have been documented recently, indicating increasing popularity of the technique (Nürnberg 2020; Renman and Renman 2022; Silvonen et al. 2022).

One such system was constructed at the Myllypohja basin of Lake Kymijärvi, southern Finland in 2018. The system is designed primarily to remove P through precipitation and capture in a sand filter. The geochemical functioning of the treatment unit has been thoroughly examined before (Silvonen et al. 2022), as well as the hydrodynamic limitations of the method at Myllypohja basin (Silvonen et al. 2021).

A key aspect of the design of closed-circuit HWTS is to ensure that effluent water returned into the treated lake does not risk harmful fertilization of the epilimnion during the operational time of the system. If nutrient retention in the HWTS is inefficient, treated water may boost primary production during the growth season when discharged into the epilimnion (Nürnberg 2020), temporarily negating the effects of the restoration measure. When establishing a new HWTS therefore, it is necessary to assess the extent to which discharged water may alter epilimnetic nutrient concentrations, and to evaluate how leakage of nutrients could delay the recovery process of the lake.

In the current study, we examined the effectiveness and potential impacts of the HWTS on Myllypohja basin by monitoring water quality in the lake and the treatment unit and estimating the effects of the returned water on the epilimnetic nutrient concentrations. We additionally discuss the expected time required to detect significant changes in lake water quality based on the observed efficiency of the system.

Materials and methods

Study site and experimental setup

Lake Kymijärvi is a stratifying dimictic lake located in the city of Lahti, southern Finland. The HWTS pilot is operational in the northwestern basin of the lake, Myllypohja (0.9 km^2; mean depth 4.3 m; Fig. 1, Table 1), which is a relatively independent system due to its separation from the southeastern basin by a shallow (depth < 3 m) strait, and the location of the lake outflow at the eastern end of Lake Kymijärvi. The lake became eutrophic in the mid-twentieth century due to nutrient loading from human activities in the catchment area, and even after significant reductions to external loading, water quality parameters such as epilimnetic total P (TP) and chlorophyll-*a* concentrations still exceed the threshold values for good condition defined in the Finnish lake typology for 'Shallow humus-poor lakes' (Aroviita et al. 2019). Hence, the ecological status of Lake Kymijärvi is classified as poor, which manifests itself in recurring algal blooms. This

Table 1 Basic morphological characteristics of Lake Kymijärvi and its Myllypohja basin

	Lake Kymijärvi	Myllypohja basin
Area (km^2)	6.5	0.9
Mean depth (m)	2.8	4.3
Max depth (m)	10.1	8.8
Volume (million m^3)	18.4	4.2
Water residence time (yr)	1.5	0.6

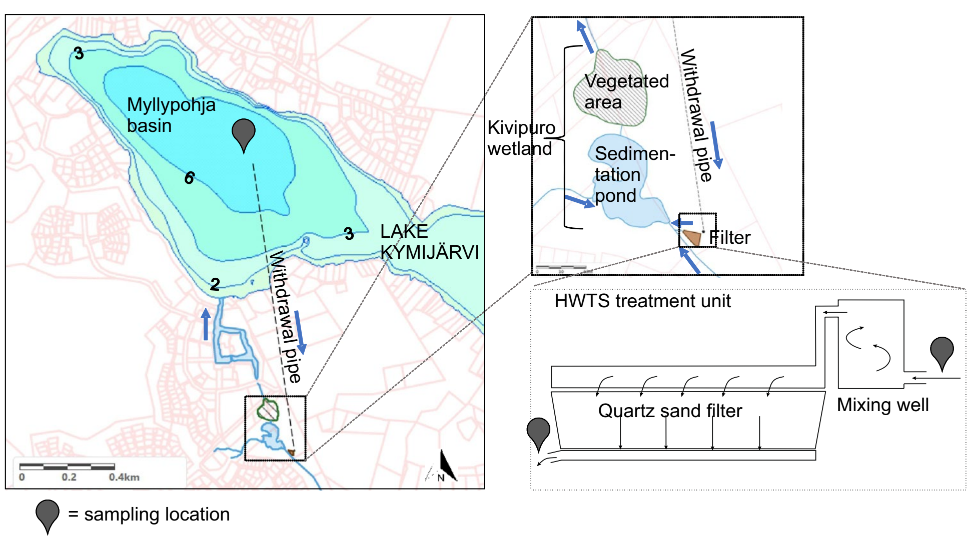

Fig. 1 The location of the HWTS pilot and the Kivipuro wetland at Myllypohja basin, Lake Kymijärvi, Lahti. The arrows indicate water flow direction. Map contains data from the Finnish Environment institute (depth curves) and National Land Survey of Finland (base map) 5/2022

implies that internal nutrient loading is currently a significant factor maintaining the eutrophic state of the lake.

In the HWTS at Myllypohja basin, anoxic near-bottom water is extracted from the deepest point (8.8 m) of the basin. The system relies on the dissolution and diffusion of P from the sediment into the overlying water in low redox conditions, which results in elevated concentrations in the deep water. The water is pumped through a withdrawal pipe into a treatment unit (Fig. 1). In the mixing well, turbulence facilitates aeration which initiates the oxidation of reduced substances, including dissolved ferrous iron (Fe(II)) abundant in the near-bottom water of Myllypohja basin (7–13 mg/L; Silvonen et al. 2022). The oxidized iron forms a precipitate and simultaneously binds dissolved P (Silvonen et al. 2022). This process can additionally be enhanced by the addition of treatment chemicals (Silvonen et al. 2022). The formed precipitate is captured in the treatment unit by slow sand (quartz) filtration, after which the water flows back into Myllypohja basin via the Kivipuro wetland and an adjacent channel (Fig. 1). The wetland was originally constructed in 2008–2011 for treating stormwaters from the surrounding urban area in the city of Lahti, and it consists of a sedimentation pond of 6430 m^2, max. depth 1.5 m, and a vegetated area of 5760 m^2 (Punttila 2014). The hydraulic retention time (HRT) of the sedimentation pond varies between approximately 1–14 days depending on flow rates of stormwaters and groundwater. As wetlands are known to reduce concentrations of nutrients and other elements from agricultural runoff (e.g., Koskiaho et al. 2003; Uusi-Kämppä et al. 2000) and municipal wastewaters (Wang et al. 2017), the inclusion of a wetland in the HWTS can benefit the system by providing an environment for additional nutrient removal and by buffering other water quality changes before the treated water is introduced to the epilimnion of Myllypohja basin.

The functioning of the HWTS has been studied during operation in years 2019−2020 through experimental pumping runs (Silvonen et al. 2022). In the current study, we focus on the 59-day-long experimental period in 2020 (10^{th} of July to 10^{th} of September), during which water filtration was carried out with a 200 m^2 quartz sand filter and no added treatment chemicals. This period consisted of multiple pumping experiments (duration 2–6 d) with varied flow rates (1.5–10.2 L/s) set through the electronic pump control panel, and intervening maintenance breaks (Fig. 2). The mean pumping rate of hypolimnetic water over the entire season including the maintenance breaks was 4.5 L/s.

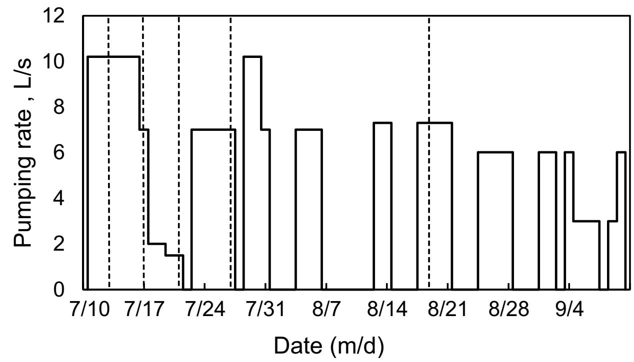

Fig. 2 The pumping rates of hypolimnetic water through the HWTS in 2020. Sampling dates in the treatment unit (7/13, 7/17, 7/21, 7/27, 8/19) are marked with dashed lines

Sample collection and measurements

Before the first experimental runs of the HWTS in 2019–2020, water column temperature and dissolved oxygen (DO) as well as epilimnetic nutrient concentrations were monitored in Myllypohja basin during the thermally stratified season in two reference years (2017 and 2018), 1–5 times each month (June/July–August). Temperature and DO were measured from surface to bottom at 1 m intervals using a YSI-6600 V2 sonde (Yellow Springs Instruments, USA). Water samples were collected from surface to bottom with a Limnos tube sampler (h = 1 m, V = 7.5 L) at 1 m intervals in duplicate at each depth. From each Limnos cast, a sample of 250 mL was taken into a polyethylene bottle for analysis of total phosphorus (TP, 2017 and 2018) and total nitrogen (TN, 2018 only). Additionally, smaller subsamples were filtered from each 250 mL bottle with a syringe filter (pore size 0.2 µm) into centrifuge tubes: 1) 10 mL for phosphate (PO_4–P, 2017 and 2018), 2) 10 mL for ammonium (NH_4–N, 2018 only). Subsample for PO_4–P was acidified for preservation with 100 µL of 4 M H_2SO_4.

In the HWTS in 2020, water samples were collected on four dates (Fig. 2) from the withdrawal pipe before the treatment unit (untreated water) and from the filter effluent (Fig. 1) directly into 250 mL polyethylene bottles in duplicate for each location for TP and TN analysis. Subsamples for PO_4–P and NH_4–N were taken and preserved as described above for the lake samples. Temperature and DO of the untreated hypolimnetic water and the filter effluent were measured with a YSI-6600 V2 sonde.

Concentrations of TP, TN, PO_4–P and NH_4–N in the water samples were analyzed by spectrophotometry with Lachat Quikchem® 8500 Flow Injection Analysis System (Lachat instruments, Loveland, USA).

Calculations

The depth of the thermocline in Myllypohja basin was determined as the layer with maximum temperature change (Keller et al. 2006) in the temperature data in the reference years. Epilimnetic reference concentrations of TP, TN, PO_4–P and NH_4–N were defined as the mean values of these variables in the depth interval between the lake surface and the thermocline in the years 2017–2018.

The effect of the effluent discharged from the treatment unit of the HWTS on Myllypohja epilimnetic TP and TN concentrations was estimated with five withdrawal and discharge scenarios:

1) 4.5 L/s, duration 59 d.
2) 5 L/s, duration 80 d.
3) 10 L/s, duration 80 d.
4) 20 L/s, duration 80 d.
5) 45 L/s, duration 80 d.

Scenario 1 represents the conditions in the HWTS piloting year 2020 (mean withdrawal rate and total duration of all experiments including maintenance breaks), while Scenarios 2–5 are a selected range of withdrawal rates over the entire stratified season in Myllypohja basin in summer, which is 80 d according to Silvonen et al. (2021). The maximum withdrawal rate in the present study (Scenario 5, 45 L/s) was set based on the hydrodynamic simulations by Silvonen et al. (2021) to avoid significant disturbances to the thermal stratification of Myllypohja basin.

The effects of these withdrawal and discharge scenarios were calculated as the final epilimnetic concentrations (*fec*) of TP and TN in Myllypohja basin after the entire withdrawal period during one season, assuming complete mixing of the discharged water into the epilimnion. We simulated two discharge options: a) direct discharge of filter effluent from the HWTS into the epilimnion, and b) discharge of filter effluent from the HWTS into the epilimnion via Kivipuro wetland, with retention efficiencies of 33% for TP and 38% for TN as previously estimated for Kivipuro wetland by Punttila (2014):

$$fec_a = \frac{V_w \times \mu c_w + V_{epi} \times \mu c_{epi}}{V_w + V_{epi}} \quad (1)$$

$$fec_b = \frac{V_w \times \left(\mu c_w - \mu c_w \times rm\right) + V_{epi} \times \mu c_{epi}}{V_w + V_{epi}} \quad (2)$$

where *V* is the total volume of the withdrawn hypolimnetic water (*w*) and epilimnion (*epi*); *μc* is the mean concentration in the withdrawn hypolimnetic water (*w*) and epilimnion (*epi*), and *rm* is the expected nutrient removal efficiency percentage of Kivipuro wetland.

The nutrient removal efficiency of Kivipuro wetland was not measured empirically in this study due to the short durations of individual experimental runs of the HWTS (Fig. 2) relative to the wetland HRT range, and due to uncertainty of the rate of groundwater discharge into the wetland. The HRT of Kivipuro wetland is expected to remain within a range in our withdrawal and discharge scenarios (flow rates 4.5–45 L/s) similar to that calculated from stormwater flow rates measured in spring and autumn (0–50 L/s; Punttila 2014), because stormwater flow is expected to be low in the summer months, in which the HWTS is operated. Because HRT is a key factor in the nutrient removal efficiency of wetlands (e.g. Conn and Fiedler 2006; Koskiaho et al. 2003; Walker 1998;), the same nutrient removal efficiencies as estimated by Punttila (2014) are assumed here.

Results

Measurements in Myllypohja basin and the HWTS treatment unit

The mean temperature in the surface layer of Myllypohja basin was approximately 18–21 °C in the reference years 2017–2018 (Table 2). The near-bottom water temperature was 8–11 °C. The thermocline in both years was at approximately 5–6 m depth in both years, beneath which DO concentrations declined below 2 mg/L. The thickness of the hypolimnion was thus approximately 4 m. The mean TP concentration in the epilimnion in the reference years was 35 μg/L, of which 3 μg/L was PO_4–P (Fig. 3). The epilimnetic TN concentration was 737 μg/L, and of this 14 μg/L was NH_4–N. All original data on the reference years can be found in Table S1.

In the experimental runs of the HWTS in 2020, the mean temperature of the inflowing hypolimnetic water (untreated water) was 12.4 °C with 0.4 mg/L DO, while the filter effluent was 14 °C with a mean DO concentration of 4.1 mg/L. The mean TP concentration in the untreated water was 255 μg/L, mostly consisting of soluble PO_4–P (210 μg/L; Fig. 3). The concentrations varied during the experimental period between 150–355 μg/L (TP) and 125–287 μg/L (PO_4–P). The filter effluent contained 85 μg/L of TP and 42 μg/L of PO_4–P on average, implying that the mean removal efficiency of the filter was 67% for TP and 80% for PO_4–P.

The TN concentration in the untreated water ranged between 1910 and 3700 μg/L with a mean value of 2575 μg/L (Fig. 3). In the filter effluent, the mean concentration was 2220 μg/L, but considerably higher concentrations than this were measured on one date (3190–3250 μg/L). Similarly, there was a small decline in the mean NH_4–N concentration from the 1455 μg/L of the untreated water to the 1212 μg/L of the filter effluent, but higher filter effluent values (1550–1600 μg/L) were also measured. Based on the mean values, the filter removed 14% of TN.

Table 2 Mean and standard deviation (SD) of temperature and dissolved oxygen (DO) in Myllypohja basin in the reference years (2017–2018) in June/July–August. Hypolimnetic strata are highlighted with grey fill color

Depth (m)	Reference year	Temperature (°C)		DO (mg/L)	
		Mean	SD	**Mean**	SD
1	2017	18.1	1.5	9.0	0.8
2	2017	18.1	1.5	8.9	0.8
3	2017	18.0	1.5	8.9	0.7
4	2017	17.9	1.5	8.2	0.9
5	2017	17.1	1.4	4.5	2.7
6	2017	15.3	2.1	2.0	3.2
7	2017	12.9	2.2	0.9	1.1
8	2017	11.4	2.4	0.3	0.1
9	2017	11.4	1.7	0.2	0.0
1	2018	20.8	3.2	9.4	1.6
2	2018	20.3	2.7	9.4	1.6
3	2018	18.9	1.6	8.1	1.7
4	2018	18.0	1.6	6.6	1.9
5	2018	16.4	1.1	4.3	2.8
6	2018	12.6	1.1	0.8	0.6
7	2018	9.6	0.6	0.2	0.2
8	2018	8.4	0.5	0.1	0.1
9	2018	7.9	0.5	0.1	0.1

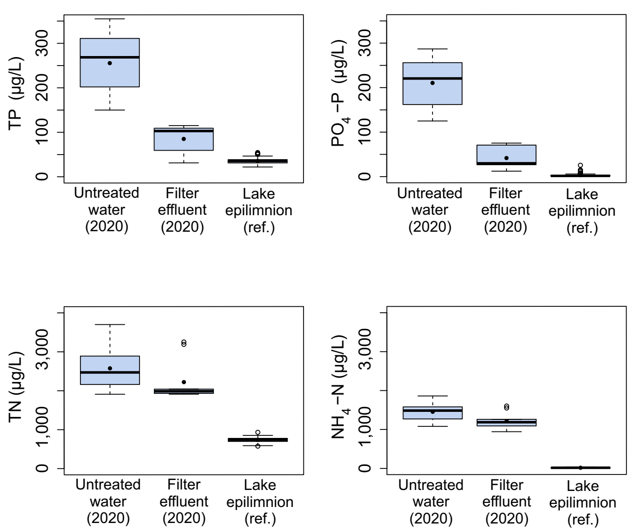

Fig. 3 Concentrations of TP, PO_4–P, TN and NH_4–N in untreated hypolimnetic water and filter effluent in the experimental runs of the HWTS in 2020, and reference concentrations in the epilimnetic water of Myllypohja basin during the stratified seasons in 2017–2018. Lower and upper boundaries of box plot represent 1st and 3rd quartiles, respectively. A horizontal line and closed circle represent median and mean, respectively. Whiskers and open circles represent range and outliers, respectively

Effect of water discharge from the HWTS on the epilimnetic TP and TN concentrations

In the discharge option 'a' (filter effluent discharged directly to Myllypohja basin), the fec_a of TP was calculated to increase slightly, with concentrations varying from 36 to 40 µg/L depending on the withdrawal scenario (Table 3). However, these values still fall within the standard deviation (SD) of the reference concentration in Myllypohja epilimnion. For TN, Scenario 5 (45 L/s, 80 d) was estimated to cause the most distinct increase in the epilimnetic concentration with fec_a of 860 µg TN/L, exceeding the measured SD of the reference concentration of TN.

These effects are slightly less pronounced in the calculations in which the wetland is included in the HWTS (discharge option 'b'), especially in the scenarios with the highest withdrawal rates. For TP, the fec_b in all of the scenarios varies from 36 to 37 µg/L (0.5–5.9% lower than in discharge option 'a'), while the range for TN in the different scenarios is 741–790 µg/L (0.7–8.1% lower than in discharge option 'a'). In the case of TN, fec_b falls within the SD of the reference measurements in all of the scenarios (Table 3).

Despite the unequal removal of TP and TN by the HWTS in the discharge option 'a', the N/P mass ratio in Myllypohja

Table 3 Reference concentrations (Ref.) of TP and TN in the epilimnion of Myllypohja basin as mean values ± standard deviation, and the estimated impacts of the closed-circuit HWTS on the final epilimnetic concentrations (*fec*) at the end of the hypolimnetic pumping period with different withdrawal and discharge scenarios in two discharge options: a) direct discharge of filter effluent into Myllypohja epilimnion, b) discharge of filter effluent into the epilimnion via Kivipuro wetland with retention efficiencies of 33% for TP and 38% for TN (Punttila 2014). Values exceeding measured reference concentration (Ref.)

Withdrawal scenario	Discharge option	*fec*, μg/L	
		TP	TN
No withdrawal	Ref	35.5 ± 6.7	736.8 ± 76.0
4.5 L/s, 59 d	a	35.8	746.6
5 L/s, 80 d	a	36.0	751.5
10 L/s, 80 d	a	36.5	766.0
20 L/s, 80 d	a	37.4	794.0
45 L/s, 80 d	a	39.6	859.7
4.5 L/s, 59 d	b	35.6	741.0
5 L/s, 80 d	b	35.7	743.1
10 L/s, 80 d	b	35.9	749.4
20 L/s, 80 d	b	36.3	761.5
45 L/s, 80 d	b	37.3	789.8

epilimnion (20.8) is barely affected by the discharge of the filter effluent: the estimated ratio varies between 20.8 and 21.7 in Scenarios 1–5. Due to the higher retention of TN in the wetland, discharge option ‘b’ equalizes the removal efficiency differences between the two elements, and the resulting epilimnetic N/P mass ratio is expected to range between 20.8 and 21.2.

Discussion

Impacts of filter effluent discharge on the lake

The HWTS reduces concentrations of TP and PO_4–P from the inflowing hypolimnetic water to such an extent that even direct discharge of the filter effluent into the epilimnion of Myllypohja basin is not expected to cause major changes to the epilimnetic TP concentrations. This conclusion holds across the full range of simulated scenarios, including the 45 L/s, 80 d protocol estimated to be optimal for restoration of Myllypohja basin (Silvonen et al. 2021). Moreover, a large fraction of the effluent TP was non-PO_4–P. As Silvonen et al. (2022) found, the hypolimnetic water of Lake Kymijärvi is rich in iron (7–13 mg/L), and it binds dissolved P effectively in HWTS upon water aeration. Hence, roughly half of the effluent TP likely consisted of particulate iron-bound P, and therefore a major fraction of the leaching P is unlikely to boost algal growth in the oxic epilimnetic water of the recipient system.

For TN and NH_4–N, removal in the HWTS was expectedly lower, because N is not efficiently retained in the captured precipitate (Silvonen et al. 2022). The slight decline in the concentration of NH_4–N in the HWTS was likely due to oxidation of NH_4^+ into nitrate (NO_3) upon water aeration, and thus the concentration of total bioavailable N did in fact not decrease markedly during the filtration. Because the concentration difference of TN between the filter effluent and the epilimnion of Myllypohja basin was considerable, and a large fraction of this is in a bioavailable form, the use of the wetland as a buffer zone between the HWTS filter and the lake appears justified in this setting. With the wetland considered in the simulations, estimated impacts on epilimnetic TN concentrations were mostly minimal. Wetlands are known to effectively remove the most bioavailable fractions of TN, including NH_4^+ and NO_3^-, by plant uptake or coupled nitrification–denitrification (Lin et al. 2002; Tanner et al. 1995; Wetzel 2001). Due to the high concentrations of NH_4–N in the filter effluent (1212 μg/L), this functionality is particularly beneficial in the case of Myllypohja.

A slight increase in the mass ratio of N/P in the epilimnion may occur in the discharge option ‘a’ with the highest withdrawal rates (Table 3). However, this is not expected to trigger changes in the phytoplankton community structure in the lake; although there is no single N/P ratio that can be determined as a threshold for N or P limitation for productivity in lakes throughout the entire growth season (Elser et al. 2007; Sterner 2008), mass ratios above 20 are more likely to suggest P limitation, which is typically the case in high-latitude stratifying lakes (Downing and McCauley 1992; Räike et al. 2003; Søndergaard et al. 2017). A potential increase in the N/P ratio in Myllypohja basin due to the closed-circuit HWTS is thus rather expected to only reinforce the prevailing P limitation.

If considerable impacts on the epilimnion would be expected due to the filter effluent discharge, an alternative configuration would be to pump the filter effluent back into the hypolimnion instead of at the lake surface, as is done in Lake Bornsjön, Sweden (Nürnberg 2020). In this case, nutrient transport from hypolimnion to epilimnion during the operational season of the HWTS is avoided.

In the HWTS at Myllypohja basin, this has not been considered a primary option for two main reasons. First, the withdrawn hypolimnetic water warms up in the HWTS circuit while being exposed to sunlight and high air temperatures during summer months. Returning this warmer filter effluent (14 °C) into the cold hypolimnion (8–11 °C) could increase the impact of the HWTS on the thermal stratification and, in the worst case, trigger an overturn during the growth season and boost algal production through nutrient supply to the photic zone. Second, introducing filtered, partially oxygenated water into the anoxic hypolimnion could negate the P extraction efficiency of the HWTS due to both dilution and oxidation effects, despite of the fact that warming of the hypolimnion could in theory improve the P removal potential of the HWTS by enhancing sedimentary decomposition processes and P release.

In enclosed treatment plants with greater capacity and shorter water residence time, such as the system in Bornsjön, the warming effect of the treatment system may be more minor and thus not pose a significant risk to the stratification, but in open treatment units it should be considered more carefully. In the HWTS of Myllypohja basin, discharging the filter effluent into the epilimnion may not entirely eliminate this risk either: the temperature of the filter effluent (14 °C) is close to that measured near the metalimnion (Table 2), which means that the discharged effluent would sink to the metalimnetic strata. This could potentially decrease the thermal stability of the water column by dissipating the metalimnion. This ensures that the inclusion of a wetland in the HWTS, which allows further equilibration of the water temperature and DO concentration with the atmosphere, cannot have the strong impact on the epilimnion.

Implications of nutrient leakage from HWTS on expected restoration results

At present, the HWTS at Myllypohja basin is a pilot with pumping rates up to 10 L/s. In terms of lake restoration, greater withdrawal rates are beneficial to achieve sufficient P removal goals within a more reasonable timeline, especially if the efficiency of the system is enhanced by a wetland. On the other hand, the overall efficiency of the HWTS also affects the timeframe during which results can be expected in the target lake. Using the same approach as Silvonen et al. (2021) but with the TP removal efficiency of the HWTS considered (67% in discharge option ‘a’, additional 33% in discharge option ‘b’), we estimated the effects of pumping rate and HWTS efficiency on the required time to decrease the epilimnetic TP concentration of Myllypohja basin through the closed-circuit HWTS by applying the empirical regression by Nürnberg (2020). With the target epilimnetic concentration of < 25 µg TP/L (threshold value for good ecological status for ‘Shallow humus-poor lakes’ defined by Aroviita et al. (2019), we calculated the required total areal TP export (TP_{RTAE}) to decrease the epilimnetic TP concentration in Myllypohja basin to 24.5 µg/L:

$$TP_{RTAE} = 10^{\frac{TP_{\Delta epi} - 0.471}{-0.331}} \tag{3}$$

where $TP_{\Delta epi}$ is the required change in the epilimnetic TP concentration to reach the desired concentration, expressed as a (negative) fraction of 1.

Based on the reference concentration of TP in Myllypohja epilimnion (35 µg/L) and the target concentration 24.5 µg/L, TP_{RTAE} receives the value 213 mg/m^2, which equals to 192 kg TP for the entire Myllypohja basin. With mean TP concentration of 255 µg/L in the inflowing hypolimnetic water (Fig. 3) and an 80 day pumping period each year, the target concentration of epilimnetic TP is expected to be reached in 3–33 years depending on the withdrawal rate (5–45 L/s) and filter effluent discharge option (see Fig. S1 for all estimated durations). On the other hand, Silvonen (2022) estimated that if the withdrawn water is instead discharged downstream of the lake (conventional hypolimnetic withdrawal) by replacing 30% of the natural outflow of Lake Kymijärvi with it, the same goal is reached within approximately 4 years. This implies that P removal via conventional hypolimnetic withdrawal may be more efficient if the outflow rate of the lake is high enough to allow an optimal withdrawal rate for most of the time.

Similarly to the results shown in Table 3, the inclusion of the wetland in the circuit makes a slight difference to the efficiency of the system, reducing the restoration time by a theoretical 0.5–4.6 years, or 14%. In practice, several factors, however, contribute to uncertainty in estimated restoration time. For example, interannual fluctuations in the chemical characteristics of the near-bottom water affect the TP removal efficiency, while variations in epilimnetic nutrient concentrations affect the progress towards the target TP value. This is reflected in the shorter estimated durations for the 45 L/s scenario (3–4 years) in this study compared to those reported by Silvonen et al. (2021) (ca. 5 years), even though the latter assumed a 100% removal efficiency. This is due to the higher hypolimnetic TP concentrations measured in the current study, and the lower mean epilimnetic TP of the reference years 2017 and 2018 (35 µg/L instead of 40 µg/L). Moreover, the nutrient removal efficiency of the wetland may vary seasonally and between years: e.g., heavy precipitation and hence shorter HRT may significantly decrease the efficiency.

Conclusions

Although fractions of both TP and TN removed from the hypolimnion via HWTS pass through the system and are circulated back to the epilimnion, the impacts of the HWTS filter effluent on the epilimnetic TP and TN concentrations of Myllypohja basin are mostly minimal. Inclusion of a wetland into the circuit can reduce the impacts further. The net removal of TP by the HWTS is high enough to have significant restoration effects in P-limited lakes on timescales of years to decades, particularly with higher withdrawal rates and even in systems without wetlands. In the long run, the benefits of the closed-circuit HWTS in such lakes are therefore likely to outweigh possible temporary negative impacts of the filter effluent on the epilimnion. In the case of TN, removal in a water aeration and slow sand filtration-based HWTS is less efficient, and a N-removing treatment phase is required to supplement nutrient drawdown. Thus, in systems in which N has a stronger role as a regulator of productivity, we recommend the use of wetlands as an integral part of the design of future hypolimnetic withdrawal and treatment systems.

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