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RESTORATION OF EUTROPHIC LAKES

Review Paper

Hypolimnetic withdrawal as a lake restoration technique: determination of feasibility and continued benefits

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Abstract The withdrawal of hypolimnetic water enriched with nutrients and reduced substances has been used as a lake restoration technique (hypolimnetic withdrawal, HW) for more than 60 years. By reducing internal phosphorus loading, HW treats the cause of much of the water-quality deterioration in eutrophic stratified lakes, including cyanobacteria blooms. To support future applications, a feasibility study is presented that determines the applicability of HW to a drinking water source lake for the City of Stockholm as an example. Necessary treatment of the HW water includes a technically advanced facility. The possible application of passive siphoning by gravity limits recurring energy costs. The most efficient performance is ensured by the monitoring of HW operational variables and water quality in the source and receiving water. A review of the scientific literature and the worldwide web confirms that new and continued HW applications improve water quality in stratified lakes with anoxic hypolimnia. A previously developed model for the prediction of epilimnetic TP decreases from the long-term TP export via HW was supported by results from several new applications. Benefits of flow regulation considering climate change variability have been reported, suggesting that HW could play a progressively important role in lake management.

Keywords Internal phosphorus load · Prediction · Stratified lakes · Anoxia · Eutrophic · Treatment

Introduction

Thermally stratified lakes can develop an anoxic hypolimnion when the microbial decomposition of organic substances removes dissolved oxygen in the deep water. Sediments underlaying such hypolimnia often become a phosphorus (P) source, especially after accumulation of legacy P that leads to enrichment in easily available sediment P (Nürnberg et al., 2018; Wang et al., 2018).

Such internal P loading is especially problematic when external P input has been reduced, but trophic state and water quality have not improved satisfactorily. In this situation, a lake restoration treatment is needed that can decrease the influence of internal P loading on water quality. Restoration methods exist and include chemical inactivation by aluminum compounds that adsorb phosphate or by lanthanum-amended clay (Phoslock) that binds phosphate

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permanently in the sediments (Copetti et al., 2016; Spears et al., 2016; Huser, 2017; Araújo et al., 2018). Less effective technologies to reduce internal P loading are aeration and oxygenation (Niemistö et al., 2016; Tammeorg et al., 2017) despite their widespread use (Bormans et al., 2016), because they are not directly targeted at phosphorus.

In contrast to these relatively modern methods, the withdrawal of hypolimnetic water enriched with nutrients and reduced substances has been used since the mid-twentieth century. The first such application employed a wooden elongated box to withdraw hypolimnetic water by gravity instead of surface water during summer (Olszewski, 1973; Dunalska et al., 2007). Since then the pipe is often called Olszewski Pipe in the European restoration literature, and the technique is called hypolimnetic withdrawal (HW), bottom or selective withdrawal. This technique is powerful, and water-quality improvements have been documented in numerous applications (Nürnberg, 1987, 2007; Dunalska et al., 2007; Bormans et al., 2016). It is the most useful in stratified lakes with hypolimnia enriched in nutrients and oxygen-depleting substances. In lakes that were subjected to HW, hypolimnetic maximum TP concentrations were 2.2–90 times that of the epilimnion during summer and fall (Fig. 1).

The option of using passive siphoning that does not require any continuous energy input and only limited maintenance may be the reason that HW has been applied in situations of "natural beauty" and "pretty landscapes," e.g., lakes in the European Alps (Piburger See and Reither See, Austria and Lago Avigliana Grande, Italy), and in a popular USA State Park (Devil's Lake, Wisconsin (Lathrop et al., 2005)).

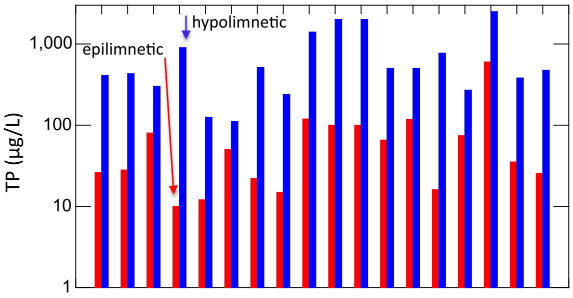

Fig. 1 Epi- and hypolimnetic total phosphorus (TP) concentration in 18 stratified lakes with anoxic hypolimnia before they experienced hypolimnetic withdrawal (Data from Nürnberg, 2007)

Following the installation of HW systems, 50% of epilimnetic TP concentration decreases could be explained by the accumulated TP export via HW (Nürnberg, 2007). Such appraisals of restoration success using a treatment variable (measured TP removal) is lacking when only water-quality improvements are reported. Long-term climate and hydrological variability, unmonitored external P inputs and other unconsidered variables can render simple before–after evaluations inconclusive.

Also, internal load reduction via HW reduced or eradicated the metalimnetic cyanobacteria *Planktothrix rubescens* (De Candolle ex Gomont) or related *P. agardhii* (Gomont) in at least four lakes, possibly by interrupting the metalimnetic flux of nutrients (Nürnberg et al., 2003).

Despite the apparent success of HW to diminish the influence of internal P loading on lake water quality, and despite low-energy application possibilities, its use is still rare. To help increase the knowledge about HW and facilitate the evaluation of HW suitability, I here present the steps needed to determine the feasibility of a recently initiated HW project in a specific lake. Bornsjön serves as this example lake, a backup drinking water supply for the City of Stockholm, where a detailed feasibility study led to the construction of a technically advanced HW application. The evaluation of risks as well as benefits is important, and HW requires special attention to "treatment waste," i.e., the impact of the HW water on downstream environments. In addition, this paper reviews information on worldwide HW applications. Such summaries were provided before (Nürnberg, 1987, 2007), and the present study highlights new, continued, and discontinued applications as of 2019.

Feasibility study to determine the potential risks and benefits of hypolimnetic withdrawal

Not all lakes can be restored by HW. Oligomictic and polymictic lakes with only cursory or nonexistent thermal stratification do not develop a separate and nutrient enriched deep-water layer so that HW does not increase P export (e.g., Lützelsee, Nürnberg, 2007). Lakes with a low flushing rate may not have enough water load to sustain the withdrawal volume required for an effective treatment. To avoid treatment failure, it is necessary to determine whether HW is applicable, and how much it would benefit a lake after implementation. In this section, I present an example for the determination of the applicability of HW as the restoration technique of choice to the Swedish lake, Bornsjön. Based on the feasibility study, HW was introduced in 2017.

Bornsjön characteristics

Bornsjön is a natural, oligo-mesotrophic lake that serves as a backup for drinking water to more than a million inhabitants of Stockholm, Sweden. Bornsjön has been studied extensively (Freshwater Research, 2012) and consists of three basins (Fig. 2) that are separated by sills at about 10 m depth. The two northern basins (Nordväst, NV; and Eastern, E) are relatively deep compared to their surface areas, so that their morphometric index is high (Table 1). The higher the index, the stronger is the summer stratification. Indices above 5 m/km^2 usually indicate a strong thermal stratification. Accordingly, Bornsjön can be classified as a dimictic stratified lake because it has a full circulation twice a year, with ice cover in the winter.

Bornsjön's trophic state variables (based on the classification in Nürnberg, 1996) indicated mesotrophic conditions with respect to summer nutrient (phosphorus and nitrogen) content and chlorophyll *a* concentration and oligotrophic conditions with respect to Secchi disk transparency and hypolimnetic anoxia (Table 1). Despite these relatively good water-quality conditions, some cyanobacteria species occurred occasionally. For example, the potentially toxic *Dolichospermum* (former *Anabaena*) was recorded in several years. Other cyanobacteria included: *Anabaena spp, Aphanizomenon spp, P. agardhii,* and *Snowella spp.* Some of these species are wide spread in Swedish lakes and have been found to produce cyanotoxins (e.g., Willen, 2001). It was feared that the increased eutrophication may increase cyanobacterial blooms, potentially compromising lake use as potable water source, and a preventative measure was sought.

While external load has been mitigated for more than 30 years, internal load was substantial (at least 140% of external load) and had increased in the last 13 years (Fig. 3), regardless of a hypolimnetic aeration treatment in one basin (E). Two (NV and E) of the three basins were judged as suited to receive hypolimnetic withdrawal treatment, as they were strongly stratified with obvious accumulation of nutrients and reduced substances in their hypolimnia.

Maximizing HW efficiency

The most efficient period for hypolimnetic withdrawal, the time when hypolimnetic TP concentrations are highest (Fig. 4a), coincides with naturally low discharge rates in Bornsjön (Fig. 4b) as is often the case in temperate lakes. A short withdrawal period even with limited withdrawal volume during the period of elevated bottom TP concentrations in late summer and fall would still decrease TP concentration, albeit slowly. Because the HW benefit depends on TP export, it is advantageous to maximize HW volume, which has to be conducted without affecting the long-term lake level. There are several hypothetical ways to maximize the water volume available for HW:

1. Flow augmentation could be achieved by leading additional surface water into the lake. This technique was applied in Devil's Lake, Wisconsin, USA (Lathrop et al., 2005).
2. Hydrological management could increase the water volume available for withdrawal by maintaining the high spring water level for a longer period into the summer. However, the increased flows could rapidly decrease the hypolimnetic volume and destabilize the lake potentially leading to earlier mixing (Section *Evaluation of destratification risk*). HW efficiency is maximal for long stratification periods that lead to elevated TP concentrations at the intake of the HW pipe.
3. The withdrawn water could be led back into the lake after near P removal by water treatment. Such flow routing is limnologically problematic if conducted in the hypolimnion of a single-basin lake, because treatment elevates the temperature and would dilute the hypolimnetic P concentration so that the basin stratification could be affected and efficiency decreased. If conducted to the epilimnion, care has to be taken to ensure that phosphate has been removed to levels low enough to not inadvertently fertilize the surface water.

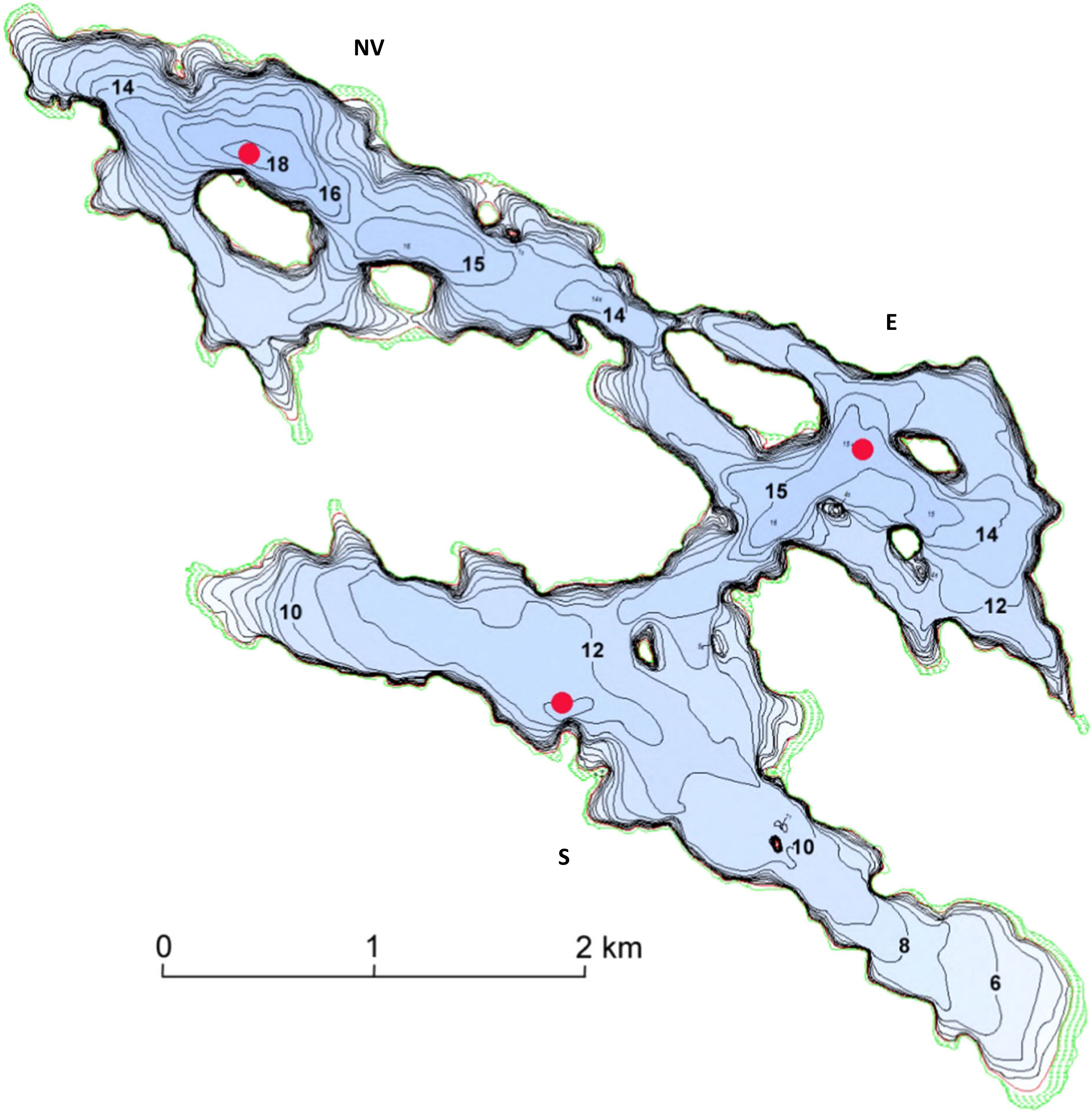

Fig. 2 Contour map of Bornsjön (in m), indicating the three basins and main sampling locations: NV, north western basin, also Edebybassängen; E, eastern basin, also Bornsjöbassängen; S, southern basin, also Skårbybassängen (Graph provided by *Stockholm Vatten*)

In Bornsjön, HW back-routing (3) seemed the best option and is possible because the withdrawn water can be taken out of the deepest basin (NV) and led back into the hypolimnion of the slightly shallower basin (E) which exhibits higher temperature, high hypolimnetic TP concentration, and is anoxic. Consequently, the treated HW water is of better quality (lower TP and less anoxia) than the water in the receiving basin (E), without compromising HW efficiency in the withdrawal basin (NV).

Evaluation of destratification risk

Destabilization of the thermostructure can negatively affect water quality and increase eutrophication if it occurs during the growing season, when enhanced

Table 1 Long-term mean limnological characteristics (1995–2009) and growing period water quality (1986–2011) for Bornsjön and its individual basins before HW treatment (Freshwater Research, 2012)

Characteristics	NV	E[a]	S	Total	Trophic state[b]
Area, A (km^2)	2.15	1.74	2.72	6.60	n.a.
Volume, V (10^6 m^3):	22.37	19.47	23.20	65.04	n.a.
Mean depth, z (m)	10.41	11.22	8.54	9.85	n.a.
Maximum depth (m)	18	15	13	18	n.a.
Morphometric index[c] (m/km)	7.10	8.51	5.18	3.84	n.a.
Annual water load (q_s, m/year)	–	–	–	1.19	n.a.
Total phosphorus (µg/l), epilimnetic	20	20	21	–	Mesotrophic
Total phosphorus (µg/l), hypolimnetic July–October maximum[d]	436	123	184	–	n.a.
Total nitrogen (µg/l), epilimnetic	397	396	398	–	Mesotrophic
Chlorophyll *a* (µg/l), epilimnetic	4.0	4.5	4.5	–	Mesotrophic
Secchi disk transparency (m)	4.5	4.5	4.3	–	Oligotrophic
Anoxic factor[e] (days/summer)	18	11	7	–	Oligotrophic

[a] Basin E was aerated from 1987 to 2011 except for 2004

[b] Based on (Nürnberg, 1996), n.a., not applicable

[c] The morphometric index is computed as $z/\sqrt{A}$

[d] The hypolimnetic P was 83–95% soluble reactive (SRP)

[e] The anoxic factor represents the number of days in a season or year that a sediment area equal to the lake surface area is anoxic (Nürnberg, 1995). Anoxia at the sediment water interface is assumed when the DO concentration in the overlaying water falls to 2 mg/l and below

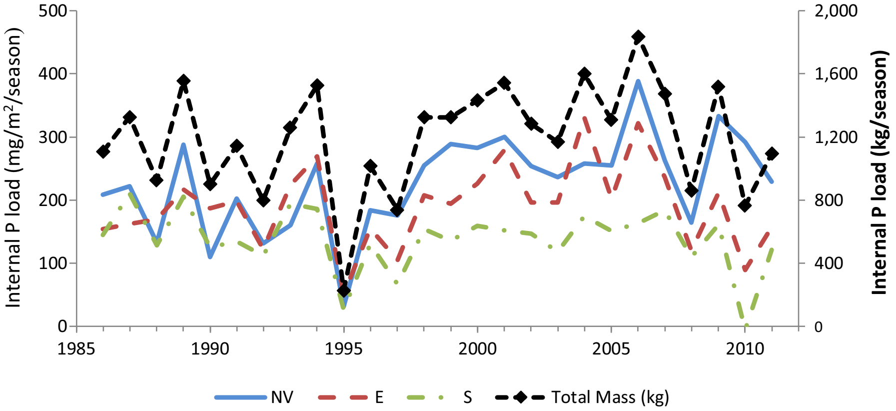

Fig. 3 Internal load estimates, determined from increases in volumetric water-column average TP, during the stratified season (Nürnberg, 2009), for each of Bornsjön's 3 basins as areal load (mg/m^2/season, left axis) and for the whole lake as total mass (kg/season, right axis) for the period 1986–2011 (Freshwater Research, 2012). These in-situ summer internal load estimates were calculated from the difference of the volumetric TP concentrations between July, after the spring clear phase, and October, just before fall turnover

nutrient exchange across the thermocline would stimulate primary production (James et al., 2015; Horppila et al., 2017). If too much cold hypolimnetic water is withdrawn from a lake, it is replaced by water from shallower depths with elevated temperature. In such a situation, the lake can eventually destratify long before the naturally occurring turnover. Destratification was deliberately introduced to manage cyanobacteria in the first known application of hypolimnetic withdrawal, in Lake Kortowskie, Poland, in 1956

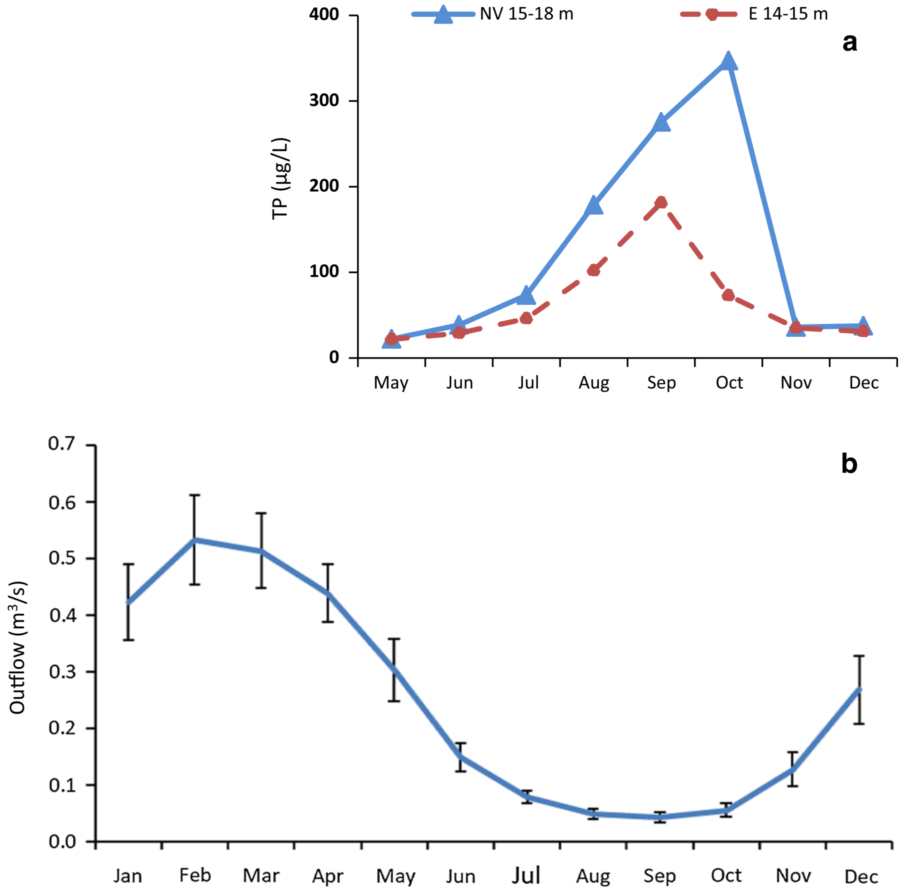

Fig. 4 Bornsjön monthly bottom water TP concentration average for the period 1986–2011 in the two deep basins (**a**) and outflow rate for 1995–2009 (**b**), showing average values and standard error bars), provided by *Stockholm Vatten*

(Olszewski, 1973). Consequently, nutrient influx from the hypolimnion caused an algal bloom that was more severe than in pretreatment years. Flow rates were subsequently adjusted and led to one of the longest and best-documented HW applications to date (e.g., Olszewski, 1973; Dunalska et al., 2007).

Nonetheless, in many HW applications, neither the thermocline depth nor the onset of fall turnover changed, except for oligomictic (frequently mixed) and meromictic (never completely mixed) lakes (Nürnberg, 2007). Summer mixing and erosion can simply be avoided by adjusting HW timing as late as feasible during summer stratification. Late HW also ensures that water is available for treatment at the time of the highest hypolimnetic TP concentration. However, if high summer TP concentration and water volume allow an earlier application, the risk of destratification can be evaluated from HW-related parameters. Using changes in summer bottom temperature (1 m above bottom during July and August) as predictor of fall turnover date (Nürnberg, 1988), Nürnberg (2007) found that induced turnover is unlikely (because the bottom water temperature does not change) as long as the annual amount of withdrawn water per lake area (HW-water load, q_s_HW, i.e., annual HW volume/lake area) is below 1 m/year.

In Bornsjön, negative effects on the thermostructure were not expected for several reasons. First, the withdrawal late in the season in September and October obviously does not affect thermal conditions in the summer. Second, the expected q_s_HW in Bornsjön is about 0.11 m/year for the design-scenario (HW-Flow volume for Scenario 3, Table 2, divided by lake area, Table 1), which is far below the threshold of 1 m/year. Third, Bornsjön is a strongly stratified, dimictic lake with a tendency of increased stability in

Table 2 Withdrawal scenarios for the deep NV basin of Bornsjön

Scnario[a]	HW flow		Estimated HW TP export		Predicted change in TP_{epi} for 1 year HW[b]		Predicted TP_{epi} (µg/l)	
	Rate (m^3/h)	Volume (10^6 m^3/year)	kg/year	mg/m^2/year	Proportion	Concentration (µg/l)	1 year	3 years[c]
0	1999–2011							
	0	0	0	0	0	0	19.6	19.6
1	Recorded flow (1995–2009)							
	179	0.258	107	16	0	0	19.6	17.9
2	Lake level increase (not possible because of restrictions)							
	1,308	1.883	772	117	− 0.21	− 4.48	15.1	11.8
3	Flow for plant average capacity							
	500	0.720	294	45	− 0.07	− 1.13	18.5	16.1
4	Flow rate for 2017 and 2018							
	300	0.432	177[d]	27	− 0.002	− 0.03	19.6	16.7

TP_{epi} epilimnetic TP concentration

[a] Scenario 0 represents long-term observed epilimnetic TP concentration. Scenario 1 is based on the historic outflow rate with assumed TP_{epi} change = 0 in 1 year, because TP export is too small for using Eq. 1 (out of range, Fig. 5); Scenarios 2 and 3 present fictive and Scenario 4 accomplished flow rates

[b] Predicted from Eq. 1

[c] Predicted from Eq. 1 using triple annual HW export

[d] Compares to observed export of about 160 kg

recent years. (July–August bottom temperature at all three basins decreased significantly from 1990 to 2011. For example, in NV, bottom temperature decreased from about 9 C in the early 1990s to 7 C in the recent years.)

Modeling lake TP concentration changes to predict HW benefits

Long-term continuous export via HW decreases the epilimnetic TP concentration. Changes in the epilimnetic growing season TP concentration (TP_{epi}, expressed as proportion of the pretreatment concentration) were predicted from a significant regression with accumulated areal TP export for 11 lakes with HW (logarithmically transformed to the base of 10, Eq. 1, Fig. 5; $n = 11$, $R^2 = 0.50$, $P < 0.01$, Nürnberg 2007). TP_{epi} during HW was determined as follows: If a trend was apparent, last available values were used to evaluate the changes from before and during treatment; otherwise (and in most cases) data were pooled, and medians were compared.

$$TP_{epi}\text{change} = 0.471 - 0.331\ \log(\text{total areal TP export}) \tag{1}$$

HW-related P export in Bornsjön was estimated for different scenarios and was used to predict expected TP concentration decreases (Table 2) using the model based on 11 HW studies (Eq. 1, Fig. 5). The enhanced TP export is predicted to decrease epilimnetic TP concentrations for the more feasible scenarios 3 and 4 (Table 2) only slightly in the first year, but by about 3 µg/l in 3 years. Because of the low concentration in Bornsjön and the uncertainty associated with the model, any decrease of epilimnetic TP caused by HW may not be directly obvious. Nonetheless, this trajectory can be used as an instructive prediction on the time it takes for obtaining a desired TP concentration. When using numerous treatment years for predictions, it has to be considered that the hypolimnetic TP concentration decreases over time if the treatment is effective, and therefore, annual TP export and benefit also decrease.

Expected benefits on water quality include decreased potential of cyanobacterial blooms because of diminished fertilization of the mixed water layer by sediment-released phosphate. Such results are apparent from the decreased chlorophyll *a* concentration and the increased water transparency, and the decreased metalimnetic cyanobacteria species as described in previous case studies (Nürnberg et al., 2003; Nürnberg, 2007) and in Section "Continued, new, and discontinued applications."

Disposal and treatment of the HW water

Provisions have to be made to dispose of the HW water in a way that does not contaminate downstream systems. In the end, the level to which the withdrawal water has to be treated depends on what is acceptable in the receiving water. It appears that acceptability of low-quality, odorous outlet water is diminishing with increased awareness and population, as noted in Lake Kortowskie, Poland, described later.

Many different approaches to treat HW water have been used in past applications (for further references refer to Nürnberg, 2007). They include chemical precipitation and flocculation in water treatment plants or movable P elimination devices in the more recent applications, irrigation of fields and golf courses and release into constructed wetlands, diversion in a long pipe away from populated areas without treatment, and the stripping and adsorption of reduced gases in constructed buildings and oxygenation plants. In the older applications, the water has often been left untreated. In Lake Kartowskie, for example, studies proved that high concentrations of hydrogen sulfide (up to 4–5 mg/l) in the outflow produced an odor that was unacceptable, while H_2S concentration had declined by 50% at 500 m downstream (Tandyrak et al., 2016). That study also determined that odor intensity and the concentration of reduced gases depends on the ratio of lake water to outlet stream water and resulted in variable extent of odor between years.

Obviously, the most acceptable HW treatment would be conducted in dedicated treatment plants before discharge. The HW application to Bornsjön is unique in that its withdrawal water is being treated by Stockholm Vatten in a combination plant that purifies epilimnetic Bornsjön water for drinking water most of the year, but treats HW water from the NV basin in September and October. Treatment consists of P stripping (from 490 to 10 µg/l, Johanna Ansker, Stockholm Vatten och Avfall AB, personal communication) and oxygenation before the HW water is lead into the anoxic hypolimnion of the slightly shallower and warmer E basin (Fig. 2, Table 1). In this way, not only is phosphate exported but also oxygen added to the same lake, albeit in different basins.

Continued, new, and discontinued applications

Data collection for HW case studies

To expand the case study dataset of Nürnberg (2007), the scientific and other literature was consulted as well as internet searches conducted for applications worldwide. Colleagues involved with HW as referred to below were approached for more recent information. For example, a hitherto unrecorded HW application in Lago Annone, Italy was discovered through the generous communication by colleagues at the University of Brescia.

Continued applications (mentioned in Nürnberg, 2007)

Several of the operations described previously (Nürnberg, 2007) are still being monitored and maintained (Table 3). In most cases, consistently improved water quality with perceived acceptable outlet water quality are the reasons for HW continuation. Also, additional benefits with respect to climate change were identified in several lakes as presented later.

In semi-arid *Pine Lake*, Alberta, Canada, HW had to conform to specific water-level targets throughout the growing season (all data from Al Sosiak, retired from Alberta Environment, personal communication). Based on long-term climatic conditions, enough water for withdrawal was predicted to be available in 7 of 10 years, and HW was indeed possible for 4.5 out of 7 years in 1996–2005. Decreasing trends in TP, total dissolved P, and hypolimnetic anoxia continued as described previously (Nürnberg, 2007). Chlorophyll *a* 1999–2007 average concentration during treatment showed a clearer, 40%, decrease, and Secchi transparency almost reached the guideline of 3 m in the HW years, while cyanobacterial blooms were fewer and less extended. These water-quality improvements occurred despite apparently unchanged long-term external and internal loads.

Table 3 Limnological characteristics and hypolimnetic withdrawal specifics for lakes with new and continued treatment since the review by Nürnberg (2007) and for selected lakes with discontinued treatment, in order of start of operation (For data sources, see text and Nürnberg, 2007)

Lake[a]	Location	Start	Area (km^2)	Volume (10^6 m^3)	Mean depth (m)	Maximum depth (m)	Morphometric index (m/km)	Annual water load (q_s, m)	Pipe diameter (mm)	Pipe Length[b] (m)	Elevation Differential[c] (m)
New and continued											
Kortowskie	Poland	1956	0.90	5.29	5.9	17.2	6.2	3.87	600	250	1
Piburger	Austria	1970	0.13	1.84	13.7	24.6	37.5	7.21	89	639	11
Reither	Austria	1976	0.02	0.07	4.5	8.15	36.2	16.48	100	50	1
Pine	Alberta	1999	4.12	20.60	5.0	12	2.5	0.56	530	1,400 (2)	10.2
Devil's	Wisconsin	2002	1.51	13.90	9.2	14.3	7.5	1.18	510	1,676	2.2
Pławniowice	Poland	2004	2.25	29.00	12.9	15	8.6	6.74	–	1050 (3)	–
Avigliana Grande	Italy	2005	0.91	17.75	19.5	28	20.4	n.a.	500	140	0.2
Annone, East[a]	Italy	2008	3.8	–	–	11.3	–	–	–	–	–
Bornsjöna	Sweden	2017	6.60	65.04	9.8	18	3.8	1.19	–	4,500 (2)	–
Liesinger	Austria	2017	0.002	0.004	2.0	4.3	45	0.2	50	35	~0.05
Discontinued											
Schlachten[a]	Germany	1981	0.42	1.97	4.7	9.5	7.2	9.38	–	~400	–
Wononscopomuc[a,d]	CT	1981	0.24	15.50	8.5	15.2	17.4	2.13	–	~450	0
Waramaug[a]	CT	1983	2.87	24.76	8.6	12.8	5.1	10.32	317.5	~500	0
Varese[a]	Italy	1999	14.52	153.65	10.6	24.4	2.8	5.54	–	3400 (3)	–

[a] Active pumping; unmarked lakes used passive siphoning

[b] When more than one pipe was involved, the number of separate pieces is indicated in parentheses

[c] Difference between the average elevation of the lake surface and the elevation of the pipe outflow

[d] The metalimnetic cyanobacteria *Planktothrix rubescens* disappeared after 2 years of HW

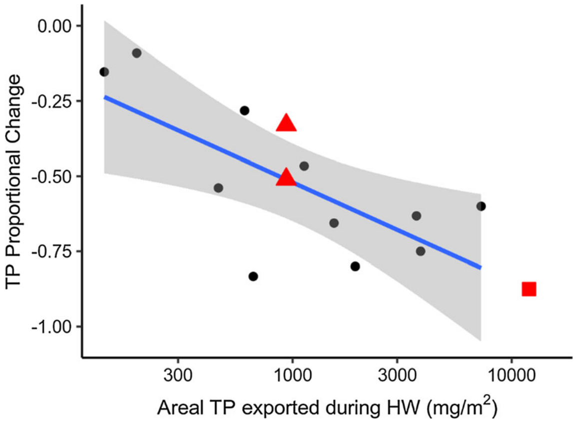

Fig. 5 Proportional change in epilimnetic summer TP as function of TP exported during the corresponding period (3–30 years) by hypolimnetic withdrawal. Regression line with 95% confidence band are shown for data from Nürnberg (2007) (filled circles). Separate symbols present epilimnetic phosphate concentration changes in Pławniowice Reservoir (square) and median (higher value) and extreme (lower value) fall turnover TP changes in Annone East (triangles) in response to accumulated TP export via HW

In *Devils Lake*, Wisconsin, a HW siphon was used in addition to augmented inflow to regulate the water budget in this seepage lake starting 2002 (Table 3), and HW continues to improve water quality. While the treatment was designed to only operate in September and early October, the period with highest hypolimnetic P concentrations, the siphon system was modified in 2009 to assist in flood prevention in the surrounding park as regional precipitation has increased dramatically in recent decades (Dick Lathrop, retired from Wisconsin DNR, personal communication).

The efficiency of HW can increase during climate change conditions as described in *Lake Kortowskie*, Poland (Dunalska et al., 2012). In an extremely wet year (2011, 220% of average precipitation), external TP load was slightly elevated but export was almost twice that of long-term (1973–2005) export so that in balance, about 120% TP was exported indicating negative TP retention compared to about 5% positive retention in typical water years. Increased rain storms and flash floods resulting in increased P input and P export are expected in many regions.

In some lakes, an additional restoration treatment is deemed necessary. For example, in *Reither See*, Austria, the problematic floating islands of benthic cyanobacteria (*P. rubescens, Oscillatoria limosa cf.*, personal communication Karen Finsterle and Said Yasseri, Limnological Solutions International) were treated with Phoslock, a lanthanum-amended clay that binds phosphate (Copetti et al., 2016) and the planting of the macro algae, *Chara* (systema GmbH, Vienna, Austria), while HW was still continued. Apparently, HW controlled the accumulation of phosphorus and redox-related metals in the hypolimnetic water, where P concentrations were only twice as high as in the oligotrophic surface water. However, the benthic cyanobacteria could thrive on the interstitial nutrients (before they were removed via HW) and tended to float to the surface during summer.

The need for monitoring and limnological observations is demonstrated in *Piburger See*, where decreased flow from the HW pipe led to an investigation that determined deformation and bent parts in the 44-year-old pipe. After repair of the pipe in 2014, the expected flow and P export were restored (Niedrist et al., 2018; Psenner et al., 2018). Piburger See is one of the longest HW applications with continuous monitoring and started in 1970. TP concentration decline in the HW outflow has occurred throughout the treatment period demonstrating the decrease of sediment P release due to the slow impoverishment of mobile sediment P (Fig. 6). Even though the HW TP concentration is relatively small, it is still almost 4 times larger than epilimnetic TP. The HW treatment thus successfully combats eutrophication of this mountain lake that provides valued recreational opportunities for bathers and hikers in the summer.

Recent applications (2005–2018)

The *Pławniowice Reservoir* (Table 3) is a former sandpit (created in 1975) that became hyper-eutrophic after about 20 years so that an in-lake treatment was required. Hypolimnetic withdrawal was conducted via three pipes, and results for the first 8 years of operation (2004–2011) were reported (Kostecki & Suschka, 2013). P export via HW (where 99% was phosphate) was 2.5–3 times larger than P input so that the P retention was negative, about − 300%. Considering that the predicted retention of Pławniowice Reservoir based on its water-detention time (τ) and mean depth (z) is 61% of external load ($R = 15/(18 + z/\tau)$, $z = 12.9$ m, $\tau = 1.9$ (Nürnberg, 1984)), this increased export, and change in the reservoir's P cycle can explain the reported water-quality improvement.

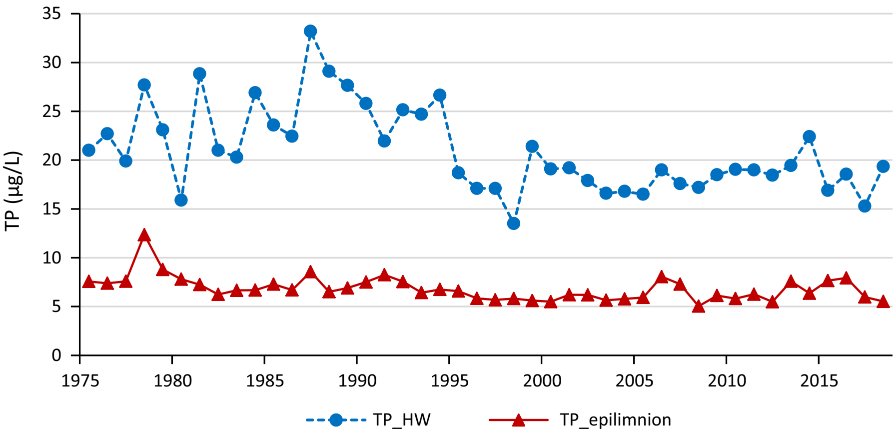

Fig. 6 Long-term (1975–2018) Piburger See, average of monthly median epilimnetic TP concentrations for the summer stratification period (May–Oct) and median annual TP concentration in the hypolimnetic withdrawal outflow. HW started in 1970. (Data provided by Roland Psenner, Ruben Sommaruga, Gry Larsen, Salvador Morales Gómezand Elias Dechent, Innsbruck University, Austria)

Epilimnetic and hypolimnetic phosphate concentrations decreased, e.g., the maximum hypolimnetic phosphate in the first year of withdrawal, 2004, was 1,250 µg P/l and steadily decreased to 250 µg P/l in 2011, while summer epilimnetic phosphate decreased from 80 µg P/l to below the detection limit (based on Fig. 6 of Kostecki & Suschka (2013), where phosphate was analyzed using method PN-89/C-04537/02); the sediment P-release rate decreased by 64%, and mean P export was 2.5 times of the input during the 8-year period of HW (Kostecki & Suschka, 2013). Secchi transparency increased from 1.4 m (1997–1998) to 3.2–3.9 (mean 3.5 m, 2004–2011) indicating decreased phytoplankton blooms, and the anoxic period declined from 225 days in 1998 to 77 days in 2011 without any change in stratification duration (Kostecki, 2014).

The total TP export for the 9-year HW period was 27 tons (12 g/m^2), which should lead to a 88% decrease in epilimnetic growing period TP according to Eq. 1 and Fig. 5. This compares to an 87% decrease in the summer epilimnetic phosphate concentration reported above, assuming a detection limit of 10 µg/l. While no TP data are available, the approximate estimate for the observed change in phosphate supports the model of Eq. 1.

There are several more recent applications in northern Italy (Table 3), such as in the Avigliana lakes, where the author encountered an installation in *Lago Avigliana Grande* (0.91 km^2, since 2005, designed for HW-rate of 40–100 l/s) during a visit in northern Italy, and *Lago Annone*, where the eastern larger basin, Annone East, has had an HW system since 2008. (Information on these lakes was provided by Matteo Cancelli and Giacomo Ferrari, University of Brescia, Italy, personal communication, March 2019, and Cancelli & Ferrari, 2019).

Total TP export via HW was 631 kg or 693 mg/m^2 in Avigliana Grande during the recorded period of 6 years (2005–2010). According to Eq. 1 and Fig. 5 such export should lead to a 47% decrease in epilimnetic growing period TP. Only water-column average TP concentration at fall turnover is available for the treatment period (2005–2010) and ranged from 70 to 138 µg/l, without any obvious trend between years. If the model also applies to fall turnover concentration, pretreatment TP would have been about twice as high. No data are available for testing this prediction.

The water-column average TP concentration at fall turnover in Annone East (median of 93 µg/l for 6 years in 2002–2007) decreased by 33% during the observed treatment years (median of 62 µg/l in 2009–2014, no obvious trend) except for the initial year of 2008 (TP concentration still 107 µg/l). The most extreme decrease from 2008 to 2013 (107 down to 52 µg/l) is 51%. TP HW export was more than 6 times of surface outflow in 5 of 7 years and 1.5–13 times for all years. According to Eq. 1 and Fig. 5 the total HW export of 935 mg/m^2 during the 2008–2014 treatment period would lead to a 51% decrease in epilimnetic growing period TP (or to 49% decrease excluding the first HW year 2008). Considering that growing period concentration is compared to fall turnover concentration and in view of errors involved in observed and predicted values, the predictions support the model of Fig. 5.

There are likely some more HW systems operating in lakes that are not documented in the scientific literature. This treatment is a "low key" solution and sometimes just requires the opening of a lower gate in an outlet structure. It is therefore not necessarily accompanied by a limnological study, which is also obvious from discussions with attendants at conferences of the North American Lake Management Society (NALMS.org) about smaller privately owned lakes in the USA.

One such small application was conducted in the small pond *Liesinger Weiher*, Austria (Table 3, Dr. Karin Pall, systema GmbH, Vienna, Austria, personal communication, June 2019). This mesotrophic lake (20 µg/l TP and 3 m Secchi transparency) established a hydrogen sulfide-rich hypolimnion that prevented the development of newly planted charophytes. Using well water to double the natural inflow, hypolimnetic water was withdrawn during the summer months of severe anoxia by a simple hose, installed in 2017. By 2018, the charophytes were re-established and survived the formerly hydrogen sulfide-rich summer period.

An indication that HW is considered worldwide is its being recommended for an Indian high altitude *Lake Nainital* (50 ha, 27 m maximum depth), close to the Tibet mountains (Kumar & Arun, 2008). The detailed plan included two siphons for the two deep basins. However, apparently a hypolimnetic aeration treatment was installed instead, which would make HW ineffective.

A slightly different version of HW is at experimental stage in *Kymijärvi*, Finland (6.5 km^2, Jukka Horppila, University of Helsinki, Finland, personal communication). In this application, the water is pumped from the hypolimnion, treated with calcium hydroxide, conveyed through filters and a wetland, and then led to a creek that enters the lake naturally, close to the HW location. In this way, HW water does not affect downstream waters and is being treated before re-entering the lake. Simultaneous monitoring guarantees that phosphate and other constituents are sufficiently reduced before reaching the epilimnion of the lake.

Discontinued applications

There are different reasons to discontinue a HW treatment in a lake. Several of the operations were discontinued because of the apparent lack of efficiency. When the external load is controlled and the water quality is largely influenced by internal P loading from the lakebed sediments, the efficiency of HW decreases with time of operation. As noticed in the recent Pławniowice Reservoir application (Kostecki & Suschka, 2013) as well as in longer running HW treatments (e.g., Piburger See, Roland Psenner, personal communication, Fig. 6), the efficiency of HW decreased with the increasing water quality. The longer and the more mobile sediment P is exported, the smaller becomes the sediment P-release rate, internal P loading, and the influence of hypolimnetic P on lake water quality, so that algal blooms become less frequent and Secchi transparency increases.

All discontinued well-documented applications of HW required energy for active pumping, which may be one reason for discontinuation. In contrast, most of the old continued applications have employed passive siphoning (Table 3).

Schlachtensee, a small lake in Berlin, Germany, had several treatments including a large external load reduction and HW from 1981 to 1996 (Nürnberg, 2007; Schauser & Chorus, 2007). While in the first year HW export was 15% of the total lake's TP content, export decreased consistently and was only 5% of lake TP in the last operating year of 1996. As the trophic state appeared to be satisfactory, the HW treatment was discontinued.

More reasons for HW discontinuation are related to the deteriorated outflow quality. In *Lago Varese*, Italy, an ambitious hypolimnetic withdrawal project was installed that exported hypolimnetic water from three locations to allow for HW from the main deep basin via pipes of a total length of 3.4 km. While the first 2 years of hypolimnetic withdrawal (2000–2001) indicated water-quality improvements of decreased hypoxia and algal blooms (Premazzi et al., 2005), which may have been partially due to a rigorous external load abatement, the analysis of 4 years (2000–2003) of hypolimnetic withdrawal apparently did not show consistent improvement with respect to

TP and phosphate concentrations, although internal loading decreased by 70% (Zaccara et al., 2007). In 2004, HW was discontinued as a consequence of deteriorated water quality and because of odor and nutrient enrichment in the outlet (Crosa et al., 2013), despite the addition of liquid oxygen (Premazzi et al., 2005).

As described previously (Nürnberg, 2007), hypolimnetic withdrawal in the lakes *Waramaug and Wononscopomuc*, Connecticut, USA, was discontinued after at least 5 years despite promising initial results (Nürnberg et al., 1987) for reasons of noncompliance of the outlet water quality with regulatory rules. The discharge water was too high in metals and reduced substances because the intended treatment of baffles and passive aeration systems via fountains was ineffective.

HW via outlet gates in reservoirs

It can be expected that HW is prevalent in reservoirs and man-made lakes, where the outlet structures operate at variable depths. While any adequate hypolimnetic withdrawal in eutrophic reservoirs can be expected to benefit its water quality, just as hypolimnetic withdrawal treatment does in lakes, the limnological effect on the reservoir's water quality is rarely considered because the quality of the withdrawn water is usually more important as discussed in Nürnberg (2007). Reservoirs are usually managed to minimize undesirable downstream effects such as elevated temperature and anoxia, especially when the withdrawn water is used as a drinking water source. A literature review (Austin et al., 2015) on the influence of large impoundments on downstream temperature, water quality, and ecology does not offer any information about treatment of the withdrawal water, but reports artificial destratification of a reservoir (which would likely deteriorate reservoir water quality), and diluting and diverting withdrawal water with the sole goal to minimize the effects of low temperature and anoxia on downstream biota.

The recently described applications in reservoirs operate on the principle of affecting the water circulation in an urban reservoir to manage cyanobacteria (Lehman et al., 2009) or to increase mixing and prevent stratification to improve outlet water quality (Anderson et al., 2014). There were no observations to indicate that the water quality in the reservoirs may have improved.

The importance of intake pipe elevation was investigated in a US–GS exercise on a drinking water reservoir in Ohio, USA (Vonins & Jackson, 2017). Lower depth withdrawal was compared to mid-gate withdrawal for 2 days in August 2015. However, the results were deemed inconclusive because unsettled weather elevated external load and no nutrient concentrations were measured, not to mention the short experimental time.

A modeling exercise (2D water quality and laterally averaged hydrodynamic model, CE-QUALW2) for a Tunisian reservoir used for drinking water and irrigation (the Sejnane Dam, 7.35 km^2, 86.5 m average pool elevation) investigated the influence of withdrawal depth on reservoir water quality (Zouabi-Aloui et al., 2015). The study supported HW as a potential treatment and determined that deeper withdrawals in late summer and fall were preferable to withdrawals from shallower depths because they decreased the expanse of anoxic water and assured increased discharge of nutrients, iron, and suspended solids.

Conclusions

New and continued HW applications still improve water quality in stratified lakes with anoxic hypolimnia. A previously developed model for the prediction of epilimnetic TP decreases from long-term TP export via HW was supported by results from several new applications. Benefits in regulating flows in view of the increased summer precipitation due to enhanced climate variability have been reported, suggesting that HW may play an increasingly important role in lake management. Increasing attention is being given to the treatment of the HW water, culminating in the technically advanced treatment by a modern drinking water facility.

HW treats the cause, internal loading, for much of the water-quality deterioration in eutrophic stratified lakes, including cyanobacteria blooms. The possible application of passive siphoning by gravity limits recurring energy costs. To ensure the most efficient performance, the monitoring of HW operational variables as well as the water-quality development in the source and the receiving water is recommended.

Extensive thermal stratification is a prerequisite for HW success (Nürnberg, 2007). This is not only because there are no major bottom water accumulations of nutrients and reduced substances in an occasionally mixed lake. It is also because in less thermally stable lakes much of internal P loading originates from bottom sediments in shallower, not stratified sections, especially if the lake is meso- or eutrophic (Tammeorg et al., 2017). Internal loading from areas overlain by mixed, aerated water is not treated by HW. Chemical inactivation may be necessary to permanently bind P to enriched sediments in shallow lakes.

A direct demonstration of the working mechanism of HW to impoverish sediment of mobile, releasable P (Hupfer et al., 2009) in reference to P adsorbing sediment constituents (Nürnberg et al., 2018; Wang et al., 2018) seems to be still missing. A sediment fractionation study for before and during the treatment could test and confirm the expected decrease in the mobile sediment P fractions and increase in P-retention capacity. Continued epilimnetic water-quality improvement by HW demonstrates that sediment-released P influences epilimnetic water quality in the long term.

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