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Negligible effect of hypolimnetic oxygenation on the trophic state of Lake Jyväsjärvi, Finland

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ABSTRACT

Hypolimnetic oxygenation by pumping oxygen-rich surface water to the hypolimnion (HLO) is a commonly used tool for the restoration of nutrient-loaded dimictic lakes. However, in recent years its effectiveness has been questioned. In this case study we evaluated monitoring data covering a period of 23-years to show that, although experimental cessation of HLO drastically changed the lake's temperature and dissolved oxygen regimes, it did not significantly affect its trophic status. Thus, we recommend that the limited financial resources available are better directed towards further lowering the lake's external phosphorus load than continuing HLO.

1. Introduction

Different methods of hypolimnetic oxygenation (HO*x*) have been suggested for the restoration of eutrophic lakes to prevent deep water anoxia and the consequent accelerated internal loading of phosphorus during stratification (Beutel and Horne, 1999; Gantzer et al., 2009b; Singleton and Little, 2006). Hypolimnetic oxygenation by pumping oxygen-rich surface water to the hypolimnion (HLO) is a form of HO*x* often used in restoration of dimictic lakes in Finland (Lappalainen and Lakso, 2005; Salmi et al., 2014). The aims of HLO are to maintain thermal stratification in summer, oxygenate the hypolimnion and sediment, and allow aerobic decomposition in near-bottom layers (Lappalainen, 1994). However, the method causes increased hypolimnetic temperatures in summer and is expected to promote cooling of the water column under ice (Lappalainen, 1994; Salmi et al., 2014).

HLO is considered a cost-effective restoration method to prevent undesirable effects of progressive anoxia, especially when a lake has a high socio-economical value. This has been the case with Lake Jyväsjärvi, an urban humic lake in the city of Jyväskylä, Central Finland. The lake has been transformed from one of the most heavily polluted lakes in Finland in the 1970s to a scenic part of the townscape of the city with high recreational value (Salonen et al., 2005). Much restoration effort has been put into the lake during its history, including legal obligations for the paper industry. Due to a gradual decrease in the external anthropogenic nutrient loading, the role of HLO in restoration of the lake has recently been questioned, although local environmental authorities have been cautious about stopping the HLO. Results from HO*x* in general and HLO in particular have been variable (Bryant et al., 2011; Horppila et al., 2015; Lappalainen and Lakso, 2005; Liboriussen et al., 2009), and recently even the key role of dissolved oxygen (DO) in regulating internal nutrient load has been questioned (e.g. Gächter and Müller, 2003; Müller et al., 2012; Orihel et al., 2015).

In this case study we investigated seasonal and long-term effects of experimental shutdown of HLO on a dimictic lake with the aid of automated water quality monitoring (AWQM). Effects of HLO on the trophic status of Lake Jyväsjärvi were studied with time series analyses of 23 years of data for nutrients, algal biomass measured as chlorophyll a (Chl a) concentration, DO and water temperature. Our aim was to evaluate whether there is still a need to apply year-round HLO to treat the symptoms of eutrophication in the lake by comparing the last three years without HLO to long-term trends in the lake. We also evaluated seven years of AWQM data to study the seasonal variability in DO and temperature structure of the lake with and without HLO.

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2. Material and methods

2.1. Study site

Lake Jyväsjärvi (3.1 km^2) in Central Finland (62°14.5′N, 25°46.2′E) is surrounded by the city of Jyväskylä and has an urban catchment area of 38 km^2. The lake has a maximum depth of 25 m and a mean depth of 5.8 m. The volume of Lake Jyväsjärvi is 1.8×10^{-2} km^3 with a mean water retention time of 2.7 months. The lake is typically ice-covered from late December to the beginning of May.

Lake Jyväsjärvi suffered from massive eutrophication in the past (Salonen et al., 2005). The lake received a heavy load of untreated paper mill and municipal wastewaters until the establishment of a sewage water treatment plant in the mid-1970s. As frequent DO depletion in the deep water of the lake was observed, HLO was initiated in 1979 and improved in the 1990s when a new HLO system (Mixox-1100, Water Eco Ltd., Kuopio, Finland), pumping 1 m^3 s^{-1} surface water (from 3 m) to the hypolimnion (12 m), was installed at the deepest point of the lake. Since then HLO has been operated year-round with one to three devices, apart from some breaks due to instrument malfunction. The local paper mill, which previously was the most important polluter, was legally obliged to continue HLO until 2010. After this obligation ended, the city of Jyväskylä was advised by the local environment authorities to continue HLO of the lake because a continuing tendency for low DO conditions in the hypolimnion during summer was considered a risk for lake biota and trophic status, and hence for the recreational value of the lake. HLO was stopped on April 10th 2012 for this experiment. However, due to frequent instrument malfunctions during 2011 meaning ineffective HLO, that year was considered the first OFF year in statistical analyses.

2.2. Data

2.2.1. Water quality monitoring

Lake Jyväsjärvi was monitored for DO, temperature, total phosphorus (P), total nitrogen (N) and Chl a concentrations in summer (June–August 1992–2014) and for DO, temperature, P and N in winter (January–March 1993–2015) at its deepest point (sampling station 510, Finnish Environment Institute database). The sampling occasions represent summer and winter stratification periods after the last substantial change in external loading to the lake. Samples were collected with a Limnos-sampler from depths of 1, 20 and 23 m. DO was analyzed with Winkler titration, P spectrophotometrically (SFS–EN ISO 6878:2004) and N by standard method SFS-EN ISO 11905-1:1998. Epilimnetic samples from the depth of one metre and averages of hypolimnetic samples from depths of 20 and 23 m were used for the time series analysis. Calculation of annual averages of DO, temperature, P and N was based on 3–4, 1–3, 4–6 and 2–4 samples for summer epilimnion, winter epilimnion, summer hypolimnion and winter epilimnion, respectively. Chl a concentration was measured spectrophotometrically after ethanol extraction (SFS 5772:1993) from a 0 to 2 m composite sample taken 3 to 8 times between June and August and the seasonal averages were calculated for the time series analysis.

2.2.2. Automated water quality monitoring

Since 2008 an AWQM station, situated 300 m north from the deepest point of Lake Jyväsjärvi, has measured hourly profiles of temperature and DO (Oxygen Optode 3835, Aanderaa Data Instruments, Bergen, Norway) from 1 to 15 m at intervals of 0.5 m (max depth 16 m at AWQM location). Data were supplemented for temperature (Thermochron 1922L, Express Thermo, San Jose, CA, USA, ±0.5 °C) and DO (YSI6600-V2, YSI Inc., Yellow Springs, Ohio) in cases of instrument malfunction during the 7-year dataset (www.paijanne.org). Winter 2011 data were not used for analysis of the AWQM data.

2.3. Data analysis

The effects of shutdown of HLO (OFF years) on the trophic status of Lake Jyväsjärvi were studied with time series analysis of the 23-year dataset by first fitting linear regressions for the log-transformed annual averages of P, N and Chl a measured from the summer epilimnion in 1992–2010 (ON years), and for P, N, DO and water temperature measured from summer hypolimnion (1992–2010) and winter hypolimnion (1993–2010). The second and third degree polynomials were also fitted but did not explain the data significantly better ($p > 0.05$) than the first degree models. Constant functions (y became a constant value) were used for the P and water temperature data from the winter hypolimnion because the higher degree polynomials did not explain the data significantly better than the constant functions. Secondly, deviation of observed annual values from those estimated by linear regression or by subtracting the constant value (see Table 1 for methods used for each variable) was calculated for all variables and for winters and summers for both ON and OFF years. There was no temporal autocorrelation between the deviations of any variable ($p > 0.05$). Differences in the deviations of P, N, DO, Chl *a* and water temperature between ON and OFF years were tested with *t*-test. Winter ON years were 1993–2010 and 2012, and OFF years were 2011, 2013, 2014 and 2015. Summer ON and OFF years were 1992–2010 and 2011–2014, respectively.

Effects of HLO on winter and summer temperature and DO structure were also analyzed with the 7-year AWQM dataset. A summer

Table 1
Statistical test results (*t*-test) for Chlorophyll a (Chl a), total phosphorus (P), total nitrogen (N) concentrations, water temperature and dissolved oxygen (DO) concentration in winter and summer at different depths between ON and OFF years. The deviations of observed values of each variable from the trend line were compared by *t*-test between ON and OFF years. The *t*-value, degree of freedom (df) and *p*-value of *t*-tests are given separately. The detailed implementation of the *t*-tests is explained in Section 2.3.

Season	Depth	Variable	Type of time series model	*t*-Test between ON and OFF years		
				t	df	*p*
Summer	Epilimnion (1 m)	Chl a	linear regression	0.337	20	0.739
		P	linear regression	0.184	20	0.856
		N	constant function	1.990	21	**0.047**
	Hypolimnion (20 and 23 m)	P	linear regression	0.655	21	0.519
		N	constant function	1.847	20	0.080
		Temperature	linear regression	13.599	21	$\boldsymbol{p < 0.001}$
		DO	linear regression	2.609	20	**0.017**
Winter	Hypolimnion (20 and 23 m)	P	constant function	0.080	19	0.937
		N	linear regression	3.280	18	**0.011**
		Temperature	constant function	3.341	21	**0.003**
		DO	linear regression	10.645	21	$\boldsymbol{p < 0.001}$