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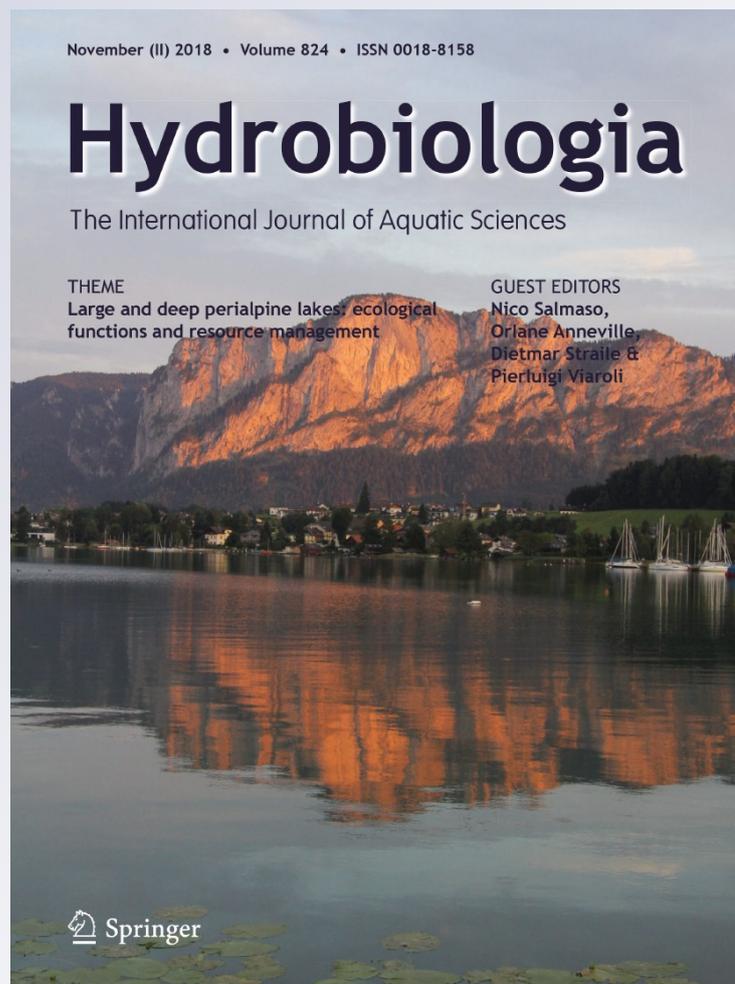
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Hydrobiologia

The International Journal of Aquatic Sciences

ISSN 0018-8158
Volume 824
Number 1

Hydrobiologia (2018) 824:229-242
DOI 10.1007/s10750-018-3575-2



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Effects of winter weather and mixing regime on the restoration of a deep perialpine lake (Lake Lugano, Switzerland and Italy)

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Received: 28 May 2017 / Revised: 15 February 2018 / Accepted: 2 March 2018 / Published online: 15 March 2018
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Abstract Long-term (1987–2015) monitoring data from Lake Lugano (Switzerland/Italy) were used to examine the effects of winter weather, solar radiation and mixing regime on the recovery of the trophic state of a lake undergoing nutrient management. Main hypotheses were that (H1) trends in trophic state were influenced not only by nutrient management, but also by winter weather and solar radiation, and (H2) the effects of management were more pronounced in the holomictic South basin than in the meromictic North basin of the lake. External loadings of phosphorus were strongly reduced during the study period, but key indicators of trophic state, including phosphorous

concentration, primary production, chlorophyll *a* and deep-water oxygenation, showed inconsistent responses. Supporting H1, winter weather (parameterized using an index of the East Atlantic pattern) influenced temporal variation in phosphorus concentration and primary production in the North basin. Supporting H2, the effects of management on trophic state were clearer in the South basin, where most trophic-state indicators declined. Meromixis affected the restoration of the North basin lake by transmitting effects of climatic variation on trophic state. The added variability obscured the effects of restoration and caused sudden deteriorations in water quality, indicating that the restoration of meromictic lakes presents unique challenges.

Guest editors: Nico Salmaso, Orlane Anneville, Dietmar Straile & Pierluigi Viaroli / Large and deep perialpine lakes: ecological functions and resource management

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Keywords Deep lakes · Eutrophication · Lake restoration · Nutrient management · Path analysis · Southern Alpine lakes

Introduction

Since the twentieth century, inland waters worldwide have been impacted by increasing inputs of phosphorus (P) originating from inadequate wastewater treatment and fertilizer overuse. This anthropogenic eutrophication has often resulted in increased phytoplankton productivity, proliferation of toxic cyanobacteria, deoxygenation of deep waters, incomplete processing of organic matter and production of

noxious gases in the sediments (Smith et al., 1999; Smith, 2003). In turn, these effects have impaired the ecological functioning and the socio-economic services provided by lakes (e.g. drinking water supply, fisheries and recreation). Accordingly, during the last decades, national and local environmental agencies have invested considerable resources in efforts intended to restore eutrophied lakes (Jeppesen et al., 2005; Schindler et al., 2016).

Most restoration programmes aim at mitigating or eliminating the undesired effects of eutrophication by reducing the external loadings of phosphorus (L_{EXT} ; Smith et al., 1999). This approach is based on well-established mathematical models, which predict that reductions in L_{EXT} result in proportional declines in P concentration and phytoplankton biomass (e.g. Voltenweider, 1968; Dillon & Rigler, 1975). Moreover, this approach assumes that L_{EXT} is the main factor controlling phytoplankton biomass in lakes (Dillon & Rigler, 1975), as well as other symptoms of eutrophication (e.g. deep-water anoxia). Although L_{EXT} management is widely used and often successful, growing evidence suggests that this approach, alone, can be insufficient to restore lake ecosystem to a pre-eutrophication state (Smith, 2003).

Factors hindering lake restoration can be internal and external. With regard to internal factors, in lakes with a long history of nutrient pollution, the effects of L_{EXT} management can be delayed by release of 'legacy' nutrients from the sediments (internal loading, L_{INT} ; Nürnberg & Peters, 1984; Søndergaard et al., 2001; Gulati et al., 2008). With regard to external factors, climate warming can reinforce some of the symptoms of eutrophication, for example by favouring dominance of cyanobacteria (Wagner & Adrian, 2009; Moss et al., 2011; Posch et al., 2012; Winder, 2012). Furthermore, coincidental changes in solar radiation and (or) land use (e.g. deforestation and urbanization) may interfere with trophic restoration by affecting temperature and oxygen distribution in lakes (Schmid & Köster, 2016). During the last decades, external (e.g. climate, radiation and land use) changes have often accompanied L_{EXT} management in lakes, raising questions regarding their influence on ongoing restoration programmes.

In addition, the effects of restoration can be influenced by internal lake characteristics such as depth, water residence time and mixing regime. In deep lakes, where turnovers are infrequent

(oligomixis) or incomplete (meromixis), deep waters tend to become depleted in oxygen and enriched in P (Gulati et al., 2017). In these lakes, normal turnovers cannot re-oxygenate deep waters or fully replenish surface waters with P (Salmaso et al., 2013). Conversely, events of deep mixing can lead to re-oxygenation of deep waters and sudden surges of P in surface waters. These events are often accompanied by release of noxious substances including methane and hydrogen sulphide (Holzner et al., 2009; Lehmann et al., 2015). Because the depth of mixing is controlled by weather conditions during the weeks or months preceding turnovers (cold spells favour deep mixing, warm spells favour stratification), oxygen and P dynamics often show temporal variation, driven by corresponding variation in weather (Salmaso et al., 2013). This variation may obscure the effects expected from L_{EXT} management (Lepori & Roberts, 2017).

Reflecting global trends, during the twentieth century, several deep perialpine lakes were affected by eutrophication (Mosello et al., 2010). Starting in the 1970s, several of these lakes (including Lake Lugano, Lake Maggiore, Lake Geneva, Lake Constance and Lake Zurich) were subjected to restoration through L_{EXT} management (Barbieri & Mosello, 1992; Imboden, 1992). To date, because of management, L_{EXT} in these lakes has been substantially reduced and in-lake P concentrations have declined (Lepori & Roberts, 2017). However, the effects on trophic state have varied. Whereas some lakes have regained oligotrophic status (e.g. Lake Maggiore), others, including Lake Lugano, Lake Zurich and Lake Iseo, appeared to have recovered more slowly and less completely (some symptoms of eutrophication, such as deep-water oxygen deficits, persist unchanged).

The mechanisms behind these incomplete recoveries are probably multiple and may include insufficient L_{EXT} management, development of L_{INT} and global warming (Lepori & Roberts, 2015, 2017; Pareeth et al., 2016). Additionally, solar radiation has increased in the Alpine area (Sanchez-Lorenzo & Wild, 2012; Schmid & Köster, 2016) and this increase could potentially affect primary production. Furthermore, in deep Southern perialpine lakes, restoration effects might be further obscured by natural climatic oscillations. In these lakes, the depth of mixing during late-winter turnovers is strongly associated with the East Atlantic (EA) pattern, a teleconnection that controls winter weather over the Mediterranean region

(Salmaso et al., 2013; Lepori et al., 2018). Therefore, cold winters during negative EA phases can cause surges in epilimnetic phosphorus and deep-water oxygenation, whereas warm winters can have opposite effects (Salmaso et al., 2013). At least in the short-to-medium term (years to decades), these climatic effects can overshadow or even reverse the effects of L_{EXT} management.

This study evaluates recent (1987–2015) trends in trophic state in Lake Lugano (Switzerland and Italy), a Southern perialpine lake that is undergoing L_{EXT} management and has the unusual characteristic of being split into two basins differing in mixing regime (the meromictic North basin and the holomictic South basin). The objectives of the study were twofold. The first objective was to examine whether changes in background environmental conditions (unrelated to L_{EXT}) had measurable effects on the expected restoration of the trophic state of the lake. The second objective was to assess whether the effect of L_{EXT} management on trophic state varied between basins. Using nearly three decades of monitoring data (1987–2015), we tested the hypotheses that (1) in both basins, trends in trophic state were influenced not only by L_{EXT} management, but also by concurrent changes in winter weather (represented by the EA pattern) and solar radiation, and (2) the effect of L_{EXT} management on trophic state was stronger in the holomictic South basin, whereas it was partly obscured by climatic variation in the meromictic North basin.

Methods

Study site

Lake Lugano (45°59'0"N, 8°58'0"E, 271 m a.s.l.; surface area: 49 km²) is a deep (maximum depth: 288 m) natural lake located at the southern edge of the Alps (Switzerland and Italy), in a humid subtropical climate zone (Fig. 1). The North basin of the lake is deep ($Z_{max} = 288$ m) and essentially meromictic, owing to a long water residence time of 12 years (Barbieri & Mosello, 1992). Exceptionally, however, this basin turned over following the cold winters of 2005 and 2006 (Holzner et al., 2009). Almost certainly meromixis is not the natural state of this basin, but it became established during the eutrophication phase

owing to increased primary production and precipitation of calcite in summer (Holzner et al., 2009). By comparison, the South basin is shallower ($Z_{max} = 95$ m), holomictic and has a water residence time of 1.5 years (Barbieri & Mosello, 1992). The lake has a warm-monomictic turnover regime, with turnovers occurring in late winter (February–March). The South basin, which collects the effluent of the largest sewage treatment plant in the catchment, receives approximately twice as much L_{EXT} as the North basin and, therefore, tends to be more eutrophic (Lepori & Roberts, 2017). The lake has been monitored for physical, chemical and biological characteristics at monthly intervals since 1983 (www.cipais.org). In this study, we used data collected both in the North basin (at a sampling station near Gandria) and the South basin (near Figino, Fig. 1).

The anthropogenic eutrophication of Lake Lugano started around the 1930s (Barbieri & Mosello, 1992) and peaked between the 1970s and early 1980s. Since the 1970s, to restore the lake, L_{EXT} has been managed through improvements in the treatment of municipal wastewater and a ban on the use of phosphate detergents (DA, 1982). The main goal of the restoration programme was to restore mesotrophic conditions (Barbieri & Mosello, 1992; Imboden, 1992). At the onset of the restoration programme, these conditions were defined by (1) total spring phosphorus concentrations < 30 mg m⁻³, (2) annual primary production < 150 g C m⁻² year⁻¹ and (3) dissolved oxygen concentrations > 4 mg l⁻¹ throughout the lake (Imboden, 1992; Swiss Water Protection Ordinance, WPO, available online at: <https://www.admin.ch/opc/en/classified-compilation/19983281/index.html>). To account for the different mixing regimes, criteria (1) and (3) were applied to the entire water column in the case of the South basin, but only to the 0–100 m layer (considered an approximation of the mixolimnion) in the case of the North basin (Barbieri & Mosello, 1992). These restoration targets have remained essentially unchanged until present.

Data compilation and parameterization

This study used data collected for the monitoring programme of Lake Lugano coordinated by the Administration of Canton Ticino (1987–2007) and the University of Applied Sciences and Arts of Southern Switzerland (SUPSI, 2008–2015). The data

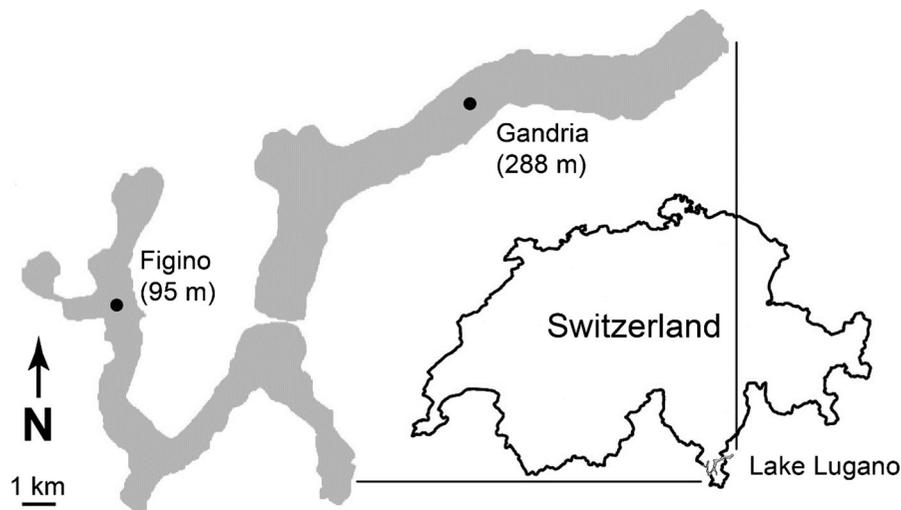


Fig. 1 Geographical position of Lake Lugano and the sampling stations near Gandria (North basin) and Figino (South basin)

were available from published reports (www.cipais.org) and unpublished databases. Additional climatic data were obtained from the Swiss Federal Office of Meteorology MeteoSwiss (www.meteoswiss.admin.ch). For this study we used data from 1987 onward, when detailed vertical profiling of oxygen concentration and conductivity was added to the monitoring programme.

Trophic state was assessed using three indicators explicitly used to classify trophic state by the lake's restoration programme (P concentration during turnovers, primary production and deep-water oxygen concentration; Imboden, 1992) and two additional ones (chlorophyll *a* concentration and Secchi depth) that are well-established criteria for trophic-state classifications (Dillon & Rigler, 1975; Carlson, 1977; OECD, 1982).

Phosphorus concentration (hereafter TP_{MIX} , in $mg\ m^{-3}$) was parameterized as the concentration of total phosphorus (TP) during late-winter turnovers. For the holomictic South basin, TP_{MIX} was calculated as the average concentration across the water column. For the meromictic North basin, the average concentration across the mixolimnion (0–100 m) was used. Monthly TP concentrations were measured from water samples collected at discrete depths using Niskin bottles. The concentrations at discrete depths were averaged to obtain an integrated water column (South basin) or mixolimnion (0–100 m, North basin) value. The date of the late-winter turnover was identified as

the date when the depth of vertical mixing was greatest (see below).

Annual primary production (PRODUCTION, in $g\ C\ m^{-2}\ year^{-1}$) was measured using the radioactive bicarbonate (^{14}C) method. This method was used in situ to measure hourly production rates ($g\ C\ m^{-2}\ h^{-1}$) between 10:00 h and 14:00 h monthly, throughout the year, at 11 discrete depths between 0.4 m and 20 m. The hourly production rates were subsequently used to estimate annual production rates using the method described in Franchini et al. (2017).

Chlorophyll *a* concentration (CHLA, in $mg\ Chl\ a\ m^{-3}$) was measured from water samples collected at discrete depths within the 0–20 m layer at biweekly-to-monthly intervals. Phytoplankton was filtered and chlorophyll was extracted in ethanol. Subsequently, chlorophyll *a* concentration was measured spectrophotometrically following standard methods (Rand et al., 1975). The chlorophyll *a* concentration from all samples was averaged and rescaled to the concentration within the euphotic zone (Z_{eu} , 1% light penetration). The depth of euphotic zone Z_{eu} was calculated from light profiles or, where these were unavailable, from lake-specific empirical regressions between Secchi depth and Z_{eu} . CHLA was averaged across sampling occasions and was expressed as an annual average.

Oxygen concentration ($OXYGEN_{MIN}$, in $mg\ l^{-1}$) was measured using a multi-parameter instrument and was parameterized as the minimum annual

concentration in deep waters (between 50 m and the bottom in the South basin and 50 and 100 m in the North basin). The minimum deep-water concentration provided a useful index of oxygenation because it allowed a direct comparison with the oxygen restoration criterion (Imboden, 1992; Swiss WPO). Oxygen concentrations in deep water layers were obtained from vertical profiles measured using a multi-sensor instrument fitted with a membrane oxygen sensor. During the study period, oxygen profiles were measured approximately monthly with a vertical resolution of at least 1 m.

Secchi depth (SECCHI, in m) was measured biweekly using a standard Secchi disk and was parameterized as the annual average.

The external loadings of TP (L_{EXT} , in t), representing the annual amount of TP entering the lake from all major sources (tributaries, precipitation), were calculated based on TP concentrations, daily discharge in the tributaries and an estimate of the annual atmospheric deposition. The methods are described in Lepori & Roberts (2017), from which the L_{EXT} data were sourced.

The EA pattern, representing winter weather variability, was parameterized using the winter index of the East Atlantic pattern (EA_{WINTER} , dimensionless; Salmaso, 2012; Salmaso et al., 2013). The EA index is calculated using Rotated Principal Component Analysis upon monthly anomalies of the geopotential at 500 hPa in the north Atlantic/European sector (20°N–90°N; e.g. Salmaso, 2012; Salmaso et al., 2013). The winter EA index is the average of the December, January and February values. The EA values used in the paper were obtained from NOAA-CPC (<http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml>).

Using only the EA to represent the variability of winter weather introduced a simplification in the analysis, because the local weather is also influenced by the North Atlantic Oscillation (NOA) and global warming (Lepori & Roberts, 2015). Nevertheless, this simplification was justified by the results of exploratory analyses (*not shown*), which indicated that, during the study period, the effects of these other sources of climatic variability on limnological variables (e.g. mixing depth) were overshadowed by the stronger effect of the EA.

Global radiation over the lake (RADIATION, in $MJ\ m^{-2}$) was quantified as the cumulative yearly radiation based on daily values recorded at a Swiss

Federal Meteorological Station adjacent to the lake (46.00 N, 8.96 E, 273 m a.s.l.).

Finally, because it was assumed that EA had an indirect effect on TP_{MIX} through an intermediate effect on the depth of mixing during late-winter turnovers (Salmaso et al., 2013), the analysis included a measure of this additional variable. Mixing depth (MIXDEPTH, in m) was estimated as the maximum depth at which conductivity (adjusted to 20°C) differed by $> 3\ \mu S\ cm^{-1}$ from the surface values (0–2 m) during the late-winter overturn (Lepori et al., 2018, *this issue*).

Data analysis

Temporal trends in the trophic-state indicators, L_{EXT} and other environmental variables (EA_{WINTER} , RADIATION) were tested using Mann–Kendall's test and Sen's slope. The effects of L_{EXT} , EA_{WINTER} and RADIATION on the lake's trophic state were explored using two complementary methods, Principal Component Analysis (PCA) and Path Analysis. To identify the trophic state of the lake, the targets of the restoration programme (namely, spring TP concentrations $< 30\ mg\ m^{-3}$, annual primary production $< 150\ g\ C\ m^{-2}\ year^{-1}$ and dissolved oxygen concentrations $> 4\ mg\ l^{-1}$; Imboden, 1992) were used to define the boundary between mesotrophic and eutrophic conditions.

PCA was performed on the set of trophic-state indicators (log transformed) and the resulting first principal component was used as an integrated eutrophication index (IEI). For each basin, the IEI was subsequently related to potential explanatory factors (L_{EXT} , EA_{WINTER} , MIXDEPTH and RADIATION) using stepwise forward multiple regression (Çamdevýren et al., 2005).

Path analysis evaluates hypothesized causal relationships within a system of variables, by testing these relationships against empirical data (Wright, 1934). To perform the analysis, a causal model depicting all hypothesized relationships between L_{EXT} , EA_{WINTER} , RADIATION (representing the exogenous variables in our model) and MIXDEPTH, TP_{MIX} , PRODUCTION, and $OXYGEN_{MIN}$ (the endogenous variables) was outlined (Fig. 4). The indicators CHLA and SECCHI were not included in this analysis because their explanation would require factors not included in this study (grazing, sedimentation rates, etc.).

Subsequently, standardized regressions were used to estimate the path coefficients for all the links considered in the causal model and the associated determination coefficients R^2 (Wright, 1934). Path coefficients (represented by the letter β) indicate the strength of the causal effect of a variable on another, and have a similar interpretation to correlation coefficients. The strength of each effect was interpreted using Cohen's (1988) conventions, where coefficients < 0.1 indicate weak effects, coefficients near 0.3 a moderate effect and coefficients > 0.5 a strong effect.

Results

During the study period, in both basins, L_{EXT} displayed a significant decrease (Table 1, Fig. 2). Between the first and last 5 years of the study period (1987–1991 and 2011–2015, two periods used throughout this section to express percentage changes), L_{EXT} decreased from 32 t to 18 t in the north basin (-44%) and from 64 to 30 t in the south basin (-54%). RADIATION showed an increase from 4402 to 4847 MJ m^{-2} ($+10\%$), whereas EA_{WINTER} and MIXDEPTH (Fig. 2) showed no significant trends.

At the beginning of the study period (1987–1991), eutrophic conditions prevailed in both basins of the lake (North basin: $TP_{MIX} = 66 \text{ mg m}^{-3}$, $OXYGEN_{MIN} = 2.1 \text{ mg l}^{-1}$, $PRODUCTION = 467 \text{ g C m}^{-2} \text{ year}^{-1}$; South basin: $TP_{MIX} = 98 \text{ mg m}^{-3}$, $OXYGEN_{MIN} = 0.5 \text{ mg l}^{-1}$, $PRODUCTION = 578 \text{ g C m}^{-2} \text{ year}^{-1}$). Subsequent changes differed depending on trophic-state indicator and basin (Table 2). In the North basin, SECCHI increased ($+10\%$), CHLA decreased (-38%), while PRODUCTION and $OXYGEN_{MIN}$ displayed no significant trends (Table 1, Fig. 3). TP_{MIX} concentrations decreased (-43%), although the trend was only marginally significant ($P < 0.1$; Table 1). At the end of the study period (2011–2015), a TP_{MIX} of 38 mg m^{-3} , alongside the high and nearly unchanged PRODUCTION ($447 \text{ g C m}^{-2} \text{ year}^{-1}$) and the low $OXYGEN_{MIN}$ (2.9 mg l^{-1}) still indicated a prevalence of eutrophic conditions.

In the South basin, TP_{MIX} , PRODUCTION and CHLA decreased (-66 , -17 and -69% , respectively), SECCHI increased ($+73\%$), while $OXYGEN_{MIN}$ displayed no trends (Table 1, Fig. 3).

Despite these changes, the final values of TP_{MIX} (33 mg m^{-3}), PRODUCTION ($482 \text{ g C m}^{-2} \text{ year}^{-1}$) and $OXYGEN_{MIN}$ (0.8 mg l^{-1}) indicated that the desired mesotrophic status had not been reached by the end of the study period.

PCA analysis

In the North basin, the first component of the PCA based on classic trophic-state indicators (IEI_North basin) explained 42% of the variance. This component was positively correlated with TP_{MIX} ($r = 0.62$, $P < 0.001$), PRODUCTION ($r = 0.81$, $P < 0.001$) and CHLA ($r = 0.79$, $P < 0.001$), whereas it was negatively correlated with $OXYGEN_{MIN}$ ($r = -0.49$, $P = 0.007$) and SECCHI ($r = -0.46$, $P = 0.012$). Similarly, IEI_South basin, which explained 58% of the variance, was positively correlated with TP_{MIX} ($r = 0.88$, $P < 0.001$), PRODUCTION ($r = 0.78$, $P < 0.001$) and CHLA ($r = 0.85$, $P < 0.001$), and negatively correlated with SECCHI ($r = -0.86$, $P < 0.001$). Therefore, based on these correlations, high values of IEI indicate more eutrophic conditions.

During the study period, IEI_North basin showed wide year-to-year fluctuations and no apparent trend, whereas IEI_South basin displayed a trend towards lower values, although its values appeared to stabilize during the last 5–10 years of the study period (Fig. 4). According to the results of the stepwise regression, IEI_North basin was marginally correlated with RADIATION ($R^2 = 0.14$; $P = 0.04$), whereas IEI_South basin was explained by a polynomial function of L_{EXT} and RADIATION ($R^2 = 0.57$; $P < 0.001$).

Path analysis

Path analysis supported the existence of causal links between winter weather, external TP loadings, mixing, phosphorus concentrations and primary production. In addition, the analysis indicated that the pathways linking these variables varied between basins. In the North basin, MIXDEPTH and L_{EXT} had strong (MIXDEPTH, $\beta = 0.64$) or moderate (L_{EXT} , $\beta = 0.34$) effects on TP_{MIX} (Table 2, Fig. 5). EA_{WINTER} had a strong negative effect on MIXDEPTH ($\beta = -0.70$) and, therefore, a strong negative indirect effect on TP_{MIX} (total effect = $-0.70 \times 0.64 = -0.45$). TP_{MIX} had a strong effect on PRODUCTION ($\beta = -0.46$), whereas RADIATION

Table 1 Lake Lugano (1987–2015): temporal trends in external TP loadings (L_{EXT}), winter East Atlantic index r (EA_{WINTER}), solar radiation (RADIATION) and five indexes of trophic state (phosphorus concentration during turnovers,

TP_{MIX} ; Secchi depth, SECCHI; average yearly chlorophyll a concentration, CHLA; total yearly primary production, PRODUCTION; and minimum deep-water oxygen concentration, $OXYGEN_{MIN}$), by lake basin (North and South)

Time series	Test Z	P	Q	Qmin95	Qmax95	Mean (CV) 1987–1991	Mean (CV) 2011–2015	% Change
North basin								
L_{EXT}	- 3.43	***	- 0.51	- 0.86	- 0.18	32 (0.21)	18 (0.17)	- 44
EA_{WINTER}	- 0.19	NS	0.00	- 0.05	0.04	0.4 (1.08)	0.1 (7.02)	65
RADIATION	4.23	***	22.53	12.61	31.54	4402 (0.04)	4847 (0.03)	10
TP_{MIX} (0–100 m)	- 1.86	+	- 0.90	- 1.63	0.07	66 (0.09)	38 (0.24)	- 43
SECCHI	2.16	*	0.06	0.01	0.12	6.2 (0.20)	6.8 (0.09)	10
CHLA	- 2.08	*	- 0.25	- 0.60	- 0.01	21.9 (0.65)	13.6 (0.24)	- 38
PRODUCTION	0.00	NS	- 0.01	- 3.82	3.28	467 (0.19)	447 (0.14)	- 4
$OXYGEN_{MIN}$ (50–100 m)	0.79	NS	0.03	- 0.04	0.09	2.1 (0.45)	2.9 (0.27)	42
South basin								
L_{EXT}	- 4.15	***	- 1.26	- 1.78	- 0.79	64 (0.10)	30 (0.24)	- 54
TP_{MIX} (0 m–bottom)	- 5.93	***	- 2.72	- 3.39	- 2.12	98 (0.09)	33 (0.14)	- 66
SECCHI	4.75	***	0.11	0.08	0.14	3.4 (0.07)	5.8 (0.10)	73
CHLA	- 4.07	***	- 1.05	- 1.46	- 0.68	63.6 (0.75)	19.6 (0.27)	- 69
PRODUCTION	- 2.95	**	- 5.20	- 8.29	- 1.91	578 (0.19)	482 (0.09)	- 17
$OXYGEN_{MIN}$	0.81	NS	0.01	- 0.01	0.06	0.5 (0.92)	0.8 (0.96)	78

Z is the statistics of the Mann–Kendall’s test and Q denotes Sen’s slope (QMIN95 and QMAX95 are the lower and upper 95% confidence intervals). The same values of EA_{WINTER} and RADIATION apply to both basins and were therefore reported only once, for the North basin. The mean values during the first and the last 5 years of the study period (the value in parenthesis is the coefficient of variation, CV) were used to calculate the % change

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; + $P < 0.1$; NS nonsignificant

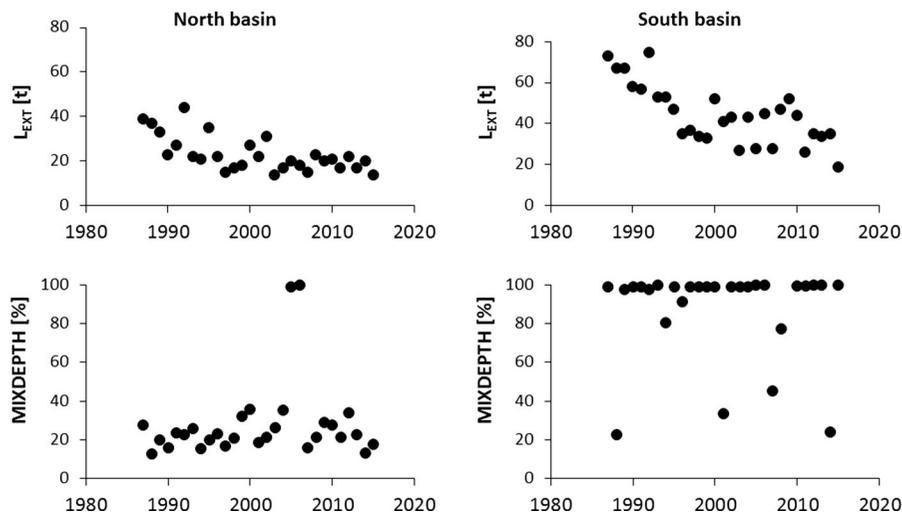


Fig. 2 Temporal trends in external P loadings (L_{EXT}) and maximum mixing depth during turnovers (MIXDEPTH) in the North and South basins of Lake Lugano between 1987 and 2015. MIXDEPTH was calculated in m (see “Methods” section) but is

shown as a percentage of maximum depth to represent it on the same scale for the two basins, despite the difference in absolute depth

Table 2 Parameter estimates for predicting the variables included in the path diagram illustrated in Fig. 4, by lake basin (North and South)

Variable	Predictor	β	SE	<i>t</i> -value	<i>P</i>	<i>R</i> ² (%)
North basin						
MIXDEPTH	EA _{WINTER}	− 0.702	0.14	− 5.12	< 0.001	49.2
TP _{MIX}	MIXDEPTH	0.64	0.14	4.39	< 0.001	46.5
	<i>L</i> _{EXT}	0.34	0.14	2.37	0.025	
PRODUCTION	TP _{MIX}	0.46	0.18	2.61	0.015	21.3
	RADIATION	0.00	0.18	0.00	0.998	
OXYGEN _{MIN}	MIXDEPTH	0.06	0.20	0.30	0.769	4.8
	PRODUCTION	− 0.23	0.20	− 1.15	0.262	
South basin						
MIXDEPTH	EA _{WINTER}	− 0.47	0.17	− 2.76	0.010	22.0
TP _{MIX}	MIXDEPTH	0.09	0.13	0.74	0.467	57.9
	<i>L</i> _{EXT}	0.76	0.13	5.96	< 0.001	
PRODUCTION	TP _{MIX}	0.53	0.22	2.44	0.022	30.2
	RADIATION	− 0.02	0.22	− 0.11	0.910	
OXYGEN _{MIN}	MIXDEPTH	0.10	0.21	0.47	0.644	14.2
	PRODUCTION	− 0.32	0.21	− 1.51	0.144	

β is the path coefficient, obtained from standardized regressions. SEs and *t*-values are the associated Standard Errors and *t* statistics, *P* is the probability value and *R*² is the determination coefficient representing the variance explained by the regressions

($\beta = 0.00$) had no effect. The hypothesized links MIXDEPTH → OXYGEN_{MIN} and PRODUCTION → OXYGEN_{MIN} were not supported by the analysis.

In the South basin, *L*_{EXT} had a strong positive effect on TP_{MIX} ($\beta = 0.76$), whereas MIXDEPTH had no effect ($\beta = 0.09$; Table 2, Fig. 5). Like in the North basin, PRODUCTION was strongly influenced by TP_{MIX} ($\beta = 0.53$) but not by RADIATION ($\beta = -0.02$). Moreover, as for the North basin, the hypothesized links MIXDEPTH → OXYGEN_{MIN} and PRODUCTION → OXYGEN_{MIN} were unsupported.

Discussion

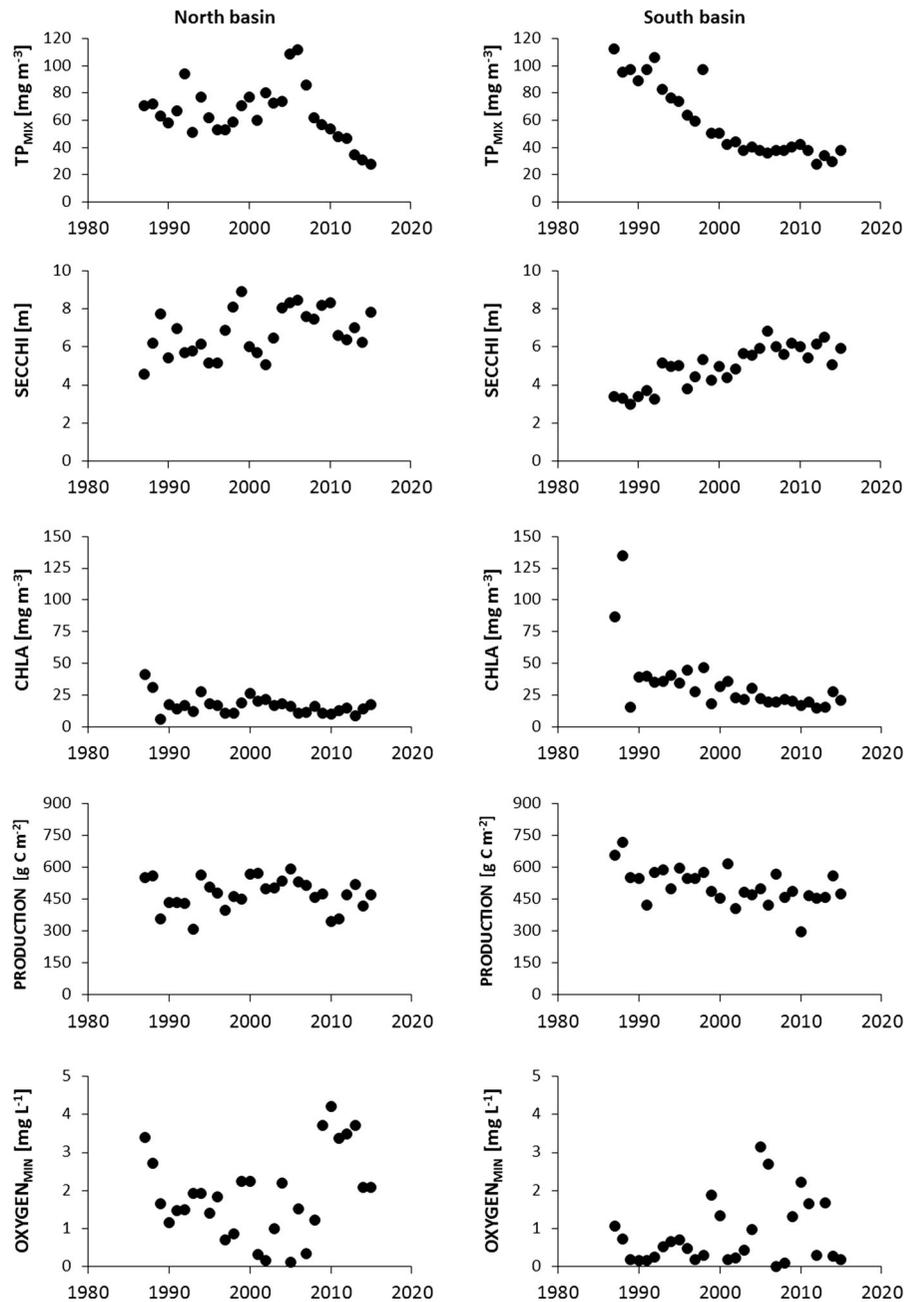
Although nutrient management caused a strong decrease in *L*_{EXT} (reduced by 44–54%), improvements in the trophic state of the two basins of Lake Lugano were weak and inconsistent. Changes in the indicators used to define the restoration goals (TP_{MIX}, PRODUCTION and OXYGEN_{MIN}) showed that, overall, the lake remained eutrophic throughout the study period. However, the temporal patterns of these indicators and the factors influencing them varied between basins. In the North basin, TP_{MIX} and PRODUCTION were influenced by variation in winter weather (parameterized as the EA_{WINTER}), whereas in

the South basin these same indicators were more strongly associated with *L*_{EXT}. Moreover, patterns across all indicators of trophic state (including CHLA and SECCHI), as well as an integrated index of eutrophication (IEI), revealed that the trophic state of the North basin oscillated with weak or no overall trends, whereas that of the South basin moved steadily towards less eutrophic conditions. These results indicate that the trophic restoration of the lake was influenced by background environmental variation, and that such influence depended on mixing regime.

Effects of background environmental changes on trophic restoration

In partial support to the first hypothesis, winter weather (EA_{WINTER}) influenced the trophic-state indicators TP_{MIX} and PRODUCTION, although only in the North basin. Moreover, path analysis identified a causal pathway explaining this effect. In this basin, TP_{MIX} was influenced by EA_{WINTER} through a two-step pathway. The first step involved a negative effect of EA_{WINTER} on MIXDEPTH, which reflects the well-known effect of cold weather on the depth of vertical mixing in deep lakes (negative EA indexes are associated with colder winters and, therefore, with deeper mixing; Salmaso et al., 2013). The second step involved a positive effect of MIXDEPTH on TP_{MIX}

Fig. 3 Temporal trends of trophic-state indicators in the North and South basins of Lake Lugano between 1987 and 2015



(deeper mixing resulted in greater replenishment of P). This second step arises from the fact that in deep lakes P concentrations increase towards the bottom, meaning that deeper mixing causes greater upwelling of P from deep waters (Lehman et al. 1998; Salmaso et al., 2013). In addition, in both basins PRODUCTION was positively associated to TP_{MIX} , which accords with the common view that lowland lakes are generally

P-limited (Schindler, 1977; Schindler et al., 2016). Therefore, in Lake Lugano, colder winters were associated not only with higher P concentrations in the mixolimnion during turnovers, but also with greater production during subsequent months. These patterns echo observations from deep lakes worldwide, including other perialpine lakes influenced by teleconnections (Straile et al., 2003) and the Rift

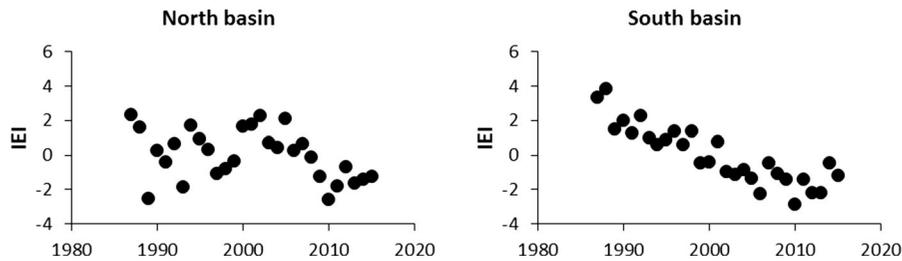


Fig. 4 Temporal patterns of the integrated eutrophication index (IEI, first component of PCA) in the North (left) and South basin (right) of Lake Lugano between 1987 and 2015

Valley lakes in Africa, where decades of warming are purported to have caused a loss of production through a reduction of vertical mixing (Verburg et al., 2003).

The influence of winter weather on the trophic state of the North basin was well illustrated by the transient surges in TP_{MIX} and PRODUCTION that followed the exceptional turnovers of 2005–2006 (Holzner et al. 2009; Lehmann et al., 2015). Because the turnovers were caused or at least facilitated by negative EA phases during the preceding winters (Salmaso et al., 2013), these events can be attributed in part to climatic variability. Notably, in addition to altering trophic state, the exceptional turnovers reduced oxygen concentration to the critical level of $1.6 \text{ mg O}_2 \text{ l}^{-1}$ across the epilimnion (in February 2005), triggering a kill of Italian shad, *Alosa agone* Scopoli (UPDA 2007, 2008). Therefore, these events caused a severe deterioration of the chemical and biological quality of the lake, if only in the short-to-medium term (e.g. 2–3 years).

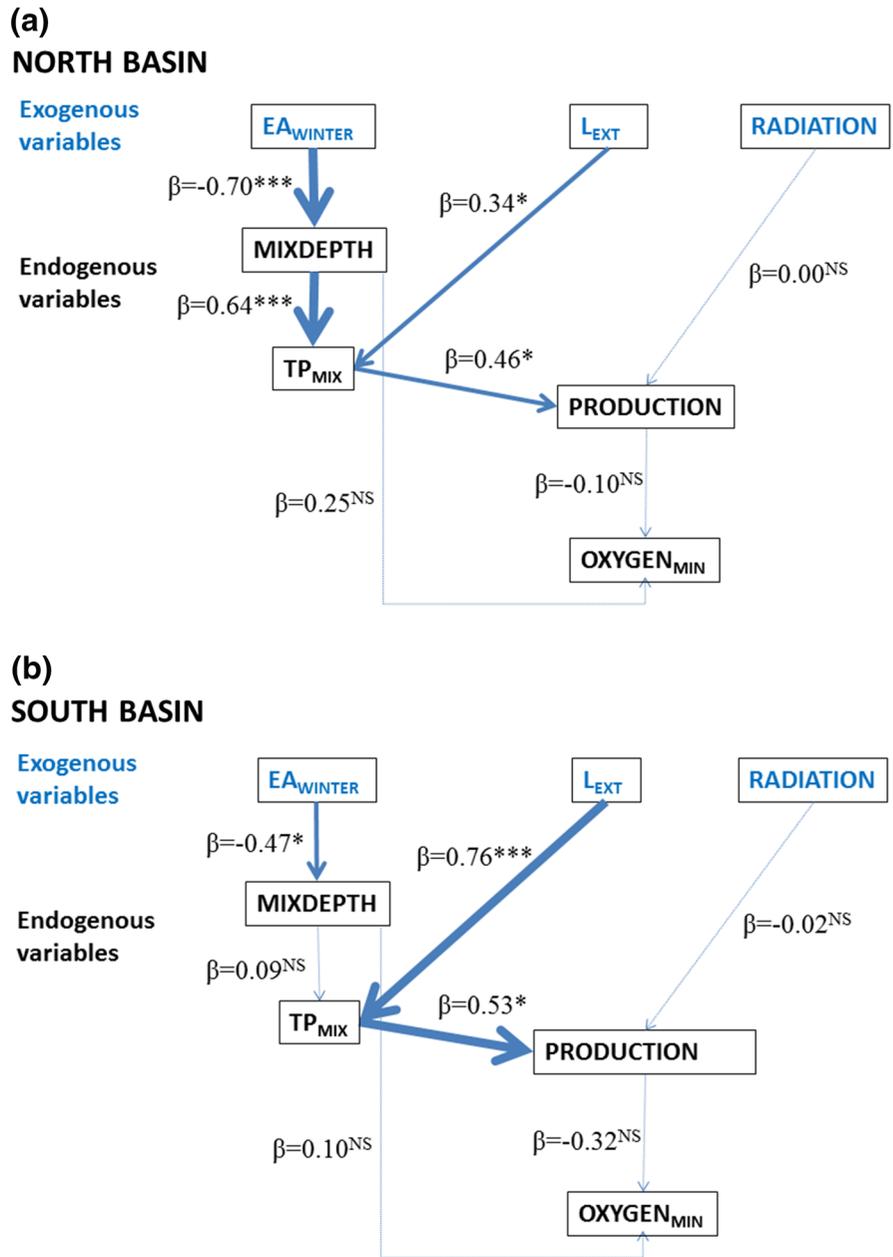
However, patterns surrounding the same events indicate that the factors influencing TP_{MIX} in this meromictic basin were complex and probably extended beyond winter weather and L_{EXT} . For example, a rise in TP_{MIX} became apparent already during the 5–6 years preceding the turnovers, even though external P loadings were decreasing and MIXDEPTH showed no obvious trends. Furthermore, after the turnovers, TP_{MIX} declined steeply to the lowest values of the study period, again without corresponding changes in MIXDEPTH or L_{EXT} . These patterns suggest that the increase of TP_{MIX} before the turnovers was caused by an upward P flux from deeper water, presumably induced by a gradual erosion of the chemocline. Likewise, the subsequent steep decline probably reflected not only the re-equilibration of TP_{MIX} with L_{EXT} , but also the reestablishment of a

strong stratification, which interrupted the flux. Therefore, in this basin, the influence of L_{EXT} on TP_{MIX} may have been complicated not only by year-to-year variation in winter climate, but also by patterns of weakening and strengthening of the meromixis, which will warrant more attention in the future.

In contrast to EA_{WINTER} , RADIATION displayed a trend towards higher values during the study period. However, path analysis indicated that this trend had no detectable influence on primary production. Although light availability can be an important factor limiting phytoplankton production in some fresh waters, light deficiency is most likely to arise in turbid lakes (Healey & Hendzel, 1980; Vanni et al., 2006). Therefore, it is perhaps not surprising that in the pelagic waters of Lake Lugano, which are relatively clear and rarely affected by inputs of sediments, light availability poses no major constraints on production. A weak influence of light is supported by a previous study, which indicated that during 1983–2014, in the North basin, radiation influenced primary production only in winter, and the magnitude of the effect was secondary to that of water temperature (Franchini et al., 2017). Although RADIATION correlated with IEI in both basins, the weak effect on primary production, combined with an absence of plausible mechanisms linking RADIATION to other trophic-state indicators, suggests that these correlations were spurious.

Of the three indicators of trophic state used in this study, $OXYGEN_{MIN}$ appeared to be only loosely coupled to TP_{MIX} and MIXDEPTH, and its temporal variation provided no evidence for recovery in either basin. In the North Basin, $OXYGEN_{MIN}$ even decreased between 1987 and the turnovers of 2005–2006. In the South Basin, $OXYGEN_{MIN}$

Fig. 5 Path analysis diagrams indicating the path coefficients (β) for all the hypothesized effects between exogenous factors (L_{EXT} , EA_{WINTER} and $RADIATION$) and endogenous factors (representing indicators of trophic state), by lake basin (North and South). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS nonsignificant effect



displayed seemingly cyclical variability, although this was unrelated to $MIXDEPTH$. Whereas the depth of mixing in Lake Lugano controlled the yearly replenishment of deep-water oxygen occurring during circulations (measured as the maximum oxygen concentration following turnovers, unpublished results), these results indicate that $OXYGEN_{MIN}$ did not depend on replenishment, but was controlled by consumption during the subsequent stratification

period. Oxygen consumption is determined by present productivity and mineralization of older sediments, and several studies suggest that productivity plays a major role, at least in shallow lakes (Gächter & Wehrli, 1998; Liboriussen et al., 2009; Matzinger et al., 2010). Presumably, the productivity of Lake Lugano remained sufficiently high throughout the study period to cause the consumption of nearly all the oxygen reaching the deep waters every year.

However, the mineralization of organic sediments that had accumulated during the long eutrophication period probably added to the depletion. Legacy effect like these may explain why deep-water oxygenation is emerging as being one of the trophic-state indicators more resistant to nutrient management.

Effects of mixing regime on restoration

Although overall weak, the effects of restoration on trophic state were clearer in the South basin, where TP_{MIX} , PRODUCTION and the IEI decreased throughout the study period towards the target mesotrophic conditions. These results provide support for the second hypothesis of this study, which predicted that the effects of restoration would be stronger in the holomictic basin. Again, path analysis provided an explanation for the difference, indicating that in the South basin TP_{MIX} was more strongly coupled to L_{EXT} . Because PRODUCTION was P-limited (see above), it is not surprising that in this basin PRODUCTION also tracked more closely patterns in L_{EXT} . The tighter coupling between L_{EXT} , TP_{MIX} and PRODUCTION observed in the South basin probably resulted from the holomictic mixing regime.

In holomictic lakes, of which the South basin is an example, TP_{MIX} arises from both internal and external P loadings. However, in these lakes, the contribution from internal loadings depends on trophic state, being greater in lakes with higher TP concentrations (Søndergaard et al., 2001). This relationship existed also in the South basin, where, according to monitoring data, deep-water P concentrations (reflecting L_{INT}) decreased between the 1980s and the 2010s, mirroring the decline in external loadings (*unpublished results*). Consequently, because TP_{MIX} arises from L_{EXT} and L_{INT} , and L_{INT} depend on L_{EXT} , TP_{MIX} should be expected to be strongly influenced by L_{EXT} . This is why in the South basin the management of L_{EXT} was mirrored by a consistent reduction of TP_{MIX} and related factors (e.g. PRODUCTION), even though L_{INT} delayed the attainment of a new equilibrium between TP_{MIX} and L_{EXT} (Lepori and Roberts, 2017).

In deep meromictic or oligomictic lakes, of which the North basin is an example, limited water renewal during periods of stratification and anoxic sediments cause P accumulation within deep waters (Gulati et al., 2017). In these lakes, the relative contribution of internal versus external loadings to TP_{MIX} depends on

mixing depth. In years of shallow-to-average mixing, when only the upper mixolimnion circulates, TP_{MIX} arises mostly from L_{EXT} . Conversely, in years of deeper mixing, when mixing reaches into deeper waters, contributions from L_{INT} can be substantial (and decoupled from L_{EXT} , because L_{INT} accumulate over decades). Therefore, in deep lakes undergoing L_{EXT} management, temporal variation in TP_{MIX} should reflect at least two effects: an effect caused by the reduction in L_{EXT} , which should cause a steady decrease of TP_{MIX} , and a second one caused by climate-driven year-to-year variation in mixing depth, which superimposes variation on the first trend. During periods of few decades, this superimposed, climate-driven variation can equal or exceed the steady effect of L_{EXT} management, and causes trophic state to oscillate without apparent trend, as observed in the North basin. Moreover, exceptional events of deep mixing can even reverse trends towards less eutrophic conditions for a few years, as observed after the turnovers of 2005–2006. This temporal variation did not eliminate the effect of L_{EXT} management on the trophic state of the lake. However, it was sufficiently strong to obscure this effect during the three-decade period covered by the study (e.g. the L_{EXT} reduction had only a marginal effect on TP_{MIX}).

Conclusions

Restoration of eutrophic lakes can be slow and difficult to achieve. Although in some deep lakes eutrophication has been successfully and quickly reversed by reductions of L_{EXT} (Edmondson & Lehman, 1981), or combinations of L_{EXT} management and biomanipulation (Jeppesen et al., 2005), in other systems the response to classic restoration measures has been delayed by years or decades owing to L_{INT} development (e.g. 25 years; McCrackin et al., 2017). Slow and uncertain recovery trajectories were anticipated in Lake Lugano, where the recovery from anthropogenic eutrophication has been hindered by legacy effects (internal loadings) and complicated by changes in food-web structure (Lepori & Roberts, 2017). In addition, results from this study indicate that the recovery trajectories can be further complicated by meromixis.

With respect to lake restoration, meromixis is a double-edged sword. In meromictic lakes, periods of stable stratification confine most L_{INT} within the

monimolimnion and therefore assist restoration. However, sudden events of deep mixing can cause extensive upwelling of deep-water P (and noxious gases), leading to temporary offsets of any restoration progress. Furthermore, human-induced meromixis, like the one occurring in the North basin, would take a very long time to reverse, and in the future the process might be counteracted by climate warming, which favours stratification (Verburg et al., 2003; Marshall et al., 2009). For this reason, induced meromixis may be considered a form of hysteresis (Sarr, 2002), in that it changes the recovery trajectory of the lake compared to the degradation trajectory by adding delay and temporal variability. Therefore, deep meromictic or oligomictic lakes present special challenges to the restoration of trophic state. These challenges might complicate lake recovery especially in warm climate zones, where meromixis is currently most common, but also in temperate zones, where climate warming appears to be favouring stronger and more stable stratification (Adrian et al., 2009; Kirillin, 2010).

Acknowledgements We thank all staff involved in the monitoring programme of Lake Lugano since the beginning of the study period and the Editors of this special issue for providing an opportunity to present our work. Nico Salmaso kindly provided the updated series of the index of the East Atlantic pattern. MB was supported from Swiss National Science Foundation Grant for Research (169552).

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