ARTICLE

Mesotrophy is not enough: Re-assessing phosphorus objectives for the restoration of a deep Alpine lake (Lake Lugano, Switzerland and Italy)

Fabio Lepori[1*], Bianca Lucchini[2], Camilla Capelli[1], Federica Rotta[1]

[1]University of Applied Sciences and Arts of Southern Switzerland, Mendrisio, Switzerland; [2]Department for Environmental Science, University of Basel, Basel, Switzerland

ABSTRACT

The restoration of eutrophic lakes requires the identification of phosphorus objectives, *i.e.*, the phosphorus reductions needed to achieve desired water quality goals. Due to inherent uncertainty, phosphorus objectives need periodic revision as the restoration progresses. We used monitoring data from a deep southern Alpine lake (Lake Lugano, Switzerland and Italy) to assess restoration progress and revise the current phosphorus objective of 30 mg m^{-3}. Because one basin of the lake is meromictic (North basin) and the other is holomictic (South basin), restoration focussed on the mixolimnion for the North basin and the entire water column for the South basin. Time series analyses indicated that, thanks to restoration, phosphorus concentrations in the lake declined to values compliant with the objective (~20-30 mg m^{-3}). In contrast, little progress was observed towards achieving the main water quality goals (chlorophyll *a* ≤4 mg m^{-3}, primary production ≤150 g C m^{-2} year^{-1} and oxygen concentrations ≥4 mg L^{-1}). Using predictive models, we estimated that achieving these goals requires a phosphorus objective of <10 mg m^{-3}, which would bring the lake back to the original oligotrophic state. The concentration of <10 mg m^{-3} is lower than the objectives predicted for other (mainly northern) deep Alpine lakes. The apparent sensitivity of Lake Lugano, which we attribute to unfavorable hydrodynamic conditions common in lakes south of the Alps (weak mixing and long stratification), calls for particularly attentive phosphorus management.

INTRODUCTION

Cultural eutrophication is the most widespread cause of water quality degradation in lakes (Smith, 2003; Jeppesen *et al*., 2005; Schindler, 2012). Consequently, reversal of eutrophication is probably one of the most common forms of lake restoration. Restoration of eutrophic lakes started half a century ago, after lake scientists found that eutrophication is caused by excess phosphorus (Schindler, 1977). Based on this finding, the restoration of eutrophic lakes requires the identification of appropriate phosphorus objectives, *i.e.*, the reductions of phosphorus needed to restore healthy lake conditions.

Phosphorus objectives are identified using fixed boundary values (cut-offs between different trophic states; Vollenweider and Kerekes, 1982; Nürnberg, 1996) or predictive water quality models (mathematical expressions predicting water quality indicators from phosphorus concentrations or phosphorus loadings; Dillon and Rigler, 1974; Vollenweider and Kerekes, 1982). Regardless of how they are identified, phosphorus objectives are laced with uncertainty. Fixed boundaries are somewhat arbitrary because trophic states tend to overlap along the axis representing phosphorus concentration (Vollenweider and Kerekes, 1982). Objectives obtained from predictive water quality models (Dillon and Rigler, 1974; Vollenweider and Kerekes, 1982) may perform poorly outside the calibration domain or when environmental conditions change during restoration. Consequently, phosphorus objectives should be considered as tentative hypotheses, which need periodic reviewing as the restoration progresses and the actual lake response becomes better known.

The aim of this study is to review the current phosphorus objective for Lake Lugano, a moderately large (49 km^2) and deep (288 m) Swiss-Italian lake that is being restored from eutrophication. The occasion for the study is provided by a significant milestone. In 1992, three decades ago, a special issue of the scientific journal *Aquatic Sciences* presented a scientific roadmap to the restoration of the lake, which became the blueprint for subsequent restoration plans (CIPAIS, 2018). Articles in the issue identified goals to improve water quality and set the phosphorus objectives needed to achieve these goals (Barbieri and Mosello, 1992; Imboden, 1992). The three decades elapsed since the publication of the special issue (and four decades since the beginning of the restoration in the early 1980s) offer a useful vantage point to evaluate the restoration's progress and review its objectives.

We focus on the progress achieved in reducing phosphorus concentrations and improving water quality (described by four variables: chlorophyll *a*, primary production, fall hypolimnetic oxygen concentration, and areal hypolimnetic oxygen depletion). We selected these water quality variables because they are explicitly tied to restoration goals and three of them (chlorophyll *a*, primary production, and areal hypolimnetic oxygen depletion) can be mathematically modelled. Additionally, because one basin of Lake Lugano is meromictic (North basin) and the other is holomictic (South basin), we focussed on the mixolimnion for the North basin and the entire water column for the South basin. We address the following questions:

1. What progress has been achieved so far in reducing phosphorus concentrations and improving water quality?

2. Based on the results, are the phosphorus objectives set thirty years ago sufficient to achieve the desired improvement in water quality?
3. If not, what new phosphorus objectives should be set?

We addressed these questions by analysing time series of monitoring data (question 1) and using a predictive modelling approach (questions 2 and 3). The time-series analysis summarizes and updates previously-published work (Lepori, 2019a; Lepori and Capelli, 2021). The predictive modelling is new.

MATERIALS AND METHODS

Study site

Lake Lugano is a natural lake located at the southern edge of the Alps (Switzerland and Italy; Figure 1). The lake is divided by a causeway into two basins, the North basin and the South basin (Figure 1, Table 1). The North basin, which is deep (288 m) and has a long residence time (12.3 years), is nearly meromictic, *i.e.*, it is stratified in an oxic mixolimnion and an anoxic, phosphorus-rich (total phosphorus concentrations: 90-270 mg m^{-3}) monimolimnion (the terms used to describe lake stratification are explained in Figure S1). Meromixis is not the original mixing regime of the basin, but was probably induced in the mid-1900s by increased precipitation of carbonates due to eutrophication (Barbieri and Mosello, 1992). Since the beginning of systematic monitoring in the early 1980s, the entire water column mixed only twice, in 2005 and 2006, following exceptionally cold winters (Holzner *et al*., 2009). The depth of the mixolimnion varies from year to year, but usually does not exceed ~100 m (the maximum depth, excluding the 2005-2006 turnovers, was of 102 m in 2000). Typical mixolimnion depths are substantially less deep; *e.g.*, the median long-term (1987-2021) depth is 63 m (DACD-SUPSI, 2022). The South basin, which is shallower (95 m) and has a shorter residence time

Table 1. Morphometric characteristics of the two main basins and one sub-basin (Figino, part of the South basin) of Lake Lugano, Switzerland and Italy.

	North basin*	South basin*	Figino sub-basin
Lake area (km^2)	27.5	21.4	8.2
Lake volume (km^3)	4.69	1.14	0.47
Mixolimnion depth	Maximum: ~100 m Median: 63 m	-	-
Z_{MAX} (m)	288	95	95
Z_{HYPO} (m)	71 (20-100 m layer) 46 (20-63 m layer)		45

*Data from Barbieri and Mosello (1992). Z_{MAX}: maximum depth, Z_{HYPO}: average hypolimnion depth.

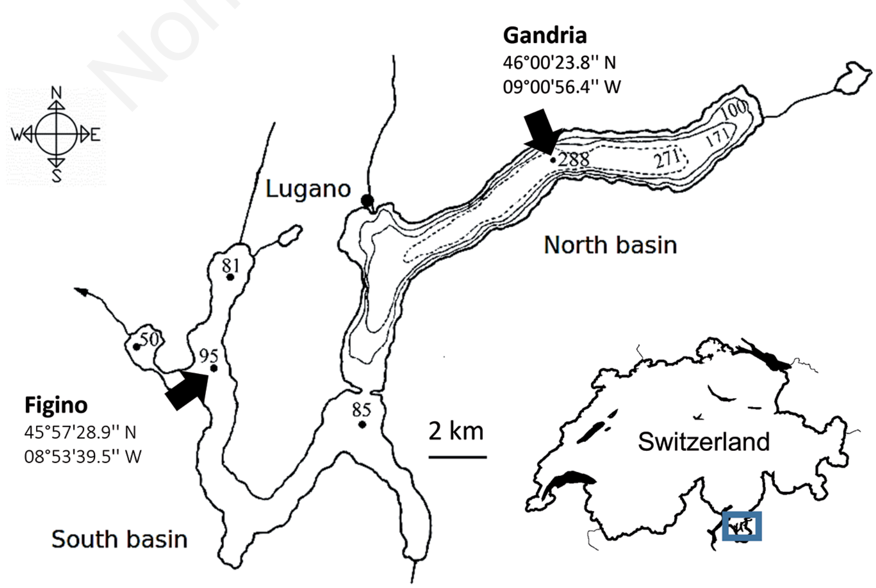

Figure 1. Geographical position of Lake Lugano and the two sampling stations.

(1.5 years), is essentially holomictic, although it has skipped complete mixing following milder than usual winters (*unpublished results*). In both basins, turnovers occur once a year in late winter, usually in January-March. Thermal stratification starts after the late-winter turnover and ends in fall (September-November), when mixing to approximately 20 m of depth erodes the thermocline and allows gas and nutrient exchange between the epilimnion and the hypolimnion.

In pre-industrial times Lake Lugano was oligotrophic (Niessen *et al*., 1992). In the 20th century, the lake underwent rapid eutrophication, reaching eutrophic state by the 1970s (Barbieri and Mosello, 1992). The first plans to restore the lake were set out in the early 1980s by the Administration of Canton Ticino (Switzerland; D. A., 1982). Since then, the management of the lake has been coordinated by an international commission (International Commission for the Protection of Swiss-Italian waters, Italian acronym CIPAIS; www.cipais.org) established in the late 1970s to manage transboundary Swiss-Italian waters. The commission proposes restoration measures to the Swiss and Italian governments and coordinates their implementation to ensure uniform application across the border. The restoration, which is ongoing, is pursued mainly through improved sewage management (Lepori and Roberts, 2017). To date, the restoration has achieved a substantial reduction in phosphorus external loadings and lake concentrations (Lepori and Roberts, 2017; Lepori, 2019a). A recent application of a phosphorus budget model (Lepori, 2019a) indicates that in Lake Lugano the phosphorus concentrations are nearly in equilibrium with the current external loadings.

Current water-quality goals and phosphorus objectives

In the special issue of *Aquatic Sciences*, Imboden (1992) presented two water quality goals and a phosphorus objective based on Swiss policy. The water quality goals for eutrophic lakes were to (1) reduce primary production to ≤150 g C m^{-2} year^{-1} and (2) increase dissolved oxygen concentrations to ≥4 mg L^{-1} (anytime and anywhere, except in meromictic lakes). Imboden (1992) does not present a rationale for the primary production goal of 150 g C m^{-2} year^{-1}, although the suggested value is close to 110 g C m^{-2} year^{-1}, which marks the boundary between oligotrophy and mesotrophy according to Wetzel (1975). The oxygen goal of 4 mg L^{-1} is an estimate of the lowest tolerable oxygen concentrations for fish egg survival (Müller *et al*., 2012). The phosphorus objective was to reduce spring total phosphorus concentrations to 30 mg m^{-3} (Imboden 1992). Again, the rationale for the 30 mg m^{-3} objective is unexplained, although it is close to the 25 mg m^{-3} cut-off between mesotrophy and eutrophy proposed by OECD (Vollenweider and Kerekes, 1982).

The international commission managing the lake (CIPAIS) adopted and operationalized these goals and the phosphorus objective, with some integrations. An important integration was the addition of a chlorophyll *a* goal (yearly average within 2.5-4 mg m^{-3}; CIPAIS, 2018). Additionally, the CIPAIS defined the operational phosphorus, chlorophyll *a*, primary production and oxygen indicators necessary to measure the progress towards the respective objective or goals, which we listed in Table 2. For the North basin, the indicators focus on the 0-100 m layer, implying that the 0-100 m and 100-288 m layers are considered to be isolated. This choice appears to follow Barbieri and Mosello's (1992) suggestion that, for modelling purposes, the North basin is best described by a two-box model where the 0-100 m layer is isolated from the 100-288 m layer. The oxygen goal was applied to the 20-100 m (North basin) or 20-95 m (South basin) layers (roughly corresponding to the hypolimnia of these basins, assuming a mixolimnion depth of 100 m), because hypolimnia present the greatest risk of becoming de-oxygenated. To simplify the analysis of hypolimnetic oxygen, we focussed on the concentrations at the end of the stratification period, when concentrations tend to reach the annual minimum (Müller *et al*., 2019). If oxygen concentrations meet

Table 2. Main objectives, goals and operational indicators for the restoration of Lake Lugano, Switzerland and Italy.

Objectives/goals	Indicators	Comments
Phosphorus concentrations ≤30 mg m^{-3}	Annual average (volume weighted) concentrations of total phosphorus in the 0-100 m layer for the North basin and the 0-95 m layer for the South basin	Assumes that the 0-100 m and 100-288 m layers are isolated (Barbieri and Mosello, 1992)
Chlorophyll *a* between 2.5 and 4 mg m^{-3}	Annual average concentration in the 0-20 m layer	The 0-20 m layer represents the euphotic zone
Primary production ≤150 g C m^{-2} year^{-1}	Cumulative annual value in the 0-20 m layer	The 0-20 m layer represents the euphotic zone
Oxygen concentrations ≥4 mg L^{-1} anytime and anywhere in the lake (except for the monimolimnion of the North basin)	Average (volume weighted) dissolved concentration across the 20-100 m layer for the North basin and the 20-95 m layer for the South basin	The 20-100 m and 20-95 m layer approximately correspond to the respective hypolimnia (Figure S1). Therefore, we refer to these concentrations as hypolimnetic concentrations

the 4 mg L^{-1} goal in these layers and at this moment, they would meet or exceed this goal nearly anytime and anywhere in the lake (except for the monimolimnion in the North basin). Finally, for Lake Lugano, the CIPAIS has identified the qualitative goal of restoring a mesotrophic state (CIPAIS, 2018), a goal consistent with the Swiss law requirement that nutrient content in standing waters "should allow at most an average production of biomass" (Swiss Waters Protection Ordinance, 1998).

Data sources

We used data from monitoring sites in Gandria (near the deepest point of the North basin) and Figino (near the deepest point of the South basin; Figure 1, Table 1). These stations will be referred to as North basin and South basin. We included data from the period 1984-2021, for which systematic monitoring data are available for both stations. The time series of phosphorus, chlorophyll *a*, primary production, and areal hypolimnetic oxygen depletion were presented in specific papers, which provide detailed method information (Lepori, 2019a; Lepori and Capelli, 2021). In short, the average yearly total phosphorus concentration in the lake (P, in mg m^{-3}) was calculated from samples collected monthly at different depths throughout the water column. The monthly concentrations were volume-weighted (North basin: 0-100 m, South basin: 0-95 m) and averaged within years.

Chlorophyll *a* (CHL, in mg m^{-3}) was measured by collecting water samples at different depths across the euphotic layer (0-20 m) at time intervals ranging from two weeks to one month, depending on the season. CHL was measured spectrophotometrically from each sample after extraction in ethanol (Rand *et al*., 1975). Yearly average values were calculated by averaging values across depths and months (fortnightly CHL values were first averaged within months).

Primary Production (PPr, in g C m^{-2} $year^{-1}$) was calculated using the ^{14}C radiotracer method from monthly samples. Yearly values were calculated from monthly values according to Gächter (1972) until 2014 and according to a mathematical procedure based on Finger *et al*. (2013) thereafter (a comparison of the approaches indicated that the results are comparable, *unpublished results*).

Fall hypolimnetic oxygen concentration (HO_{FALL}, in mg L^{-1}) is the hypolimnetic volume weighted oxygen concentration measured at the end of the stratification period in the fall. In keeping with CIPAIS' oxygen indicator (Table 2), the hypolimnion was operationally defined as the 20-100 m layer for the North basin and the 20-95 m layer for the South basin. The end of stratification was identified by the interruption of the nearly linear hypolimnetic oxygen decline observed in spring-summer.

Areal hypolimnetic oxygen depletion (AHOD, in g m^{-2} day^{-1}) is the linear rate of areal hypolimnetic oxygen content decline during the stratification period (areal oxygen content = volume-weighted hypolimnetic oxygen concentration × average hypolimnion depth). The stratified period was defined as the period starting with the late winter turnover, identified by a hypolimnetic oxygen concentration peak, and ending with fall partial mixing, identified as described above. AHOD (g m^{-2} day^{-1}) was calculated using the equation:

$$AHOD = \frac{AHO_{LW} - AHO_{FALL}}{T_{STRAT}}$$

where:

AHO_{LW} = areal hypolimnetic oxygen content (g m^{-2}) after the late winter turnover
AHO_{FALL} = areal hypolimnetic oxygen content (g m^{-2}) at the end of stratification
T_{STRAT} = duration of stratification (days)

For the North basin (Gandria's station), hypolimnetic content was calculated using the volume and surface of the entire North basin (Table 1). For the South basin (Figino's station), we used the volume and surface of the sub-basin of Figino, which represents approximately 40% of the entire South basin (Table 1).

Time series analysis

Temporal trends were analysed using Mann-Kendall tests. In cases of significant trends, we used moving averages (step = 3 years) to highlight temporal trends. In addition, we used the averages of the first and last three years of the study period (1984-1986 and 2019-2021) to quantify the magnitude of the changes in percentage. Trend analyses were performed using the Excel template application MAKESENS 1.0 (Salmi *et al*., 2002). The results report the Z statistic, the associated *P*-value, and the Sen's slope (Q), *i.e*., the linear rates of change estimated using Sen's method (Sen, 1968).

Predictive models

We predicted CHL (mg m^{-3}) and PPr (g C m^{-2} $year^{-1}$) from P by using the following OECD models (Vollenweider and Kerekes, 1982):

$$CHL = 0.28 \times P^{0.96}$$

$$PPr = 512 \times \frac{P}{28.1 + P}$$

where:

P = average yearly total phosphorus concentration (g m^{-3}) in the 0-100 m layer (North basin) or 0-95 m layer (South basin)

The P-CHL model is empirical, whereas the P-PPR model attempts to model self-shading by phytoplankton and phosphorus limitation using a saturation function.

We predicted AHOD from P by using a model based on Müller *et al*. (2019). Müller *et al*. (2019) examined the relationship between AHOD and areal phosphorus loadings in a sample of European lakes (mostly Swiss lakes located north of the Alps, including transboundary lakes and Lake Annecy, France). They found a threshold pattern where AHOD increases linearly with increasing phosphorus loadings to a threshold of 0.5 g P m^{-2}, after which AHOD reaches a plateau of 1.1 g m^{-2} day^{-1}. We developed a P-AHOD model using data annexed to the paper. Since the paper provided spring turnover concentrations, P_{SP}, we converted spring turnover concentrations to annual average concentrations using $P = 0.9P_{SP}$ (Chapra and Tarapchak, 1976; for Lake Lugano, over the period 1987-2015, empirical conversion coefficients were estimated to be 0.91 for the North Basin and 0.88 for the South basin; *unpublished results*). Next, we fitted a piecewise regression to predict AHOD from P (Figure S2). The piecewise regression yielded accurate predictions of AHOD using a sloping line below a breakpoint concentration of 17.68 mg m^{-3} and a constant concentration (plateau) above it:

$$\text{if } P < 17.68 \text{ mg m}^{-3}, \text{AHOD} = 0.363+0.0396P$$

$$\text{if } P \geq 17.68 \text{ mg m}^{-3}, \text{AHOD} = 1.06$$

This model assumes that AHOD is largely due to mineralization of primary production settling from the euphotic zone. The breakpoint separates an area of phosphorus saturation (>18 mg m^{-3}) from an area of phosphorus limitation, where PPr increases linearly with P. The model is based on temporally averaged data (each lake is represented by a mean AHOD calculated over a period of 6-36 consecutive years, depending on lake), so it is not designed to capture year-to-year variation.

For each model we assessed accuracy using the Mean Absolute Percentage Error (MAPE) and model bias using the Mean Absolute Error (MAE).

Phosphorus objectives

Phosphorus objectives can be calculated for CHL, PPr and HO goals using the models described above. Phosphorus objectives to attain the CHL goal of 4 mg m^{-3} and the PPr goal of 150 g C m^{-2} $year^{-1}$ were calculated directly using OECD's P-CHL and P-PPr models. Phosphorus objectives to attain the HO goal of 4 mg L^{-1} were calculated indirectly, by linking the HO goal to a matching AHOD goal, then using the P-AHOD model to calculate the phosphorus concentration required to attain the AHOD goal (Müller *et al*., 2019). The link between the HO goal and the corresponding AHOD goal is provided by the theoretical maximum tolerable AHOD ($AHOD_{TOL}$, g m^{-2} day^{-1}), the value that could prevent the development of hypolimnetic concentrations below a certain concentration goal. $AHOD_{TOL}$ can be calculated using the equation (Müller *et al*., 2019):

$$AHOD_{TOL} = \frac{Z_{HYPO}}{T_{STRAT}} \times (HO_{LW} - HO_{GOAL})$$

where:

Z_{HYPO} = average hypolimnion depth (m)
T_{STRAT} = duration of stratification (days; see AHOD model above)
HO_{LW} = hypolimnetic oxygen concentration during the late winter turnover (mg L^{-1})
HO_{GOAL} = hypolimnetic oxygen concentration goal (4 mg L^{-1})

The values of T_{SRAT} were obtained from our oxygen concentration data (the beginning and end of stratification were identified as indicated above). The values of Z_{HYPO} were obtained from morphometric data (Table 1). For the South basin, we used a Z_{HYPO} of 45 m, which corresponds to the 20-95 m layer. For the North basin, we defined the hypolimnion in two ways: as the 20-100 m layer (100 m is the maximum mixolimnion depth) and as the 20-63 m layer (63 m is the long-term median mixolimnion depth based on monitoring data, *see above*). We refer to these layers (Z_{HYPO} = 71 m and 46 m, respectively) as the 'maximum' and 'typical' North basin hypolimnia. However, the phosphorus objectives obtained assuming a hypolimnion depth of 71 m were unrealistic (*e.g.*, according to the results, even the observed P values would not cause hypolimnetic concentrations below 4 mg L^{-1}, which is unsupported by the data). Therefore, we report only the phosphorus objectives obtained assuming a typical hypolimnion depth of 46 m.

Values of HO_{LW} were obtained from analyses of deep oligo-mesotrophic lakes located South of the Alps (lakes Maggiore, Como, and Garda). In these lakes, the water column oxygen content at late-winter turnovers varies between approximately 6-10 mg L^{-1} depending on the depth of mixing (deeper mixing is associated with higher oxygen concentrations; Rogora *et al*., 2018). For this study we used a HO_{LW} of 8 mg L^{-1} to represent typical years, a HO_{LW} of 7 mg L^{-1} to represent years of lower-than-average mixing, and a HO_{LW} of 6 mg L^{-1} to represent years of weak mixing. Measured HO_{LW} values for Lake Lugano are currently lower (*data not shown*), but we assume that HO_{LW} would reach values in the 6-8 mg L^{-1} range following restoration to a mesotrophic or oligotrophic state.

RESULTS

Restoration outcome so far

During the study period, Phosphorus concentrations (P) declined from 76 to 21 mg m^{-3} in the North basin (a 72% decline) and from 114 to 28 mg m^{-3} in the South basin (a 76% decline, Table 3; Figures 2A-B). Chlorophyll *a* concentration (CHL) declined from 11.8 to 6.9 mg m^{-3} in the North basin (a 42% decline) and from 13.8 to 7.3 mg m^{-3} in the South basin (a 47% decline; Figures 2C-D). Primary Production (PPr) and Fall Hypolimnetic Oxygen Concentrations (HO_{FALL}) showed no trends (Figures 2E-H). Primary production fluctuated around average values of 323 g C m^{-2} $year^{-1}$ in the North basin and 368 g C m^{-2} $year^{-1}$ in the South basin; HO_{FALL} fluctuated around average values of 3.4 mg L^{-1} in the North basin and 2.3 mg L^{-1} in the South basin. The Areal Hypolimnetic Oxygen Depletion (AHOD) showed no trend in the North basin (average = 0.8 g m^{-2} day^{-1}), whereas AHOD displayed a declining trend in the South basin (from 1.2 to 0.9 g m^{-2} day^{-1} over the study period, a 25% decline; Figures 2I-J).

PREDICTIVE MODELS

The P-CHL model showed poor accuracy (MAPE: North basin = 90%, South basin = 48%; Figures 3A-B) and a tendency to overestimate the observed values [MAE (10^{th} percentile, 90^{th} percentile): North basin = 5.4 mg m^{-3} (-1.0 mg m^{-3}, 10.9 mg m^{-3}), South basin = 4.2 mg m^{-3} (0.2 mg m^{-3}, 11.0 mg m^{-3}]). In comparison, the P-PPr model showed moderate accuracy (MAPE: North basin= 23%, South basin=17%; Figures 3B-C) and no bias [MAE (10^{th} percentile, 90^{th} percentile): North basin = 31 g C m^{-2} $year^{-1}$ (-76 g C m^{-2} $year^{-1}$, 125 g C m^{-2} $year^{-1}$), South basin = -18 g C m^{-2} $year^{-1}$ (-109 g C m^{-2} $year^{-1}$, 79 g C m^{-2} $year^{-1}$)]. Concerning the AHOD model, the phosphorus concentrations included in the study were always above the threshold of 18 mg m^{-3} (Figures 3E-F). Therefore, the model predicted the plateau AHOD value of 1.1 g m^{-2} day^{-1} for all years, in both lake basins. The data supported the existence of a plateau in the North basin, whereas in the South basin AHOD decreased slightly with decreasing P. Model accuracy was moderate to modest (MAPE: North basin = 49%, South basin = 31%). The model tended to overestimate the observed AHOD values [MAE (10^{th} percentile, 90^{th} percentile): North basin = 0.3 g m^{-2} day^{-1} (0.0 g m^{-2} day^{-1}, 0.5 g m^{-2} day^{-1}), South basin = 0.2 g m^{-2} day^{-1} (0.0 g m^{-2} day^{-1}, 0.4 g m^{-2} day^{-1})]. The P-AHOD graphs (Figures 3E-F) suggest that the model estimates were closer to the upper limit of the observed AHOD values than to the average values. Additional analyses supported this idea, showing that the predicted threshold of 1.1 g m^{-2} day^{-1} matched precisely the 90^{th} percentile of the observed AHOD values in both basins.

PHOSPHORUS OBJECTIVES

Based on the P-PPr model, achieving the CHL goal of 4 mg m^{-3} would require P values of 19 mg m^{-3}, while the PPr goal of 150 g C m^{-2} $year^{-1}$ would require P values of 12 mg m^{-3}. The median duration of stratification T_{STRAT} was 210 days in the South basin and 202 days in the North basin. Using these values, achieving the oxygen goal of 4 mg L^{-1} would require AHOD values of 0.9 g m^{-2} day^{-1} during typical years (HO_{LW} = 8 mg L^{-1}), AHOD values of 0.6-0.7 g m^{-2} day^{-1} during years with lower-than-average mixing (HO_{LW} = 7 mg L^{-1}), and AHOD values of 0.4-0.5 g m^{-2} day^{-1} during years of weak mixing (HO_{LW} = 6 mg L^{-1}; double values are for the South basin and the North basin, respectively). According to the P-AHOD model, these AHOD values correspond to P of 14 mg m^{-3}, 6-9 mg m^{-3}, and 1-3 mg m^{-3}.

Table 3. Results of the time series analysis: Mann-Kendall tests (Z statistic and associate significance) and Sen's slopes (Q).

Time series	Unit	Test Z	Significance	Q
P (N.B.)	mg m^{-3}	-4.53	***	-1.4
P (S.B.)	mg m^{-3}	-7.78	***	-2.1
CHL	mg m^{-3}	-2.93	***	-0.10
CHL	mg m^{-3}	-4.80	**	-0.16
PPr (N.B.)	g C m^{-2} $year^{-1}$	0.50		0.6
PPr (S.B.)	g C m^{-2} $year^{-1}$	-0.43		-0.4
HO_{FALL} (N.B.)	g L^{-1}	-1.13		0.0
HO_{FALL} (S.B.)	g L^{-1}	-0.13		0.0
AHOD (N.B.)	g m^{-2} day^{-1}	-0.55		0.00
AHOD (S.B.)	g m^{-2} day^{-1}	-3.29	***	-0.01

Significance: ** = P <0.01, *** = P <0.001. P, annual Phosphorus concentration; PPr, Primary Production; HO_{FALL}, Fall Hypolimnetic Oxygen Concentration; AHOD, Areal Hypolimnetic Oxygen Depletion; N.B., North Basin; S.B., South Basin.

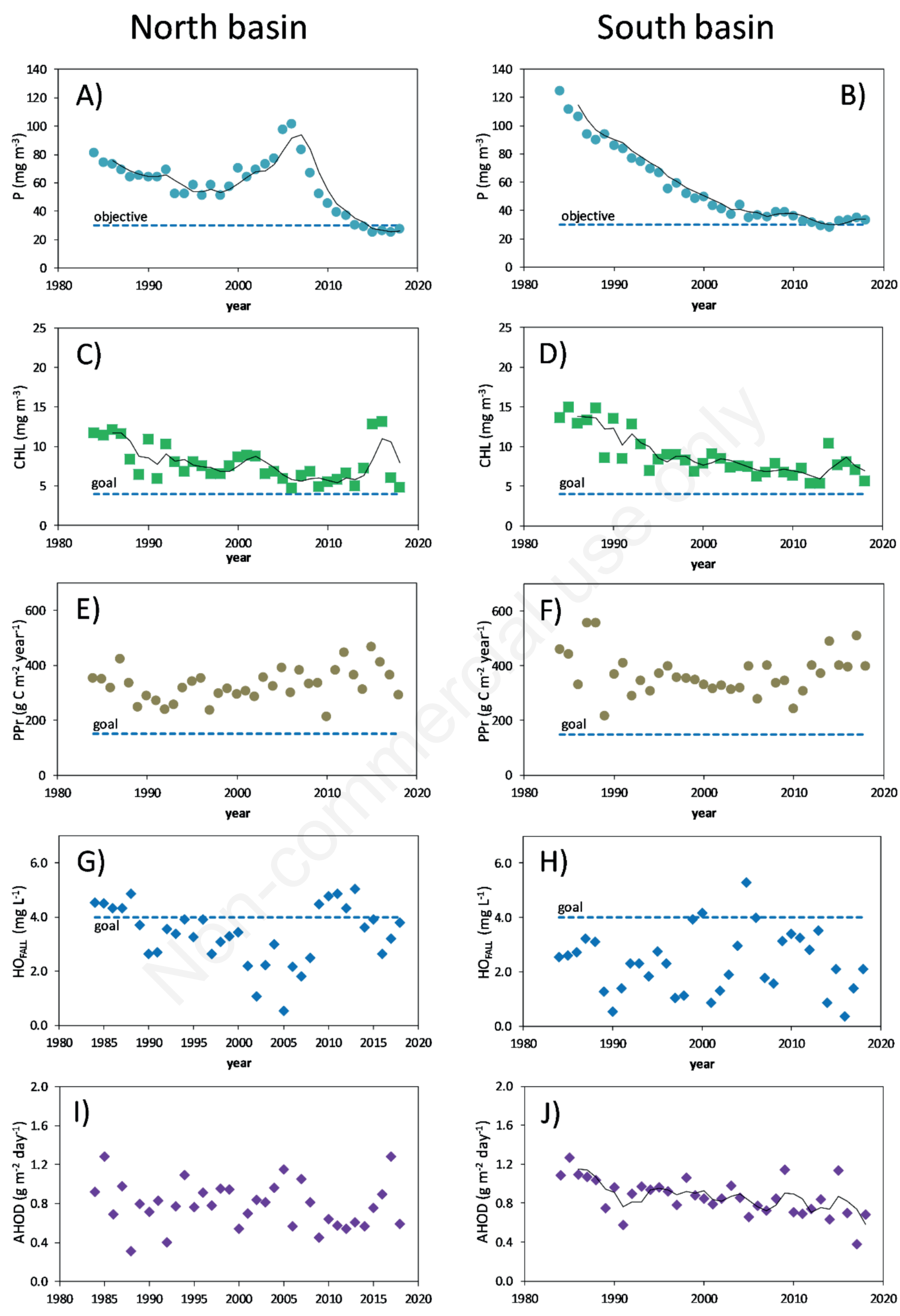

Figure 2. Temporal trends of annual Phosphorus concentrations (P), Chlorophyll *a* (CHL), Primary Production (PPr), Fall Hypolimnetic Oxygen Concentration (HO_{FALL}), and Areal Hypolimnetic Oxygen Depletion (AHOD) in the two main basins of Lake Lugano (North basin and South basin). Restoration objectives and goals are indicated where applicable (Table 2). Moving averages (step = 3) were used to highlight significant trends (Table 3).

DISCUSSION

Thanks to the restoration program, during the study period, average Phosphorus concentrations (P) declined from high values typical of eutrophic lakes (76 and 114 mg m^{-3}) to moderate values (20-30 mg m^{-3}) well within the restoration objective of 30 mg m^{-3}. Even so, the phosphorus decline did not result in the expected improvements in water quality. Only Chlorophyll *a* (CHL) declined consistently in both lake basins, although the concentrations at the end of the study period were still nearly twice as high (1.7-1.8×) as the restoration goal. Values of Primary Production (PPr) and Fall Hypolimnetic Oxygen Concentrations (HO_{FALL}) not only remained far from the respective goals, but also did not change. Therefore, phosphorus concentrations in the 20-30 mg m^{-3} range, including the restoration objective of 30 mg m^{-3}, are not sufficient to attain the CIPAIS' water quality goals in Lake Lugano.

The decline of CHL may at first glance appear consistent with the restoration's underlying tenet that phytoplankton biomass is phosphorus limited. However, increased phosphorus limitation was unlikely, because primary production showed no decline (see below). We suggest that the decline in CHL was caused, in part, by an abrupt ecosystem change observed in 1989, marked by a sudden increase in large-bodied zooplankton and (presumably) greater grazing pressure on phytoplankton (triggers may have included a mild winter and a decline of zooplanktivorous fish, but the causal relationships remain unsolved; Lepori and Roberts, 2017; Lepori, 2019b). This regime shift was not the only cause of the CHL decline, because CHL appeared to decline (less markedly) even after 1989, but at this time we cannot advance any explanations for this pattern.

The lack of significant changes in PPr and HO_{FALL} could have been expected. Based on existing empirical models, P influences PPr and AHOD at low concentrations, but the effect saturates at moderate to high concentrations. According to the OECD model used in this study, the effect of P on PPr saturates above concentrations of approximately 20-30 mg m^{-3}. Other studies suggest lower thresholds. Data from Lake Washington, USA, indicate that P limits PPr during the productive season up to concentrations of 20 mg m^{-3}, beyond which PPr reaches a plateau (Smith, 1979). Similarly, according to Müller *et al*. (2019), AHOD reaches a plateau beyond a phosphorus loading of 0.54 g P m^{-2} (areal loading during the productive season), which corresponds to a yearly concentration of approximately 18 mg m^{-3} (Figure S2). These examples suggest that a phosphorus concentration of approximately 20 mg m^{-3} marks the transition point between phosphorus control and phosphorus saturation in lakes. During the study period, phosphorus concentrations in Lake Lugano were nearly always >20 mg m^{-3}, *i.e*., in the domain where phosphorus has little or no influence on PPr or AHOD.

Our attempts to predict CHL, PPr and AHOD using models produced mixed results. CHL was not adequately predicted by using the OECD P-CHL model. The model bias and inaccuracy were not entirely unexpected, as other studies have remarked that global P-CHL models may perform poorly when applied to individual lakes (*e.g*., Smith and Shapiro, 1981). In Lake Lugano, the model's tendency to overestimate CHL might have been caused by high grazing pressure by zooplankton (Lepori, 2019b), which could reduce phytoplankton biomass yields for unit phosphorus. For these reasons, we suggest that global P-CHL models, in their current form, provide an unreliable approach for setting lake restoration goals. The P-PPr model performed comparatively better. Despite the moderate accuracy, which may indicate methodological differences, measurement error, and influence by additional factors (Tadonléké *et al*., 2009) in the calibration data set, the model yielded unbiased predictions, which could be used to set the phosphorus concentrations needed to keep the medium-term PPr average (*e.g*., 4-5 years) near the restoration goal.

The performance of the P-AHOD model was somewhat below expectations, because the model had good predictive ability for the calibration data set (Figure S2). An explanation for the model tendency to overestimate the observed values in this study is that the initial oxygen concentration (HO_{LW}) in Lake Lugano probably differed from those of the calibration set [Müller *et al*. (2019) mention 10 mg L^{-1} as a typical HO_{LW} value, whereas we observed average values of 5-6 mg L^{-1}]. This difference would bias the predictions because, in deep Alpine lakes, AHOD tends to be positively associated with HO_{LW} (higher HO_{LW} results in faster hypolimnetic oxygen depletion; Rogora *et al*., 2018, Lepori and Capelli, 2021). Therefore, in Lake Lugano, lower HO_{LW} values could have caused lower AHOD values relative to lakes in the calibration set with similar phosphorus concentrations. In addition, as expected, the model did not predict year-to-year variation, which was substantial, probably because of parallel variation in mixing depth and HO_{LW} (Lepori and Capelli, 2021).

Despite these drawbacks, the P-AHOD model provided reasonable predictions of upper-range AHOD values. A better prediction of upper-range (rather than average) values can be explained by the tendency of higher AHOD values to be associated with higher HO_{LW} concentrations, close to concentrations found in the calibration domain (*not shown*), for which the model should yield accurate results. Therefore, we suggest that the P-AHOD model may be useful to estimate the phosphorus concentrations that would keep AHOD within the maximum tolerable value ($AHOD_{TOL}$) most of the time (if the model predicted average AHOD values, the phosphorus concentrations predicted to keep AHOD at the maximum tolerable value would suffice only on average). In addition, the model bias may diminish as restoration progresses and HO_{LW} increases in the lake. However, we also suggest that, in the future, the model should be further developed to improve its mechanistic basis (*e.g.*, a AHOD model should additionally account for mixing) and predictive accuracy.

Given that the current phosphorus objective (30 mg m^{-3}) is not sufficient to attain the water quality goals, what new phosphorus objectives should be set for the lake? Excluding CHL due the uncertainty of the P-CHL model, our results indicate that attaining the restoration PPr and HO_{FALL} goals would require a reduction of P to 12-14 mg m^{-3} or lower. A reduction to 12-14 mg m^{-3} would help attain the PPr and HO_{FALL} goals in typical years, assuming HO_{LW} values close to 8 mg L^{-1}. However, a phosphorus reduction to 12-15 mg m^{-3} would not be enough to attain the oxygen goal in years when mixing during turnovers is below average or weak (causing HO_{LW} values of 6-7 mg L^{-1}), or when stratification lasts more than ~200 days. In these years, only reduction to phosphorus concentrations below 10 mg m^{-3} would keep hypolimnetic oxygen concentrations above 4 mg L^{-1} most of the time, as recommended by the restoration programme (the model predicts values between 1-9 mg m^{-3}, but given the relatively low

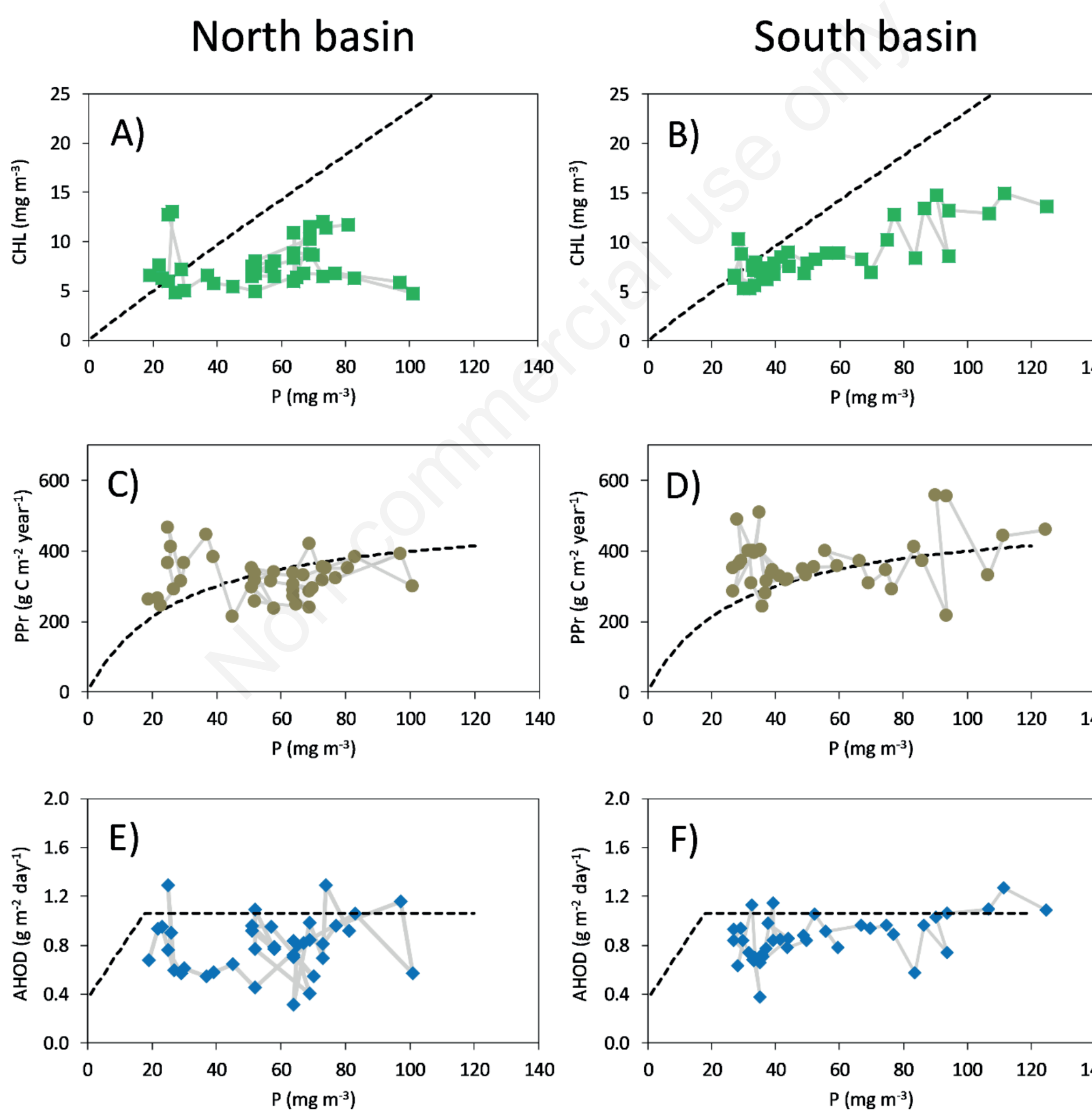

Figure 3. Observed (markers) and predicted (dashed line) Chlorophyll *a* (CHL), Primary Production (PPr), and Areal Hypolimnetic Oxygen Depletion (AHOD) *versus* Phosphorus concentrations (P). Gray lines connect data from consecutive years.

model accuracy we lump these values under the single category '<10 mg m^{-3}'). The phosphorus concentration of 10 mg m^{-3} is considered a boundary between mesotrophic and oligotrophic conditions (Vollenweider and Kerekes, 1982). Therefore, our predictions suggest that meeting the oxygen goal will require a return to oligotrophic conditions, *i.e.*, all the way to the reference state of the lake.

We were surprised by the low AHOD values (≤0.4-0.9 g m^{-2} $year^{-1}$) and low phosphors concentrations (≤14 mg m^{-3}) that were predicted to reach the oxygen goal in Lake Lugano. According to Müller *et al*. (2019), deep lakes are resistant to hypolimnetic de-oxygenation. They estimated that, in lakes with Z_{HYPO} greater than 32 m, even a plateau AHOD of 1.06 g m^{-2} day^{-1} would keep hypolimnetic oxygen concentrations at 4 mg L^{-1} at the end of stratification. Based on the P-AHOD model, in these lakes, even the highest phosphorus concentrations observed in Lake Lugano (~110 mg m^{-3}) should not cause critical hypolimnetic de-oxygenation. In contrast, although the hypolimnion of Lake Lugano is deep (Z_{HYPO} of 45-46 m), the low tolerable AHOD and P values found in this study indicate high sensitivity to deep-water de-oxygenation. This sensitivity is probably linked to the lake's location south of the Alps. In this region, the relatively milder climate causes lake hydrodynamic conditions that are unfavorable to deep-water oxygenation. First, as already mentioned, milder winters can cause weak mixing during turnovers, which result in HO_{LW} lower than 8 mg L^{-1}. Second, in southern Alpine lakes the stratification period is longer (more than 200 days according to our data, whereas Müller *et al*., 2019 suggest a typical value of 180 days for their sample of lakes). Based on the $AHOD_{TOL}$ equation used in this study, it is easy to see how the low initial oxygen concentrations and long stratification periods make hypolimnetic de-oxygenation likely even at relatively low AHOD values.

High sensitivity to de-oxygenation has important implications for the management of Lake Lugano and other deep southern Alpine lakes. For Lake Lugano and other mesotrophic or eutrophic lakes (*e.g*., Lake Iseo), only drastic phosphorus reductions could restore adequate oxygenation in hypolimnetic waters. For oligotrophic lakes (lakes Maggiore and Garda), even small enrichment in phosphorus could lead to hypolimnetic de-oxygenation. This vulnerability will be heightened by climate change, which is expected to weaken mixing and cause longer stratification periods (Fenocchi *et al*., 2018). In the future, phosphorus objectives that prevent hypolimnetic de-oxygenation may become progressively harder to attain. Thus phosphorus management and policy should be particularly attentive to deep southern Alpine lakes, especially as we progress towards a warmer climate.

A *caveat* to our conclusions is that, for the North basin, the restoration focusses on the mixolimnion, assuming isolation from the deeper phosphorus-rich, anoxic hypolimnion. This is, however, a simplistic assumption, because an analysis of internal loadings (Lepori, 2019a) indicated that during the exceptional turnovers of 2005-2006, and the decade leading to these events, high internal loadings of phosphorus were transferred from the monimolimnion to the mixolimnion. After the turnovers, the phosphorus upwelling subsided, and phosphorus concentrations in the mixolimnion quickly returned to pre-turnover levels. The upwelling was caused jointly by an increase in the monimolimnion temperature and a decrease in calcite precipitation, which weakened the density difference between monimolimnion and mixolimnion (Holzner *et al*., 2009). Similar upwelling events will probably repeat in the future. Ironically, the restoration may facilitate these events by reducing calcite precipitation induced by elevated primary production. Therefore, over the next decades, the recovery of the North basin will be punctuated by events of mixing and re-eutrophication. The magnitude and frequency of these events will be dictated by the long-term fate of the meromixis of the basin, which, lacking specific research, we are currently unable to predict.

CONCLUSIONS

Based on this study we propose the following recommendations for the management of Lake Lugano:

- The water layers that may be realistically restored in the near future are the 0-94 m layer in the South basin (whole water column) and the 0-63 m layer in the North basin.
- Predictions of the phosphorus objectives should be based on P-PPr and P-AHOD models. The P-CHL model used in this study is too uncertain to set phosphorus objectives.
- P should be reduced to at least 12-14 mg m^{-3}, possibly to lower concentrations (<10 mg m^{-3}) to ensure that the oxygen goal of 4 mg L^{-1} is met most of the time. Due to uncertainties in our predictions, and the high costs involved in reducing P, the reduction should proceed in increments, followed by further revisions of the P objectives. An objective of approximately 15 mg m^{-3} may be used as an intermediate first increment.
- A budget model can be used to estimate the corresponding reduction in external loadings needed to achieve the P objective (Lepori, 2019a).

Developing better AHOD models that improve accuracy, reduce bias, and account for variation in physical mixing during turnovers would be particularly helpful to future revisions of phosphorus objectives. As AHOD models seem to be regionally-specific, new AHOD models should be calibrated based on the characteristics of deep southern Alpine lakes.

Corresponding author: Fabio Lepori, Institute of Earth Sciences, University of Applied Sciences and Arts of Southern Switzerland, Campus Mendrisio, Via Flora Ruchat-Roncati 15, 6850 Mendrisio, Switzerland.
E-mail: fabio.lepori@supsi.ch

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