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Possibilities and limitations of lake restoration: Conclusions for Lake Lugano

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ABSTRACT

In most lakes eutrophication is linked to an excessive input of phosphorus. Lake restoration by reduction of P-input (external measure) has led to a considerable drop of the P-concentration in all major Swiss lakes as well as in many other lakes. Internal restoration measures such as artificial mixing, drainage of hypolimnetic water, flushing, aeration, biomanipulation and others serve to improve and accelerate the response of a lake to external measures. For the case of Lago di Lugano, a simple two-box model is employed to demonstrate that a reduction of the P-input to about 25% of the present values is necessary to reach the "P-criterion" (P-concentration below 30 μg/l). Internal measures could possibly accelerate the extremely slow response of the northern basin.

1. Origin of lake eutrophication

Since Vollenweider's (1968) pioneering investigation on the cause of lake eutrophication the predominant role of phosphorus (P) as the controlling nutrient for many – though not all – lakes has been confirmed over and over again (see e.g. Rast et al., 1983). However, a quantitative definition of the goal of lake restoration is ambiguous. What is considered to be a "clean" lake? According to the Swiss policy the general goal of water pollution control is circumscribed by a set of seven properties natural waters should have in order to be termed "clean". They extend from anthropogenic interests (drinking water supply, irrigation etc.) to ecological criteria (natural waters as habitat for aquatic organisms). With respect to the nutrient conditions in lakes, these general goals are substantiated by the following criteria:

A lake should belong to the oligotrophic (or mesotrophic, at most) production type. This means that:

(1) in spring, the total P-concentration should not exceed 30 μg P/l;
(2) the total annual primary production should not exceed 150 g C/m^2;
(3) the concentration of dissolved molecular oxygen (O_2) should at no time and nowhere drop below 4 mg/l, except for natural conditions which may inhibit an adequate oxygenation of the water body (e.g., due to natural meromixis).

These criteria are interdependent, but their relative restriction may be different from lake to lake. For instance, in one lake it may be easy to fulfil the oxygen criterion but difficult to reduce the P-concentration adequately while in another lake the situation may be reversed.

In this article the various tools for the restoration of eutrophic lakes are shortly reviewed and their strength and weakness analyzed, especially regarding their application to the eutrophic Lago di Lugano.

2. Restoration by reduction of nutrient loading

The primary and ecologically meaningful method of lake restoration is by reduction of the external nutrient supply (especially phosphorus). This restoration measure is often called "external" – in contrast to the "internal" measures to be discussed in the next section. The possibilities and limitations of lake restoration by reduction of P-input have recently been analyzed based on eighteen European lakes (Sas, 1989). In this investigation the response of the trophic state of a lake was subdivided into two steps, the first one referring to the change of the P-concentration in the lake due to the change of the P-input, the second one referring to the change of biomass concentration and biomass composition due to the change of P-concentration. It turned out that the processes involved in step 1 can be described more easily in terms of simple concepts (such as the concept of mass balance) than the processes involved in step 2. The latter depend on complex ecological structural changes; they may be time-delayed and depend on properties of the lake which are not described by the basic data sets commonly employed for the monitoring of lakes.

The following considerations will focus on step 1. The response of the P-concentration in lakes to P-input reduction can be best demonstrated by looking at the dramatic changes measured in all major Swiss lakes during the last 40 years (Fig. 1). In most lakes, the P-concentration sharply increased during the fifties and sixties and then started to decrease in the mid-seventies, when a concentrated effort was made to reduce phosphorus in domestic waste water. A delayed decrease was measured in Zugersee, Sempachersee, and Lac de Neuchâtel, lakes with long water residence times (larger than 10 years) and thus, in accordance with the mass balance model, with slow response.

The potential for reducing the external nutrient supply is limited by two factors, the cost of P-elimination (Table 1) and the relative importance of diffuse P-input such as by export from soil by natural runoff or by phosphorus in the precipitation falling onto the water surface. In lakes with relatively little water throughflow and with intensive agricultural production in their drainage basin, the diffusive sources can easily exceed the total tolerable P-input (Fig. 2).

3. Restoration by internal measures

In addition to external restoration measures, internal measures may become adequate provided that, because of the reasons mentioned above, the external

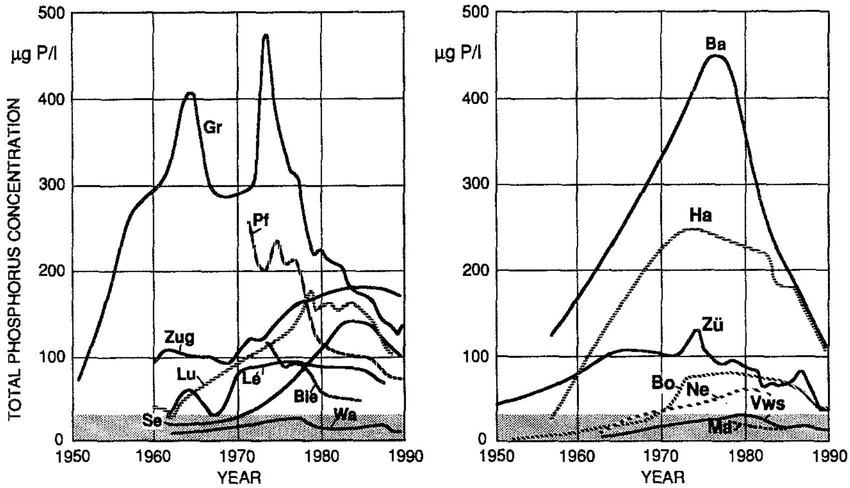


Figure 1. Temporal evolution of total P-concentration in several lakes of Switzerland and neighboring countries. Gr = Greifensee, Pf = Pfäffikersee, Zug = Zugersee, Lu = Lago di Lugano (Southern Basin), Lé = Lac Léman (Lake Geneva), Bie = Bielersee, Se = Sempachersee, Wa = Walensee, Ba = Baldeggersee, Ha = Hallwilersee, Zü = Zürichsee, Ne = Lac de Neuchâtel, Vws = Vierwaldstättersee, Bo = Bodensee, Ma = Lago Maggiore. From Ambühl (1982), completed by additional information from H. Ambühl and the Federal Office for the Environment, Forest and Landscape (BUWAL)

Table 1. Typical costs for phosphorus elimination from water

	Cost (Swiss francs per kg P)	Initial P-concentration (µg/l)	Degree of elimination (%)
Sewage treatment/plant			
Simultaneous precipitation	10	4000	80
Floculation filtration	100	800	75
In situ removal from lake[1]	500	200	80

[1] For instance, reduction of P-concentration in the lake water by pumping water from the deep layers of the lake into a floculation filtration plant built on the shore and reintroduction of treated water into the lake

measures cannot be extended as far as necessary or the lakes respond slowly to external measures (mechanism of hysteresis, see Imboden, 1987 a). A list of the more common internal restoration measures is given in Table 2. Table 3 summarizes implementation of internal measures in Swiss lakes. The method of biomanipulation (Benndorf, 1987) and *in situ* P-removal (Ripl, 1976) has not been employed in Swiss lakes till now. A preliminary attempt in a small lake for the chemical treatment of the sediments was unsuccessful and abandoned.

As far as the internal restoration method directly affects the P-balance of the lake (drainage of water, increase of water throughflow, artificial mixing, *in situ*

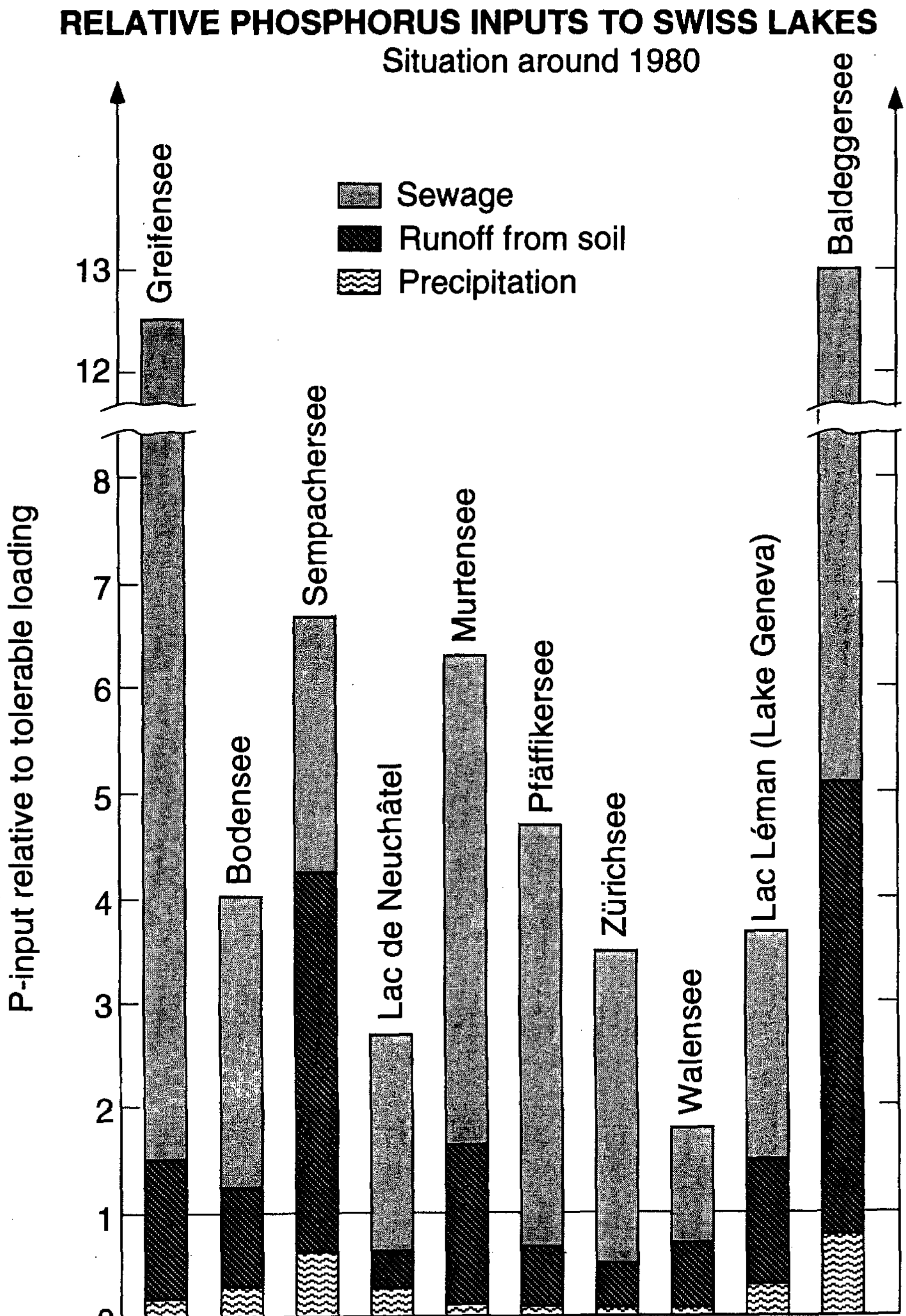


Figure 2. P-input into several Swiss lakes in the early 80ies in relation to the maximum tolerable P-input calculated from Vollenweider (1976), separated into the major sources (sewage, runoff, precipitation onto lake)

Table 2. Internal restoration measures for eutrophic lakes

Method		Goal of method
DR	Drainage of deep water	Export of nutrient-rich, O_2-poor water from lake
MIX	Artificial mixing	Increase of vertical water exchange during the winter to replace the O_2-poor (or anoxic) deep water
OX	O_2-input	Input of oxygen into the hypolimnion to improve the O_2-concentration during the summer and to reduce the redissolution of phosphorus from the sediments
HY	Increase of water throughflow	Change of hydraulic regime of lake by flushing the lake volume with additional water in order to increase the nutrient export
EL	*In situ* elimination of P	Reduction of *in situ* P-concentration (see Table 1)
SED	Chemical treatment of sediments	Reduction of P-redissolution by chemical measures; especially by changing the *in situ* redox potential
BIO	Biomanipulation	Change of ecosystem structure in order to reduce the biomass concentration Example: Remove carnivorous fish to increase concentration of herbivorous zooplankton and thus to reduce phytoplankton concentration

Table 3. Internal restoration measures in Swiss lakes[1]

Lake	Area (km^2)	Method[2]	Implementation
Rotsee	0.48	HY	1922
Mauensee	0.55	DR	1968
Burgäschisee	0.21	DR	1977
Wilersee	0.03	OX	1981
Baldeggersee	5.3	OX (summer), MIX (winter)	1982
Lützelsee	0.11	DR	1983
Hüttnersee	0.18	OX (summer), MIX (winter)	1983
Seeweidsee	0.01	HY	1983
Sempachersee	14.5	OX (summer), MIX (winter)	1984
Hallwilersee	10.3	OX (summer), MIX (winter)	1985/86
Türlersee	0.46	MIX (winter)	1988
Pfäffikersee	3.3	MIX (winter)	1991/92

[1] Completed list based on information from the Federal Office for the Environment, Forest and Landscape (BUWAL), Schriftenreihe Umweltschutz Nr. 46, Bern, November 1985
[2] See Table 2 for abbreviations

elimination of P), the response of the P-concentration in the lake can be predicted reasonably well (Imboden, 1987 b). Methods, which aim at an increase of P-retention in the sediments (O_2-input, artificial mixing, chemical treatment of sediments) are more difficult to evaluate. According to Table 3, a combined method (artificial mixing and O_2-input) has been adapted for the three largest lakes in Switzerland so far treated by internal measures (Baldeggersee, Sempachersee, Hallwilersee). The impact of hypolimnetic oxygenation on the P-retention has been questioned (Gächter et al., 1989), but the P-concentration in all three lakes has significantly dropped during the last years (Fig. 1), though it is not easy to isolate the effects of the internal from the external measures. Obviously, enforcing the oxygen criterion by artificial oxygenation without reducing the nutrient concentration has only little impact on the overall tropic state of the lake. The fish may occupy a larger water volume, but the natural reproduction of salmonid fish may still be severely hampered, since the oxygen concentration at the sediment surface remains low as long as the settling flux of biomass to the sediments is large (Müller, 1992).

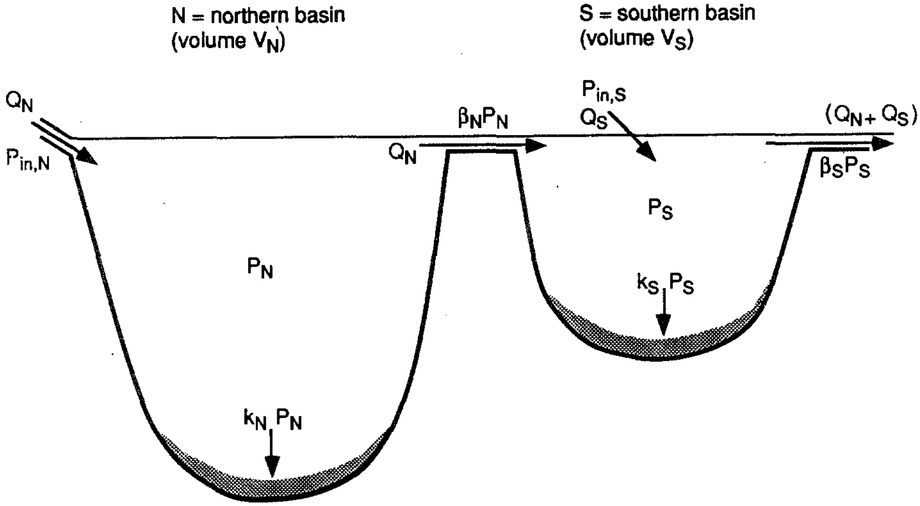
4. The case of Lago di Lugano

The physical, chemical and biological characteristics of Lago di Lugano are extensively treated in this volume. Zamboni et al. (this issue) present the results of a model to evaluate the response of the southern basin of the lake to various external and internal restoration measures. The aim of this section is to use simple mass balance arguments to obtain some rough estimates for the response of the lake to external measures and the time scale of response of the northern and southern basin of the lake.

The two-box model of Lago di Lugano treats the lake as a chain of two fully mixed basins connected by a unidirectoral flow from the northern to the southern basin (Fig. 3). It represents a straight-forward extension of the one-box model with first-order sedimentation and stratification parameter as described by Gächter and Imboden (1985). The model clearly oversimplifies the long-term chemical stratification observed in the northern basin (Wüest et al., this issue). Yet, the stratification of the basins is taken care of by the phosphorus stratification parameter β_i, the ratio of the mean annual P-concentration at the surface (or more precisely in the outlet) and in the total lake, respectively. In fact, in the northern basin β_N is much smaller than one ($\beta_N = 0.3$, see Table 4). This reflects the permanent chemical stratification of this basin.

The model equations of Fig. 3 are solved for the characteristic data listed in Table 4. First-order sedimentation rates, k_i, as well as the stratification parameters, β_i, are estimated based on the data given by Mosello and Barbieri (this issue). Note that the measured P-concentration in the N-basin corresponds to the steady-state value for the present conditions (150 µg/l) while in the S-basin the actual value (96 µg/l) is slightly below $C_{s,\infty}$ (110 µg/l).

This simple model can be used to evaluate the response of the two basins to a significant reduction of the external P-input (Table 4, Fig. 4). Though it is certainly not correct to assume that k_i and β_i do not change when the P-concentrations are



Dynamic equations

$$\frac{dP_N}{dt} = q_N P_{in,N} - q_N \beta_N P_N - k_N P_N$$

$$\frac{dP_S}{dt} = \eta q_N \beta_N P_N + q_S P_{in,S} - (\eta q_N + q_S)\beta_S P_S - k_S P_S$$

Steady state solution

$$P_{N,\infty} = P_{in,N} \frac{q_N}{\beta_N q_N + k_N}$$

$$P_{S,\infty} = \frac{\eta q_N \beta_N P_{N,\infty} + q_S P_{in,S}}{(\eta q_N + q_S)\beta_S + k_S}$$

Figure 3. Two-box model for Lago die Lugano. See Table 4 for definitions and numerical values

significantly altered, the simple calculation still allows to draw some qualitative conclusions:

(a) Reduction of P-input to the N-basin, J_N eventually leads to a proportional reduction in P_N (Table 4, cases 1 and 3). However, the response of P_N is slow; the response time (defined as the time to reach a new steady-state within 37%) is $\tau_N = (\beta_N q_N + k_N)^{-1} = 17$ a. This is a consequence of the small water renewal rate q_N, the small stratification parameter β_N and the small sedimentation rate k_N.

(b) Reduction of P-input to the S-basin, J_S, without reduction of J_N (Table 4, case 2) causes a significant reduction of P_S. The response time is small: $\tau_S = [(\eta q_N + q_S)\beta_S + k_S)^{-1} = 1.8$ a.

Thus, it is certainly meaningful to concentrate the restoration efforts on the S-

Table 4. 2-box model for Lago di Lugano: Definitions and numerical values of variables

	Northern basin (N)		Southern basin (S)
Volume V_i (km^3)	4.69		1.14
Surface area (km^2)	27.5		20.3
Mean depth (m)	171		55
Input of water from drainage basin Q_i ($km^3 a^{-1}$)	0.38		0.39
Total output of water, Q_N and ($Q_N + Q_S$) ($km^3 a^{-1}$)	0.38		0.77
Rate of water renewal from drainage basin, $q_i = Q_i/V_i$ (a^{-1})	0.081		0.342
Total rate of water renewal (south: $(Q_N + Q_S)/V_S$) (a^{-1})	0.081		0.675
Volume ratio $\eta = V_N/V_S$		4.11	
Stratification parameter for P, β_i	0.30		0.55
Sedimentation rate k_i (a^{-1})	0.034		0.178
P-input from drainage area J_i ($tP\,a^{-1}$)	41		52
Mean input concentration, $P_{in,i} = J_i/O_i$ (µg/l)	108		133
Steady state concentration for present conditions $C_{i,\infty}$ (µg/l)	150		110
Present concentration (1989) (µg/l)	150		96
Change of concentration in lake, dC_i/dt ($\mu g\,l^{-1} a^{-1}$)	0		−5
New steady-state concentrations after input reduction (µg/l)			
(1) $J_N = 10\,t\,a^{-1}$, $J_S = 52\,t\,a^{-1}$	37		89
(2) $J_N = 41\,t\,a^{-1}$, $J_S = 13\,t\,a^{-1}$	150		48
(3) $J_N = 10\,t\,a^{-1}$, $J_S = 13\,t\,a^{-1}$	37		27

Notes: – Index i stands for N (northern basin) and S (southern basin)
– Values refer to average conditions in the last five years prior to 1990 (Mosello and Barbieri, this issue)

basin, even if a corresponding input reduction in the N-basin is not immediately possible.

(c) Simultaneous input reduction in both basins causes a proportional reduction of both concentrations, P_N and P_S. The response in the N-basin is controlled by τ_N, while the S-basin reacts relatively fast (time scale τ_S) to the intermediate value of about 50 µg/l and then as τ_N to the final value of 27 µg/l.

(d) Internal measures, if any should be considered, should be aimed at a reduction of the response time of the N-basin, τ_N, either by increasing β_N (artificial mixing) or by increasing the sedimentation rate k_N. However, based on the experience on other Swiss lakes it is not sure whether the latter can be achieved by increasing the oxygen concentration in the deep waters. While it does not seem to be necessary to decrease τ_S, in the S-basin, an increase of the stratification parameter β_S significantly decreases $P_{S,\infty}$ for a givn P-input J_S.

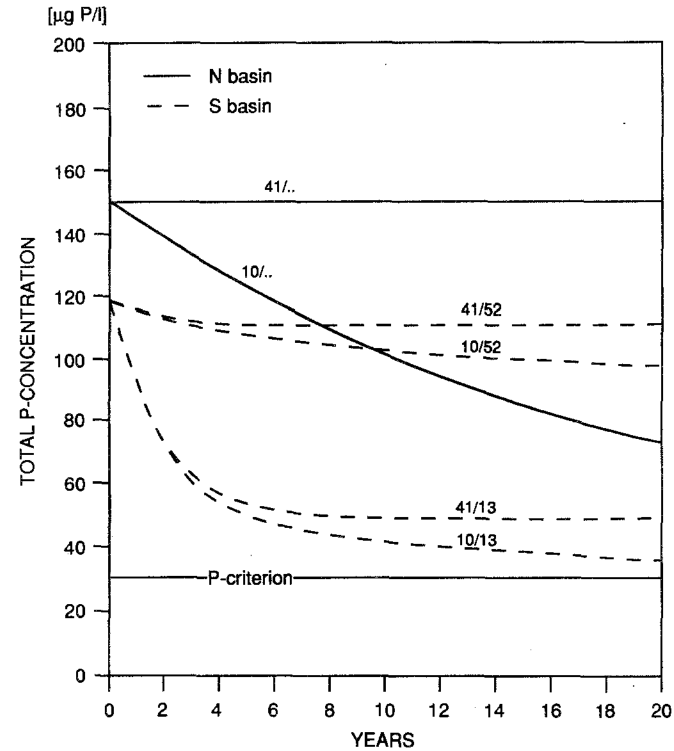


Figure 4. Response of P-concentration in the two basins of Lago di Lugano following a sudden reduction of P-input by 75% into either basin or into both basins. Calculated from two-box model presented in Fig. 3. Numbers x/y indicate annual P-loading (in t/a) into the N and S basin, respectively. Note that the concentration in the N basin does not depend on loading into the S basin

Note that the above considerations are only discussed in relation to the P-concentration criterion. They demonstrate that the external P-input into both basins should roughly be reduced to 25% of the present values in order to achieve the P-criterion. In principle, hypolimnetic oxygenation could be adopted additionally in order to fulfil the oxygen criterion. However, from an ecological point of view such an approach is not meaningful. Finally, it is interesting to see that the above conclusions which are based on an extremely simple model are in accordance with the results from calculations with the more refined lake model described by Zamboni et al. (this issue).

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