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Phosphorus evolution in three sub-alpine lakes: Annecy, Geneva and Lugano: Influence of lake restoration managements

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Key words: Phosphorus, lakes, lake restoration

ABSTRACT

Concentrations of total phosphorus (TP) in three sub-alpine lakes (Lake Annecy, Lake Lugano and Lake Geneva) between 1960 to 1990 are compared. For the three case studies, an increase of P concentrations was observed in the mid 1960's. Later the P-evolution diverge due to the different remedial measures adopted. In Lake Annecy, restoration has been spectacular due to a complete diversion of all wastewater effluents. In the other lakes, reductions of P have been observed in the water column after the peak concentrations in the late 1970's. Since this time, significant decline rates of TP have been noted ranging from –3 to –5 µgTP l^{-1} yr^{-1}. These improvements are clearly related to restoration measures such as a partial sewage diversion for Lake Lugano or the ban on phosphates in detergents for Lake Geneva. One notable exception is deep hypolimnic waters of the northern basin of Lake Lugano, where the rate of P accumulation is about +3 µg TP l^{-1} yr^{-1}.

RESUME

Le suivi des concentrations en phosphore total (TP) depuis 30 ans dans 3 lacs sub-alpins (Lac d'Annecy, Lac de Lugano et le Léman) a permis d'évaluer l'impact des mesures d'assainissement. Après le maximum de concentration atteint à la fin des années 1970, une décroissance globale du phosphore est notée, comprise entre –3 et –5 µg TP l^{-1} an^{-1}. Cette amélioration résulte directement des mesures prises pour limiter l'emploi du P dans les lessives et du développement de la déphosphatation dans les stations d'épuration. Seul le bassin nord du Lac de Lugano demeure à un niveau trophique élevé, avec un taux croissant en P de +3 µg TP l^{-1} an^{-1} dans les 200 derniers mètres de la colonne d'eau.

1. Introduction

Since the 1940's extensive fertilization of the waterbodies has induced rapid deterioration of water quality such as decrease of water transparency, hypolimnetic oxygen depletion, excessive algal blooms or taste and odour impairment. Numerous environmental studies have been undertaken to develop appropriate restoration and survey programs (Vollenweider 1981, OECD 1982).

The experience over recent years demonstrates that fortunately eutrophication can be reversed. As phosphorus is one of the keys to the problem, reduction of nutrient influx

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(mainly phosphorus) has been undertaken in different lake settings. Within the context of 20 years of efforts to reduce nutrients in major lakes throughout the world, an overview of achievements and an evaluation of the restoration programs are necessary. A recent example is given by a special issue of the Journal of Great Lakes Research on the restoration of Lake Erie (Dolan 1993, Bertram 1993).

In the present work three strategies to restore lakes from cultural eutrophication are discussed. A comparison of long-term trends of phosphorus reduction programs over the past 30 years is made for three peri-alpine lakes: Lake Annecy (France), Lake Geneva (Switzerland – France) and Lake Lugano (Switzerland – Italy).

2. Methods

All sampling sites (water column and surficial sediments) are situated in the deepest parts of each lake basin or sub-basins (Fig. 1). The sites correspond to the reference stations chosen for limnological research by different official surveyers. Data of total phosphorus and dissolved oxygen concentrations in the water column have been provided by SILA for Lake Annecy, CIPEL for Lake Geneva and CIPAIS for Lake Lugano. Sediment cores (about 50 cm long) have been recovered using an Ambühl gravity corer for Lake Geneva and a modified Phleger corer for the others. Details on the methods used for the analysis of sediment samples are described by Span et al. (1993). However, the definition of particulate phosphorus forms in sediment is briefly summarized here. The chemical extraction procedure (Williams et al. 1976, Burrus et al. 1990) separates P in organic and inorganic forms:

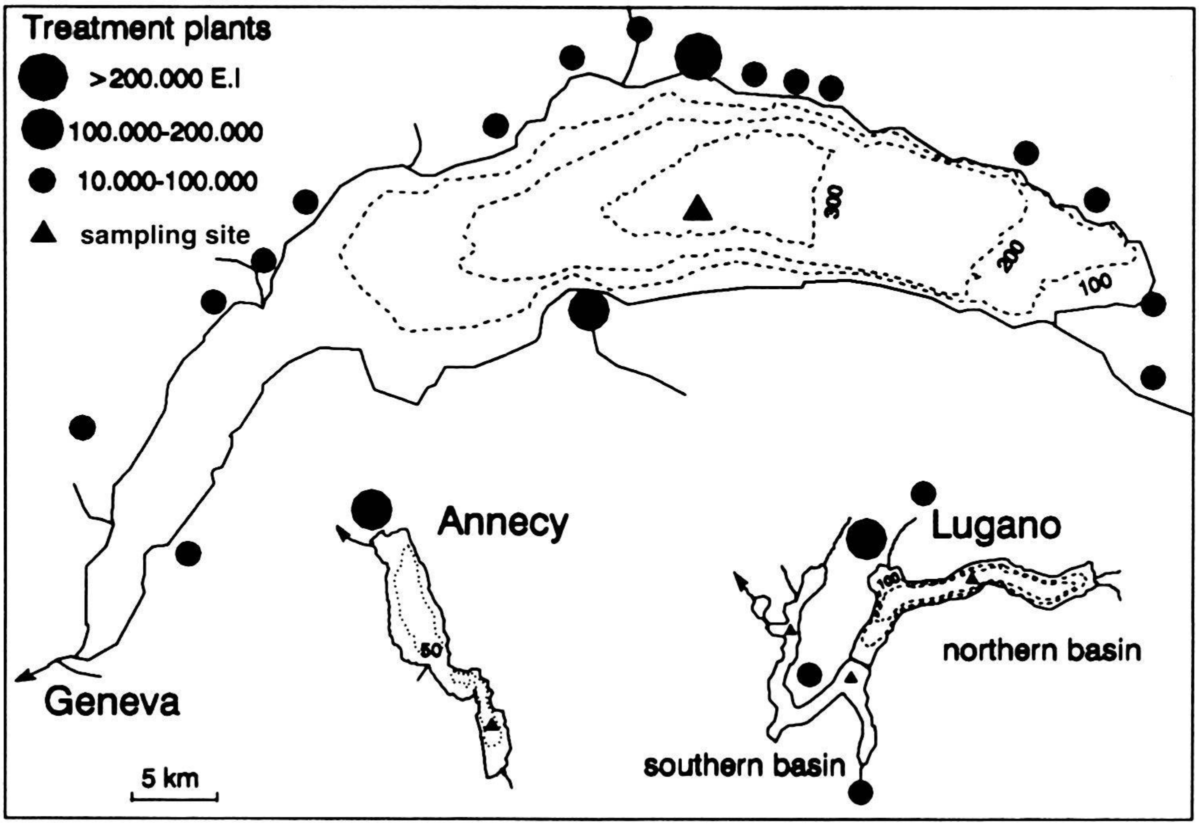
1 Organic Phosphorus (O-P) associated with allochthonous and autochthonous organic material. Its availability for phytoplankton growth after bacterial decomposition is significant.
2 Inorganic Phosphorus, principally present in the form of iron-bound and calcium-bound phosphate. The extraction procedure allows to distinguish between:
   - Apatite Inorganic Phosphorus (AI-P) major constituent of apatite minerals. This form is not remobilizable under the conditions normally encountered in surface sediments.
   - Non Apatite Inorganic Phosphorus (NAI-P) co-precipitated with Fe and possibly with Mn and Al hydroxides or adsorbed onto clays. This form may be considered mobile and potentially available if redox or pH conditions change in sediments.

3. Factors affecting lake restoration

The factors influencing lake restoration are numerous and interact within the lake ecosystem (Meybeck et al. 1989). In summary, they can be divided in two groups.

3.1 Natural factors

They are related to the physiography of the Lake and its watershed. These factors are *morphological:* volume of the lake, number of sub-basins, mean depth; *hydrological:* number of tributaries, water residence time, mixing; *climatological:* temperature, light,



Lake	surface (km^2)	volume (km^3)	depth (m) mean	depth (m) max.	mean residence time of water (yr)	trophic state
Lake Geneva	582.4	89.0	59	310	11.9	mesotrophic
Lake Lugano	48.9	5.9				eutrophic
northern basin	27.5	4.7	171	288	12.3	
southern basin	20.3	1.1	55	95	1.4	
Lake Annecy	26.5	1.1	42	65	3.2	oligotrophic

Fig. 1. Comparison of the main physiographic characteristics of the three lakes (morphology, hydrology, principal treatment plants with their Equivalent-Inhabitants). The relative geographical location of each lake is arbitrary.

wind; *biological:* organic matter production, plankton community structure, nutrient availability and *sedimentological:* recycling of nutrients, sedimentation rate.

3.2 Anthropogenic factors

In addition to natural factors, man activity interferes directly or indirectly with the lake ecosystem. Direct influence is based on the reduction of nutrient load (Balmer & Hultman 1988, Imboden 1992, Holtan et al. 1988). This can be achieved by external measures as total or partial diversion of effluents, treatment of wastewater effluents, reduction of P content in detergent and the control of fertilization in agricultural areas. In general, these methods are well adapted to control point sources (Cullen & Forsberg 1988), whereas the problems of diffuse loads from uncultivated soil or from precipitation are left partially unresolved. Indirect influences are dependent on the population density patterns and the predominant activities in the watershed. Obviously, these factors are difficult to control. For example, modification of agricultural practices such as restricted use of fertilizer, requires a long-time response.

Measures inside the waterbody (internal measures) are less developed and generally applied to small lakes or reservoirs only. The methods are *chemical* with elimination of P by flocculation, inactivation or surficial sediment by changing the redox conditions; *physical* with aeration of lake water by O_2-input or *biological* with the use of herbicides, algicides or biomanipulation. However in view of environment pollution, these latter manipulations may only be considered in isolated sites and with many precautions.

4. Case histories of Lakes Annecy, Geneva and Lugano

The three lakes are very different in their morphological and hydrological characteristics (Fig. 1). Before World War II, these lakes were originally oligotrophic. Signs of modification of the water quality appeared during the sixties (Barroin 1980). The first symptoms of eutrophication were the drastic perturbations in fish communities or excessive growth of macrophytes, and in some cases an increase of bacteria population. These changes in the lake ecosystem forced local authorities to establish restoration programs. The objective of restoration management was to improve water quality by reducing, more or less rapidly, the loads of nutrients. Different technical solutions were applied, resulting in different responses, as discussed below.

4.1 Case of Lake Annecy; a complete diversion of wastewater effluents

Lake Annecy is the smallest of the studied lakes and comprises two sub-basins: the "Grand Lac" and the "Petit Lac" (Fig. 2). Annecy, the main town, is situated near the outlet of the lake. In the 1940's, the first symptoms of eutrophication were a rapid efflorescence of phytoplankton blooms and a decline of salmonid populations (Servettaz 1977). Chemical studies started in 1966, well after the first observations of the water quality deteriorations. The mean total P concentrations in the water column of the "Petit Lac" (Fig. 2b) show a decrease from 1966 to 1972. Then, due to an efficacious protection against eutrophication, the P contents stabilize within a range of 10 to 15 $\mu gTP\ l^{-1}$. The variations observed in the end of the 1980's are doubtlessly influenced by the P release from sediments during low oxygen periods in the deepest water. Indeed, this lake was a forerunner in lake restoration management in France (Barroin 1980). An association of the riverain towns of the lake was created in 1957 to choose the appropriate restoration measures. A total diversion of the wastewater effluents was subsequently adopted. Construction of the sewage system began in 1962 and was finished in 1976–78 (F. Berthier pers. comm.). It consists of two parts (Fig. 2a):

- a peripheral collector around the lake collecting wastewater from all towns and villages in the drainage area (total length: 344 km)
- only one wastewater treatment plant (160,000 inhabitant-equivalents) equiped with a secondary treatment (biological treatment and activated sludge).

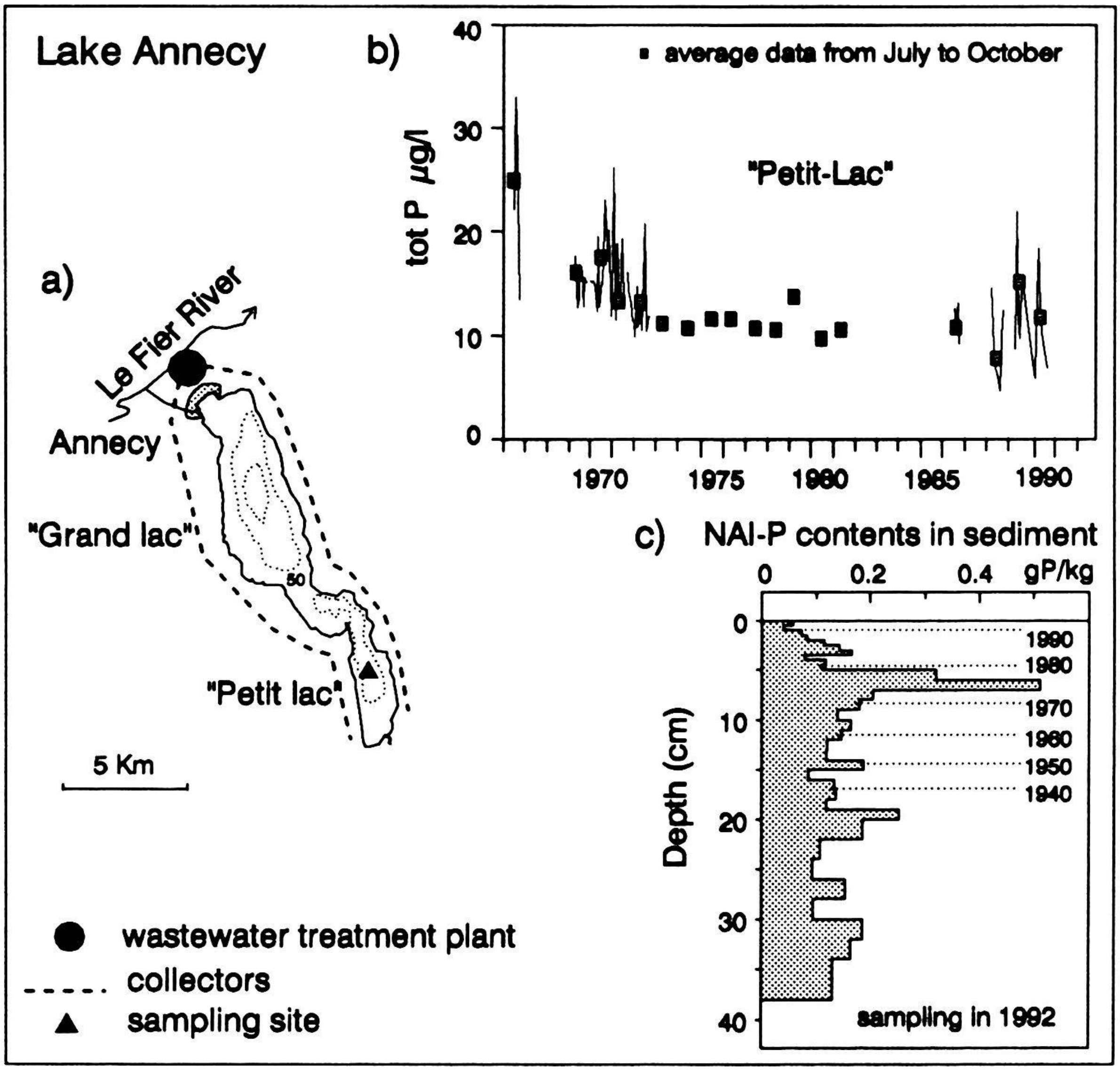


Fig. 2. Schematic diagram of the complete diversion of effluent in Lake Annecy performed in early 1970's (a), P-response in the water column (data from SILA) (b) and in sediments (c). Dating is based on ^{137}Cs profile in sediment (unpublished results from Institute F.-A. Forel).

The discharge is released downstream of the lake to the "Fier" River. The total cost of the system reached 90 million \$. The total diversion of the effluents put the lake back on the road to recovery. It is now considered to be the "cleanest" french lake. Nutrient concentrations are at oligotrophic level with a mean total phosphorus of 15 μgP l^{-1} (SILA 1992).

The sedimentary record of particulate phosphorus, especially in the labile form (NAI-P), indicates a peak between 1970 and 1980 (Fig. 2c), coinciding with the completion of the sewage collectors. In the upper centimeters, the NAI-P values decline sharply due to the reduction of P loading.

Diverting effluents is an advantageous strategy if appropriate conditions exist around the lake. Several factors favour the spectacular restoration of this lake. The largest part of the population around the lake is living downstream, near the outlet. This kept low the total volume of wastewater effluents to be diverved. The early positive response of politicians to the urgent need of a restoration program was another very important point.

4.2 Case of the northern basin of Lake Lugano: a partial diversion

Lake Lugano has a more complex morphology than Lake Annecy. It is made up of three distinct sub-basins with deep slopes (Figs. 1 and 3). The northern basin which is the deepest, is meromictic and eutrophic (Barbieri & Mosello 1992). Below 80–90 m, the northern part of the lake is anoxic. The depletion of oxygen, starting on the lake bottom probably around 1965, has progressed towards the lake surface. The last complete overturn of the northern basin occured apparently in 1964, a year in which meteorological conditions favoured vertical circulation (Barbieri & Mosello 1992). The permanent stratification of the hypolimnion is a consequence of the excessive loadings of nutrients since 1960. Tritium-Helium measurements indicate a minimum age of 20 years for the deep waters (Wüest et al. 1992). The degradation of the high load of biomass in the deep waters releases important amounts of dissolved solids, mainly HCO_3^- and Ca^{2+} that contribute to the density stratification. In addition, the mountains around the northern basin partly protect it from winds, thus reducing the energy available to trigger a vertical mixing.

The principal town in the drainage area (Lugano) located on the lakeshore of this sub-basin and the absence of an effective sewage treatment on the Italian side are largely responsible for the eutrophication. In 1960's, total phosphorus concentrations increased sharply (LSA 1992; Barbieri & Mosello 1992).

Since 1976, a partial diversion of effluents has been applied by the Swiss authorities to restore the northern basin. The wastewater effluents of Lugano were shifted from the northern to the southern basin, through the "Vedeggio" River (Fig. 3 inset map). Before entering into the southern basin (near Figino) the effluents are treated in a large sewage treatment plant. A complete biological and chemical treatment including P flocculation process is applied (Barbieri & Polli 1992). Figure 3 shows the evolution of the total phosphorus in the northern basin over the last two decades. The upper 100 meters of the water column are marked by a decrease of P contents since 1978. In the deeper part of the basin, the sharp increase was stopped after 2 or 3 years, but the mean concentration of P still increases. Consequently, a significant source of P is accumulated in the hypolimnic waters. A recent numerical model (Karagounis et al. 1993) was applied for to calculate the effects of internal or external measures to the northern basin. It seems that the best results could be obtained by a drastic reduction of P loadings but the recovery will take a long time. Internal measures would destroy the chemical stratification and would increase the nutrient inventory available for the biomass. The eutrophication problem will thus be accentuated.

4.3 Case of Lake Geneva: restoration by substitution of phosphate detergents and decentralized wastewater treatment

Lake Geneva is the largest of the sub-alpine lakes. The major tributaries are the "Dranse" River and the "Rhône" River. The latter is the principal source of P to Lake Geneva (Burrus et al. 1990). The population located around the lake and along the

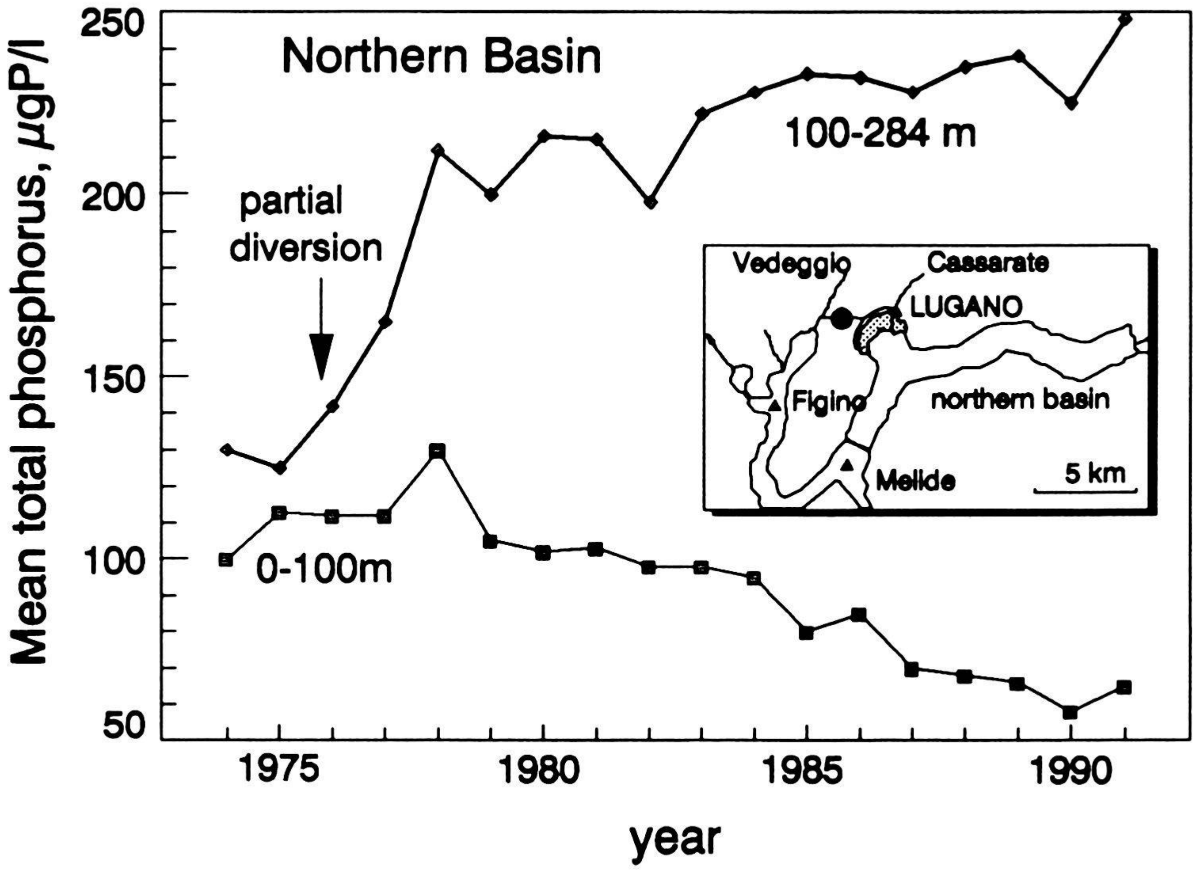


Fig. 3. Influence of a partial diversion of municipal sewage on total phosphorus in the northern basin of Lake Lugano. Data are given for the epilimnion and hypolimnion (data from LSA 1992).

alpine "Rhône" River exceeds 1.5 million. The evolution of P concentration may be characterized by two periods (Fig. 4):

- an increase of the concentrations between 1962 to 1975 due to the release of P-untreated wastewater into rivers and lake and the important consumption of phosphate in detergents. The first peak in 1964–65 is not fully explained. It could be related to the preceeding cold winter in 1963 which forced a rapid homogenization of P in the entire water column (Monod et al. 1984);
- a period of decrease since 1980 as the result of an intense restoration program.

The size of the lake and the decentralization of the population do not permit a possible diversion of the wastewater effluents. The strategy applied to Lake Geneva, in a first phase, was to control the nutrient loading by the construction of treatment plants, with elimination of P-coprecipited or absorbed to iron hydroxides by flocculation. The wastewater treatment plant capacity has been multiplied by 10 from 1975 to 1985 (Rapin et al. 1989). A clear improvement was observed with a decrease rate of 2 µgP l^{-1} yr^{-1} between 1979 and 1986. The delay of several years is due to the high mean residence time of the lake water (Fig. 1 and 4).

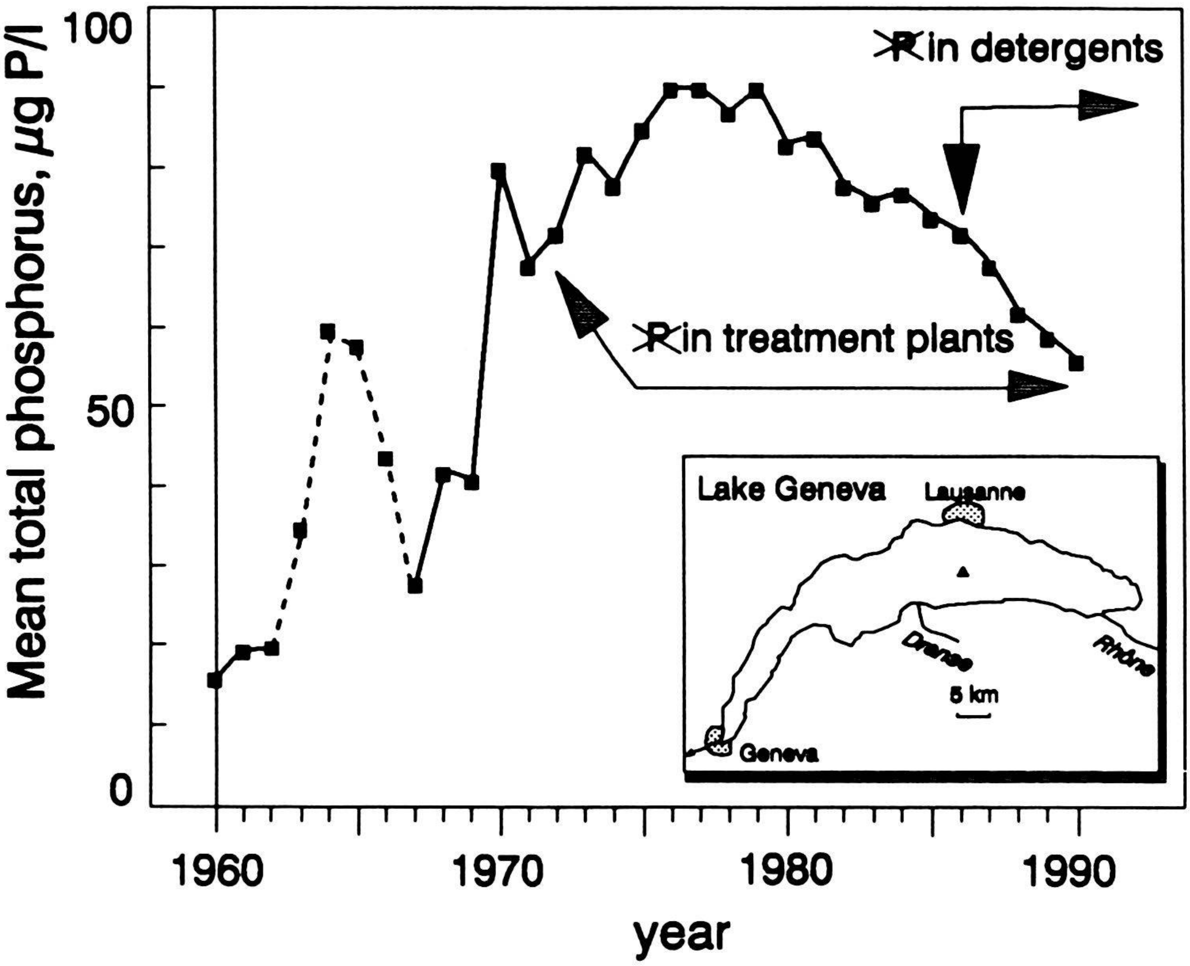


Fig. 4. Influence of two basic strategies used for reducing nutrients in Lake Geneva on the total phosphorus in the water column (data from CIPEL).

With the reduction of phosphates in detergents imposed by law in Switzerland in 1986, the decrease observed since 1980 has accelerated with a mean rate of 3.3 µgP l^{-1} yr^{-1}. Now the evolution shows a recovery trend from eutrophic to mesotrophic state with a mean total P concentration of 50 µgP l^{-1} in 1992 (Blanc et al. 1993).

The trophic evolution of these three lakes can also be observed by other factors such as: primary production, transparency, planktonic composition. Concerning this latter, the variations observed in Lake Geneva and Lake Lugano give a moderate response contrary to the chemical parameters. The present trends show an increase of little forms and the come-back of diatoms (Druart et al. 1992, Polli & Simona 1992). However characteristic species of eutrophic conditions such as Cyanophyceae remain still present. The mean composition of the phytoplankton population in 1990 for the three lakes is compared (Tab. 1) and reflects their respective trophic states.

5. Natural conditions affecting P concentrations

The three examples of phosphorus controls by external measures show positive reactions. Natural factors could however interact with these measures and influence their efficien-

Lakes	Diatoms	Dinophyceae	Cyanophyceae	Chrysophyceae	Cryptophyceae	Other
Annecy	63	17	0.7	2		2
Geneva	18	15	7.0	9	30	9
Lugano						
southern basin	44	5	25.0	9	9	9
northern basin	37	8	21.0	8	8	8

Tab. 1. Percentage composition of the phytoplankton in 1990 in the three lakes (data from SILA 1992, Polli & Simona 1992, Druart & al. 1992).

cy. The influence of bottom water oxygenation and sediment composition on the phosphorus cycle will be discussed for Lake Geneva and Lake Lugano.

5.1 Climatological conditions

The annual evolutions of P content in the hypolimnion of the two lakes discussed here present generally strong seasonal variations. They are directly related to the evolution of dissolved oxygen in the bottom water. The complete monitoring of the chemistry of Lake Geneva since 1957 offers an interesting example of climatological influence. The evolution of the dissolved oxygen content (Fig. 5a) at 307 m depth shows several cycles. Periods of progressive oxygen consumption are followed by oxygen recharge, with a cyclicity of 4 to 8 years. Since 1957, only few winters have been cold enough to induce complete circulation of the water and to reoxygenate deep water with 10–11 mgO_2 l^{-1} (1956, 1962–63, 1970–71, 1979 and 1985). Between these cold winters, the oxygen inventory decreases over a number of years. Superposed to this evolution a seasonal cycle with a minimum in late summer is observed. The progressive degradation originates from processes linked with eutrophication. The excessive production of biomass in the epilimnion leads to a high consumption of oxygen by organic decomposition in the water column. The depletion of oxygen close to the sediment/water interface generates a release of mobile P bound to sediment. The evolution of total P in bottom water (Fig. 5b) shows a progressive increase since 1970 with a maximum in 1978 concomitant with a minimum of oxygen. The incomplete mixing of the hypolimnic water in 1976–78 leads to a spectacular increase in P in water and low P content (NAI-P) in sediment (Fig. 5b). The surficial sediments act as an important source of P. During this period of sub-anoxic conditions, the phosphorus associated with Fe and Mn oxyhydroxides is desorbed and migrates to the bottom water (Baccini 1985).

After 1980, the P behavior is totally inverted due to the better oxygenation of bottom water. Sediments show significant enrichment in P, at least 5 times higher than during the late 1970's. The recent period (1986–91) is marked by a similar decrease of dissolved oxygen content as 1976–78, but induces only a moderate increase of P in the hypolimnion. The P content in sediment remains high, but a significant decrease is noted. The phosphorus response to oxygen depletion is attenuated in comparison with the preceeding stagnation period. These observations suggest that either the duration of oxygen depletion is not long enough for P regeneration or that the phosphorus leadings have actually diminished. Indeed, if the primary production remains high (Druart et al. 1992), the

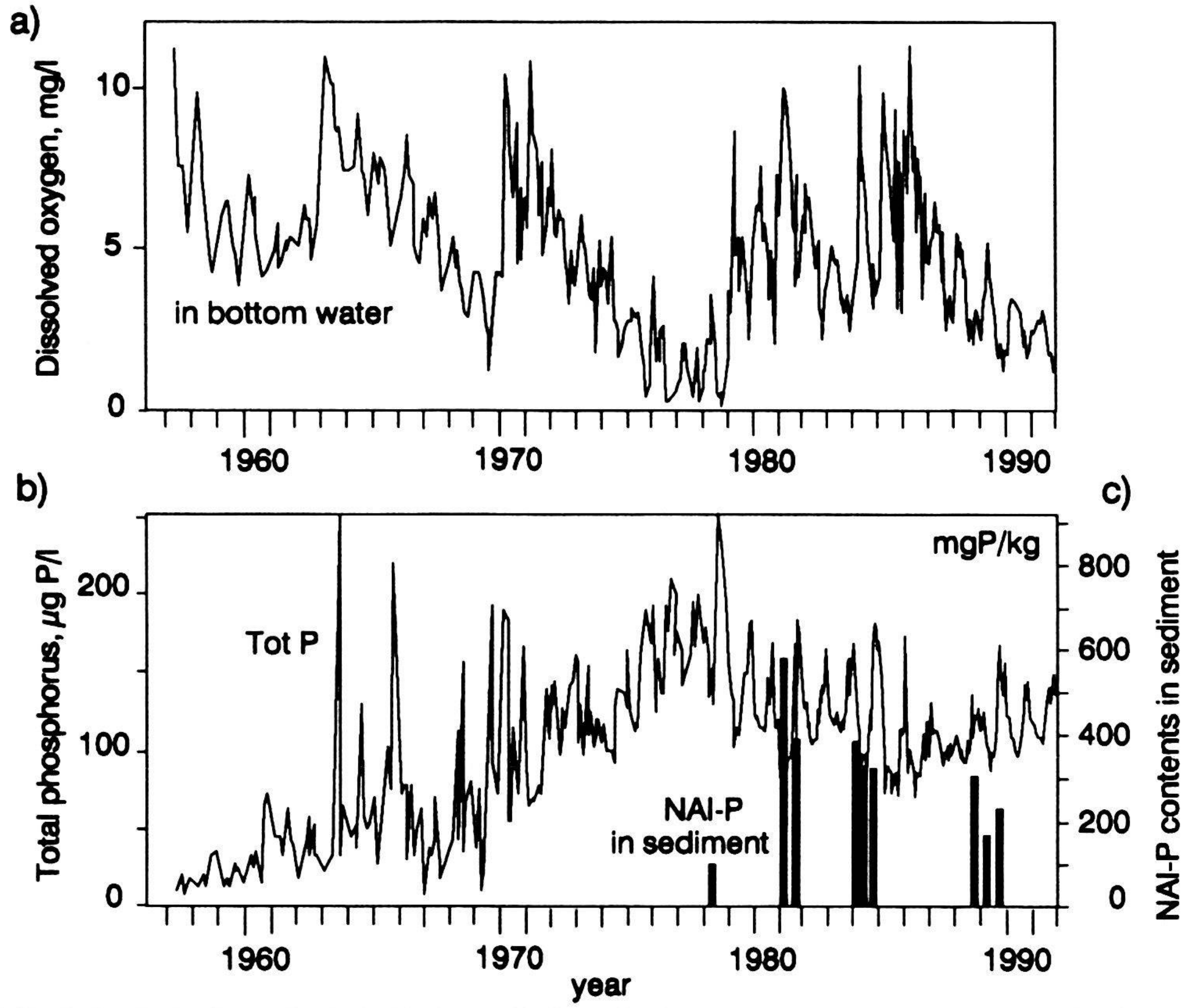


Fig. 5. Dissolved oxygen (a) and total phosphorus (b) in bottom water of Lake Geneva (data from CIPEL) and NAI-P content (c) in surficial sediments (same sampling station 307 m depth).

qualitative composition of the planktonic population has changed in favour of a dominance of small sized forms. The fresh organic matter is more rapidly degraded and recycled in the upper layer of the water column. Consequently, the quantities of settling material with associated P are lower and thus less dissolved oxygen is consumed in bottom waters. The results of P fluxes obtained in sediment traps in 1986 and 1991 confirm these observations. The average annual O-P (Organic Phosphorus) fluxes in 1991 compared to 1986 have diminished (Dominik et al. 1993).

Response time depends in part on the duration and the extent of hypolimnic oxygen depletion and on the rate at which nutrients are brought into sediments.

5.2 The role of sediment

The P release is limited to the pool of mobile P available in sediment such as NAI-P. Table 2 presents the different proportions of each phosphorus forms in surficial sediment. In Lake Geneva sediments, the fraction of inert P (AI-P) contributes to 50% of to-

Lakes	Fe %	Mn %	O.C. %	$CaCO_3$ %	Tot P %	NAI-P %	AI-P %	O-P %
Lugano (southern basin)								
Melide	1.2	0.15	12	30	0.17	0.08	0.02	0.05
Figino	4.6	0.73	10	15	0.49	0.35	0.05	0.07
Geneva	2.7	0.15	3	28	0.08	0.02	0.04	0.02

Tab. 2. Mean composition of several constituents (in %) of Lakes Lugano and Geneva sediments (0–5 cm).

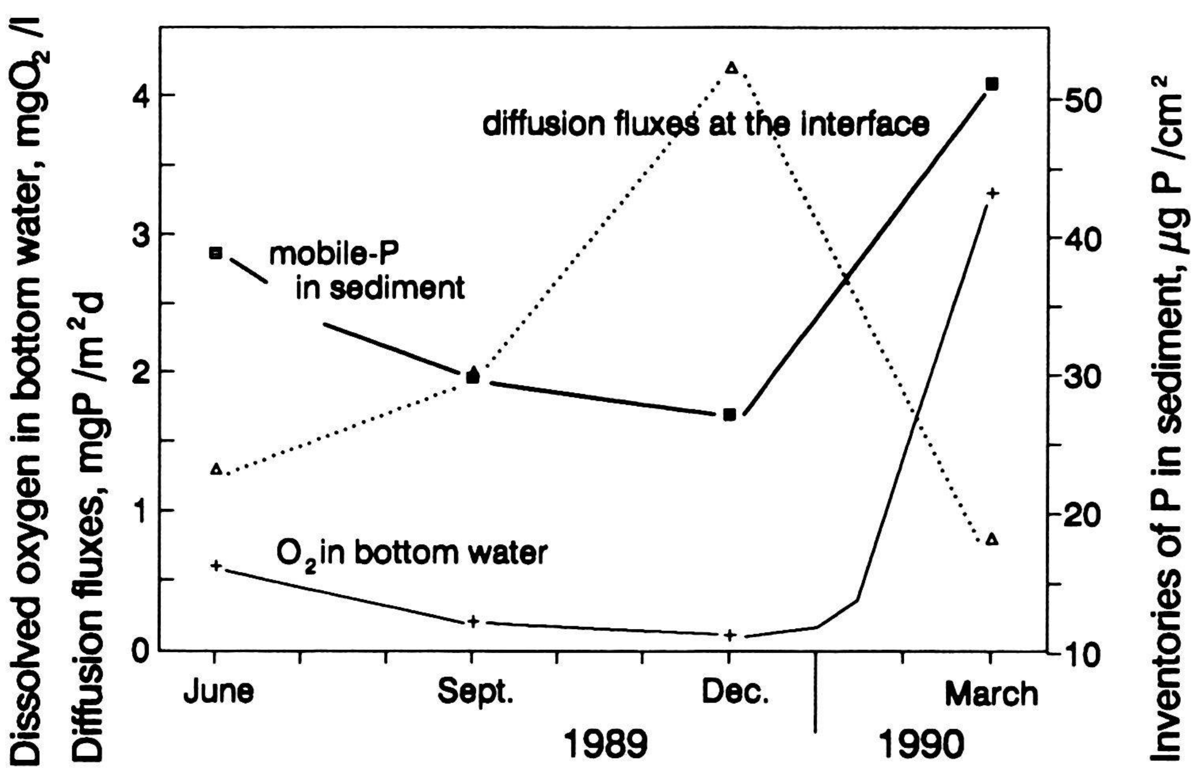


Fig. 6. Relationship between mobile-P (NAI-P and O-P) in surficial sediments, diffusion fluxes of soluble P at the interface and dissolved oxygen concentrations in bottom water in site Melide (data from LSA for dissolved oxygen content).

tal phosphorus and thus the amount of P remobilizable is proportionally low compared to Lake Lugano sediments, where the major form is NAI-P. Indeed the quantities of NAI-P in sediments of the southern basin of Lake Lugano are high and characteristic for an eutrophic environment. On a seasonal basis, these sediments are very "active" with respect to P recycling. However the behaviour of P in sediment for each sub-basins (Melide Figino) is quite different, though they have an equal depth and are subjected to similar seasonal variations in oxygen content (Span et al. 1992a). During the stagnation period (O_2 depletion), the hypolimnetic phosphorus concentrations at the site Melide are two times higher than at the site Figino, 0.65 and 0.30 mg P l^{-1} respectively (LSA 1992). At site Melide the mobility of P at the sediment/water interface is characteristic, with

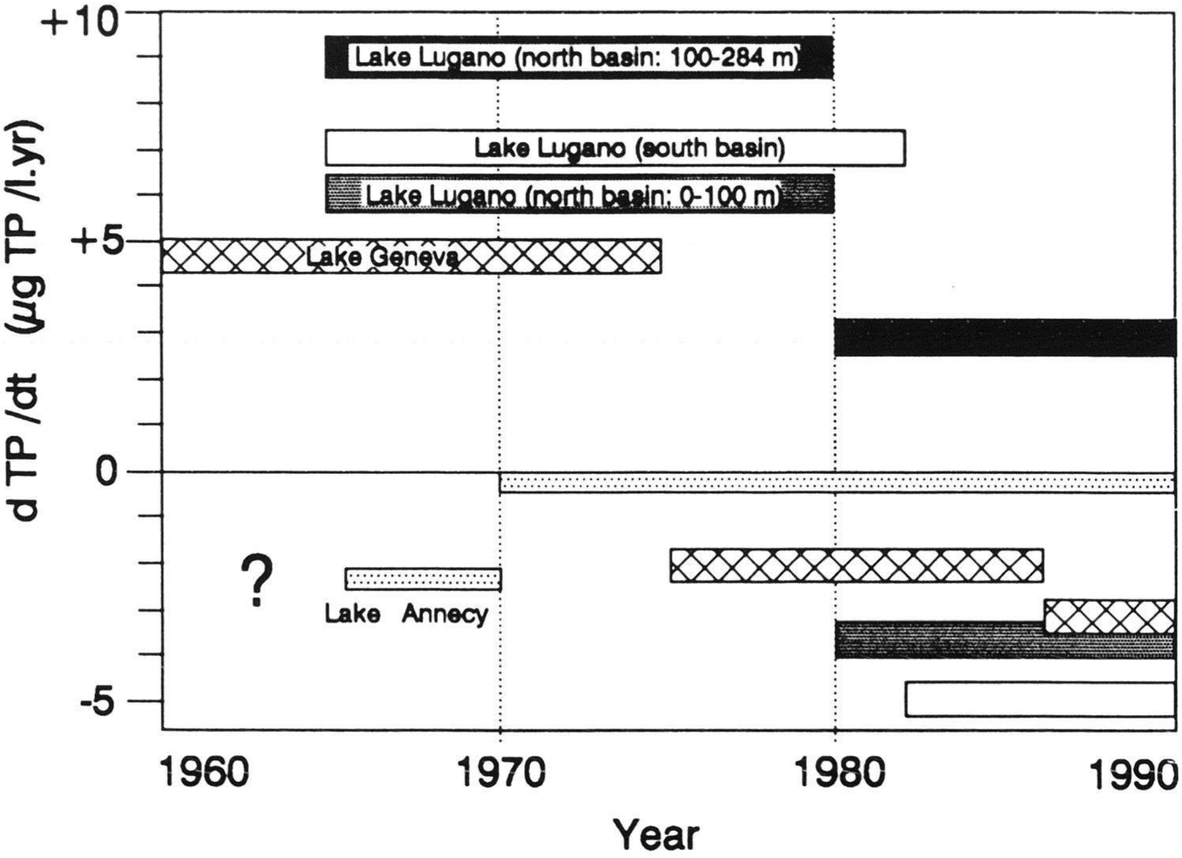


Fig. 7. Total phosphorus rates of accumulation in different sub-basins of the studied lakes from 1960 to 1990 (see text for explanation).

P-release under anoxic conditions and P-trapping under oxic conditions. The phosphorus exchange between water and surficial sediment is presented in Figure 6. In March the P-trapping is maxima with a limited P-release. This situation lasts for a few weeks only, then the P inventories in sediment especially NAI-P and O-P decrease. The important fluxes of particulate matter produced just after the overturn accelerate the exhaustion of the available oxygen in bottom water. Concomitantly P-release from sediment becomes significant and increases the P content in the hypolimnion. In the present example, the sediments act as an important internal source of P. The net loss of the inventory of P (NAI-P and O-P) between opposite periods corresponds to 50% of the P-pool initially present in the first centimeter of sediment.

At site Figino, the P behaviour is different. Despite the fact, that this site is close to the most important inlet ("Vedeggio" River), which has collected since 1976 the treated effluents of 50% of the population living around the Lake Lugano, and despite a seasonal deficiency of oxygen at the bottom, P is cycled in bottom water with moderate intensity. The quantities of P (NAI-P and O-P), Fe and Mn in sediment are very high (Tab. 2). Moreover, the Fe/P and Mn/P ratios in the interstitial water are high (Fe/P = 5 to 10; Mn/P = 3 to 5) compared to those at Melide (1 to 3; 1 to 3, respectively) (Lazzaretti & Hanselmann 1992). The large content o Fe and Mn acts on the high retention capacity for P in site Figino.

			Lu	Ge	An
	morphology	volume of the lake number of sub-basins drainage basin surface/ lake volume ratio mean depth	–	–	+
Natural factors:	*hydrology*	mean residence time of water number of tributaries dynamics of water mixing	–	–	+
	climate	primary productivity	–	–	+
	sedimentology	rate of sedimentation composition of deep-sediment quality of the sediment-water interface origin and nature of particulate phosphorus	(+)	+	+
	sewerage	number of Sewage Treatment Plant (STP) discharge outside or inside the drainage basin percentage of resident connected technology of the wastewater treatment	(+)	+	+
Human factors:	*population*	density location of the principal towns activities (agricultural or urban areas)	–	–	+
	politic	substitution of phosphates in detergents control of fertilization in agricultural areas	+	+	(–)

Fig. 8. Qualitative effects of the different factors controlling the trophic state of the Lake Lugano (Lu), Lake Geneva (Ge) and Lake Annecy (An).
The degree of influence are schematized by: + favourable effects and – unfavourable effects.

The presence of many thin detrital layers in the upper centimeters of this metal-rich sediment participates in P-trapping. Indeed, deposition of detrital material with generally lower porosity than the varved sediment may immobilize a significant amount of P below the turbidite layer (Span et al. 1992b). Despite the increased inputs of phosphorus in this part of the southern basin, the role of sediment seems to be dominant and positively influences the water quality of the hypolimnion.

6. Conclusions

What has been the impact of the external measures to limit the P concentration of the three lakes?

In general (Fig. 7), between 1960 and 1975–80, the mean P content in the water column increased with significant rate of P-accumulation: +5 to +9 μgTP l^{-1} yr^{-1}, excepted for Lake Annecy due to its early protection. Since their respective peaks in the late 1970s, the nutrient trends have been reversed with different rates of P-reduction. The breaks observed in Figure 7 coincide with the principal operations of restoration. Except for the deep part of the northern basin of Lake Lugano, the P-response of the external measures appears to be relatively rapid, about 4 or 5 years. Despite the present eutrophic state in Lake Lugano, the southern basin presents the most important rate of decline in total P with -5 µg TP l^{-1} yr^{-1} and is tending toward better conditions. The upper layers of the northern basin show also an improvement. Unfortunately, these layers lie on highly loaded hypolimnic waters. The recovery of the northern basin requires efficacious measures such as to complete the sewage system on the Italian part of the catchment area.

In conclusion, the qualitative effects of the factors controlling the trophic state of lake waters can be summarized in the following Figure 8.

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- CIPAIS: Commissione Internazionale per la Protezione delle Acque Italo-Svizzere, Via Fabio Filzi 22 I–20124 Milano.

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