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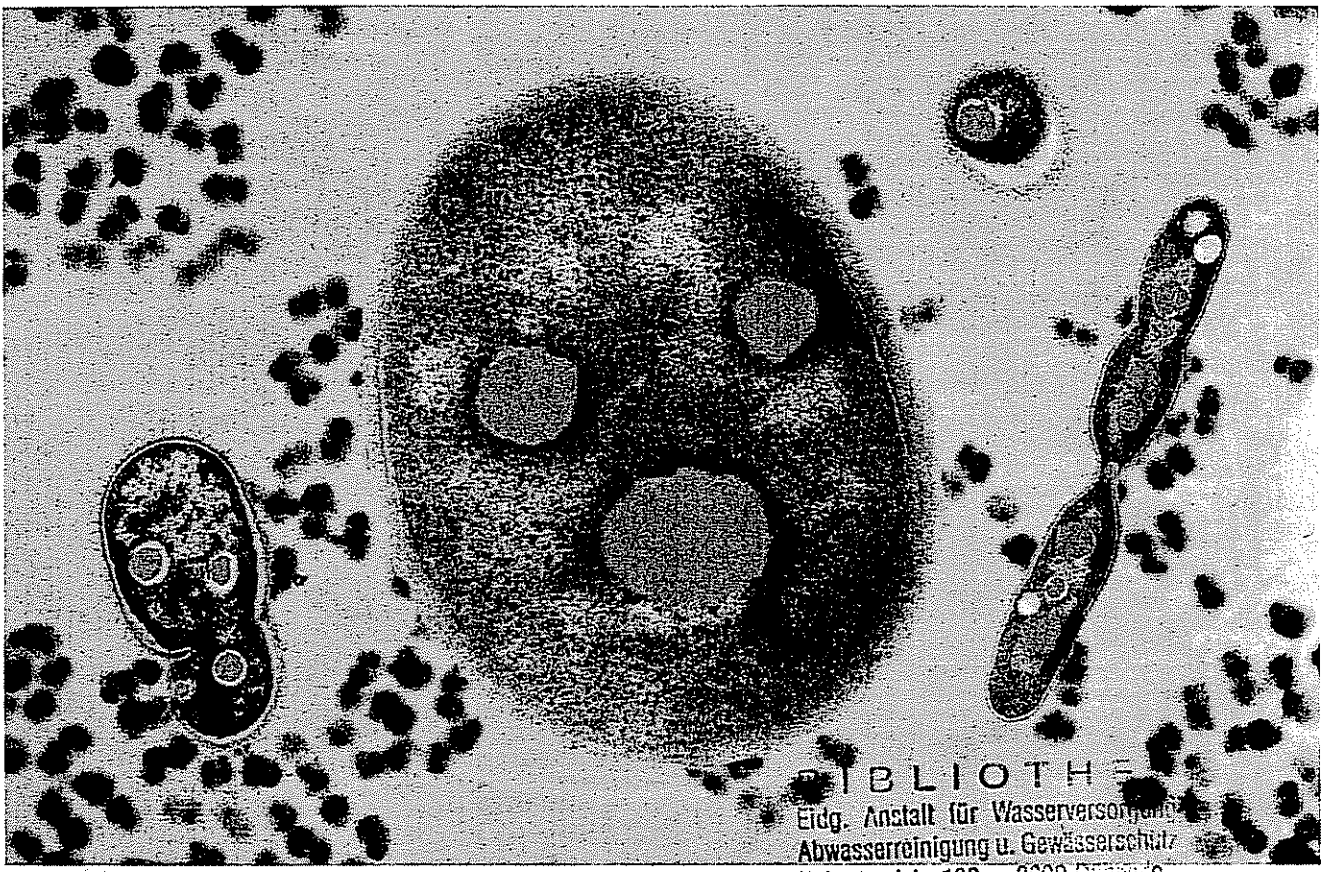
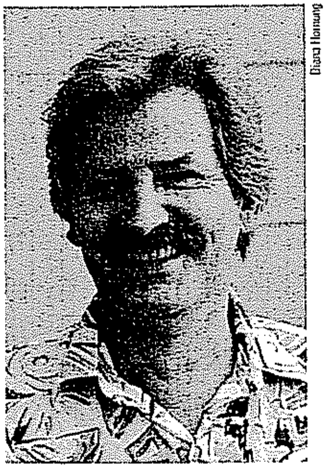


Janus – The Two Faces of Phosphorus


Diana Hornung

Like the Roman god Janus, the chemical element phosphorus shows two different faces in the environment. One face is that of overabundance; the other is of scarcity. While industrialized countries struggle with the symptoms of excessive phosphorus release, a severe phosphorus shortage limits food production in developing countries. In light of this fact, it is especially ironic that countries struggling with a phosphorus surplus release phosphorus as a waste product into surface waters, which ultimately finds its way into the oceans.

On the 10th anniversary of Switzerland's banning of phosphates in detergents, EAWAG revisited the topic "phosphorus" at its yearly information meeting. The objective was to discuss both the successes and shortcomings of strategies used to reduce eutrophication of Swiss waters. We also attempted to illustrate global interdependencies between mass fluxes and to present a new approach for the sustainable management of essential elements like phosphorus, where conservation and worldwide appropriate nutrient supply should be the driving forces.

The positive developments in the water quality of Swiss lakes are impressive and well documented, and a sign that most of the technical measures have been and continue to be highly effective. One might be tempted to think of eutrophication as a problem of the past. The fact is, however, that continuing to prevent nutrients from entering surface waters will require a significant effort well into the future. Renewed demands for the elimination of phosphorus as well as nitrogen suggest that material fluxes do not end at the boundaries of individual countries, but instead are connected over large watersheds and ultimately linked to the oceans.

From the materials management perspective, nutrient fluxes must be considered on an even larger scale. The relatively modest nutrient fluxes into aquatic ecosystems (which are actually rather sensitive even to small changes) are linked to larger fluxes in the geosphere and atmosphere. Nutrient balances exhibiting overall losses for small or large watersheds are an indisputable sign of inadequate management. Changes in human behavior and targeted redirection of material fluxes are needed which will, in the long run, lead to the active control of individual elements like phosphorus, as well as of other anthropogenic elements and compounds.

Janus has often been portrayed above archways, where he gazes in two opposing directions. With respect to phosphorus, we too look in two different directions: to the past where we can pat ourselves on the back and flaunt the successes that restrictions on phosphorus use have brought to urban water management, and to the future, where we must accept the challenge of establishing smaller nutrient and water cycles which will insure the sustainable use of valuable resources.

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EAWAG

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Cover

Bacteria with inclusions of polyphosphate
Biochemical studies using Acinetobacter johnsonii 210A have demonstrated that polyphosphate may be used as a source of energy by bacteria during waste water treatment.
The electron micrographs shown were taken at EAWAG for the Microbiology Department of the Agricultural University in Wageningen, NL (© A.J.B. Zehnder and Department of Microbiology, Agricultural University, Wageningen, The Netherlands).

Edwin Müller

Banning Phosphates in Detergents:

Preventing Contamination at the Source


Diana Hornung

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The detrimental effects in natural waters that were caused by certain components of detergents during the 1950s were the impetus for preliminary work on legislation to regulate detergents used in laundry, dishwashing and other cleaning agents. By 1977, the first regulations on phosphates were issued in Switzerland; the phosphate standards were subsequently tightened in 1981 and 1983. The phosphate ban on laundry detergents in 1986 resulted in a reduction in the phosphorus load to Swiss waterways by about 5000 tons per year. Phosphate substitutes have apparently not had any detrimental effects on natural waters, and the washing efficiency of phosphate-free products is satisfactory.

The Phosphate Ban: the 30 Year Road to a Law

The degradation of Swiss lakes due to over-fertilization by phosphorus began in the 1950s with the expanded construction of domestic sewage systems, the use of phosphates in modern detergents and intensified agriculture. The Water Protection Law of 1955 required the construction of wastewater sewers and more effective sewage treatment plants. The prevention and reduction of contamination at the source, however, was not a public issue at the time, even though it was generally accepted that phosphorus played a key role in the excessive growth of algae in the lakes.

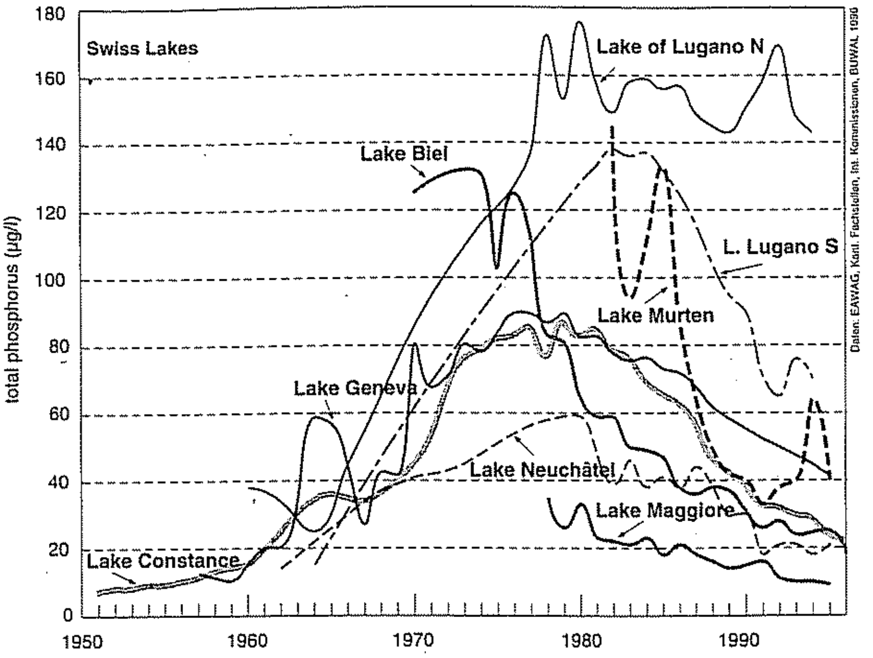
Phosphates were regarded as one of the key players in causing the eutrophication of lakes and rivers, but was not seen as the only culprit. From a technical point of view, the ideal components of new detergents stood in the crossfire of criticism. Dispensing completely with phosphates (i.e., a phosphate ban) was not viewed as the only measure needed to improve water quality.

After the first procedural request to the parliament by National Council member Freiburghaus on the problem of water pollution by detergents in 1961 (see Table 1), the federal authorities decided to create a legislative basis for imposing regulations on the components of detergents. For this reason, the Swiss Federal Department of the Interior accepted the suggestion made by the Commission on Detergents in 1962 to include the article of authorization in the Water Protection Law dated 16 March 1955. It was then taken into consideration in its full length version when the law was re-

Table 1
Thirty years passed until the phosphate ban went into effect after P was proved responsible for the eutrophication of lakes.

Development of Legislation from Introduction of the First Phosphate-Free Detergents to the Enforcement of the Phosphate Ban

1950	Phosphates found to cause eutrophication in lakes.
1961	*Postulate of National Council member Freiburghaus:* the Federal Council should assess measures to counter the dangers of synthetic laundry detergents.
1962	EDI (Swiss Federal Department of the Interior) creates Commission on Detergents.
1964–1968	Further parlamentary procedural demands against phosphates in detergents. *Ordinary question ("Kleine Anfrage") of National Council member Martin to the Federal Council:* what legislation on phosphates is being planned in the future? Answer: *No viable phosphate substitute available.*
1967	Letter of EDI (Swiss Federal Department of Interior) to Cantons: introduction of phosphate removal in sewage treatment plants.
1969	Report of the Commission on Detergents: Regulations pertaining to water pollution control; *no phosphate ban.*
1971	Supplement to Water Protection Law regulations on products entering wastewaters.
1972	Federal Council issues regulations on compounds in detergents, *but no restrictions on phosphate content.*
1974	Voluntary agreement of detergent industry on maximum amount of phosphate.
1977	*Ordinance on Detergents: maximal amounts of phosphates.*
1981–1983	Stepwise tightening of phosphate concentration standards.
1982	*Motion of National Council member Gerwig:* Demands phosphate ban in Water Protection Law with 3 year transition delay.
1982–1983	*Report of the Federal Commission on Water Protection (Gewässerschutzkommission): phosphates should not be used in detergents.*
1985	Federal Council issues phosphate ban.
1986	*Phosphate ban goes into effect on 1July 1986.*



Daten: EAWAG, Kant. Fachstellen, Int. Kommissionen, BUWAL 1996

Fig. 1
As a result of the chemical removal of phosphorus in sewage treatment plants and the ban on phosphates in detergents, phosphate concentrations dropped considerably in Swisslakes.

vised in 1971. In a slightly modified version, it was again taken into consideration during the 1991 revision:

> Art. 92c: The Federal Council issues regulations on substances which may enter bodies of water resulting from their use and which could, due to their properties or consumed amounts, pollute natural waters or be detrimental to the operation of hydrological installations.

Environmental Compatibility of Phosphorus Substitutes

The detergent industry attempted to move away from phosphates in the 1950s. At the time, organic complexing agents were being discussed as substitutes. In its answer to the inquiry ("Kleine Anfrage") made by National Council member Martin in 1968, the Federal Council referred to the negative observations:

> "The substitutes found in detergents recommended outside the country containing a reduced amount of phosphates indeed do not possess growth-promoting effects; they do, however, demonstrate an insuppressible aggression towards nonferrous and heavy metals. For this reason, the danger of both corrosion and bleaching on the one hand and toxic effects on the other arises. As these additives also cause an increased permeability in cell walls, the detrimental effects of metals and metal compounds on organisms is enhanced and accelerated. Damage to bacteria in the activated sludge of sewage treatment plants in the presence of zinc and the new products (substitutes) was clearly demonstrated in Sweden. [Conclusions:] Special regulations which aim to reduce or eliminate the phosphate fraction in laundry, dishwashing and cleaning detergents cannot yet be developed for the above-mentioned reasons."

In the mid 1970s zeolites and NTA appeared as possible phosphate substitutes. It quickly became obvious that the zeolites were harmless, but there was great resistance to the use of NTA.

Guaranteed Washing Efficiency

In order to support the breakthrough against the phosphates, various small producers of laundry detergents brought phosphate-free detergents based on soap and soda onto the market in the mid 1970s. Their success was minimal, however, as the required washing efficiency could not be met using these products and the effort of washing with them was too great.

The working group [1] set up in 1982 by the Federal Commission for Water Protection worked intensively on the technical washing criteria. The standards of the former Swiss Household Management Institute were use for judging washing quality; these standards are still used today.

Flanking Measures

It was already clear in the 1960s that the road to phosphate-free detergents was going to be a long one and that the causes of eutrophication in lakes was not due to the phosphates in detergents alone. For this reason, the Swiss Federal Department of the Interior issued the following recommendations on 19 June 1967 to the cantonal governments [2]: the domestic sewage treatment plants of lakeside communities and larger communities and regional groups of the various catchment areas of the lakes must install a third treatment stage designed to remove phosphates from wastewater using chemical precipitation. The requirement by law to install phosphorus removal in sewage treatment plants in the drainage areas of lakes followed eight years later as the Ordinance on Sewage Effluents went into effect.

Effects of the Phosphate Ban

At the same time that the phosphate ban was activated on 3 July 1985, the former Swiss Federal Office for Environmental Protection was authorized to carry out a comprehensive investigation of NTA in natural waters: NTA was expected to appear in detectable concentrations in lakes and rivers in spite of its limited use in laundry detergents and its high biodegradability.

The scepticism first encountered to NTA could be almost completely allayed in Switzerland when it was detected in only trace amounts in surface waters and was practically undetectable in drinking water and in groundwater (see results of ten year study on NTA and EDTA in Swiss waters [3]).

The elimination of phosphates from laundry detergents is but one of the measures taken to counter the eutrophication of lakes in Switzerland. It must, however, be mentioned that the stepwise reduction in the phosphate content of laundry detergents from its initiation in 1981 to a total ban in 1986 has lead to a drastic reduction in the phosphate content of

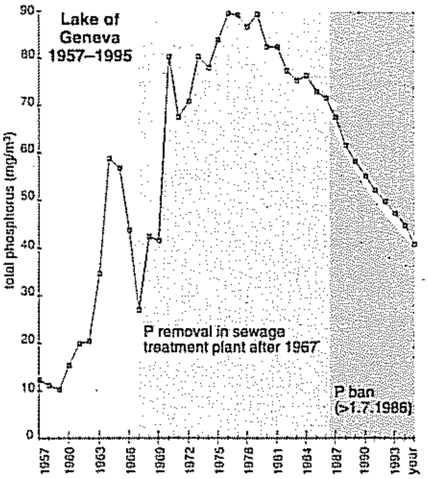


Fig. 2
The sewage treatment plants around the Lake of Geneva began removing phosphorus after 1967, leading to a reduction in phosphorus concentrations after that time. This result was intensified by the phosphate ban in 1986.

domestic sewage, resulting in a considerable reduction in the contamination of natural waters.

The declining concentrations of P in most lakes (Fig. 1) and in the largest rivers has resulted from both the phosphate ban and the simultaneous introduction of a chemical phosphate removal stage in domestic sewage plants. Fig. 2 shows a clear decline in phosphorus concentrations after 1979 in Lake Geneva – 6 years before the phosphate ban went into effect in Switzerland. Lake Murten shows a distinct trend as well, largely as a result of the phosphate ban (Fig. 3). Between 1985 and 1995, P concentrations dropped from about 100 µg/l to about 40 µg/l. The oxygen content of the lake water should not be less than 4 mg O_2/l at any time and at any depth without using artificial means; exceptions include unfavorable conditions due to natural causes.

A distinct decline in phosphorus concentrations as a result of the construction of several large sewage treatment plants and reduced amounts be measured in rivers such as the Rhine in Basel (Fig. 4) after 1980. After the phosphate ban went into effect in 1985, the phosphorus concentrations again decreased markedly. The additional reduction in phosphorus concentrations after 1990 is a result of introducing phosphorus removal in sewage treatment plants with capacities of over 20'000 per capita units in the drainage area of the Rhine downstream from the lakes.

Switzerland's Pioneering Role in Europe

Switzerland was the only country in Europe to introduce the phosphate ban. An exchange of information took place during a conference involving numerous European experts in 1988.

The Swiss experts in water pollution control tried to convince the other participants at the meeting about the effects and success of the phosphate ban. At the time, a general reluctancy to ban phosphates in detergents existed throughout Europe. Neither other European countries nor the European Community (EC) were expected to follow Switzerland's example. In spite of this, phosphate-free detergents are mostly being sold in Europe today, especially in Germany and in The Netherlands.

The Phosphate Ban: a Positive Report

When the phosphate ban on P in laundry detergents went into effect in 1985 and for the first time in Switzerland's short history of environmental legislation, a successful measure was introduced to reduce water pollution at its source.

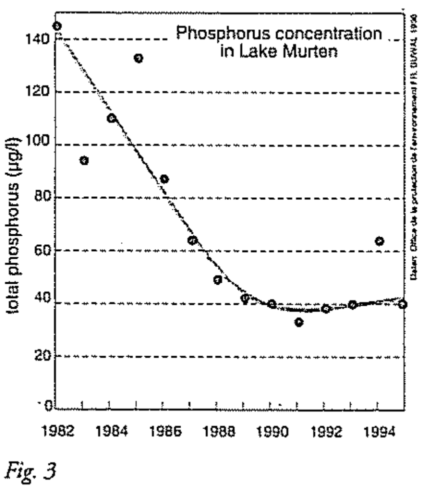


Fig. 3
The decline in phosphorus concentrations in Lake Murten observed in the early 1980s has continued to the present as a result of the phosphate ban of 1986. The phosphorus concentrations dropped by half during this time.

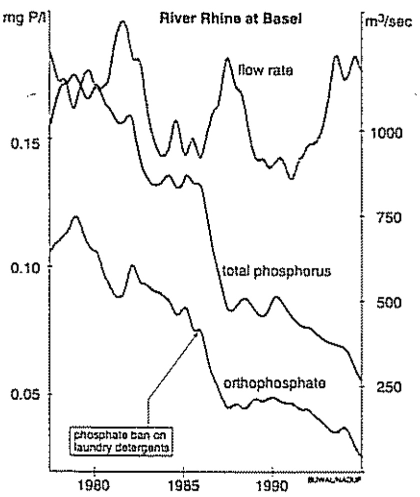


Fig. 4
As a result of the phosphate ban, distinctly markedly reduced phosphorus concentrations have been measured in the Rhine in Basel since 1986.

Although the EC has not yet issued a comparable law, Switzerland's phosphate ban has nevertheless had a distinct influence on the trends of detergent development in Europe.

The phosphate ban remains one of the main measures employed to combat eutrophication of natural waters in Switzerland. A considerable decrease in phosphorus pollution in lakes has already been realized.

No negative consequences for consumers have resulted from the phosphate ban which demanded new solutions in the development of detergents. The washing quality has also be maintained using the new phosphate-free detergents.

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[1] Federal Office of Environment, Forests and Landscape (BUWAL) 1983: Waschmittelphosphate. Bericht der Eidg. Gewässerschutzkommission über die Phosphorbelastung der Seen und die ökologischen sowie die waschtechnischen Auswirkungen bei einem Verzicht auf Waschmittelphosphate. Schriftenreihe Umweltschutz, Nr. 14.

[2] EDI (Swiss Federal Department of Interior), Letter to Cantons, 1967: introduction of phosphate removal in sewage treatment plants

[3] BUWAL 1996: NTA dans les eaux (mit deutscher Kurzfassung). Cahier de l'environnement, No 264.

Alfredo C. Alder, Walter Giger and Christian Schaffner

Phosphate Substitutes in Laundry Detergents and Cleaning Agents

Devils in Disguise?

Diana Hornung

Alfredo C. Alder

Laundry detergents and other cleaning agents are products used in large amounts by both the general public and industry for cleaning textiles and solid surfaces. In Switzerland in 1994, for example, the amount of detergents consumed was about 20 kg per person. Their disposal mainly occurs with other wastewaters as sewage. These chemicals illustrate clearly how measures in environmental protection have evolved from reactions to recognized problems to the development of precautionary plans and action [1].

Detergents contain various components which differ considerably in their chemistry and action: active compounds (surfactants), builders, bleaching agents and additives. The builder system is the main component of powdered laundry detergents, amounting to 35–45% of the detergent. Its main function is to reduce water hardness; that is, to bind calcium and magnesium ions. Two chemical processes can be used for this purpose: complexation and ion exchange. The objectives of using builders are to: a) sustain the function of the surfactants, (b) prevent depositions (incrustations on textiles) and to c) enhance the effectiveness of washing (soil removal).

Triphosphate (also known as "tripolyphosphate" or simply phosphate), first introduced in the 1940s, proved to be an ideal builder regarding its application technology. The eutrophication of lakes eventually led to lower allowable amounts of phosphate in detergents and even to bans on using phosphates in many industrialized countries. An increase in the spread of phospate-free detergents can be observed internationally.

The functions of phosphate in detergents cannot be replaced by a single substance; a combination of various compounds, so-called phosphate substitutes, are needed (Fig. 1, Table 1). With reference to an earlier publication [2], only those builders and cobuilders which are utilized in detergents containing either no phosphate or reduced amounts of phosphate are discussed here. When substituting an entire builder system for a single substance like phosphate, the question arises as to whether a "devil in disguise" situation has not been created, where "bad" has been replaced by "worse".

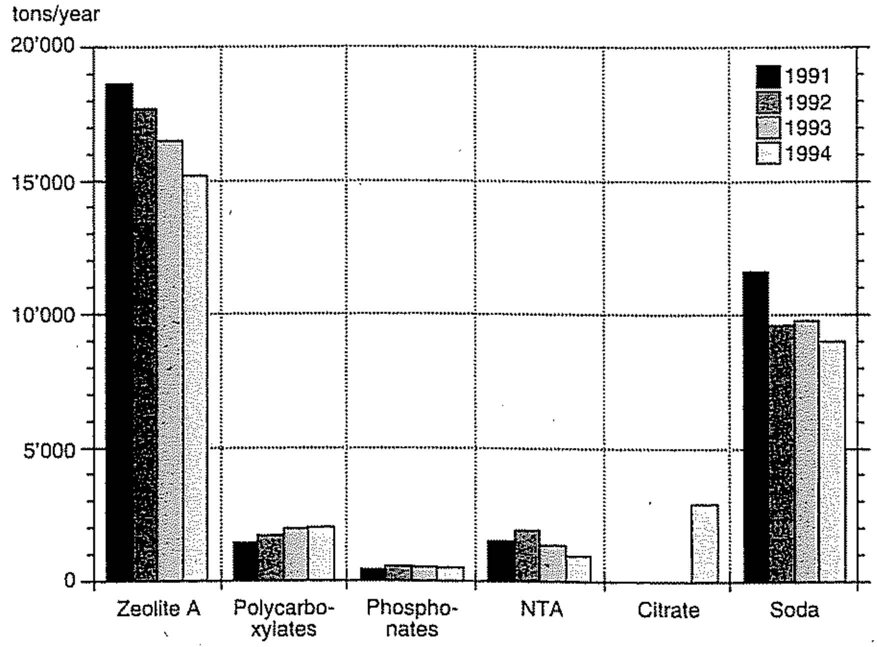

Fig. 1
Amount of builders used from 1991–1994 in products consumed by the general public as well as by industry according to information from the Association of the Swiss Soap and Detergent Industry (SWI).

Zeolites

For the past decade, the most important builder in detergents has been the synthetically produced zeolite A. Zeolites are naturally or synthetically produced sodium-aluminum silicates with the following general composi-

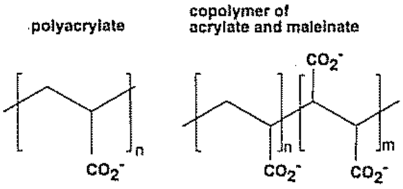

Fig. 2
Chemical structures of polycarboxylates.

tion: Na_2O x Al_2O_3 x $aSiO_2$ x bH_2O. Zeolite A has a known crystalline structure with an average particle size of 2.5 to 3.5 µm.

The main function of zeolite A in detergents is to soften water through ion exchange; sodium ions in the pore-water are replaced by calcium and magnesium ions from the wash water. The fraction of zeolite A in detergent formulations amounts to 15–25%, together with a so-called cobuilder. Through the addition of these polycarboxylates or phosphonates, the capacity of the zeolite for ion exchange improves. It is noteworthy that zeolite A also has a good carrying capacity for liquids such as surfactants. A detergent in powder form needs a liquid carrier like zeolite A. The detergent industry has produced a major achievement in developing compact laundry detergents based on zeolite. The compact detergents currently in use in Europe are almost exclusively based on zeolite A.

Zeolite A, a fine insoluble powder, is removed to 95% in the sewage sludge during mechanical-biological sewage treatment, leading to an additional increase of 15'000 tons/year of dried sewage sludge in Switzerland [3]. Zeolite A, as well as the newly-developed zeolite P, undergo a slow process of hydrolytic decomposition in the environment, yielding aluminum oxide and aluminum silicate. The partially soluble, newly developed layered silicates are also effective detergent builders, but their use remains restricted due to their instability above 60 °C.

Polycarboxylates

Polycarboxylates are water-soluble, linear polymers characterized by numerous carboxylate groups (Fig. 2). The high charge density and the chain length of the polymers determine the physical and chemical properties of this class of substances. In detergents, they are used in the form of polyacrylates as well as copolymers of acrylate and maleinate, with an average molecular mass of approximately 70'000 atomic mass units.

The main function of polycarboxylates in detergents is their "threshold effect"; that is, they act as dispersing agents to prevent the deposition of salts on the fabric. In contrast to the complexing agents, polycarboxylates are used in sub-stoichiometric amounts, so that a fraction of 2% to 6% in detergents in combination with other builders is sufficient. At high excess amounts of free calcium ions, the almost insoluble calcium polycarboxylate precipitates, and the dispersing effect is lost. Softening the water, by addition of zeolite A or a complexing agent, is required for the polycarboxylate to function effectively.

In wastewater, polycarboxylates precipitate as insoluble calcium polycarboxylates due to surplus calcium. Experimental work conducted to date has not yet indicated that there are any detrimental effects on wastewater treatment processes. Strong adsorption can be expected when sludge containing polycarboxylates is applied to soils as fertilizer, especially by high molecular weight compounds.,

The polycarboxylates and the phosphonates described below have three significant disadvantages with regard to their environmental compatibility: incomplete biodegradation during sewage treatment, concentration in sewage sludge, and the lack of analytical techniques to monitor their fate in the environment. Their detection in the environment is extremely difficult due to the composition of complex mixtures of this class of substances.

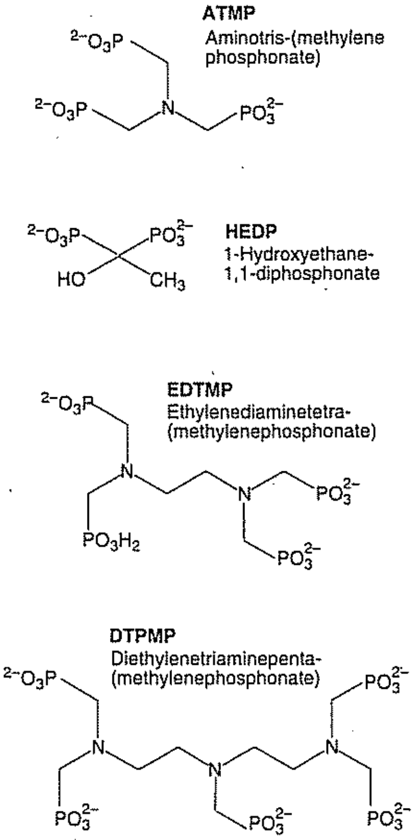

Fig. 3
Chemical structures and abbreviations of phosphonates.

Phosphonates

Phosphonates, the salts of the organic phosphonic acids, are characterized by the presence of several PO_3^{2-} groups in each molecule. Phosphonates have been used for decades in large quantities in hydrotechnology for preventing scale build-up in cooling water circuits and steam boilers. Four different phosphonates are commonly used in detergents (Fig. 3).

Phosphonates in detergents both prevent the deposition of incrustations on fabric as well as stabilize the bleaching agent during washing and storage. Because of the phosphonates' threshold effect (optimal effectiveness at very low concentrations), they comprise only 0.2–0.5 parts by weight of deter-

Phosphate Substitute	Chemical Effect	Function in Washing Process
zeolite A, zeolite P, layered silicates	ion exchange	reduction of water hardness
nitrilotriacetate (NTA), citrate	complexing agent	reduction of water hardness
polycarboxylates, phosphonates	threshold effect	inhibition of precipitation

Tab. 1
Chemicals used as substitutes for phosphate in detergents and other cleaning agents.

gent components in combination with other builders.

Phosphonates are almost nondegradable in mechanical-biological sewage treatment plants under aerobic and anaerobic conditions and can only be removed partially [4]. Although phosphonates are very water soluble, they exhibit a strong affinity for the mineral fraction in the sediments. In addition, various phosphonates have different complexation behaviors so that each phosphonate must be investigated separately in order to assess its environmental compatibility.

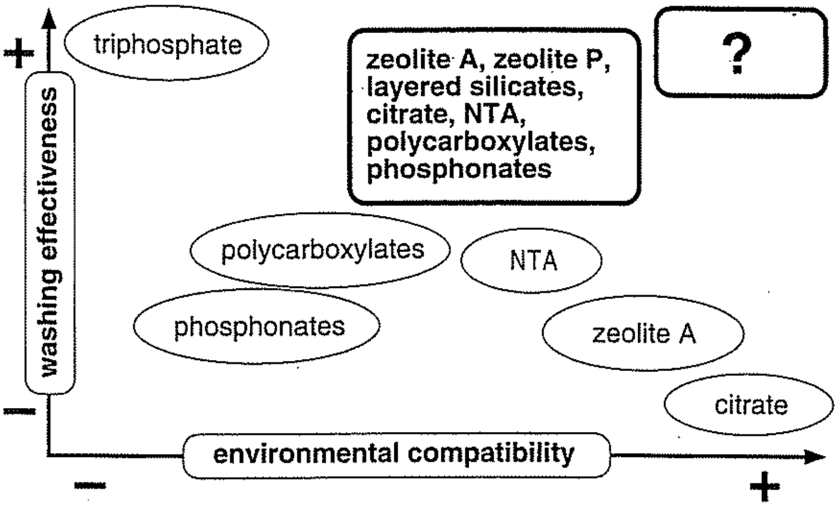

Fig. 4
Distribution of builders used in detergents and cleaning agents according to their washing effectiveness and environmental compatibility.

Nitrilotriacetate (NTA)

The softening effect of NTA on water is based on the complexing of calcium and magnesium ions. Comprehensive investigations on NTA and the related compound EDTA have been carried out in Switzerland [5, 6]. The good biodegradability of NTA has been extensively documented. The phosphate ban and the partial substitution of NTA for phosphate in detergents has not led to an increase in NTA concentrations in lakes. Thanks to the availability of a specific and quantitative analytical technique to detect NTA, it is possible to carry out both monitoring and process-oriented field studies.

Citrate

Similar to NTA, citrate has a softening effect on water which occurs via the complexing of anions responsible for hard water. The environmental compatibility of citrate is very high as it is a naturally occurring compound and is quickly biodegraded. However, the fact that the builder effect decreases above 60 °C is a disadvantage. Detergent formulations may contain up to 10% citrate.

Amount of Builders Consumed in Switzerland

The amount of builders and cobuilders consumed in Switzerland from 1991 to 1994 are depicted in Fig. 1. The amount of zeolite A used in 1994 was 15'000 tons, a 20% reduction over four years.This is probably the result of lower washing temperatures making the increased use of citrate possible. Zeolite A remains an important component of detergent formulations. Its use may decrease, however, by partial substitution with zeolite, zeolite P and novel silicates. Approximately 2000 t of polycarboxylates and 500 t of phosphonates were also used, the trend of the former rising, that of the latter remaining unchanged. In 1994, only 1000 t NTA were used. Due to international efforts towards integration in Europe, the use of NTA as a phosphate substitute is also been expected to decline. Soda (sodium carbonate) is regarded as a builder; as a cobuilder, it causes an increase in the pH of the washing water.

Environmental Compatibility and Washing Efficiency

Phosphate substitutes are depicted in Fig. 4 according to their environmental compatibility and washing effectiveness. Triphosphate is effective, but its use is problematic on the environmental side. Conversely, citrate is environmentally highly compatible, but is inefficient above 60 °C. As mentioned above, polycarboxylates and phosphonates show certain disadvantages in their environmental compatibility. Polycarboxylates, being near-natural compounds, are more easily accepted than the phosphonates. Phosphonates are judged more negatively because of their complex chemical behavior.

The builder systems used today wash highly effectively. To date, however, optimal environmental compatibility has not yet been achieved. In summary, we can state that phosphate in detergents has been replaced by chemicals which current research assesses as marginally compatible with the environment.

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[4] Gledhill W.E. and T. Feijtel, 1992. Environmental Properties and Safety Assessment of Organic Phosphonates used for Detergents and Water Treatment Applications. In: Detergents, eds. de Oude N.T., 3, Part F: Anthropogenic Compounds, 261–285. Springer-Verlag, Berlin.

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Giger W., Micropollutants in the Environment, from Environmental Monitoring to Process-oriented Field Studies, EAWAG news 40E, 3–7

[6] Hourier J.-P., 1996. NTA dans les eaux
(a) Cahier de l'environnement No 264,
(b) Documents Environment No 54, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern.

Hansruedi Siegrist and Markus Boller

Effects of the Phosphate Ban on Sewage Treatment


Diana Hornung

Hansruedi Siegrist

As a result of the Swiss phosphate ban, the dissolved P load in raw sewage has been reduced by over 50%. But what effects has the phosphate ban had on municipal drainage and the operation of sewage treatment plants? In what ways can biological phosphate removal result in a reduction in the consumption of precipitation agents? How does the phosphorus flow in municipal drainage influence the P-balance of Switzerland and the exportation of P to neighboring countries?

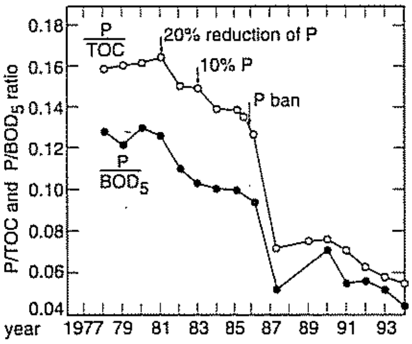

Fig. 1
P/TOC and P/BOD$_5$ ratios in primary effluent of the treatment plant Zurich-Glatt from1978 to 1994.
Simultaneous precipitation was introduced in 1990. The P load in the primary effluent could be additionally reduced by returning the iron-containing excess sludge to the primary clarifier.

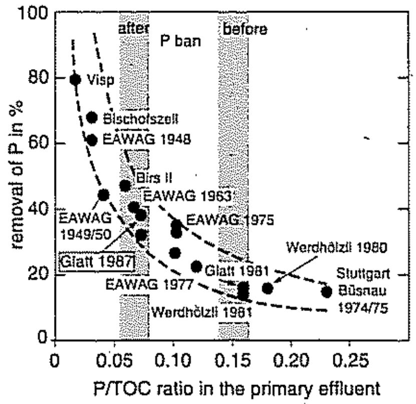

Fig. 2
On account of the P ban, the removal efficiency through the incorporation of phosphorus by the biomass has become similar to that before the introduction of polyphosphates in laundry detergents.

Changes in the Composition of Sewage

Since the phosphates used in detergents were largely composed of soluble polyphosphates, a shift towards an increased solid fraction was realized following the phosphate ban, in addition to the substantial reduction in total P loads. Today, polyphosphates are used almost exclusively in dishwashing detergents. Only about 2% of the P load consists of non-degradable phosphonates originating from laundry detergents and cleaning agents [1]. The fraction of phosphorus originating from feces and domestic waste exists as particulate and organically-bound forms. Almost all of the orthophosphate fraction originates from urine (see Table 1).

The dissolved P load has decreased by more than 50% since 1980 and currently amounts to about 70–80% of the total P load in primary effluent.

Raw sewage	1980 g P c^{-1} a^{-1}	1994 g P c^{-1} a^{-1}
Urine	450	450
Faeces	200	200
Household wastes	100	100
Laundry detergents	750	50
other detergents and cleaning agents	170	110*
runoff from urban areas	50	50
Total	1720	960

Tab. 1
Total (gross) phosphorus loads per capita entering raw sewage according to the phosphorus source [1, 2, 3, 4].

Since sewage has become more concentrated over the past 15 years, due to the intensive separation of extraneous water, we have chosen the ratio of P/TOC as an indicator of the decline of P in sewage.

Assuming that the C load remained relatively constant, a decrease of >50% in the P/C ratio in primary effluent between 1980 and 1990 was realized. This decline can be clearly seen, both for the stepwise reduction in the concentration of P in detergents in 1981 and 1983 as well as for the phosphate ban in 1986 (Fig. 1).

Effects on Sewage Treatment

Plants with Mechanical and Biological Treatment

In conventional sewage treatment plants with both mechanical and biological steps, some of the particulate phosphorus is removed in the mechanical treatment stage (10–20% of the P load of the raw sewage). The extent of P removal in the biological step depends on the biomass production and the phosphorus demand of the microorganisms. As the rate of sludge production is largely determined by the amount of organic compounds in the sewage, the percentage of P removal in a sewage treatment plant mainly depends on the ratio of the nutrients, i.e., the ratio P/TOC in the primary effluent. In sewage composed exclusively of domestic wastewater, the efficiency of P incorporation in activated sludge is 30–50% of the P load in the primary effluent (before

	1980 (connected to sew.tr.pl. 70%)			1994 (connected to sew.tr.pl. 92%)		
	Amount of water 10^6 m^3 a^{-1}	**Concen-tration** g P m^{-3}	**P loads** t P a^{-1}	**Amount of water** 10^6 m^3 a^{-1}	**Concen-tration** g P m^{-3}	**P loads** t P a^{-1}
Mech-biolog. treated	800	3.4	2710	400	1.6	640
with chem. P precipit.	900	0.8	720			720
with flocculation filtration	–	–	–	180	0.2	40
diffuse sources	50	4.0	200			50
sewer overflow	250	3.5	870	250	1.8	450
Total wastewater	2000		4500	2050		1900

Tab. 2

Comparison of the total net P loads from watewaters incl. sewer overflows in 1980 and 1994. An additional 1900 t P a^{-1} originate from diffuse agricultural sources.

the P ban, it was 15–20%). Currently, 50–60% of the P load is being removed from raw sewage without using P precipitation.

Results of previous and current assessments demonstrate that as a consequence of the phosphate ban for detergents, the conditions prevailing in 1960 may be attainable (Fig. 2). In catchment areas below lakes, where the precipitation of phosphorus was not mandatory, a reduction of about 60% in the P load was achieved as a result of the phosphate ban.

Effects on the Chemical Precipitation of P and on Flocculation Filtration

Because of the phosphate ban, lower concentrations of P in the outflow were observed, despite a 50% reduction in the use of precipitation agents. Several reasons may account for this:

- The residual concentration of P for precipitation was reduced by 60%.
- Non-precipitable fractions of polyphosphates declined markedly.
- The P content of the activated sludge, i.e., also the particulate load of P in the secondary effluent, decreased by about 40%.

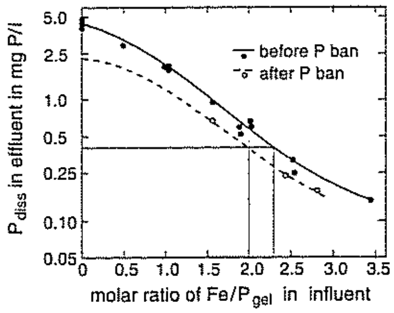

Fig. 3

Effect of Fe/P_{diss} ratio in the precipitation basin of waste water treatment plants on the attainable residual dissloved phosphorus concentration in the secondary effluent.

In the past, a ratio of Fe/P_{diss} >2.3 was needed to attain concentrations of <1 g P_{tot} m^{-3} corresponding to <0.4 g P_{diss} m^{-3} (the particulate fraction being 0.5–0.6 g P m^{-3}) in the outflow. Today, however, concentrations of 0.4 g P_{tot} m^{-3} (the particulate fraction being 0.2–0.3 g P the m^{-3}) at a ratio of Fe/P_{diss} >2 can be attained (Fig. 3).

It is obvious that the slightest effect of the P ban can be observed in sewage treatment plants with flocculation filtration because the removal was already above 95% before the ban. The sewage plant which has been observed most regularly for the longest period is ARA Hochdorf. The residual P concentrations after flocculation filtration were reduced by about 0.05 to 0.1 g P m^{-3} after 1986.

Enhanced Biological Removal of P

Parallel to the introduction of continuous pre-denitrification, enhanced biological phosphorus removal should be investigated as a possibile tool for at least partially replacing chemical precipitation. Using an anaerobic/anoxic/aerobic flow scheme, the activated sludge can be enriched with polyphosphate-accumulating bacteria [5]. The advantage of these phosphorus-storing organisms is that they can accumulate a substrate in an environment which inhibits the growth of other bacteria. Other bacteria can only utilize the readily degradable substrate efficiently if a corresponding electron acceptor (oxygen or nitrate) is available, as they do not possess the ability to store it. Depending on the hardness of the water, a portion of the phosphate is precipitated as "calcium phosphate" because of the increased concentrations of phosphate in the anaerobic tank. This amounts to about 50% of the polyphosphate content of the excess sluge resulting from the sewage of the city of Zurich[6].

As the ratio of COD:N:P of Swiss domestic sewage is 60:6:1, most of the dissolved phosphorus can be stored using enhanced biological P removal. Due to the strict effluent standards in Switzerland it is usually necessary to carry out the precipitation of residual P in order to bridge over times of decreased substrate availability. In addition, a residual precipitation with iron in the activated sludge tank would bind the hydrogen sulfide produced in anaerobic sludge treatment and thus prevent corrosion problems in the utilization of biogas.

Prior to the P ban, the enhanced biological removal of phosphate made little sense – an additional massive precipitation would have been necessary. This would have interfered with biological Puptake. As the amount of precipitated sludge is reduced through enhanced biological P removal, it can be assumed that the integration of the latter into a well-designed denitrifying treatment plant would not lead to an enlargement of reactor volume. The nonaerated reactor space would be slightly enlarged at the expense of the aerated tank. In a sewage treatment plant with biological removal of phosphorus a simultaneous thickening of primary and secondary sludge will cause a partial release of the stored polyphosphate in the primary clarifier and the sludge thickener, and thus lead to a recontamination of the waterflow with PO_4 [6]. For this reason, a separate dewatering of the excess sludge can be advantageous.

Phosphorus Load in Sewage Sludge

The P ban caused an average decrease in the concentration of P in sewage sludge from 32 in 1984 to 23 g P g^{-1} dry matter (dm) in 1989 [7]; P declined from 40 to 27 g P g^{-1} dm in those plants with simultaneous pre-

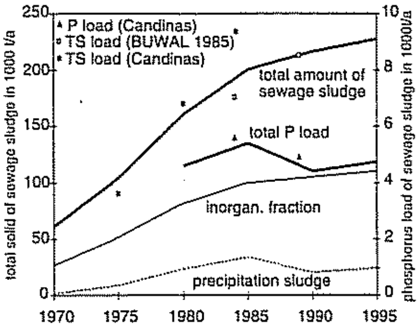

Fig. 4
Production and total phosphorus loads of sewage sludge in Switzerland.

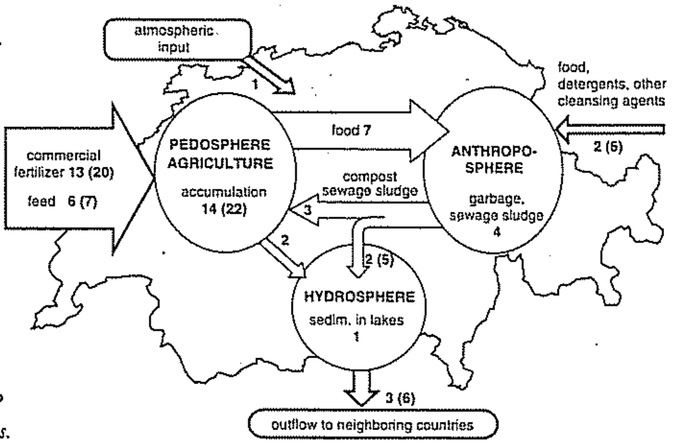

Fig. 5
Phosphorus balance of Switzerland in 1994 (flow rates in 1000 t P a⁻¹).
The flow rates for 1983, i.e. before the P ban, are in parentheses.

cipitation. As the amount of sludge increased during this time and precipitation and flocculation filtration systems were installed in many plants, the P load in 1994 once again reached the level of 1980 (Fig. 4). The specific load of sewage sludge per capita has hardly declined because zeolites have been introduced as substitutes for phosphates; these amount to roughly 6% of the dry solids of the digested sludge.

Phosphorus – the Current Situation in Switzerland

Municipal Drainage – Domestic Sewage

As a result of the P ban and improved sewage treatment, 2600 t P a^{-1} could be prevented from reaching natural waters (comparing 1980 to 1994); 1500 t solely through chemical precipitation (Table 2). By installing P precipitation in all sewage treatment plants, the P load can be reduced by a further 400 t a^{-1}.

The P load in sewage sludge amounts to approximately 5000 t a^{-1}. Without the P ban, the pollution of natural waters with P would rise to over 2300 t a^{-1} and the P load in sewage sludge to over 9000 t a^{-1} even if the precipitation of P became widespread in sewage treatment.

Comparison with the Total Turnover of Phosphorus in Switzerland

The turnover of phosphorus in Switzerland has been calculated from several sources [1, 9, 10, 11, 12] (Fig. 5). The total P load in sewage (ca. 7000 t a^{-1}), compost, and garbage corresponds roughly to the consumed P load in the form of food, laundry detergents, and cleaning agents (approx. 9000 t P a^{-1}). About 2000 t a^{-1} enter natural waters; around 5000 t P a^{-1} are stored in sewage sludge.

The diffuse load of P entering natural waters from agriculture, approximately 2000 t a^{-1}, corresponds to the amount from treated sewage. Taking into account the sedimentation of P in lakes, the P load exported through natural waters has declined during the past few years from 6000 to approximately 3000 t P a^{-1}.

Due to the reduction in the use of commercial fertilizers, the accumulation of P on agricultural land has decreased to 14'000 t a^{-1}. The input of P is, however, more than twice as high as the P demand. The P load in the utilized sludge would suffice, in combination with the imported feeds, to cover the P demand in agriculture (removal through foodstuffs and soil leaching). Without a P ban, many resources containing P would be lost through incineration and (landfill) disposal of sewage sludge.

Conclusions

As a result of the phosphate ban and improved sewage treatment, the total load of phosphorus from municipal drainage (treated wastewater, stormwater overflow, diffuse sources) has decreased during the past 15 years by about 60% to approximately 2000 t P a^{-1}. Approximately the same P load runs off agricultural land into our natural waters. Taking into account the sedimentation of P in lakes, the P load exported through natural waters has been reduced during the past 15 years by 50%, from 6000 to approximately 3000 t P a^{-1}. Lower effluent concentrations can be realized at this time using half the amount of precipitation agents utilized before the P ban was put into effect because the dissolved residual phosphate has been reduced by 60% after mechanical-biological treatment. In sewage treatment plants with denitrification the amount of precipitation agents can also be drastically reduced if enhanced removal of P is introduced. Prior to the P ban this strategy would not have been very useful as high residual precipitation inhibits the polyphosphate storage.

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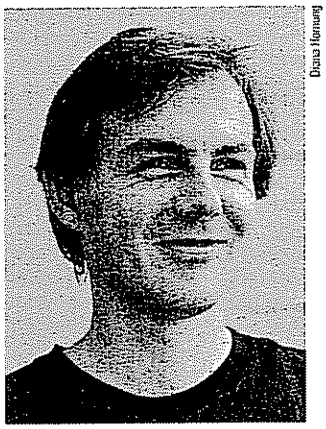
Bernhard Wehrli, Alfred Wüest, Heinrich Bührer, René Gächter and Jürg Zobrist

Decreasing Eutrophication in Swiss Lakes



Diana Hornung

Bernhard Wehrli

Has eutrophication of lakes decreased as a result of the phosphate ban or because of phosphorus removal by sewage treatment plants? The answer can be found using simple balance models; one such model is that substituting phosphates in detergents has accelerated lake restoration. The P ban, in combination with phosphate removal in sewage treatment has lead to decreasing phosphorus inputs into Lake Geneva and Lake Zürich by 50% and 60%, respectively.

The reality of exponential growth curves had a lasting effect on the political consciousness of Swiss citizenry from 1950 to 1970. Increases have been noted in not only the length of the highway network, the number of apartments, airline passengers, and washing machines, but he concentration of phosphorus in the lakes has also increased more rapidly from year to year as a result of this growth. Detrimental effects to lakes occurred quickly and drastically and have also exponentially motivated public awareness and concern for Switzerland's lakes. A series of measures, unique in the world, was developed to reverse the eutrophication process in the lakes: introduction of phosphate precipitation in sewage treatment plants, initialization of a phosphate ban for textile detergents, introduction of control measures in agricultural practices and, in difficult cases, installation of artificial aeration in lakes.

In order to test the effectiveness of the various measures, we began to analyse the phosphorus fluxes in lakes using a ubox model (Fig. 1). The phosphorus content of a lake decreases when the inputs via inflowing rivers and the atmosphere are lower than the sum of the export via outflow and net sedimentation: Change in content = input - outflow - net sedimentation

$\Delta P/\Delta t = P_{in} - P_{out} - S$

The change in the phosphorus content P can usually be easily determined because phosphorus concentration is measured several times per year. The outflow is determined using the phosphorus concentration at the surface of the lake and the outflowing amount of water. These two quantities are known quite precisely. Using longterm measurements, one can calculate the ratio of β, the average concentration in the outflow to the average P concentration in the lake. This enables us to extrapolate in what way the concentration Pout in the outflow will change in the future when the content in P decreases:

$P_{out} = \beta/\tau\, P$

The lower the hydraulic residence time t of the lakewater the higher the annual export of phosphorus. Because the lake of Zurich has a residence time of 1.2 years, a large fraction of the phosphorus flows out through the Limmat River. An analogous approach can be postulated for net sedimentation:

$S = \sigma \cdot P$

The net sedimentation will also decrease when the phosphorus concentration in the lake declines. This however, can only be expected to occur when the sedimentation of biomass decreases due to a slow down of the algal growth rates. In general, too few reliable data on net sedimentation have been acquired for Swiss lakes. Assuming that both phosphorus sinks – outflow and net sedimentation – depend linearly on the phosphorus content, future trends can also be forecast:

$\Delta P/\Delta t = P_{in} - (\beta/\tau + \sigma) \cdot P$

If the inputs remain constant, a stationary state $(\Delta P/\Delta t = 0)$ will be reached after a long enough time in which the phosphorus content is determined by:

$P_{stationary} = P_{in}/(\beta/\tau + \sigma)$.

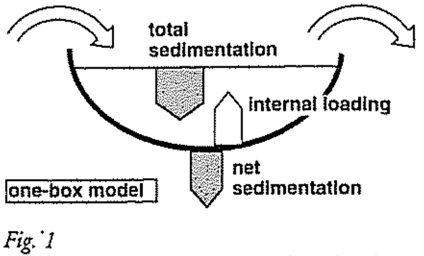


Fig. 1
Simple model for assessing the phosphorus balance in lakes. Shaded arrows depict the fluxes of particulate phosphorus.

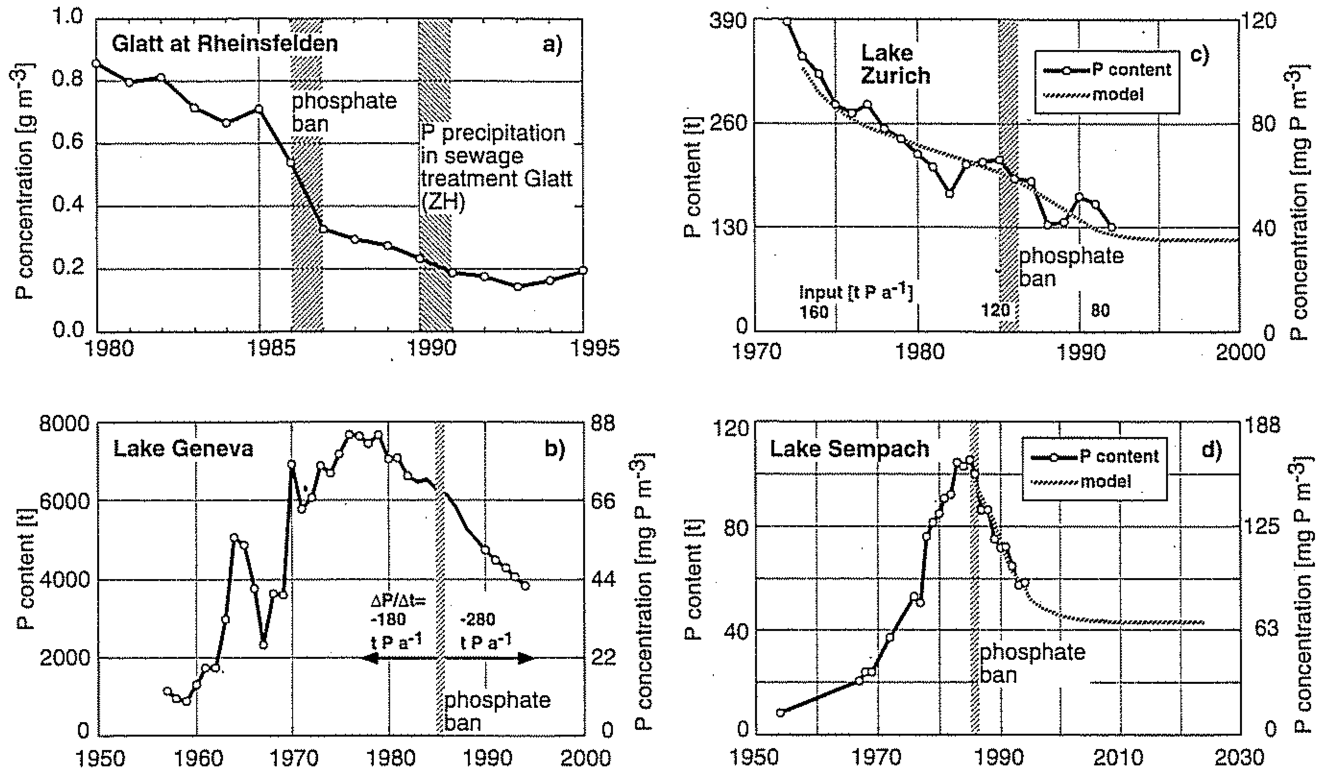


Fig. 2

Effects of the phosphate ban after 1986 on the P concentration in a) Glatt River, b) Lake Geneva, c) Lake Zurich and d) Lake Sempach.

This means that the phosphorus inputs directly determine the final state of the lake. It is difficult, however, to determine the exact input amounts. In order to carry out a survey of inflowing waters, a whole network of sampling stations usually has to be set up. Apart from this, new on-line measurements have shown that a few strong rain events are responsible for a large fraction of the annual phosphorus load in rivers. Rapid transport through soil macropores contributes significantly to the large nutrient input during such periods of high discharge [1]. In this context, the simple balance model of the lake helps in assessing the quality of monitoring programs of the river input. The simple balance model helps in assessing the quality of the investigation program/sampling and measurements carried out in inflowing waters using data from the lake.

The phosphate ban has clearly reduced pollution in running waters carrying a large fraction of wastewater. At the confluence of the Glatt with the Rhine, the effects of restrictions in the use of phosphates in detergents were already visible in 1983. By 1986, the ban had reduced the phosphorus concentration by 60% (Fig. 2a). Phosphate precipitation was only introduced after 1990 in the largest sewage treatment plant in that drainage area; the reduction of the load from Lake Greifen is insignificant. These observations support the calculations by Siegrist & Boller [2], who report a level of 40% less phosphate as was previously originating from textile detergents, combined with the improved biological phosphorus removal efficiency, have reduced the P load in the effluent of sewage treatment plants by a total of about 60%.

There is clear evidence that the phosphate ban has reduced the input loads in those lakes where the improvement of sewage treatments plants was still in early stages in 1986. The substitution of phosphates in textile detergents has helped gain time in such cases. Lake Geneva is a good example (Fig. 2b). The increased number of communities connected to sewage treatment plants with a biological stage already effected a change for the better by 1979; such an improvement is noticeable in the average phosphorus concentration in the lakewater. Since that time, the phosphorus content has been decreasing by around 180 tons a year. As a result of the phosphate ban in Switzerland, the change in content has risen to a decrease of 280 tons/year since 1986. As we can assume that the rates of net sedimentation and the outflow have not changed significantly, the input must have decreased by about 100 tons annually after 1986. This corresponds to a reduction in pollution by about 40%.

In the drainage area of Lake Zürich, the extension of the sewage treatment plants was more advanced when the P ban was put into effect in 1986 (Fig. 2c). For this reason only a small decrease of the P concentration in the lake is observed In spite of this, the input via storm drains decreased from 6 to 3 tons a year. Input estimates for 1985 and 1992 show a reduction from 120 to 80 tons per year. The P ban, combined withthe technology of phosphate precipitation in sewage treatment has reduced pollution by 60%. Because of the short residence time, the lake reacted quickly to the lower nutrient load. Using the model, a stationary state of approximately 35 mg P m^{-3} has been calculated. The concentration level set by the restoration goals amounts to moderate algal growth [3] and usually corresponds to a maximum of 30 mg P m^{-3} in deep Swiss lakes. This level has almost been achieved in Lake Zürich!

The reduction in phosphorus from wastewater has not shown the desired effect in all lakes. The input of phosphorus into Lake Sempach via wastewater has been reduced by over 80%. In spite of this, the model forecasts that a longterm stationary condition in the range of 60–70 mg P m^{-3} can be expected [3]. This means that the input values are too high by a factor of about 2. While P levels in waste water have been reduced, a concurrent trend is not seen in agricultural runoff; in fact, these levels have increased. The farmlands draining into the lakes of the Lucerne plateau support a large number of animals and were already considered problem cases in the early 1970's. Artificial aeration of lakewater was expected to increase the net sedimentation of phosphorus and to accelerate lake restoration. An analysis of the comprehensive investigations [3] showed, however, that the oxygen input did not modify the deposition of phosphorus into the sediment. For this reason the cantons and community associations strengthened their efforts to combat pollution at its source, their motto being "No healthy lake without a healthy catchment". Even Lake Sempach could be helped with a new agricultural policy. The first signs are positive: already 50% of the farmers are switching to integrated production.

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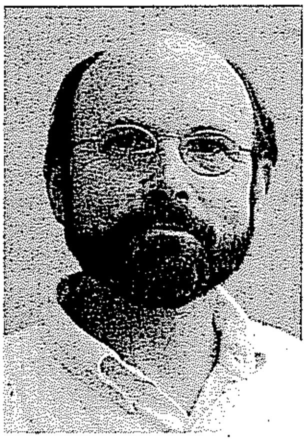
Urs Uehlinger, Hans-Rudolf Bürgi and Rudolf Müller

Changes in the Ecology of Lakes and Rivers Due to Sinking Phosphate Levels



Diana Hornung

Urs Uehlinger

The phosphorus load of Lake Lucerne has decreased sharply since 1977. Current algal concentrations are only insignificantly lower than in 1977, although algal production has clearly decreased during this time. The increase in size of the slow-growing whitefish is retarded due to the production decrease, as they have to expend more energy to obtain food. The reduction in phosphorus is assumed to cause minimal effects in streams and rivers.

Changes in the Food Chain in Lakes

This article mainly addresses the effects of the reduction in phosphorus levels on the open-water food chain in lakes. A food chain describes the ways elements and energy are exchanged between the organisms of an ecosystem. At the bottom of the open-water food chain are the algae (Fig. 1). With the help of chlorophyll, in the presence of sunlight, these organisms produce organic substances from inorganic nutrients (Fig. 2a). This process is called primary production. In a lake, primary production is confined to the upper illuminated layer of the water column. Some of the algae become food for the herbivorous zooplankton (herbivores). These are in turn consumed by predatory zooplankton. At the top of such a food chain are the fish.

Food chains or foodwebs are basically controled by "bottom-up" forces, i.e., by the primary producers; removal of primary producers causes system collapse [1]). In a lake, phosphorus exerts the main influence on the food chain via primary production. If phosphorus is a limiting factor, primary production can be stimulated by increasing the amount of available phosphorus. Conversely, reduction in

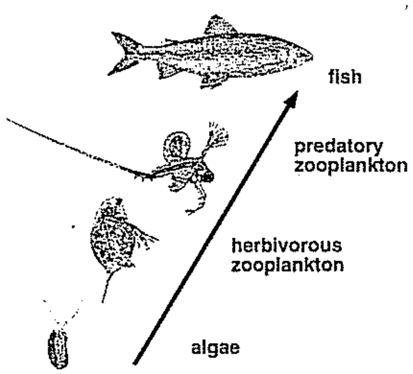


Fig. 1
Food chain in the open water zone of a lake.

the available amount of phosphorus results in a production decrease. The magnitude of a change in the phosphorus level depends on how strongly phosphorus limits primary production (Fig. 2b).

Forces from the top of a food chain, that is, "top-down" forces such as as predation or grazing, can also influence the structure of a food chain. For example, if the grazing pressure of the fish on the predatory zooplankton is too high, the pressure on herbivorous zooplankton is subsequently relieved; high levels of herbivores in turn keep the concentration of algae low (Fig. 3a). If predatory zooplankton, however, control herbivorous zooplankton (e.g, because the feeding pressure from fish on the former is low) then the concentration of algae remains high (Fig. 3b).

The example below, the now oligotrophic Lake of Lucerne, will help illustrate what changes occurred in the food web of the open-water zone when the phosphorus levels decreased sharply.

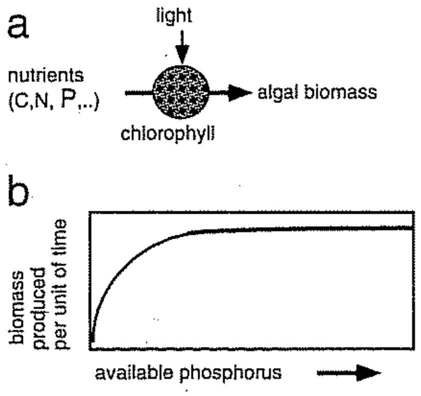


Fig. 2
a) Primary production
b) Dependence of the primary production on the availability of phosphorus.

The Complex Food Web in the Lake of Lucerne

The food web of the open water is quite complex in the Lake of Lucerne. More than 100 species of algae comprise the primary producers. These species are confronted with 18 species of herbivorous zooplankton. The predatory zooplankton includes 10 species. At the top of the food chain are zooplankton-consuming fish, primarily whitefish.

Reduction of Phosphorus Load and Primary Production

The introduction of phosphorus removal in the sewage treatment plants of the drainage area of the lake caused the phosphorus load to drop from 103 tons in 1976/77 to 14 tons a year in 1989. As a consequence of the reduced phosphorus input, the average concentration of orthophosphate dropped from 20 mg P/m^3 in 1978 to the current level of 2 mg P/m^3 (algae assimilate phosphorus as orthophosphate, Fig. 4). At the same time, algal production also sank distinctly. As algal production strongly depends on weather conditions, the annual production amounts varied considerably in subsequent years.

Chlorophyll and Algae

Chlorophyll, the green pigment in plants, plays a central role in primary production, as mentioned above. The concentration of chlorophyll also largely determines the extent to which light is absorbed in the water column and so also the depth to which primary production is possible. The average concentration of chlorophyll in the productive layer declined during summer from 6 mg/m^3 in 1980 to 2.7 mg/m^3 in 1993. At the same time, the productive layer increased in depth from 12.5 m to 17 m, meaning that the lake is more "transparent" to date.

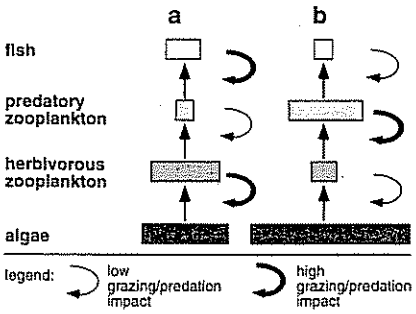


Fig. 3
"Top-down" effects in the food chain of a lake. The boxes represent the biomass of the various links of the food chain. The vertical arrows depict the direction of the energy and element flux along the food chain.

The biomass of the planktonic algae changed only slightly; it even increased a little between 1985 and 1995. This signifies that the average chlorophyll content of the algae has been decreasing. We know from experiments with cultures that the chlorophyll content of algal cells decreases with increasing phosphorus deficiency. Assuming that the algae are mainly restricted to the productive layer, the concentration of

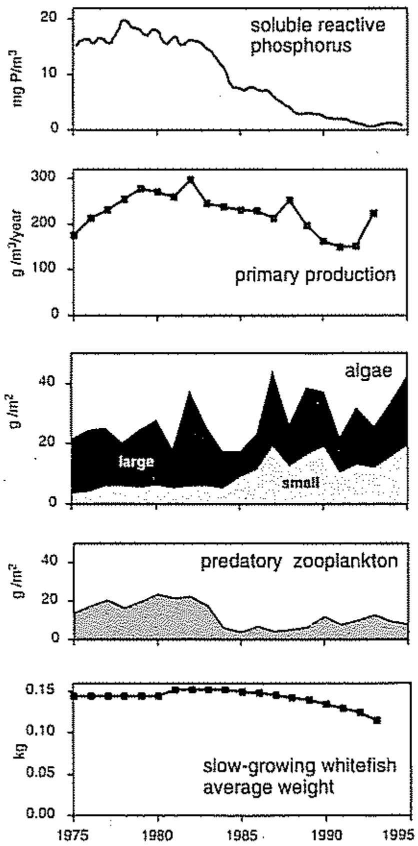


Fig. 4
Lake Lucerne: temporal course of orthophosphate concentration, primary production, biomass of algae and zooplankton and average weight of slow-growing whitefish in a catch.

algae has decreased by about 10 to 20%. The relative proportion of small algae (nanoplankton) – the preferred food of herbivorous zooplankton – is distinctly higher than in 1980. Their concentration to date is also higher, although the productive layer has increased in depth. The amount of food available for the herbivorous zooplankton has increased. Apart from size distribution, the species composition of the algal community has also changed. The fraction of diatoms – these being relatively heavy and so tending to sink rapidly out of the productive layer – fell from 50% to 30%; Chrysophyceae and Cryptophyceae, however, are more numerous to date.

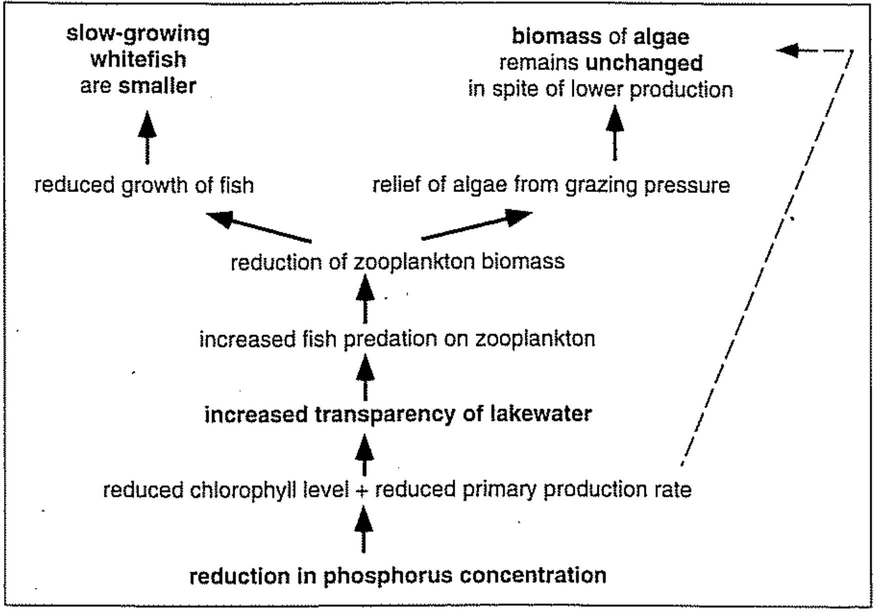


Fig. 5
Hypothetical relationship between the decrease in phosphorus, algal biomass and growth of slow-growing whitefish in Lake Lucerne.

Zooplankton

The biomass of the herbivorous zooplankton changed only slightly, but one group, the daphnia, has been declining since 1986. Daphnia are efficient consumers of algae and an important food source for whitefish. The biomass of the predatory zooplankton is distinctly lower to date than in 1980. This decline mainly pertains to the larger species which are the preferred food of normal as well as slow-growing whitefish. The zooplankton data suggest that during the past decade food has clearly become scarce mainly for the slow-growing whitefish, which almost exclusively feed on zooplankton.

Whitefish: Slower Growth in Spite of a Full Gut

Neither the size nor the age structure of the stock of slow-growing whitefish in Lake Lucerne is known. The catch statistics from the professional fishermen, however, supply us with valuable information on relative changes in the fish stock. The slow-growing whitefish catch (number of fish per year) increased until the middle of the 1980's. A distinct collapse of the population occurred in 1988 and in 1992. The short recovery in 1990 and 1991 was probably due to the minimum mesh-size allowed by law for fishing nets which was reduced from 28 to 27 mm. A closer look at the catch suggests that between 1983 and 1993 the average age of the fish caught by the professional fishermen increased by one year. At the same time, the average weight of the fish declined from 153 g to 115 g. This means that the slow-growing whitefish's growth has been slowing down since the mid 1980's.

The analysis of the gut contents of the slow-growing whitefish caught in nets suggested that they hardly suffer from hunger at present [2]. The fish prey very selectively on Bythotrephes, a relatively large (energy-rich) predatory zooplankton species which can be found only in low population densities. Daphnia, a small but more abundant zooplankton genus comprises an additional important food source for the fish. As the stomachs of the fish are still relatively full in spite of the reduction in food concentration, we can assume that the fish have to swim further per unit of time in order to fill their stomachs. They can only do this by investing more energy in the search for food. With the energy intake remaining constant, less energy remains available for building up biomass and thus, the fish grow more slowly.

The changes in the food chain of Lake Lucerne after 1980 can be summarized as follows:

- The primary production sank distinctly;
- Regarding the phytoplankton, the concentration of those species increased which are food sources for filter-feeding zooplankton;
- Regarding the zooplankton, the fraction which is a food source for slow-growing whitefish has decreased;
- The slow-growing whitefish distinctly grew more slowly.

Why does the biomass of the algae hardly change although production has decreased and why does the herbivorous zooplankton population decline although the availability of food has improved?

A Hypothesis

This phenomenon could be explained as follows: the slow-growing whitefish hunt their prey using their vision. Their success increases with diminishing water turbidity. If the chlorophyll concentrations decrease, the water becomes more transparent and the fish can see their prey better. As a result, the grazing pressure on the zooplankton increases. This reduces the food concentration for the fish and presumably also decreases the grazing pressure on the small algae by herbivorous zooplankton (Fig. 5).

The Importance of Biological Processes

In Lake Lucerne, the declining phosphorus load was paralleled by a distinct reduction of primary production, which apparently resulted in lower fish production. However, the relationship between primary production and fish appears to be rather complex. "Top-down" forces were presumably responsible for the uncoupling of primary production and algal biomass. The example of Lake Lucerne indicates that the response of a lake to a reduction of the phosphorus load depends not only on the chemical and physical charecteristics of the system but also on biological processes (grazing and predation) in the open water.

Does a Reduction in P also have an Effect on Running Waters?

The phosphorus problem was not a priority water protection issue for rivers and streams in Switzerland, although in some streams nutrients (phosphorus) may have favoured proliferation of water plants (algae and macrophytes). The pollution of running waters with phosphorus only receives attention when the rivers and streams play a role as the means of nutrient transport to downstream lakes. River monitoring programs have mainly focused on water chemistry but usually neglected the assessment of benthic organisms. Therefore, we lack reliable information regarding how the significant decrease of the phosphorus concentration in many Swiss rivers may have influenced the "biology" of these systems. However, there are several reasons why the effect of this decrease could have been small.

Limititation only at Low Phosphate Concentrations

Investigations in artificial and natural streams have shown that the transition from phosphorus as the limiting factor and saturation of algal growth often takes place around 5 of 15 mg/l phosphate-P [3]. In many streams and rivers phosphate concentrations are still higher than the above mentioned threshold concentrations. Only alpine rivers, some prealpine streams and few outlets of large mesotrophic lakes may be potentially phosphorus limited.[4].

Dominating Influence of Other Factors

In running waters, the relationship between the production of the benthic algae and the availability of phosphorus may be less obvious than in lakes because:

- disturbances in the form of floods sweep away algae;
- depending on the size of the stream, the vegetation on the banks can strongly reduce illumination; in glacier stream suspended solids absorb a large fraction of the incident light;
- because the current has a "eutrophicating" effect (the effect being equivalent to the doubling of the phosphorus concentration for biological production can, e.g., be substituted by an increase in flow velocity).

In many, mostly small streams a large fraction of the energy originates from adjacent terrestrial ecosystems (leaves, dissolved organic material). This external energy source is independent of changes in the availability of phosphorus, in contrast to the primary production of the algae.

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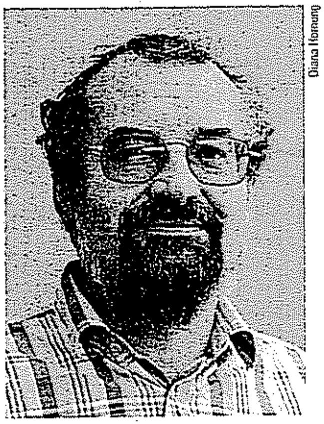
Best *IAWQ Pergamon Press* Publication for 1996

At the 1996 International Association for Water Quality (IAWQ) conference held in Singapore in June, Daniel Wild (left), Albena Kisliakova and Hansruedi Siegrist (all at EAWAG) were awarded a gold medal for best paper for their work entitled "Phosphorus fixation by magnesium, calcium and zeolite A during stabilization of excess sludge from enhanced biological phosphorus removal". The IAWQ meeting is held every two years.

Peter Bossard and René Gächter

Controversial Hypotheses Related to the Ban on Phosphates

Was Banning Phosphates in Detergents a Mistake?



Peter Bossard

The eutrophication of lakes was an important water pollution control issue in Switzerland in the 1950s and has remained so ever since. In 1968, Vollenweider [1] demonstrated that excessive phosphorus is the cause of eutrophication. In doing so, he showed the easiest way towards lake restoration: reduce the P load.

Apart from constructing sewage treatment plants and improving wastewater treatment techniques, the prohibition of detergents containing phosphates issued in 1986 was an additional measure aimed at counteracting the eutrophication of Switzerland's lakes. The producers of laundry detergents protested the ban, but eventually modified their formulations. Recently, the polyphosphate industry has tried to spread uncertainty and challenge the ban with headlines in the daily newspapers such as "Phosphate-free detergents damage our lakes" or "Turning point for detergents?" Their reasoning and some of the statements made in their internal reports [2–5] are summarized below:

- Phosphates from detergents and fertilizers are not the only cause of excessive algal blooms in lakes and coastal waters. Other decisive factors include heavy metals, oils, pesticides and surface-active additives in phosphate-free detergents which are poisoning the zooplankton and thereby decreasing the grazing pressure on algae.
- As the evidence shows that the phytoplankton biomass is determined by nutrients as well as by the grazers, the phosphate industry claims that lakes with an equivalent algal biomass could cope with 10 times the amount of phosphate if they were not contaminated by environmentally toxic substances that adversely affect the grazers.
- Viewed from an ecotoxicological point of view, polyphosphate substitutes represent more of a hazard than the polyphosphates themselves; therefore, the rationale for removing phosphate-containing detergents from the

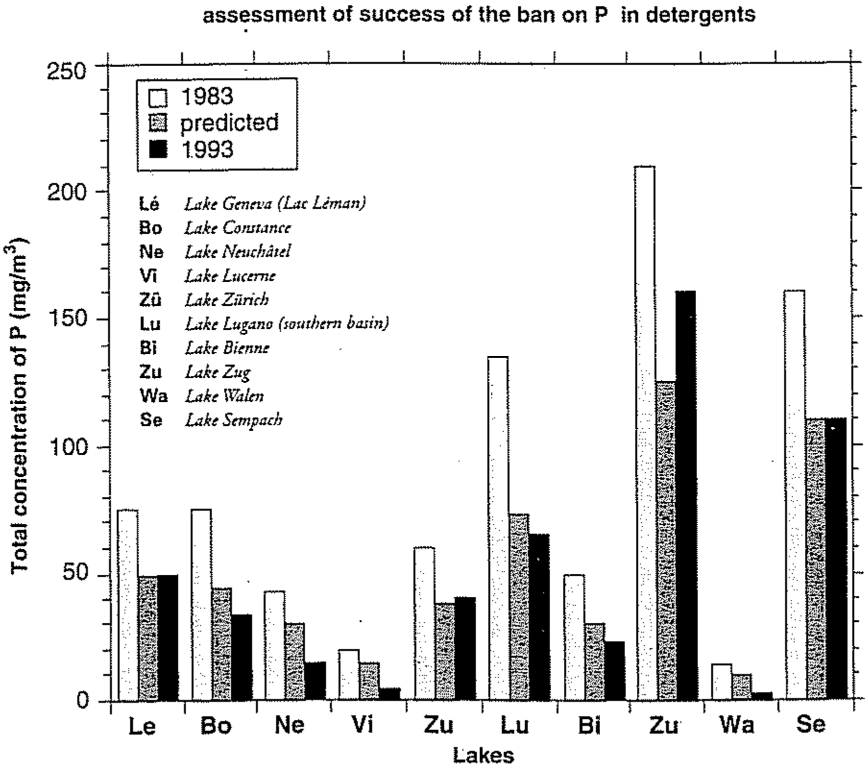


Fig. 1
A comparison of the total phosphorus concentrations measured in Swiss lakes in 1983 (tot P), and the prognosis of the BUWAL in 1983 on the reduction of the tot P levels, assuming a ban on phosphates in laundry detergents was going to be issued, with the actual tot P levels measured in 1993.

shelves is not only unfounded but they should even be preferred.

The scientific evidence speaks clearly against such arguments. In addition, they are easy to counter with practical results from recent work in water pollution control.

Based on sediment research by Züllig [6], it has been demonstrated that algal proliferation had already occurred in several Swiss lakes around the turn of the century. This means that algal blooms existed before phosphate-free detergents were introduced, before mineral oils contaminated our waters and before the word "pesticide" even existed. Even at that time, the zooplankton could not always control the excessive algal growth.

The intentional addition of fertilizer that contained phosphate salts in Canada lakes in the early 1970s caused eutrophication symptoms analogous to those seen in Swiss lakes [7]. The experimental lakes were situated far from any civilization so that any possible contamination by environmentally hazardous oils, pesticides and surface-active additives from phosphate-free detergents could be ruled out.

There is not question that phytoplankton biomass depends both on the rate of production (which is dependent on the availability of nutrients) and on the rate of algal loss due to grazing. During the course of a year, sometimes the algae dominate; at other times, the zooplankton do. Obviously, the zooplankton are able to significantly reduce the algal biomass; consequently, the increase of algal numbers following such phases cannot be the result of zooplankton poisoning.

Not only Switzerland, but also Norway, Germany and Canada have been using phosphate-free detergents for some time without any problems. Although residues of phosphate substitutes can be identified in concentrations of µg/l in lake water using sophisticated chemical trace analysis techniques, no direct or indirect damage to phytoplankton, zooplankton or fish in the lakes has been reported to date. Furthermore, studies carried out by Bernhardt [8] and by the German Federal Department for Environmental Protection (Umweltbundesamt) [9] suggest that NTA, polycarboxylates, carboxymethyl-cellulose and zeolite (a sodium-aluminum silicate) are ecotoxicologically harmless in the concentrations found in lakes. These trace amounts are also toxicologically insignificant for humans.

By 1983, the Swiss Federal Office for the Environment, BUWAL, had completed its assessment of the role played by phosphates in detergents in the pollution of 14 Swiss lakes [10]. Their study came to the conclusion that eliminating polyphosphates from laundry detergents would reduce the P pollution of these lakes by 15%–45%; the lakes with the highest P content would profit the most from such a measure.

The impact of the phosphate ban after one decade shows that these expectations have been fulfilled or surpassed in 9 out of 10 Swiss lakes assessed (Fig. 1). Further measures, including the widespread introduction of the third sewage treatment stage in the drainage areas of large lakes, have helped to achieve distinctly lower levels than had been projected in Lakes Constance, Neuchâtel, Bienne, Lucerne and Lugano's southern section. Only in slowly reacting Lake Zug (the residence time of its water is 14 years) was the prognosticated result not yet fully achieved by 1993. Considering such positive results, one should not forget that the quality of the water did not improve "visibly" through such measures (e.g., by increasing the visibility depth and the oxygen concentration in the deep water layer). Such "visible" changes only occur when the phosphorus level in the lake is reduced to below 30 mg P/m^3. Various factors contribute to a retardation in the immediate visible reaction of a lake to a reduced phosphorus load:

- When the availability of phosphorus becomes scarce, the small fast-growing algae increase at the expense of larger algae. These small algae have special capabilities to quickly assimilate and store phosphorus. Only when the small cells of the algae have consumed their P reserves can algal production be expected to decrease.

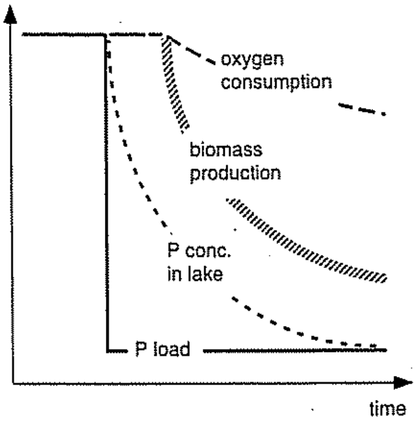


Fig. 2
The reaction of a lake to a sudden reduction of the P-load (e.g., through a ban on P in detergents). Temporal changes of the P load, P concentration in the lake, biomass, production and oxygen consumption.

- Oxygen consumption in the deep water layer of a lake depends on the amount of algae produced in the upper transparent layers. A considerable part of this biomass settles down to the lake bottom and is oxidized to mineral matter in the presence of oxygen.

Oxygen consumption in the hypolimnion depends primarily on the sedimentation rate of organic material and, secondly, on organic material which has accumulated in the sediment over many years, decomposing slowly and eventually producing methane. The organic material that accumulates in the sediment during the eutrophication phase, can cause the oxygen consumption to remain high for several years during the oligotrophication phase.

When the P load is reduced, the concentration of phosphorus in the lake initially declines. Next, the species composition of the algae changes before a decrease in algal biomass, and the transparency of the water increases as a consequence (Fig. 2). The oxygen balance of a lake reacts slowly to reduced P levels.

The change to phosphate-free detergents has countered pollution in Swiss lakes without effecting new damage. After 10 years of practical experience, we can conclude that the decision to ban polyphosphates in detergents was correct. It is a viable method for moving a step closer to meeting our water pollution control goals.

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Carlo C. Jaeger, Almut Beck, and Gregor Dürrenberger

Innovative Environmental Policy and the Phosphate Ban

The introduction of phosphate-free detergents is an example of successful environmental policy. It is especially significant because it questions two claims considered almost dogma in current discussions on environmental policy. The first one claims that one can only start solving an international problem when the procedures of individual countries have been determined by international contracts; the second one states that eco-taxes are the best incentive for reducing pollution.

Experiences with the phosphate ban cast serious doubt on these assertions; they do not suggest, however, that introducing bans on substances in one nation alone is advisable. But past experiences with the ban on phosphates in detergents should be carefully analyzed from an international perspective in order to glean results that may be useful in shaping innovative future policies.

Diana Hornung

Almut Beck, Gregor Dürrenberger and Carlo C. Jaeger (from left to right.).

The Standard Model of Environmental Policy

As demands for phosphate-free detergents increased, detergent manufacturers resisted with the usual argument of increased costs. This response corresponds to the general concept that the price paid for environmental policy measures is greater the more protection of the environment is pursued. Environmental economists analyze this concept using the model shown in Fig. 1, which maintains that pollutants continue to be emitted because preventing their emission costs money. The model assumes that the prevention of one unit of pollutant becomes more expensive the greater the amount that is being prevented from entering the environment. In this scenario, no company could afford to reduce a pollutant voluntarily in a market-oriented economy.

According to this model, the problem lies in the fact that the only point of equilibrium of this economic system is the point of maximum emission of a pollutant. The solution to the problem assumes that the pollutant causes external costs that are not carried by the polluter. Instead, costs are comprised, for example, of damages suffered by fishermen, tourists, hotel and restaurant owners and many others as a result of algal blooms in lakes caused by excessive phosphate concentrations. Again, it is assumed that the external costs per unit of pollutant are higher the more pollutant is emitted. The solution to this problem then is not in preventing production of the pollutant, but in making it more expensive to emit a pollutant by levying an eco-tax. This strategy shifts the equilibrium of the economic system to the point where the curves in Fig. 1 intersect.

In a global economy, this approach poses an immediate question: if an eco-tax is put into effect in one country, is the ability of a given company to compete internationally jeopardized? In times such as these, where securing jobs remains a top priority, such measures will be difficult to implement. It is possible that an eco-tax will be either relegated to "never-never land" or that its amount is so low that serious effects are neither feared nor realized.

An alternative scenario would be to subsidize pollution control with general taxes, rather than impose eco-taxes on private industry. This occurred in Sweden when the government decided against banning detergents containing phosphates and instead constructed sewage treatment plants with tertiary treatment capabilities. In certain cases, this approach may be practical, though it may drain public funds.[1]

How the Detergent Market Tipped

Completely different dynamics have developed in the detergent industry on the international scale. First, it is important to recall developments in the USA. As in most industrialized countries, detergents containing phosphates were introduced in the 1950s and soon dominated the marketplace. Many companies had already begun to search for alternatives when in the 1960s, scientific and political debate focused on eutrophication of the Great Lakes. In response, the detergent producers intensified their search for phosphate substitutes and eventually found a way to replace phosphates with NTA. But a controversy surrounding the risk of gene damage by NTA, stimulated by the U.S. Environmental Protection Agency, resulted in NTA-based products being withdrawn from the market. In the early 1970s, citizens organized demonstrations, leading to regional bans on phosphates. Citrate was offered as an alternative. In general, American households almost never wash above 60 °C; at temperatures greater than 60 °C, citrate would not have been a viable alternative. During the 1970s, the detergent industry subsequently limited the phosphate content of detergents voluntarily. In the early 1980s, existing bans on phosphates were partially withdrawn, although it did not result in an increase in the number of detergents containing phosphates. On the contrary, they were forced back even more during the 1980s by the new substitute zeolite.

It is interesting to compare developments in the USA with those in Germany where representatives of the detergent industry argued in 1973 that the problem of eutrophication should not be solved by introducing phosphate-free detergents but by improving sewage treatment. This, of course, meant increased expenditures of public money: "The additional costs [...] are estimated at approximately 2.50 DM/capita/year (1970). It can be assumed that the national economy would be burdened less by these measures than by changing the formulae of the detergents." (p. 78 in [1]). This corresponds, of course, to the model in Fig. 1. A meer ten years later though the same company (Henkel) sounded completely different: "It seems [...] probable that the main reason for the use of zeolites in the future will not be ecology alone but also economy." (p. 146 in [2]).

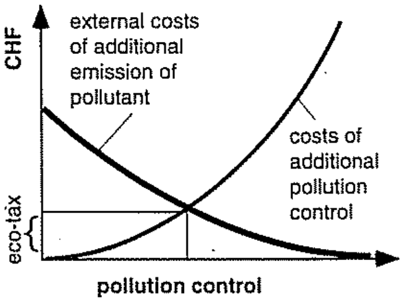

Fig. 1
Environmental problem in a world with a single point of equilibrium.

This change in opinion was supported by a joint research program between Henkel, who had held the patent for zeolite since 1973, and the German government. As a result, an ordinance limiting the concentration of phosphate in detergents was issued in 1980. The objective of the measure was to reduce the concentration of phosphate in laundry washwater by 50% by 1984. This goal was already attainable by simply indicating in the directions for product use the amount of detergent needed for a machine full of wash. The ordinance undoubtedly contributed to the introduction of phosphate-free detergents. Citrate was inappropriate as Europeans often wash above 60 °C.

In the early 1980s, detergent manufacturers began to market products containing NTA, but withdrew them due to purported health and environmental risks. In 1983, the first phosphate-free detergent based on zeolite was offered to consumers. After only four years, the market had come full circle, with the share of phosphate-free detergents reaching greater than 50%. By 1990, in Germany, phosphate-free detergents were sold almost exclusively.

In both the USA and Germany, industry did far more than simply meet the legal requirements; they far exceeded them. It is clear that these requirements were needed as were the public debates, in order to initiate a search for an environmentally compatible alternative to the status quo.

The Swiss ban on phosphates may also be regarded within this framework. It supported the development of

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[1] In the case of phosphate, the following must be mentioned: sewage treatment plants also had to be improved and extended in Switzerland because the reduction in phosphates in detergents achieved by the ban was insufficient.

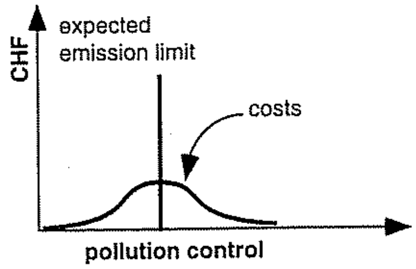

Fig. 2
Environmental problem in a world with several equilibria.

phosphate-free detergents in two ways. First, it helped to consolidate the detergent industry's assumption that an unlimited emission of phosphates would not be viable in a global economy. Secondly, it enabled industry to gain experience from the Swiss marketplace on the acceptance of innovative products. The situation changed from one in which the detergent industry had been trying to prevent the ban and later to have it withdrawn to one in which the industry had no objections to the ban. Undoubtedly, measures other than the ban would also have been possible. The process crucial to finding and using phosphate substitutes was the industry's realization of the inevitability of impending change some time before a ban was put into effect, heralded by restrictions and threats of a ban. Abstaining from any regulatory measures would have been counterproductive, as the companies would have had no incentive to intensify their search for environmentally compatible alternatives.

Models with Multiple Equilibria

The introduction of phosphate-free detergents cannot be understood using the model shown in Fig. 1. The original situation was characterized by a product (detergents using phosphates) for which an ecologically superior alternative did exist. The alternative, however, was more expensive as long as it was produced in smaller quantities.

Such situations depend on the fact that for many products the price per unit will drop when their production is increased. For this reason, it does not pay to introduce them as long as the market is dominated by another product. Likewise, if it only pays to introduce a product low in pollutants when the entire market tips, individual producers will avoid taking risks. For this reason, research and development neglects the search for such possibilities as long as the companies do not firmly believe in eventual and inevitable changes in the market.

Exactly such expectations were generated by the diverse international debates and measures surrounding the problem of phosphates in detergents. In other words, the companies did not count on being able to utilize an unlimited amount of phosphates in producing detergents over the long term. They then looked for a way to reach the expected level of production at optimum cost, a search which subsequently led to success. The costs of pollution control increased initially, but decreased to previous levels when the emission of a greater amount of the pollutant was prevented. These results are depicted in Fig. 2.

Innovation-oriented Environmental Policy

Is the case of phosphate-free detergents a rare exception based on some peculiarity of the applied technology? Probably not – although a firm answer requires more detailed investigations. There are many examples which could warrant such comparison: alternatives to batteries containing mercury, technologies for insulating houses, light weight vehicles for individual transportation, approaches towards reducing phosphate use in agriculture. The significance of such investigations can be found in the hypothesis according to which the economy shows several possible states of equilibrium, each representing a local optimum with regard to small changes. This type of situation is described by Arthur [3] as a "lock-in" phenomenon, which motivated him and his colleagues at the Santa Fe Institute to study the economy as a complex adaptive system.

These considerations are encouraging for shaping environmental policy, especially since the degrees of freedom for realization of sustainable development could be considerably larger than the single-equilibrium world allows. The internationally coordinated introduction of eco-taxes is not the only way; rather, it is just one of many measures that can bring us closer to the goal of sustainable development. The decisive incentives are not only those that effect a permanent increase in the price of products but also those that induce a serious search for novel products. These can cause the market to tilt in the direction of an ecologically more sound equilibrium. What has been found is not a cure-all for the diverse environmental problems of the present, but it offers a very promising approach towards solving them.

The introduction of phosphate-free detergents has not fixed all of our problems in water pollution control, but it does represent an example of a common learning process that included the public, the authorities and industry [4]. The introduction of phosphate-free detergents is a remarkable case study in the sense that the economy can sometimes reach a new equilibrium in which pollution is prevented without imposing significant costs. The challenge for environmental policy makers is to overcome the inertia of old economic structures that may hinder the search for ecologically viable innovations.

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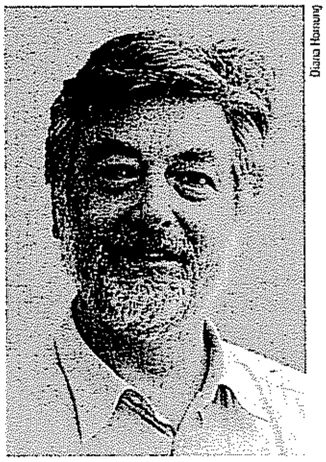
Alexander J.B. Zehnder

A Glance Across the Border



Alexander J.B. Zehnder

This article deals with two important aspects of phosphorus. The first is the development of phosphorus exports to the North Sea, the Mediterranean and the Black Sea via the rivers Rhine, Rhône, Ticino and Inn. The second is the role of phosphorus as a limited resource in sustainable development.

Export of Phosphorus

Switzerland, the "water tower" of Europe, drains into the North Sea via the Rhine, into the Mediterranean via the Rhône and Ticino, and into the Black Sea via the river Inn. In addition to water, these rivers export nutrients such as phosphorus and nitrogen. Export of phosphorus from Switzerland via these major rivers has fallen from 7200 tons total P in 1978 to roughly 3200 tons in 1995 (Fig. 1). Calculated on a per capita basis, annual amounts have dropped from 1.17 kg to 0.47 kg.

Switzerland has not been the only country to drastically reduce phosphorus export. The total P load in the river Rhine at Bimmen/Lobith near the border of The Netherlands has fallen from around 44'000 tons in 1978 to 14'000 tons in 1995 (Fig. 2). The annual per capita phosphorus input into the Rhine (The Netherlands excluded) was 1.11 kg P in 1978 and is at 0.32 kg P today. Switzerland's contribution to the total dropped during the same period from 1.2 kg P to 0.42 kg P. Over the last 20 years, the joint effort of all countries bordering the Rhine to reduce phosphorus concentrations in their streams has paid off and yielded very clear results.

Phosphorus export to the Mediterranean and Black Sea has also dropped, albeit to a smaller degree. The potential for reducing the phosphorus load released into the Rhône is significantly smaller, mostly because of the short distance between Lake Geneva and the Swiss border. The Ticino and the Inn flow through less populated areas than the Rhine, which also puts limits on potential load reductions. Switzerland's contribution to the total phosphorus load into the rivers Rhine, Rhône, Po and Danube ranges from 10% for the Rhône to 0.003% in the case of the Danube (Table 1).

It is interesting to compare area-specific phosphorus inputs on a surface area basis between the three oceans (North Sea, Mediterranean and Black Sea) and a few Swiss lakes (Table 2). Anthropogenic inputs are significantly higher for the lakes than for the oceans. It should be noted, however, that natural input exceeds anthropogenic input in the case of the North Sea. At least 70% of the P in the North Sea originates in the Atlantic. Relatively large volumes of water enter the North Sea between the British Isles and Scandi-

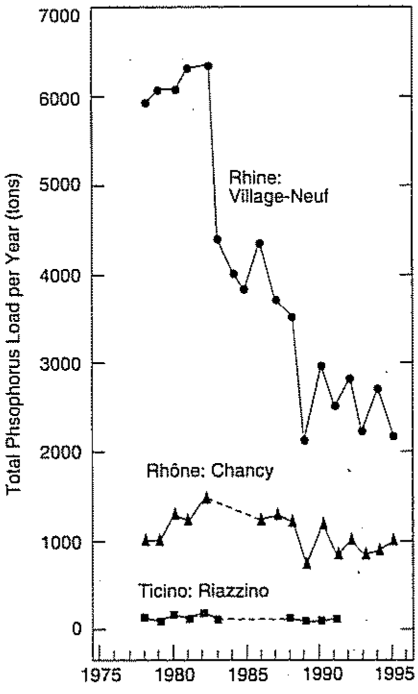


Fig. 1
Annual export of total phosphorus from Switzerland measured near Village-Neuf (Rhine), Chancy (Rhône), and Riazzino (Ticino).
Export via the River Inn near Martinsbruck is comparable to that of the Ticino and was omitted for the benefit of clarity of the graph.
Data from [1] and the NADUF program (1993–95).

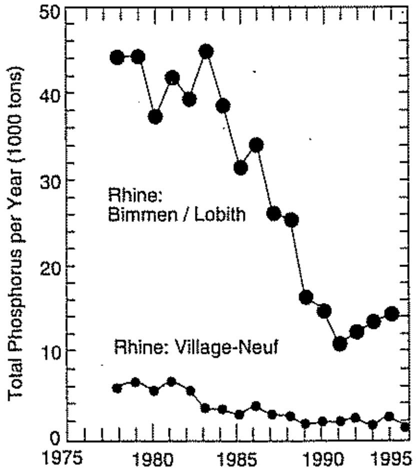


Fig. 2
Comparison of the total phosphorus load in the River Rhine near Village-Neuf (Swiss border) and Bimmen/Lobith (at the border between Germany and The Netherlands).
Data taken from compilations by the International Commission for the Protection of the River Rhine.

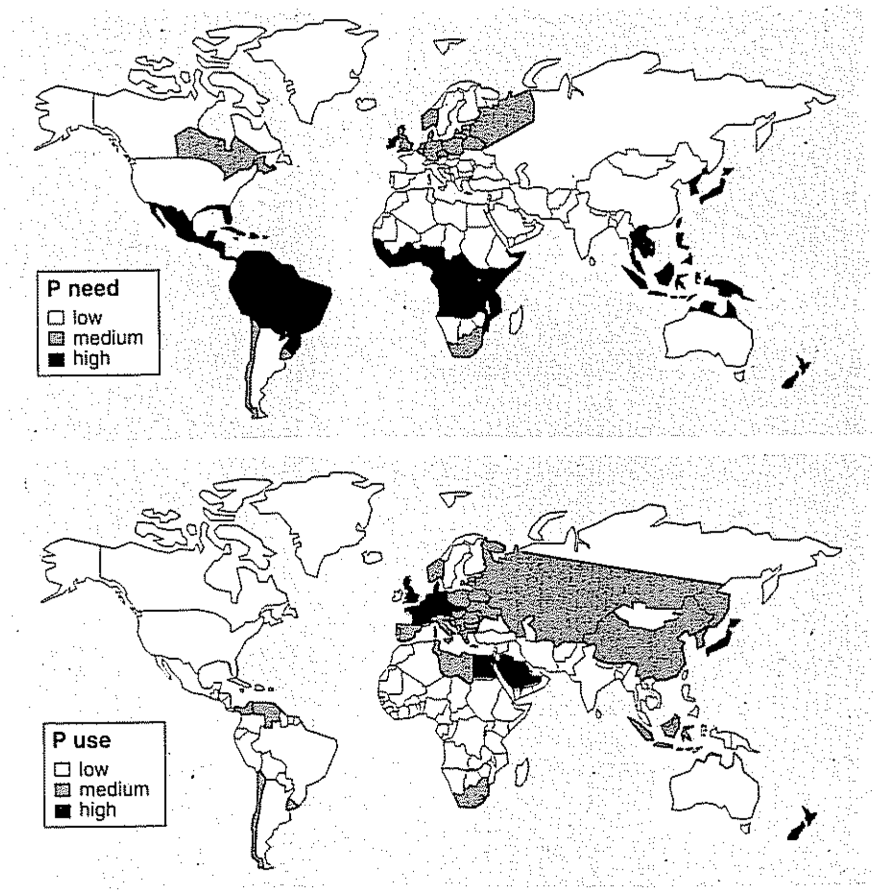


Fig. 3
Imbalance between phosphorus needs and phosphorus consumption (after [10]).
The upper map represents theoretical phosphorus needs, derived from climatic and soil conditions.
The bottom map indicates actual phosphorus consumption.

navia; a smaller amount reaches the North Sea via the English Channel. The average residence time of the water is, therefore, relatively short. It ranges from one month for surface water (e.g., the Skagerrak) to approximately four years for deeper water and for a few locations along the British Isles [8]. The high natural nutrient input to the North Sea has made it highly productive since pre-civilization times. Even today, 30–40% of the total European fish harvest originates in the North Sea [8].

The Mediterranean is naturally oligotrophic and continuously loses deep, nutrient-rich water to the Atlantic through the Straight of Gibraltar; however, parts of the Mediterranean can nevertheless become eutrophic due to nutrient input from rivers (e.g., the Adriatic Sea from the River Po).

In relation to its surface area, the Black Sea drains the largest watershed. Its characteristic stratification (it is permanently anoxic below 150–200 m) causes all of the nutrients to directly enter the productive surface layers. Most nutrients that reach deeper strata in the form of settling particulate matter are permanently removed from the productive surface layers.

Phosphorus as Limited Resource

On a global scale, there is an overall phosphorus deficit. This shortage is responsible for reduced food production, especially in developing countries. There are a few regions, however, where there is a phosphorus surplus which leads to eutrophication. We end up with the paradoxical situation of two fundamentally different areas of the world, one starved for phosphorus, the other "drowning" in it. This situation is not sustainable and requires implementation of different methods for nutrient management.

The boundary between P-rich and P-poor areas is practically identical to that between industrialized and developing countries (see Fig. 3). Over the last few centuries, agricultural production and, in parallel, industrial development has been concentrated in fertile areas. Over the period of several hundred years, intense agricultural use of the land has resulted in the accumu-

River	Year	Total Input into Ocean	Swiss Contribution	
		kt P/year	kt P/year	%
Rhine	1992[a]	25	2.2	9
Rhône	1990[b]	7	0.7	10
Po	1990[c]	11	0.06	0.005
Danube	1992[d]	33	0.1	0.003

a; b [E. Müller, personal communication]; c [2]; d [3]

Table 1
Total phosphorus load in major European rivers with contributions from Switzerland.

Ocean/Lake	Phosphorus Input in kg P/km²	
	«anthropogenic»	natural
North Sea[a]	100	232
Mediterranean[b]	92	31
Black Sea[c]	38	<10
Lake Sempach[d]	272	16
Lake Constance[e]	212	20

a [4]; b [2]; c [3], [5], d [6]; e [7]

Table 2
Area-specific phosphorus input. The sizes of the watersheds are: North Sea $4 \cdot 10^5$ km², Mediterranean $37 \cdot 10^5$ km², Black Sea $22 \cdot 10^5$ km², Lake Sempach 61 km², Lake Constance $1.1 \cdot 10^3$ km².

lation of excess P. Phosphorus concentrations in these soils are now higher than required for crop production [9].

Some countries, however, still must import P for agricultural production on a scale that allows food export. In extreme cases, as for example in New Zealand, the cost of P imports is comparable to expenditures for oil, which are only slightly higher [10].

Many of the developing countries which will significantly contribute to global population growth over the next several decades are located in tropical regions dominated by rain forests. Population growth and food shortages force the local population to cut down parts of the rain forest. The bulk of the available phosphorus in a rain forest is tied up in the vegetation itself [11]. Fire clearing releases a large portion of the P into the soil in its inorganic form. Exposed soils rapidly lose nutrients (e.g., potassium, nitrogen, sulfur) due to erosion. The degradation of soil quality is exacerbated by increased weathering rates. As a consequence, calcium and magnesium are released and leached from the soil. The result is acidic soil (pH <4.5), where dissolved iron, aluminum and manganese can accumulate and reach toxic levels. Residual phosphate is stripped from the soil by free iron and aluminum as well as their abundant oxides. In a complex process, P is immobilized in mineral forms that can no longer be used by plants, making it a limiting nutrient in many cases [12, 13]. Typically, rain forest soils become nearly infertile four years after deforestation and transform into steppe.

With controlled phosphate fertilization and appropriate measures against erosion, the steppe can be returned to fertile soil, which dramatically reduces the need for more deforestation. International assistance in the acquisition of fertilizers to countries in tropical zones would have several positive consequences. Agricultural yields would increase and the economic status of farmers would improve, allowing them to purchase fertilizer with their own profits. Long-term fertility of the soil would also protect rain forests from destruction.

Location/Formation	Amount in Giga-tons	Rock
Phosphorus Deposits, Western USA [a]	100	sedimentary
Oulab-Abdoun, Morocco	50	sedimentary
Spanish Sahara [b]	25	sedimentary
North Carolina	10	sedimentary
Tunisia	6	sedimentary
Australia [c]	3	sedimentary
Algeria	3	sedimentary
Bone Valley, Florida, USA	2	secondary-sedimentary [d]
Kola Peninsula, Russia	1.5	volcanic
Vyata-Kama, Russia	1.5	sedimentary
Kara-Tau, South Kasachstan, Russia	1.5	sedimentary

a) currently not economical to mine b) now under Morocco's control; c) newly discovered (1966); d) formed by weathering of P-rich limestone

Table 3
The most important phosphorus deposits of the world (according to [14]).

Conclusions

Phosphorus deposits have a limited lifetime; therefore, P is not a renewable resource (Table 3). The P excess in developed countries, the non-renewable nature of traditional phosphorus sources and the shortage of phosphorus in tropical areas coupled with rapid population growth alone are sufficient justifications for the phosphate ban that was enacted in 1986. Realizing the interdependencies between the different types of phosphorus problems, we should become serious about reducing the phosphorus excess originating from agriculture.

Appreciation
I would like to thank Gabriele Friedli, Rudolf Koblet, Edwin Müller, Peter Waldner and Bernhard Wehrli for supplying data for this article.

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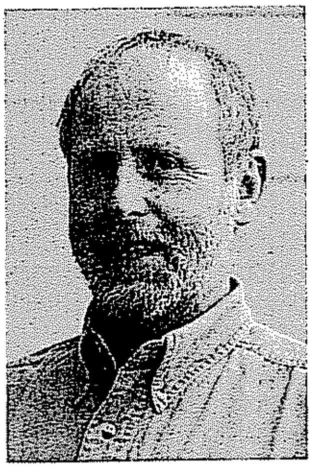
Ueli Bundi

Conclusions:

Phosphorus Leads the Way



Diana Hornung

Ueli Bundi

There are no wonder drugs or patented solutions when it comes to reducing phosphorus loads. It takes a concerted effort to tackle problems in the various source areas. In the 1970s, exactly such an approach was taken. It was probably the first time that Switzerland has successfully employed a far-reaching strategy in solving a complex environmental problem producing a critical knowledge base for the future development of environmental protection.

Thanks to an expansion in wastewater treatment and the elimination of phosphates in detergents, phosphorus loads to lakes in Switzerland have been drastically reduced. Despite such progress, several Swiss lakes, especially those in watersheds supporting intensive agriculture, still receive too much phosphorus. In addition, the export of phosphorus from Switzerland to the oceans surrounding Europe via the major river systems continues. Measures to reduce phosphorus release into surface waters need further development.

While the focus of this effort will be on agricultural sources, improvements in wastewater treatment will also be needed. In the long term, urban water management must adopt a fundamentally new way of thinking and implement entirely new, environmentally sound systems.

Agriculture

Great hope has arisen from the new orientation of the national agricultural policy. This fundamental changes will be brought about by a broad palette of economic incentives, regulations, and research, education and consulting. A recent innovation has been cash reimbursements that are directly linked to ecological achievements. According to a recent study [1], this new approach to the problem could yield a 38% reduction of nitrogen input into surface waters by agriculture by the year 2002. Over a longer period of time, a similar result may be expected for phosphorus. But in order for these reductions to become reality, it is important that agrarian reform be consistently implemented. Ecological requirements and criteria must be driving forces. The changes also make sense economically: The general cost to society will gradually decrease. Annual costs of agriculture have been projected to be reduced by 340–680 million Swiss francs by the year 2002 [1].

Offer Incentives

In order to achieve progress in environmental protection, a number of different tools have to be used. The approach taken in the case of phosphorus is a good example. Regulations mandating removal efficiencies in wastewater treatment plants and the ban on phosphates in detergents came into play as well as economic incentives for wastewater treatment (subsidies). Public research and development also played an important role. It produced mathematical models for the simulation of processes in lakes and new process technology for the removal of phosphorus in wastewater. Several cantons developed strategies for the restoration of their lakes. This, in turn, fostered new strategies for improved environmental measures, for better integration of different measures and for the improvement of cooperation between the private and public sectors, both at the cantonal and community levels.

Ecological and Agricultural Gain

The methods used to bring about a reduction in phosphorus loads have done more:they have sparked innovations which have far exceeded the original purpose. The gradual improvement in the environmental compatibility of detergents, new concepts in optimizing sewer systems based on both economic and ecological criteria, and enhancements in the implementation of water protection regulations are only a few examples. In the future, even more tools can and should be employed to further improve environmental management: financial incentives for ecological performance by farmers, taxes on fertilizers, fixed allotments on environmentally dangerous chemicals and emission quota that can be traded between different entities (companies, factories, communities). The challenge is to determine which tools will be appropriate and effective and to gain their acceptance in the political arena. In succeeding to do so, we will not only gain from an ecological perspective, but from a technical and economic one as well.

Local and Global Benefits

Beneficiaries of reduced phosphorus loads include our own streams and lakes, as well as the North Sea and the Mediterranean. In addition, there are other good reasons for cutting the use of phosphorus. Its worldwide availability is limited and would be put to better use in maintaining soil fertility in the tropics. This exemplifies once more that environmental protection on the local and international scales does not have to be in conflict. In fact, local environmental protection always brings with it benefits on a larger scale as well, provided that the original concept dealt with the problem in a comprehensive way. This means that problems have to be consistently attacked at the source and in an interdisciplinary manner. Strategies must be based on cost/benefit analyses and use environmentally sound technologies. This will also lead to a gradual reduction in (or possibly total elimination of) the export of environmentally damaging emissions (e.g., due to high energy consumption).

Despite significant progress, at least in the case of phosphorus, we are still a long way away from implementing concepts that would allow such dramatic improvements. Phosphorus is still being wasted. In the area of wastewater treatment, large turnovers in terms of finances, materials and energy are needed. Real progress is dependent on fundamental changes in both water supply and sewer systems, in agricultural practices and in consumer behavior. Problems around phosphorus clearly demonstrate the linkage between environmental protection, technology and the development of society.

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Ten years of artificial lake aeration – a review

In February 1982, the artificial aeration of Lake Baldegg was begun. Using the specifically designed aeration device TANYTARSUS, 4.5 tons of pure oxygen was released daily into the deepest reaches of the hypolimnion. This led to the reoxygenation of the deep water/hypolimnion down to the lake bottom during the course of the following summer, following many decades of anoxic conditions. This aeration procedure had two objectives:

- Higher phosphorus retention in the lake sediment resulting from improved oxygen conditions;
- Expansion of the habitat for fish and other organisms dependant on oxygen.

These same results were anticipated when similar aeration equipment was set up in the Cantons of Lucerne (LU) and Aargau (AG), in Lake Sempach in 1984 and in Lake Hallwil in 1985. All three aeration devices have been operating on the same principle since installation: artificial mixing of the lake water using bubble plumes in winter (in order to improve the natural uptake of oxygen from the atmosphere) and enrichment of deep water with pure oxygen in summer.

The reactions of the lakes and their ecosystems to such measures have been intensively monitored by EAWAG in collaboration with the Cantons of AG and LU, and now after about ten years, the time has come to present the most important results of this unique endeavor. Viable options should be considered for the future operation of the aeration installations, as well as for other necessary restoration measures. The results are summarized below:

Oxygen

As a consequence of the input of pure oxygen (summer) and the artificial mixing (winter), oxic conditions could be maintained in the entire waterbody of the three lakes of the Swiss Plateau throughout the year.

Plankton

The expansion of the oxygen-containing habitat reduces the zooplankton's grazing pressure on the algae. Consequently, the same amount of algal biomass can be maintained at a lower nutrient level. The aeration measures caused only slight changes in the species composition of the algae and the zooplankton.

Benthic organisms

Worms *(Oligochaetes)* and insect larvae *(Chironomids)* have responded most strongly to lake aeration. These organisms, comprising the basic nutrition of many fish, have moved back into the deep water zone as a consequence of the aerated conditions, remaining there to date. For this reason 20% more detritic algal material is being decomposed in the sediment since artificial aeration was initiated.

Phosphorus retention in the sediment

The permanent deposition of phosphorus in the sediment has not improved significantly as a consequence of artificial aeration (Fig. 1). Thus, one of the two main objectives of the aeration has not been met, i.e., to increase the longterm retention of phosphorus in the lake sediment and thereby reduce the phosphorus concentration in the lakewater. Oxygen is being consumed too rapidly at the surface of the sediment, and thus it cannot diffuse to sufficient depth into the sediment. For this reason sedimented phosphorus remains in an oxygen-free environment.

Fish

As a consequence of both higher nutrient content and the stocking of fish from hatcheries, the catch has increased compared to the prevailing near-natural conditions of the last century. This is particularly true for the whitefish. Artificial aeration has extended the oxygenated habitat down into the cool deep water zone. However, aeration has not improved fishing yield any further. However, aeration has not increased fishing yield any further. Aeration seems to have no significant effect on the composition of the fish populations and their reproductive capacities. The whitefish, for example, can still survive by the means of fish stocking only, as their eggs die off at the surface of the oxygen-consuming sediment. On the other hand, perch, cyprinid fish and pike are not endangered by high nutrient concentrations due to their different reproductive strategies. Artificial aeration also has no influence on the massive die-offs of whitefish fry in spring due to oxygen supersaturation leading to gas bubble syndrome.

In summary, artificial aeration can be judged as only partly successful: Expectations were met with respect to improved oxygen conditions. The expected effect on the retention of phosphorus in the sediment has, however, not occured.

The report "Ten years of artificial lake aeration: results and options" has appeared in German as Number 9 of the "Schriftenreihe der EAWAG" in August 1996 (ISBN: 3-906484-14-9). It can be obtained from Public Relations, EAWAG, 8600 Dübendorf.

Future developments

The ultimate goal of lake restoration measures is the achievement of near-natural conditions. This corresponds to a state similar to that of pre-industrial times, a state where the typical local species (algae, macroinvertebrates, fish, etc.) and biota are able to reproduce and interact naturally. A sensible quality standard for perialpine lakes in Switzerland corresponds to the nutrient input for average algal growth (i.e., about 150 g C m^{-2} per year). In such lakes biological diversity is highest, the whitefish populations can maintain themselves, and there are no significant problems in utilizing the lakewater for urban water supply.

Available finances should be utilized according to priorities in the frame of a comprehensive water protection strategy, taking into account profits and expenses. As the reduction of the phosphorus content obviously can only be achieved through the reduction of its input into the lake, the most urgent measures must be undertaken in the lakes' drainage areas. Decreasing the phosphorus in runoff from agricultural land has the highest priority, as phosphorus input from domestic sewage has been drastically reduced during the past 15 years. The present high phosphorus removal standards in sewage treatment plants should be maintained.

The artificial aeration of lakes cannot become permanent in the lakes of the Swiss Plateau. The future strategy of lake restoration – as was also originally planned – has to lead away from artificial aeration as soon as possible. In order to meet the restoration objectives, the input of phosphorus into the lakes has to be reduced by at least a third (Lake Baldegg) to a half (Lakes of Sempach and Hallwil).

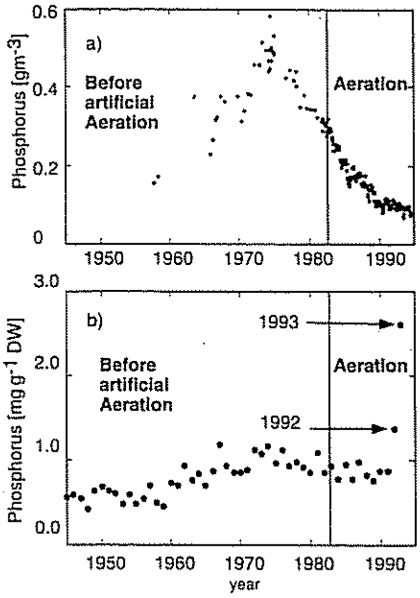
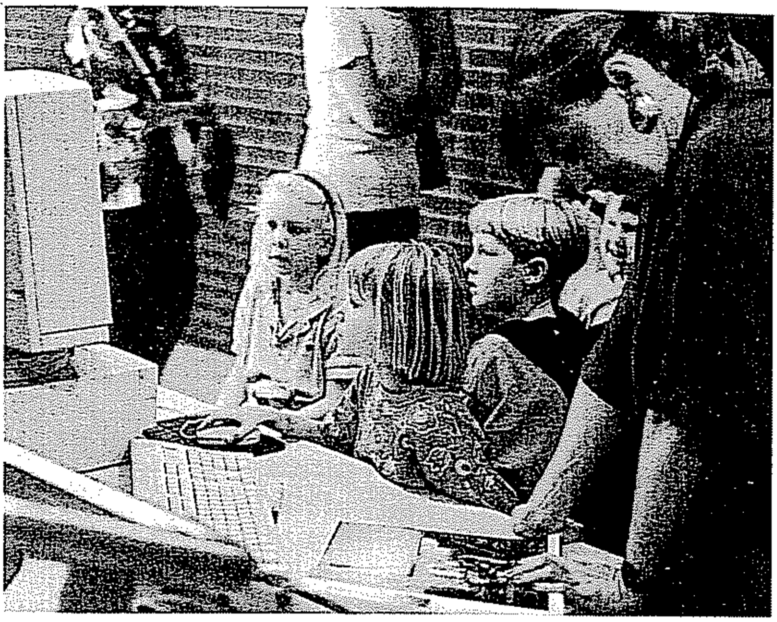


Fig. 1
a) Temporal course of the average concentration of dissolved phosphorus in Lake Baldegg: P content has decreased continuously since mid 1970's by a factor of about 6. In order to reach the level of the restoration goal, a further reduction by at least a factor of 3 is necessary.
b) Temporal course of phosphorus content in single annual layers of a sediment core sample from the middle of Lake Baldegg. No improvement in phosphorus retention in the sediment has been observed since artificial aeration. The high concentrations at the surface of the core (1992/93) indicate algal material which has not yet been decomposed. (DW = dry weight)

In the meantime, the oxygen content in lacustrine habitats can be maintained by means of artificial aeration. This is particularly the case in Lakes Hallwil and Baldegg, where an immediate cessation of the oxygen input would lead to a rapid dying of organisms on the lake bottom.

The input of pure oxygen in summer in Lake Sempach, however, can be ceased. Artificial mixing during winter guarantees a sufficiently thick buffer zone containing oxygen in the upper layers of the hypolimnion.

Alfred Wüest and Bernhard Wehrli, in collaboration with H. Bührer, U. Bundi, H.R. Bürgi, R. Gächter, D.M. Imboden, R. Müller and F. Stössel



EAWAG

Over 3000 visitors of all ages found their way to Dübendorf last spring for the EAWAG 60th Anniversary Open House.

Open House 1996 at Dubendorf

Last year, EAWAG celebrated its 60th anniversary. In order to present its accomplishments, EAWAG invited the public to its Open House on 31 May and 1 June, 1996.

Translating Research into Hands-On Experiences

It is a considerable challenge to present the multifaceted relationship connection between water and the environment in an engaging manner. With a lot of talent and effort, EAWAG personnel at all levels demonstrated to an interested public, how even seemingly harmless activities at home, at work or in recreational areas leave their traces, dig their holes or build up their piles. After long detours and often unexpectedly we are confronted with water we previously discarded. Using small tours which concentrated on single themes, the researchers tried to present the often complex systems and processes in a way that the general public could can understand, involving hands-on experiences and real-time play and experimentation wherever possible. "All of a sudden we saw the connection between seemingly meaningless knowledge in chemistry and biology, which we 'had to cram into our heads', and the practical applications of this knowledge", one visitor class commented in a letter after the Open House.

Four "theme-tours" highlighted activities at EAWAG: Drinking water and waste water, environmental archives, water as a habitat, and surviving on limited resources.

Open House 1997 at Kastanienbaum

On June 13 and 14, 1997, the Research Center for Limnology in Kastanienbaum (near Lucerne) held an Open House. About 2500 interested persons of all ages stopped by. Three exhibits revealed the secret life of lakes, showed what a precious resource our drinking water is, and show-cased the inhabitants of streams and ground waters.

Theresa Büsser

KOL-Workshop 1996

On 13–14 May 1996, the SANW Commission on Oceanography and Limnology (KOL) held its annual meeting at the EAWAG Research Center in Kastanienbaum/LU. This year's topic was: "Environment and Climate: Interactions between Continental and Marine Systems". Fifty two experts discussed how marine research can be linked to continental environment and climate programs (and vice versa), in what ways it can be made relevant for decision-makers and the socio-economic impacts of the work. Keynote speakers introduced individual problem areas which were later discussed extensively in the plenary sessions:

- *Atmospheric Transfer:* Judith McKenzie, ETH-Zürich
- *Surface Water Transfer:* Wilfried Häberli, University of Zürich
- *Archives:* Svante Björck, University of Copenhagen
- *Dissemination of Scientific Results and Society:* P. Schilliger, Lucerne, R. Volz, BUWAL-Bern.
- *Education of Environmental Scientists:* Dieter Imboden, EAWAG

The meeting was organized jointly by KOL, EAWAG, the Swiss Geological Commission and ProClim.

Michael Sturm

Rudolf Koblet

PEAK – Continuing Education – We Cannot Do Without It

The program for the PEAK courses (practice-oriented courses at EAWAG) can be accessed on the EAWAG internet homepage (http://www.eawag.ch) or ordered as a brochure from:

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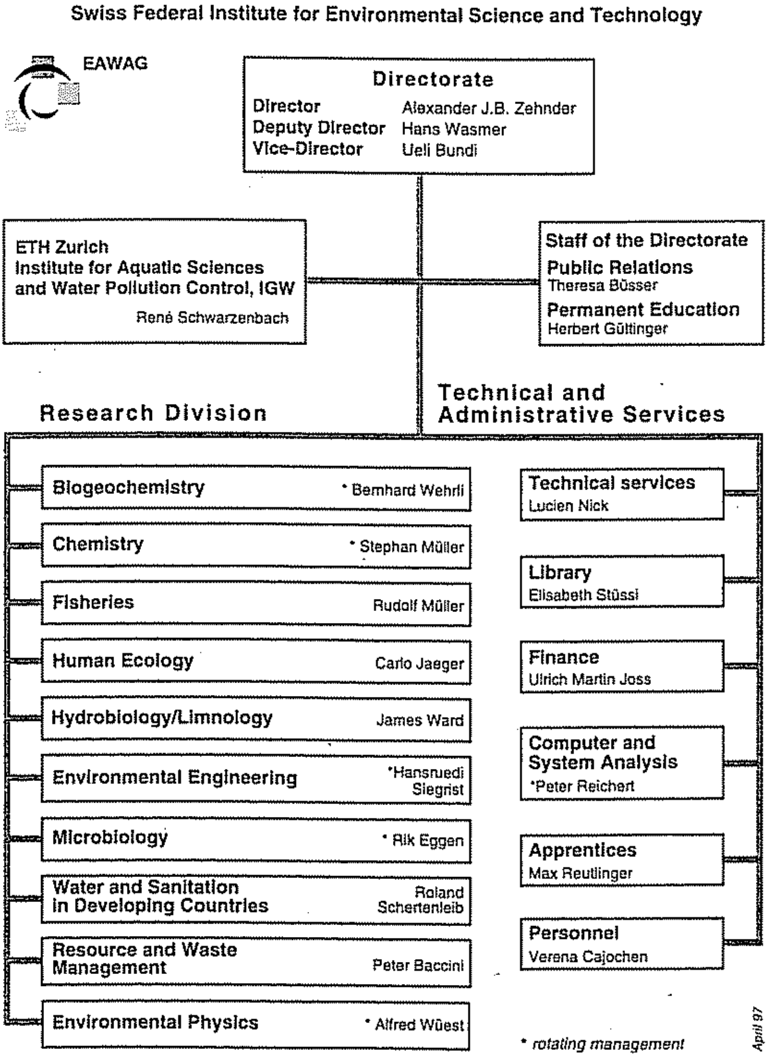
Course topics include modeling of natural systems, sanitation of human waste and wastewater in developing countries, characterization of aquatic habitats, regional sustainability, in situ measurements in streams and lakes, sizing of secondary settling basins, elimination of dissolved solids in drinking water and resource management in construction.

Prof. Bernhard Wehrli at Information Day 1996.



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