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Dear Reader

In 1992 our annual conference, "From Research to Practice", dealt with the ecological dynamics of lake restoration. During the past ten years the results of water protection measures in Switzerland have become apparent. Due to phosphate removal in wastewater treatment and the ban on phosphate in detergents, the phosphorus concentrations in lakes have shown a steady decrease. Although several lakes are in good condition now, many are still heavily polluted. The polluted lakes are mostly those that receive considerable amounts of surface runoff from agricultural land. Some of them are artificially aerated to allow higher animals to live in the entire water column throughout the year, and to speed-up the mineralization of algal material. As artificial aeration combats the symptoms but not the causes of eutrophication, it can only be a transitional measure. Future efforts have to be directed towards the reduction of the input of phosphorus into these lakes, in particular from grassland and arable land. In this issue, the responses of physical, chemical, and biological parameters of lakes to pollution, protection and restoration measures are critically evaluated. We hope that the articles on the following pages will attract your attention and contain useful information for you.

Such conferences require much preparatory work. Many have helped to make it a success. Maja Lukac and Ueli Bundi, in particular, did a marvellous job in preparing and directing the conference.

Enjoy the reading. May this issue make you feel like sitting in a fresh lake breeze!

Alexander J.B. Zehnder

## Restoration and Ecology of Lakes: Evolution and Development

### Contents

<b>The lake as an ecosystem</b> <i>Heinz Ambühl and Heinrich Bührer</i>	2
<b>The distribution of substances in lakes: interactions between physical and chemical processes</b> <i>Dieter M. Imboden, Laura Sigg and René P. Schwarzenbach</i>	7
<b>Plankton and its trophic structure as a function of the trophic level of the lake</b> <i>Hans Rudolf Bürgi</i>	12
<b>Biochemical processes at the sediment surface</b> <i>Bernhard Wehrli, Andrea Ventling and Rudolf Müller</i>	17
<b>The benthic fauna push into the lower depths in Lake Hallwil</b> <i>Fred Stössel</i>	21
<b>Effects of artificial aeration on trophic status and hypolimnetic oxygen concentration in lakes</b> <i>René Gächter and Alfred Wüest</i>	25
<b>Estimate of P-inputs to the Lake of Sempach from diffuse sources, and measures for their reduction</b> <i>Peter Hurni, Markus Braun and Felix Schärer</i>	31
<b>Reflection in the Lake of Sempach</b> <i>Markus Braun</i>	35
<b>Concluding remarks</b> <i>Alexander J. B. Zehnder</i>	37
<b>News about EAWAG and its employees</b>	39
<b>EAWAG-Publications</b>	41

# The lake as an ecosystem

## Heinz Ambühl and Heinrich Bührer

### 1. How does a lake function?

The structure of the water body in all lakes is determined primarily by the weather. From late winter to spring, it loses the heat remaining in it from the previous year to its environment; the water is cold and is churned up by winter storms. If sufficient energy of motion is supplied by these storms, the lake water undergoes mixing (down to the lake bottom, Fig. 1, or only part-way in the case of deeper lakes). The water comes into contact with the atmosphere over a large surface area, raising the dissolved oxygen concentration up to the surface saturation value and allowing volatile substances to escape. With the increase in incident solar radiation in late spring, the upper water layer warms up, thereby decreasing in density and forming a cover over the colder, deeper water, preventing further downward mixing. The lake has now altered from winter "turnover" to summer "stagnation". From this point on, only inflows and currents generated by strong winds bring motion into the deeper parts of the water body; forces due to winds and earth rotation induce weak motion in the surface water layer. The stereotype of turnover as strong, large-scale mixing is just as incorrect as the idea that the waters of a lake during "stagnation" undergo no motion: in fact, winds, waves and convection currents keep the water in a state of continual agitation.

### 2. The lake as a biological environment

We look now at the pelagic or free-water zone, and here initially at the upper layer, the epilimnion. This is populated with plankton. The plants (algae) and animals which form this community are constructed simply, but morphologically, physiologically and ethologically are highly adapted to their environment and to their continually floating or swimming mode of exist-

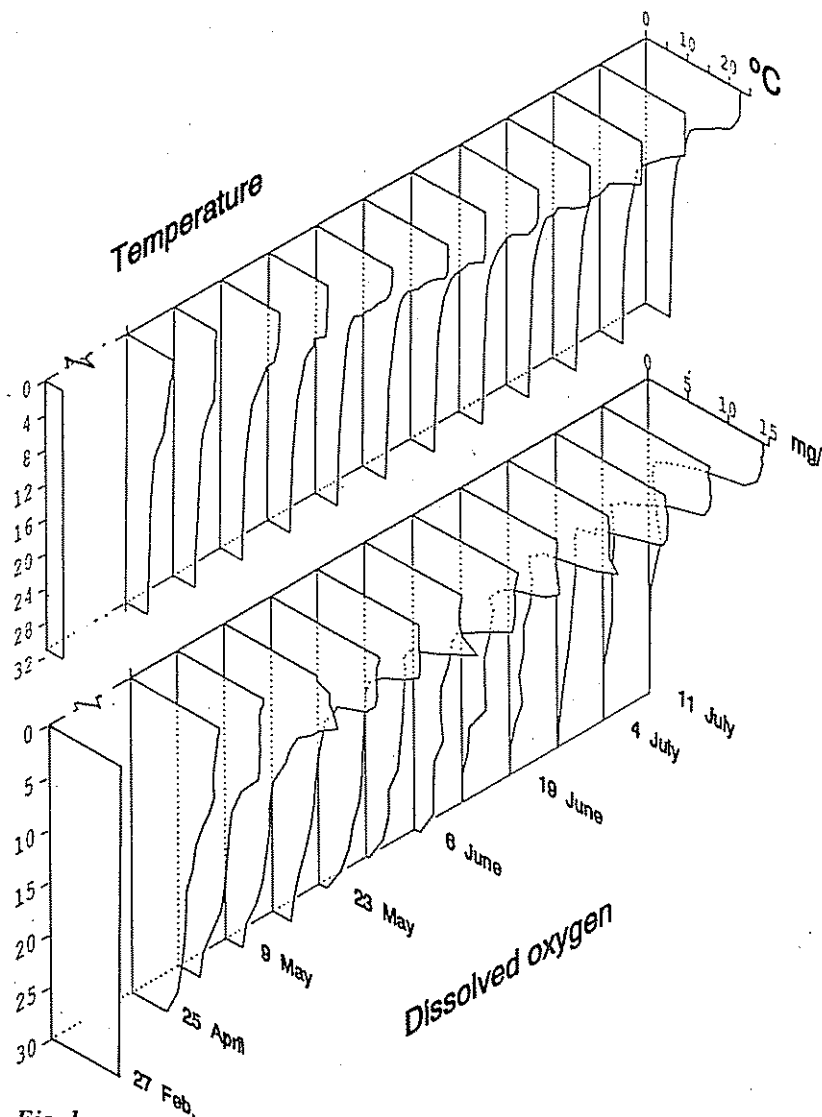


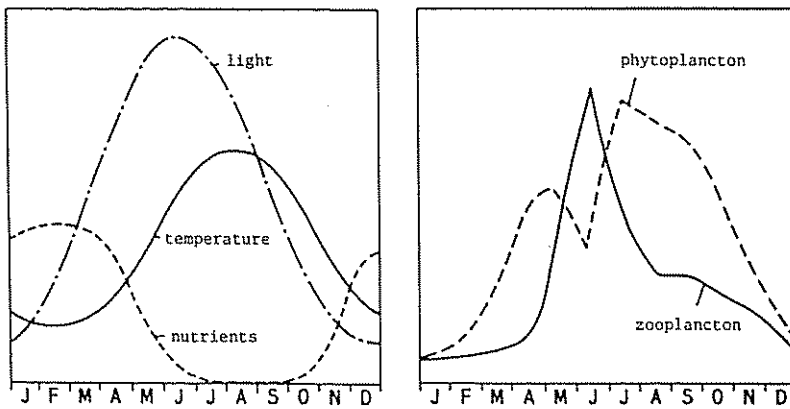
Fig. 1  
Temperature (above) and oxygen concentration in Greifensee in 1989. This series of measurements, which were sampled very frequently as part of a practical course, was broken off in July.

ence. Taken together, the plankton form a typical (classical) ecological community, which, because of its simple structure, can be regarded as a model for other communities. Thanks to the shortness of the life cycles involved, an overview of the biological and (syn)ecological functions (grazing, growth, reproduction, being grazed upon) can be obtained within the space of a few months or even weeks.

Twenty or even ten years ago, the lakes of Switzerland were, in general, overloaded with phosphate. Today the phosphorus content is decreasing, and has attained minimum values in some

lakes, whereas in others, it is still on the decrease. In order to be able to determine how far this development must proceed to bring the lake up to a given intended ecological standard, we must first understand how lakes function. In a eutrophic (nutrient-rich) lake, essentially the same processes occur as in an oligotrophic (nutrient-poor) lake, however with different weightings and different distributions of nutrients and processes within the water body. An important group of processes is missing to a large extent in oligotrophic lakes: putrefaction processes.

How does this varied system, in-

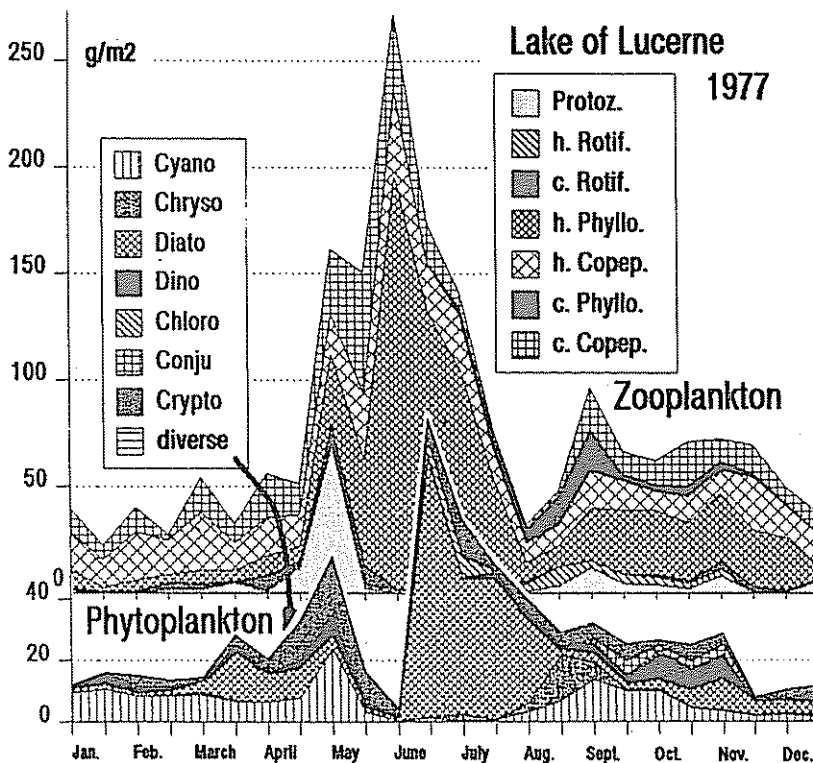


**Fig. 2**  
Seasonal variations of factors important for plankton (left) and a schematic diagram of plankton development with time (right).

habited by plants and animals, function? The upper few metres of lake water form a bioreactor; this is where the active plankton live. Only here is phytoplankton photosynthesis possible, for only here is there sufficient light (the infra-red component of which is, of course, responsible for building up the thermal stratification). New algal production, either living or in the form of detritus, sinks to the lake bottom; part is consumed (i.e. enters the

food chain) and is sedimented out in the form of faecal pellets. Different physico-chemical phenomena manifest themselves here: e.g. the adsorption and desorption of dissolved substances on to and from particles on their way to the sediment at various temperature-dependent exchange rates. The production of new biomass in oligotrophic lakes is so low that the subsequent aerobic degradation of this new biomass does not lead to a lack of

oxygen. In eutrophic lakes there are more algae, and consequently more zooplankton and more fish (even if not always exactly the species which one would like to have) than in oligotrophic lakes. Less tolerant species are replaced by more tolerant species: not the least important reason for this is the interruption of their reproductive cycle. In the deep water, oxygen is depleted; aerobic degradation is replaced by anaerobic decay, possibly accompanied by sulphate reduction and the production of  $H_2S$ . The sediment becomes black. However, assuming winter circulation to occur, this condition is limited to the period between May ( $H_2S$  appears somewhat later) to November. With the onset of autumnal cooling, the water body gradually begins to turn over. Circulation again brings oxygen into the depths, but also brings nutrients up to the surface along with the upwelling deep water. These nutrients form the "starting capital" for the beginning new spring production (Fig. 2). This carries on until April; afterwards, production is supported by an external nutrient supply or by nutrient recycling. Because the algae also require light, their development does not occur in winter, but must wait until spring. A good source of food has now been built up for exploitation by those animals (zooplankters) which graze on algae. Since zooplankton development requires higher temperatures, however, their development lags that of the phytoplankton. In May, approximately, when water temperatures are higher and thus more favourable, the zooplankton is able to undergo explosive development (Fig. 3) and finds, as it were, a table groaning with food awaiting it. A high rate of reproduction with a rapid generation turnover is attained by asexual "virgin birth" (parthenogenesis), similar to the form of reproduction employed by aphids in the garden. As a result, the nutritional demand of the zooplankton increases, overtaking the supply; the algae, i.e. the "grazing meadow" of the zooplankton, are filtered out by the zooplankton and the loss due to grazing is not able to be replaced; the turbidity of the water caused by the algae disappears and the water becomes clear (the clear-water phase in Greifensee was especially noticeable and long-lasting in



**Fig. 3**  
Growth of zooplankton (above) and phytoplankton (below) in Vierwaldstättersee (Lake Lucerne) in 1977. The mutual influences of zooplankton and phytoplankton which give rise to the "grazing gap" and to zooplankton collapse are obvious. Illustration by H. R. Bürgi.

1992). The sum total of the substance content of the lake water does not change during this process, but the form in which the substances occur certainly does.

The algal biomass recuperates rapidly, but its species composition changes: now those algae which the zooplankters were not able to graze on earlier because of their size or unwieldy shape can develop. Despite the presence of a higher (but less edible) algal biomass, the zooplankton go hungry and just tick over from now on (Fig. 3). Under these conditions, some zooplankters develop resistant forms which do not undergo growth for several months. The occurrence of further, usually less intense, clear-water phases is possible. These are triggered off by the occurrence of specific sets of conditions and cannot be predicted.

### 3. Plankton growth and limitation

In our lakes, phosphate is a key factor governing biological production. Phosphate is often understood to be an unpleasant or even damaging substance. However, alone of all the nutrients, it was phosphate which, as a result of its naturally low concentration, was responsible for the limitation of algal growth. It did not obtain its bad reputation until it began to enter lakes in large amounts (unintentionally, in wastewater) and consequently lost its limiting function. Because the production of biomass requires relatively little phosphorus (about 1/100 to 1/200 of the total biomass weight), it takes very little phosphorus to remove the limitation and restart growth. The only way of regaining control over the production (or of reinstating the limiting function) is by cutting back the external phosphate input and interrupting the internal lake cycles. Experience has confirmed that the introduction of various technical measures, especially very highly developed wastewater treatment plants, to accomplish this was correct. Their effect manifested itself not only in a reversal of the trend, but also in a marked improvement or reversal of the phosphate content of the lakes (Fig. 4). Conditions today are similar to those pertaining in the 1960s (a result which can only be dreamt of

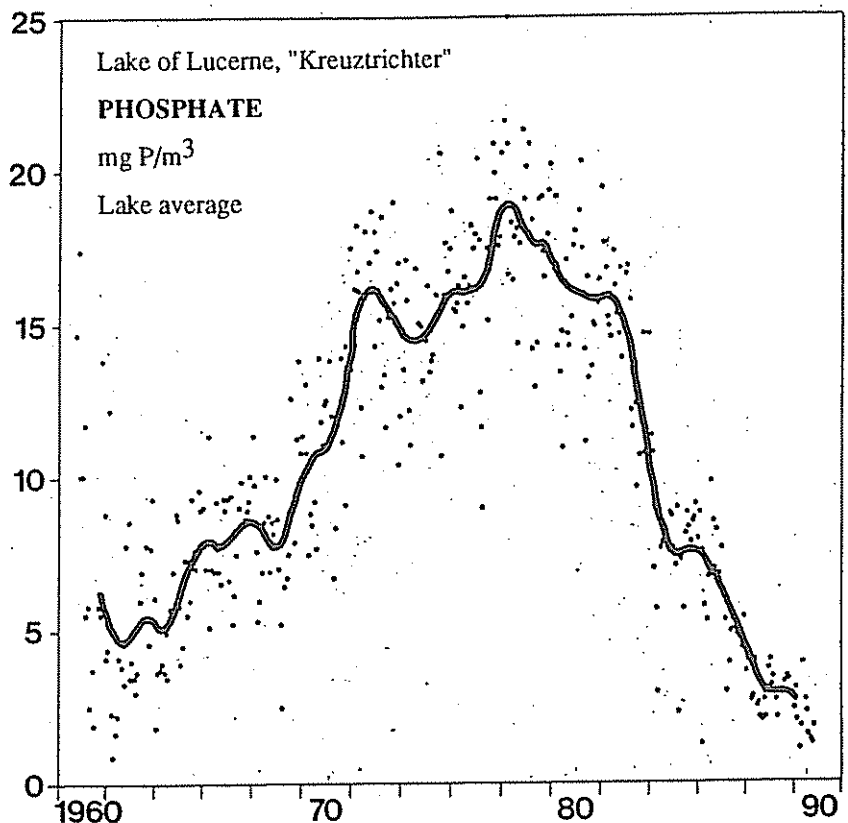


Fig. 4  
The mean phosphorus concentration at the Kreuztrichter station in Vierwaldstättersee (Lake Lucerne). The solid line represents a 12-month running mean. The scatter of the points is the result of biological, not random statistical, effects. Illustration by H. Bühner.

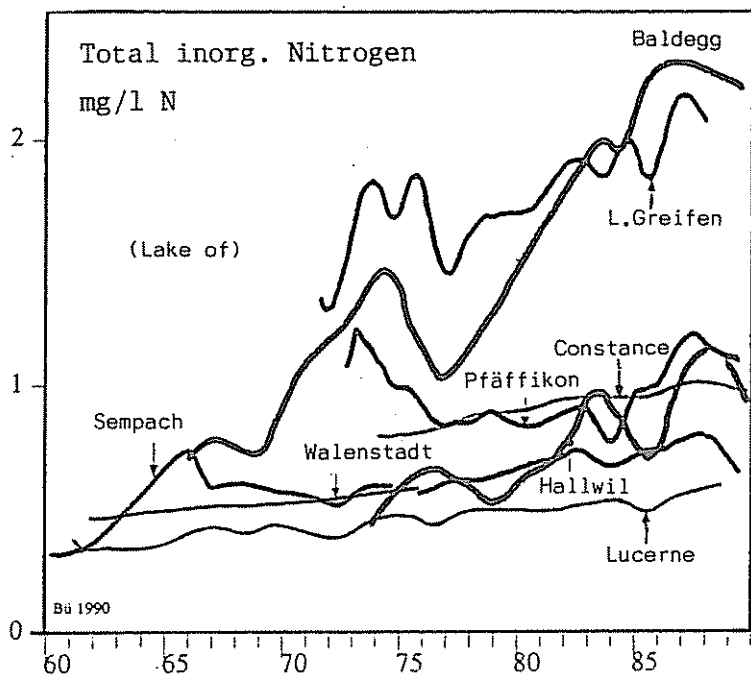
with respect to the air pollution problem). The trends are continuing, success seems to be assured. Looking at the pelagic zone, individual lakes (Vierwaldstättersee, Walensee) can today be considered restored. But even some other lakes which have come not quite so far along the road to restoration are at least out of the danger zone. At all events, phosphate is still the most influential limiting nutrient today, but also the easiest to deal with technically.

To take the discussion of the cycle of substances in a lake to its end, dead or still living organic material sinks down into the depths, undergoes further degradation and transformation, and finally becomes sediment. At this point, the nutrients are partly stored in the permanent sediment and partly find their way, as a result of degradation processes, back into aqueous solution and are returned to the nutrient-hungry epilimnion by the mixing processes occurring during winter. The processes occurring on and in the sediment have long been the subject of research.

### 4. The changing N:P ratio - a danger?

What would have happened if we had not fought to reduce lake phosphorus input? The development of the nitrogen concentration (Fig. 5) gives an indication of what might have been the case. The use of agricultural fertilizers (mainly) has led to an increase in the incidence of nitrogen compounds not only in groundwater, where the effects are especially drastic, but also, if less prominently, in surface waters.

The contrasting development of the two main nutrients (P falling, N rising) is made especially clear by looking at the quotient N:P. This is rising rapidly. Whether this will have serious biological consequences or not is at the moment unknown. However, it has been ascertained that the blue-green algae (cyanobacteria) have lost their natural selective advantage over other algae as a result of the shift between nutrients: blue-green algae are (or were) the only aquatic organisms able to satisfy their nitrogen requirements



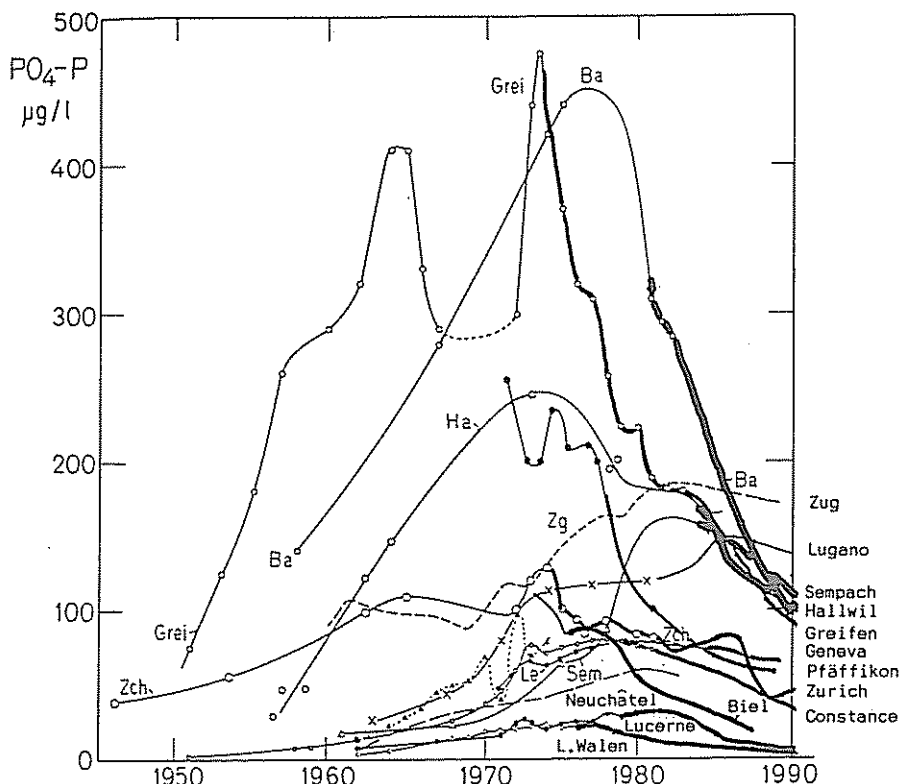
**Fig. 5**  
The evolution of inorganic nitrogen from 1960-89 in several Swiss lakes (from H. Bühner 1990).

from the inexhaustible pool of dissolved molecular nitrogen in the lake water (about 15 to 20 mg/l  $N_2$ ) using the same nitrogenase reaction (nitrogen fixation) employed by leguminous plants. Today there can scarcely be said to be a lack of nitrogen compounds in lakes, and the blooms of blue-green algae of which we have unpleasant memories from the 1950s and 1960s hardly occur at all today in the larger lakes.

### 5. Some remarks on the technology of lake restoration

Although the simple relationship "oxygen fixes phosphate, lack of oxygen results in phosphate release" is qualitatively more or less correct, we have learned (although it has actually been known for a long time) that, when a lake is treated with oxygen (using any technical means whatever), phosphate is released from the sediment even under aerobic conditions. The presence of dissolved oxygen does not prevent the release of phosphorus from the sediments; this release, however, is mediated by biochemical instead of purely chemical processes. Despite this, treatment with oxygen or air, as it is practised today, is generally very efficacious (Fig. 6), not least with re-

spect to the intensification of degradation of organic phosphorus compounds, storage of which in the sediment occurs especially under anaerobic conditions. This type of treatment alone, however, is unable to solve the prob-



**Fig. 6**  
Mean phosphate-P concentrations in Swiss lakes. Thick solid lines: lakes with internal restoration measures. Medium solid lines: lakes with especially effective protection measures in their drainage areas.

lem of phosphate eutrophication if we do not take the trouble to reduce substantially phosphate loading from the drainage area of the lake concerned. This basic measure cannot be replaced by any other: a substance can have zero effect on a lake only if it is not present in the lake. Where this conventional method can be effectively employed to reduce phosphate pollution, the direct degree of success achieved, in terms of a reduction in the phosphate content of the lake, ranges from respectable to spectacular (not only in Vierwaldstättersee, also in Bodensee: see Fig. 7).

### 6. Water quality goals

Changes in nutrient cycles initiated with the idea of lake restoration in mind should be orientated towards particular water quality goals. In the case of Switzerland, these goals are established in the Ordinance for Waste Water Discharge promulgated by the Bundesrat (Swiss Federal Council of Ministers). At the present time, these regulations are undergoing re-examination. The following - not yet official - suggestions may be taken into con-

sideration.

As far as the topic of this meeting is concerned, the "Particular Standards for Lakes" are important. According to these regulations, alterations in the water balance or the physical water quality of a lake should not cause any alterations in either water temperature, amount and distribution of nutrients, or (coupled with this) living and reproductive conditions which would be disadvantageous to lake organisms, especially to littoral organisms (but also to pelagic and benthic organisms). Biomass production in the pelagic zone should not exceed an "average value". Unfavourable natural conditions are excepted (this is meant to apply to small lakes with a relatively large drainage area, a small pelagic zone and high nutrient loading rates per unit volume or a low throughflow).

A direct result of the decomposition of bioproducts is a corresponding oxygen depletion in the depths of the lake. The parameter which is in principle the most important has been dealt with by limiting production to an average value. Why then is there also a criterion for oxygen (never less than 4 mg/l anywhere in the lake)? The intention of these regulations is not to allow the full oxygen reserve in deep lakes, in which a comparatively large water body is available for degradation processes, to be depleted down to 4 mg/l O<sub>2</sub>. A deep lake could very well be highly productive, but still its oxygen reserve might not be reduced below 4 mg/l. In shallow lakes, on the other hand, the 4 mg/l limit would be reached rapidly, since in this case even average production would cause excessive oxygen depletion. If the 4 mg/l criterion is fulfilled, i.e. if the oxygen concentration exceeds this value, the production must also be examined. A prominent example of this is Bodensee (Lake Constance). On no occasion during 1988 did the oxygen concentration at the deepest point of this lake (250 m) fall below 4 mg/l. In the same year, however, the algal biomass reached its highest level ever, pointing to a production which was certainly above average. It is therefore a matter of necessity that production be limited in addition to setting an oxygen criterion, although production measurements are by their very nature inexact and the

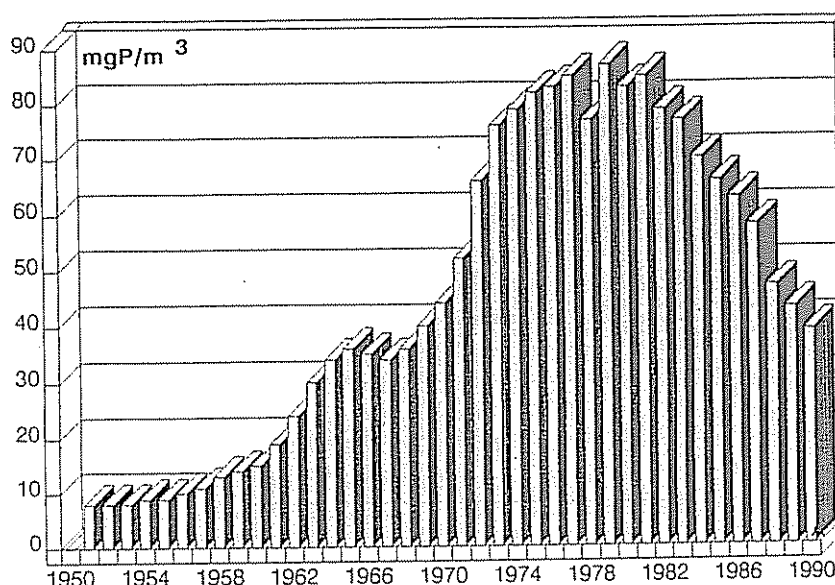


Fig. 7 Annual mean phosphate-P in Bodensee (Lake Constance) during spring turnover, 1951-90 (from the "Internationale Gewässerschutzkommission für den Bodensee").

computation of production rates still pose problems. The accuracy of oxygen concentration determinations, on the other hand, is adequate. Thus oxygen is still the only really practicable control parameter. Using technical means to get around the oxygen criterion would be equivalent to treating symptoms alone, and would render the limit senseless. The oxygen criterion must therefore be fulfilled without employing "artificial support measures".

For those lakes which exhibit "unfavourable natural conditions" and have fallen or will fall through loopholes in the present regulation, lake-specific water quality goals must be determined. The reason for this is to avoid the creation of two categories of lakes: those which must fulfill all criteria and those which get a "free pass", as it were.

Checking the oxygen concentration at the sediment/water interface (i.e. directly at the lake bottom) is both analytically and from the point of view of sampling techniques very difficult and is not feasible as part of a routine check. The biology of the lake (as a long-term indicator) can help us out here: the suggestion of EAWAG is: "Non-sensitive animals must be able to settle the lake bottom all year round". This means that the presence in the depths of the lake of certain animals

which can live at low oxygen concentrations, but still require a certain minimum oxygen concentration, can be employed as an indicator of the long-term situation with respect to oxygen.

## 7. The condition of the littoral

The lake shore is a particularly popular, key area: access to the lake is via the shore, and those who have no boat enjoy the lake from the shore. In addition, new problems have arisen in connection with windsurfing. The lake shore is often a "no-man's land" that is exploited in all manner of ways (buildings connected with shipping, harbours, arrays of buoys). On the other hand, the lake shore and littoral zone make up a special environment which is often densely populated with animals and is important for the cycling of various substances and as a "survival area" for the resistant forms of various organisms. To talk not only about the pelagic zone, but also about the littoral zone, and to direct public and political interest to this area, would be an act of justice (or a topic for another conference).

# The distribution of substances in lakes: interactions between physical and chemical processes

Dieter M. Imboden, Laura Sigg and René P. Schwarzenbach

## 1. The lake as a model ecosystem

Hardly any other ecosystem is better suited for the study of the basic principles governing the interactions of physical, chemical and biological processes than that of the lake. Lake ecosystems have distinct boundaries, are relatively homogeneous and are subject to external influences to only a limited degree. To get an idea of the structure of lakes, we can first imagine how it would behave without these external influences, and then include them, one by one, to give an increasingly complex description of the whole system.

## 2. The lake as a physical system

We will begin our examination of the aquatic ecosystem by considering a body of water contained in a depression in the ground on an earth devoid of life. In certain cases, this water body

is practically cut off from its environment: for example, when it is covered with a layer of ice. Mostly, however, it is acted upon by physical forces, for instance in the form of inflows, which are not only responsible for a renewal of the water forming the water body, but also for the input of kinetic energy into the lake, which results in mixing. Another, much more obvious, "mixing agent" is, however, the wind. Together with the heat exchange between the lake and its environment, it is the wind which mainly dominates the physical events occurring in the lake.

Imagine a lake, then, situated on a lifeless earth. It is exposed to wind and weather, water is transported into and away from it by rivers and streams, it is warmed by the sun. What can we say about such a lake, what takes place in its interior? First and foremost, a lake is an energy reservoir. Over short periods of time it can take up thermal and mechanical energy and later release it to its environment. In the long term, however, the energy input and output

balance out. Mechanical energy manifests itself as the kinetic energy of currents or as potential energy stored in the so-called density stratification, by which lighter water overlies heavier, strongly limiting the vertical exchange of water. Although the energy of motion of the water - especially during a heavy storm - can seem very spectacular, by far the greatest flow of energy is associated with the thermal energy budget of the lake. Under the climatic conditions prevailing in Switzerland, a typical lake absorbs an average of 60 Watts per m<sup>2</sup> in the form of heat between March and September and releases the same amount of heat to the atmosphere during the rest of the year. This corresponds to an annual energy turnover of about 10<sup>9</sup> Joule per m<sup>2</sup> and explains the dampening influence of lakes on local climate, as well as the attractiveness of lakes to various branches of the energy supply business, for example as receivers of unwanted heat or as suppliers of environmental heat for heat-pump operation [1].

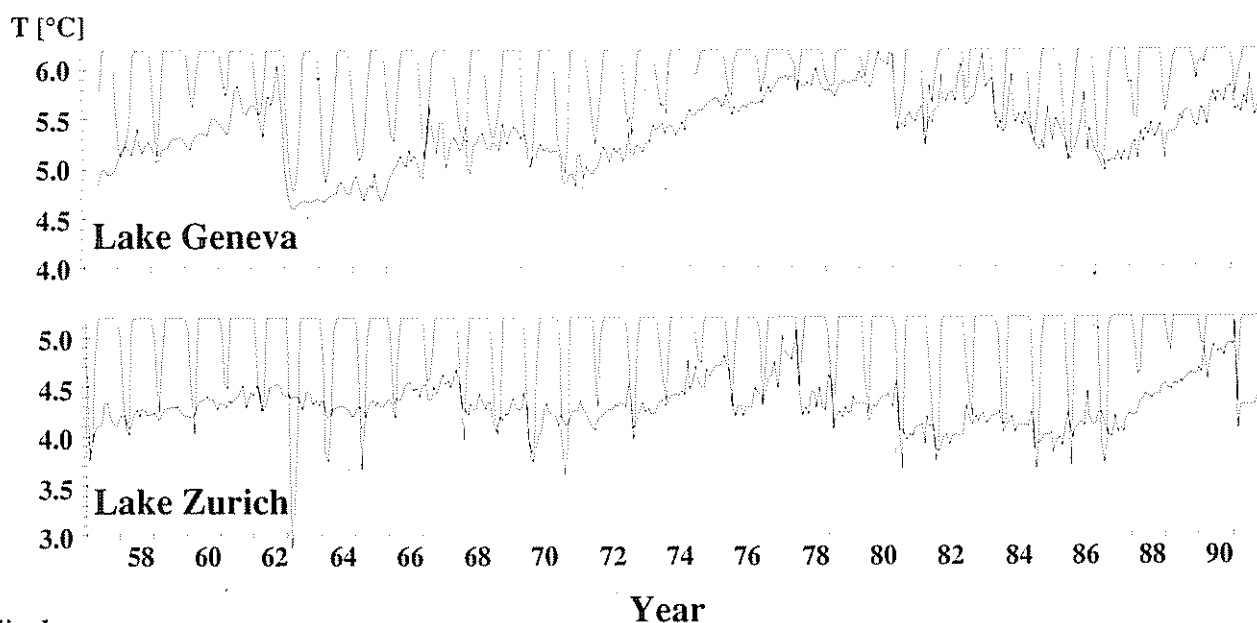
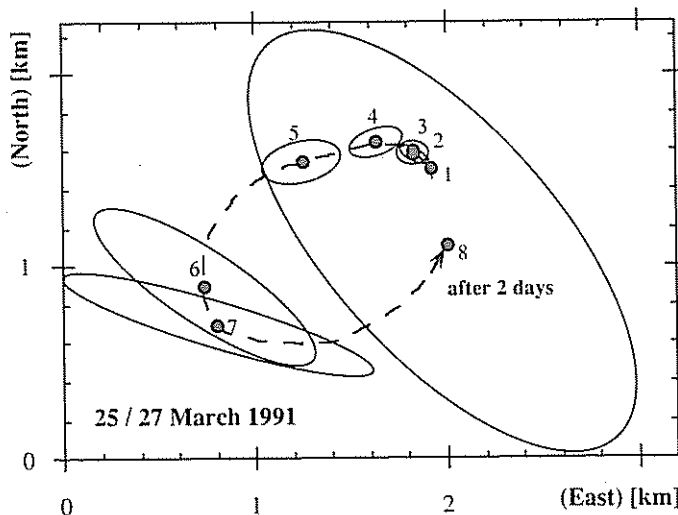


Fig. 1

Variations in the mean lake temperature (dotted line) and the temperature of the lower hypolimnion (under 100 m, solid line) in Lake Geneva and Lake Zurich from 1957 to 1991. The deep-water temperature in oligotrophic Lake Geneva is coupled directly to the climate; in contrast, the deeper water layers in eutrophic (up to 1975) Lake Zurich are to a large degree decoupled from the surface. From Livingstone [2].

Seasonal variations in the thermal energy flux result in corresponding variations in the density stratification, and consequently in the ratio of the intensity of vertical mixing to that of horizontal mixing. Examination of long-term temperature measurements in various Swiss lakes (Fig. 1) has shown that the deep water of certain lakes possesses a "memory" lasting several years which, in a manner of speaking, can be said to undergo sporadic erasure, for instance during an especially cold or windy winter. Interestingly, eutrophic lakes (e.g. Lake Zurich up until about 1975) seem to possess a tendency to chemical self-stabilization, so that the deep-water temperature hardly reacts at all to climatic events.

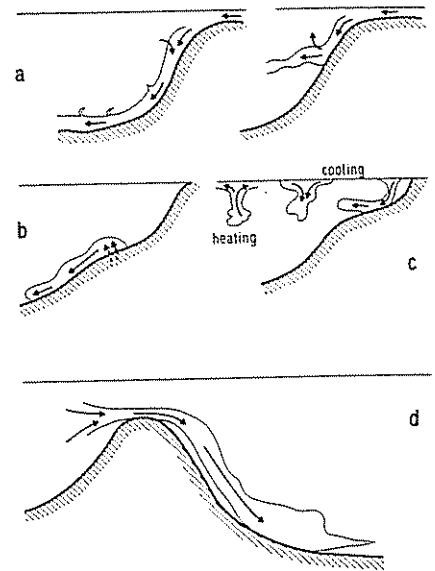
In the horizontal direction, mixing times are much shorter. Fig. 2 illustrates the horizontal spreading of an artificial dye patch at a depth of 15 - 20 m in Vitznauersee, a basin of Vierwaldstättersee (Lake Lucerne). For complete mixing in the horizontal direction, a medium-sized lake requires a period of several days to several weeks; for complete vertical mixing, however, a period of several months to several years is necessary.



**Fig. 2**  
The horizontal spreading of an artificial dye patch at a depth of 15 - 20 m in Vitznauersee, a basin of Vierwaldstättersee (Lake Lucerne) demonstrates the effect of horizontal currents and turbulence. The forms of the patch during various stages of its development are approximated by ellipses. From Peeters et al. [3].

### 3. Lake chemistry makes itself noticeable

For many chemicals, water is a good solvent. Gases and minerals dissolve in water which is in contact with the environment, so that pure water does not exist in nature. Since the density of water depends not only on its temperature, but also on its chemical composition, the chemical substances dissolved in the water have an influence on the physical processes occurring in the lake; in certain cases, this influence can be very great. Fig. 3 gives an overview of various chemically induced density currents. We will deal with a surprising and very spectacular example of such a density current later in of this article. Of importance here, however, is to realize that mixing in lakes is influenced not only by inflows and climate, but also by geochemical factors. This is well known in the oceans, with their much higher salt concentrations: the so-called thermohaline circulation, driven by the differing salt concentrations in the various oceans, is ultimately responsible for the global ocean circulation and for the renewal of the oceanic deep water, a process which occurs on a time scale of centuries.

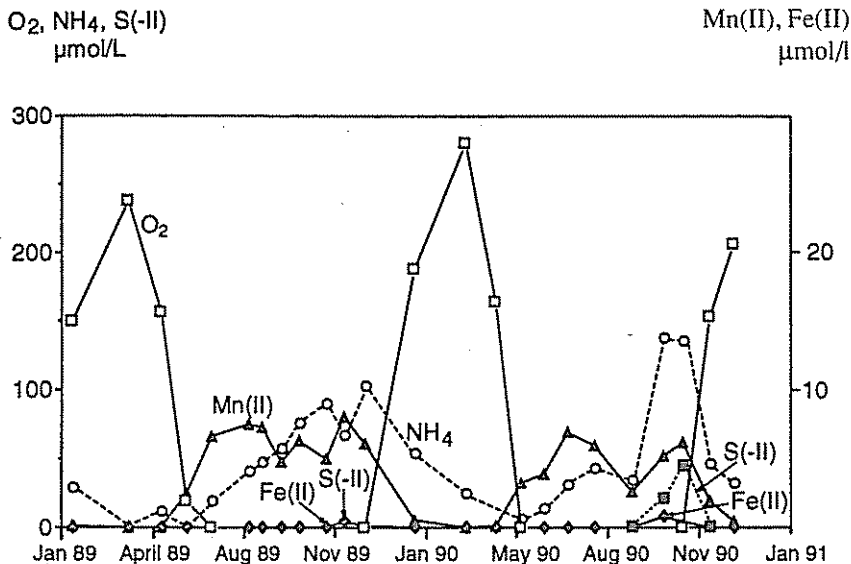


**Fig. 3**  
Local changes in water density due to dissolved chemicals or temperature changes lead to a variety of density currents. From Imboden [9].

### 4. Physics and chemistry combines: distribution and fate of chemical substances in lakes

If the chemistry of the lake water influences the physics of the lake, the reverse is, of course, even more the case. In combination with chemical and biological processes, mixing processes in lakes are responsible for the spatial and temporal distributions of various substances dissolved in the lake water. The degree of heterogeneity or homogeneity of distribution of such substances is determined by the relative rates of mixing and reaction by chemical or biological processes. Non-reactive substances or substances which react only slowly tend to be homogeneously distributed in a lake, whereas substances which react rapidly tend to be more heterogeneously distributed.

Because lakes are mostly horizontally stratified, concentration variation of dissolved substances with depth are generally much more pronounced than variations along the horizontal direction. This is especially true of those substances involved in the redox reac-



**Fig. 4**  
*The result of the appearance of various dissolved reduced compounds near the bottom (30 m) of Greifensee. From Kuhn et al. [4].*

tions associated with the photosynthesis/respiration cycle. Chemical and biological events in lakes are thus characterized by redox conditions which exhibit a typical temporal and vertical spatial structure. Fig. 4 illustrates temporal variations in the concentrations of various chemical species at 30 m depth in Greifensee. As a result of the mineralization of biological material at the lake bottom, the oxygen concentration during the summer falls to zero, and oxidation of organic material occurs by means of other processes, typically resulting in the production of nitrogen, dissolved manganese, ammonium, dissolved iron, sulphide and methane, in that order. As can be demonstrated using model calculations [5], the maximum concentrations of these products over the lake bottom depend not only on the flux of biological material from the surface, but are also sensitive to lake topography and vertical mixing.

As a further example, let us now look at the fate of xenobiotic organic compounds in a lake. Such substances have no natural sources, and so in most cases it is not known how aquatic ecosystems will react to them. Apart from substances that undergo rapid degradation (which are not particularly relevant, since they are scarcely detectable in natural waters), the concentrations of such substances vary - similarly to the concentrations of the

redox partners - first and foremost vertically, and hardly at all horizontally.

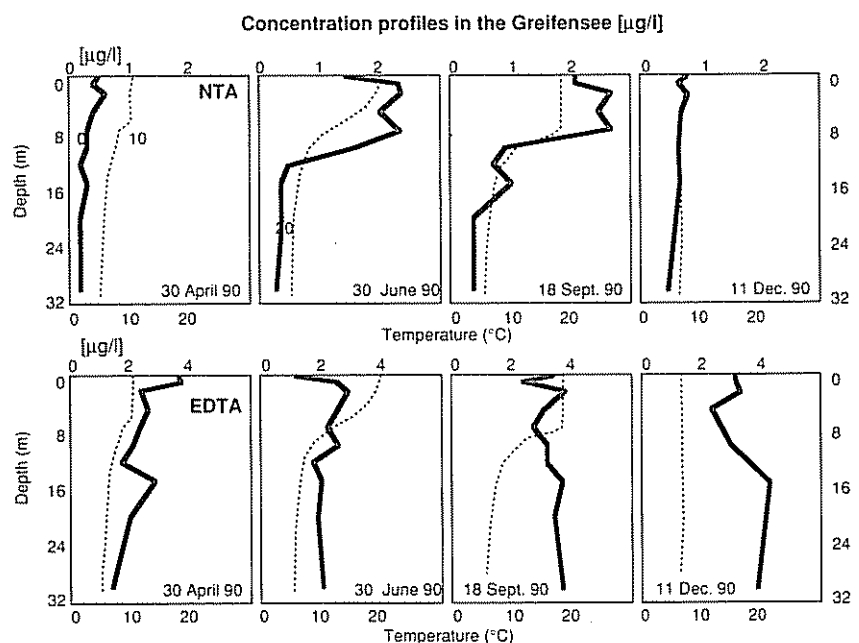
Measurements of EDTA and NTA, two complexing agents, in Greifensee are illustrated in Fig. 5. A comparison of measured concentrations with corresponding modelled values allows conclusions to be drawn about the fate

of these substances in natural waters. EDTA, for instance, appears to be adsorbed on to particulates and to sink with them to the lake bottom, where, after the disappearance of molecular oxygen, it is remobilized. In contrast, the studies yield no evidence for biological or photolytic degradation of EDTA. NTA is removed from the lake primarily via the outflow; it has a half-life of about 20 days with respect to biodegradation in lake water.

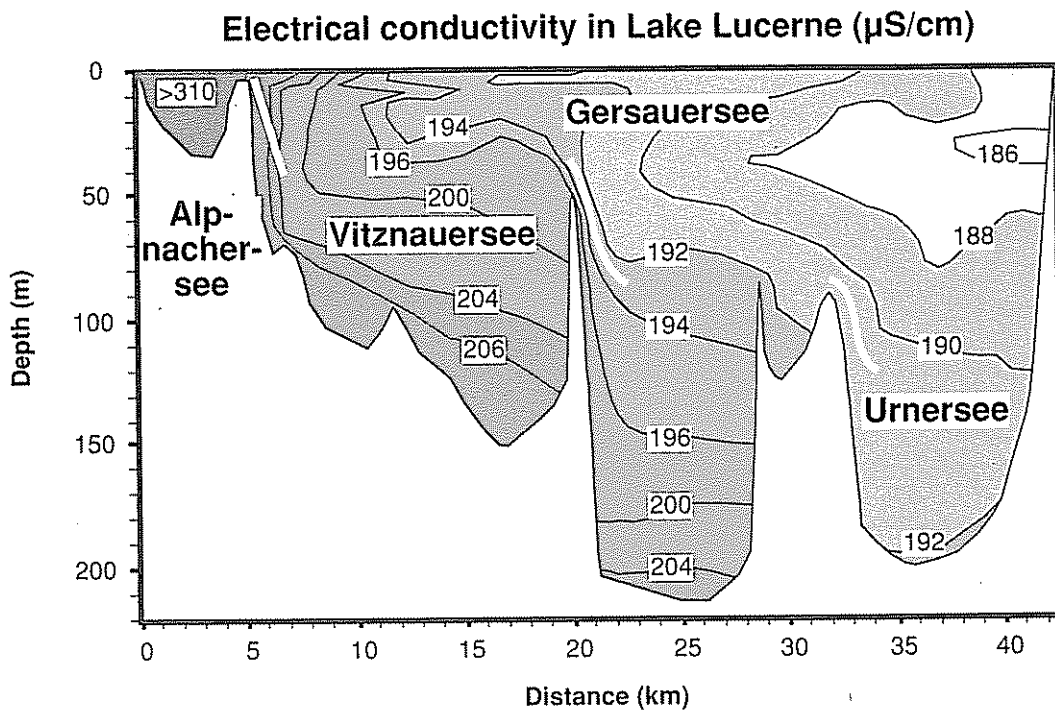
### 5. The normal and the surprising

Lakes are individuals. One can, of course, quite well make general statements about them, but in doing so, one cannot completely do justice to any one specific lake. Let us summarize the most important points:

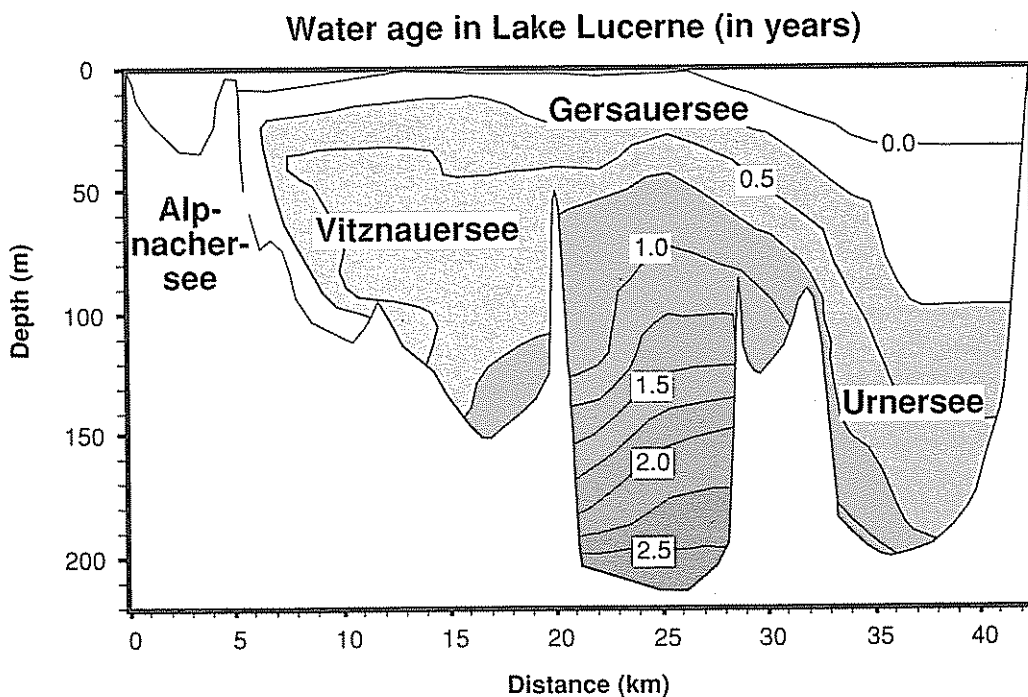
(1) The simultaneous effect of mixing, transfer and transformation processes determines the distribution of chemical substances in a lake. Conservative substances or substances that react only slowly tend to be homogeneously distributed spatially, whilst very reactive substances show great spatial differences in concentration.



**Fig. 5**  
*The vertical distribution of NTA and EDTA in Greifensee illustrates the differing reactivities of the two complexing agents. EDTA appears to be transported down to the deep water with the particle flux and to be released again in late summer under anaerobic conditions. NTA undergoes biological degradation with a half-life of about 20 days. From Ulrich [6].*



**Fig. 6**  
*The vertical distribution of electrical conductivity  $k_{20}$  (units:  $\mu\text{S/cm}$ ), a measure of the density of the lake water, in Vierwaldstättersee (Lake Lucerne). The densest water flows into Alp-nacher-see, then southward over various sills until it reaches the depths of Urnersee. The Urnersee surface water, which originates largely from the River Reuss, is comparatively light. From W. Aeschbach, Ph.D. dissertation (in preparation).*



**Fig. 7**  
*The distribution of water age (units: years) in Vierwaldstättersee (Lake Lucerne). The age of a water packet is defined as the time elapsed since the packet was last in contact with the atmosphere, and is computed from the tritogenic  $^3\text{He}$  excess and the tritium concentration of the water. The oldest water is found in the deepest regions of the Gersauersee basin, where also the lowest oxygen concentrations are found.*

(2) In most cases, the distribution of substances can be characterized by a vertical profile, and often by just two concentrations, an epilimnetic and a hypolimnetic. This is especially true of substances which, as a result of the synthesis and decomposition of organic material, are involved in redox reactions.

(3) Since many redox reactions occur in the sediment, large chemical gradients between sediment and water are typical. At the deepest point of a lake, a relatively large sediment surface area is in contact with a very small volume of water, so that especially large variations in concentration, in both time and space, are found there. High rates of oxygen consumption and rises in the concentrations of reduced substances such as methane, dissolved iron and manganese are typical examples of this.

(4) Differing substance concentrations in the inflows, combined with a complex lake topography, can lead to horizontal density currents and consequently may result in mixing conditions that deviate strongly from the classical case of the horizontally stratified lake.

To conclude, we will illustrate the surprising variety of mixing processes in lakes based on one example, Vierwaldstättersee, or Lake Lucerne. It has long been known that the concentration of molecular oxygen in the deep hypolimnion of the Gersauersee basin lies about 2 - 4 mg/l lower than that in the deep hypolimnion of a neighbouring basin, Urnersee [7]. Productivity in the two basins, which are separated by an underwater sill about 90 m under the surface, are similar. Various hypotheses have been proposed to explain the difference in oxygen concentrations. One explanation which seemed plausible invokes the fact that Urnersee is exposed to stronger winds than Gersauersee (especially during periods of Föhn), so that on the whole, more oxygen is transported into the deep water. A further explanation is based on the supposition that during floods, the most important inflow into Vierwaldstättersee, the River Reuss, becomes loaded with suspended sediment and plunges down into the deep hypolimnion, enriching it with oxy-

gen. Studies have shown that both processes contribute to the increased oxygen concentration in Urnersee [8], but the most important cause is associated with the Vierwaldstättersee drainage area. The northern part of Vierwaldstättersee has a limestone drainage area, so that the water flowing into this part of the lake is hard. The southern part of the lake, however, Urnersee, has a drainage area in which crystalline rock types dominate, and the inflowing water is softer. The hardness, and therefore also the density, of the lake water thus increases from south to north along the main axis of the lake (Fig. 6). The heaviest water, that from Alpnachersee, plunges successively via Kreuztrichter, Vitznauersee and Gersauersee down into the deep hypolimnion of Urnersee, resulting in a large degree of water renewal there. In fact, the water of the Gersauersee hypolimnion has the greatest water age with respect to contact with the atmosphere, which explains the large oxygen deficit there (Fig. 7).

This closes the circle we have travelled during our reflections. Ultimately, physical and chemical (and, of course, biological) processes cannot be separated from one another. Not until all these processes and their mutual interactions have been taken into account can we attain the degree of knowledge necessary for a deeper understanding of the lacustrine ecosystem.



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# Plankton and its trophic structure as a function of the trophic level of the lake

Hans Rudolf Bürgi

## 1. The trophic structure of plankton in meso-trophic/eutrophic lakes.

Many Swiss lakes are today in a medium (mesotrophic) to highly (eutrophic) polluted condition. The food network is complex and the food chain long. Even at the level of the plankton, in addition to the primary production level, there are three consumer stages (algal-consuming zooplankton, and predatory zooplankton). The zooplankton-consuming fish (in this case mostly whitefish) prefer to feed on Crustacea and their favourite amongst these are Cladocerans. The relevance of each of the individual members in the food chain depends on the level of pollution.

## 2. How does the appearance of a lake alter when the pollutant load changes?

Substantial pollution results in the growth of algae. The products of photosynthesis serve on the one hand as food for the zooplankton, and on the other hand affect the benthic region of the lake either directly (via sedimentation of algae) or indirectly (via the faecal pellets of animals). Both effects influence the composition of the suspended species. Nutrients are initially utilised by the fast-growing algae. These in turn are the preferred food for the Daphnia. The Daphnia are then able to rapidly multiply as a result of both the increased level of and greater suitability of the food supply. They in turn serve as an increased food supply for the predatory zooplankton. With respect to the more demanding species, (e.g. the predatory Cladocerans *Bythotrephes* and *Leptodora*) the habitat in the lower, deeper part of the lake becomes restrictive once the amount of oxygen available decreases and they disappear from the plankton. The whitefish are also only able to survive

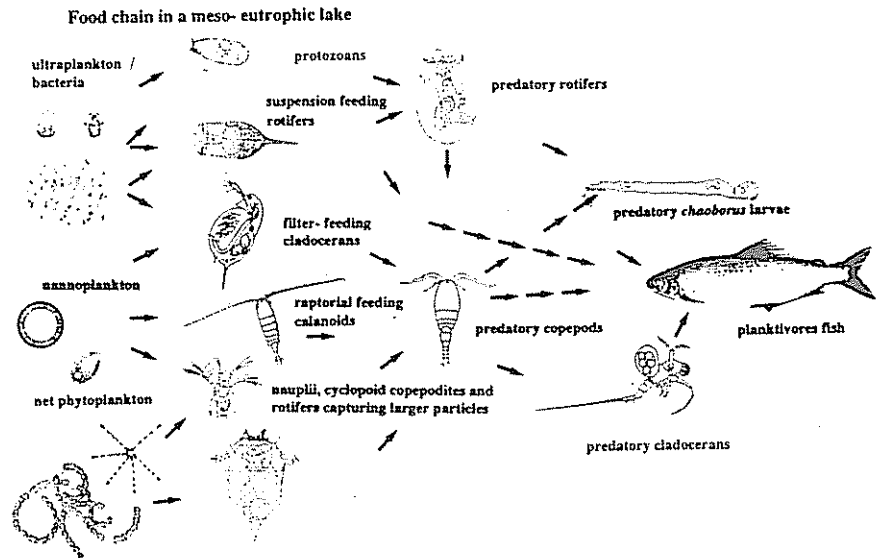


Fig. 1  
The plankton food chain.

In lakes with moderate levels of fertilizer pollution (mesotrophic) the nutritional relationships are multiply interconnected and many different algal species exist simultaneously. In over-fertilized waters, and also in extremely nutrient-poor lakes, some of the predatory or algal eating forms disappear and the nutrient network is less complex.

by adopting some drastic measures. The entire habitat becomes limiting and therefore densely populated. With the exclusion of their natural enemy, Daphnia can once again multiply freely and can continue to do so as long as the available nutrient supply is not exhausted (see Ambühl and Bührer, this volume). The intensity of this biological reaction is even greater if the preceding algal development was also proportionally more intense resulting in a larger food-source for this algal consuming zooplankton. In highly eutrophic lakes, this development, manifested as a so-called "clear water stage" can repeat itself in quick succession. Intensive pollution enables certain species to dominate the plankton within a short period of time as long as other conditions (light, temperature etc.) satisfy the requirements of the species concerned. Subsequent events are also influenced by the feeding selectivity of the momentarily dominant zooplankton species. How-

ever, at any time there are only a few dominant species whilst the other species are only temporarily of secondary importance. The diversity at any particular level is therefore low and the stability against alterations of growth conditions is, consequently, very small. During the course of one year, the cumulative spectrum of species observed provides a significant catalogue of 100-200 or more plankton species. The most obvious feature of dominance is the formation of water blooms.

Nutrient limitation also dilutes out the food chain since only specialists are able to survive. The living area of the plankton can then expand and since oxygen utilization decreases, repopulation of the deeper regions of the lake becomes possible. The density of individuals per cubic meter decreases, but a larger volume becomes inhabited. The importance of the zooplankton for the algae, decreases to the same extent as the density and quality of food for the zooplankton decreases. The mod-

erate algal development is no longer able to support a high zooplankton biomass. This lower zooplankton population is then no longer capable of filtering the algae, since each *Daphnia* can only filter between 10 to 50 ml water per day.

The effect on biodiversity is the exact opposite to that observed under conditions of a eutrophic lake. Each individual sample taken over the course of one year contains a relatively high number of species although none is individually dominant. The dynamic diversity of the species during the course of a year is considerably less dramatic. In the summer samples, one still finds the same species as were present in the spring, although in different proportions. Even pooling the whole years samples fails to show the same level of variety of species as was found in the analogous samples from mesotrophic or eutrophic lakes. Nutrients are too scarce for the development of water blooms under these conditions. Even when one particular strain begins to multiply faster, the lack of nutrients soon limits further proliferation before it has been able to establish a high biomass.

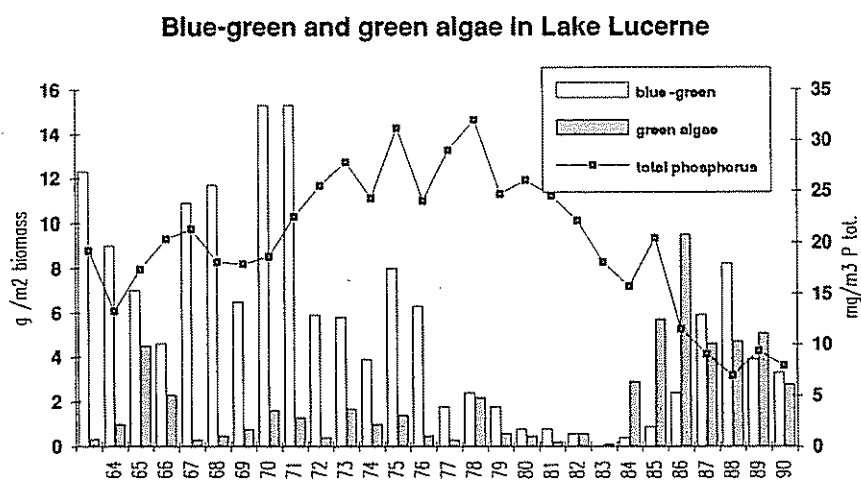
The variation in the population density and the expansion of the habitat results in a paradoxical situation, in that the plankton biomass in a meso-

trophic lake when examined on a per unit area basis shows hardly any indication of a trend once the nutrient loading either increases or decreases. Only for oligotrophic lakes does a change in the nutrient level have any marked effect.

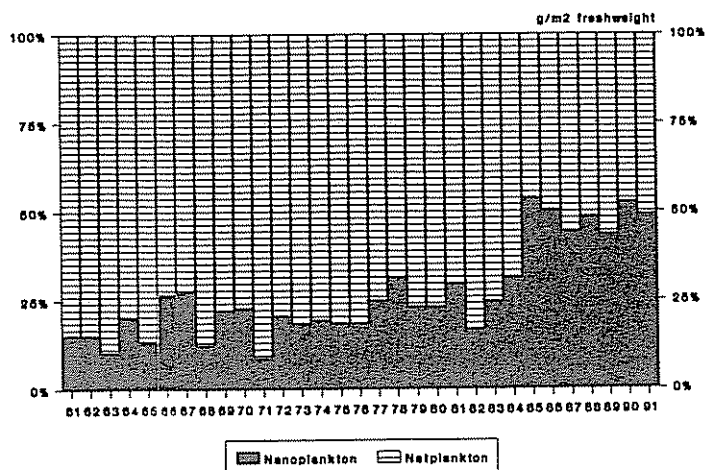
In the oligotrophic Lake Walen (Walensee), the algal development closely follows the levels of nutrients entering the lake. In contrast, the highest mean biomass concentration was measured in 1988 in the mesotrophic Lake Constance (Bodensee) despite the fact that in that particular year the P-content of the lake after decreasing continuously since 1977 only reached 50% of its earlier maximum. Both the public and the politicians want to know what their lakes will look like given a particular P-content, and to know what has to be done to ensure its aesthetic and functional well-being. Setting the standard norms for water protection requires understanding the effects of anthropogenic influences on water quality. To insist on a particular condition that is dependent on particular weather conditions does not appear in the regulations. However, above a certain nutrient level the production of algal biomass is dependent on the weather. For these reasons, scientists have been interested in understanding what parameters react to changes in

the nutrient level and how. Since the average annual biomass value for algae is not a suitable value to use (except under conditions of P-limitation) one possible option might be to use the variations in the dominant algal classes which result from differences in nutrient level. Several algal classes have already been defined for use as indicators of either good or bad conditions. Chrysophyceans and diatoms are the typical forms which generally adapt well to the available nutrient levels. In the example of Lake Lucerne theory would predict that these species should appear at the beginning and end of our study period between 1961-1992. The results appear to confirm this hypothesis, particularly with respect to the centric diatoms and for the Chrysophytes. A further frequently mentioned dependency on the P-content concerns the blue-green algae and the green algae. These classes are well known as indicators of eutrophication and should disappear. However, in the same lake their numbers increased for some reason during the low nutrient phase so much so that they became dominant (Fig. 2). Another criterion is based on the spectrum of species. This analysis assumes that the system is uniformly inoculated (the appropriate species must be initially present in order to be able to react) and that the influence of the species which are not suited to the conditions quickly disappears. Both conditions are unlikely ever to be met by the plankton in any lake. In any case the adaptation of the species present takes a very long time to occur under low nutrient conditions.

What are suitable criteria for characterising the condition of a lake? There are two possibilities, namely by monitoring the development of functional groups (e.g. small/large algae) or by examining the link between the various individual components within that ecosystem (e.g. development of the higher food chains as compared to the algae). Both criteria partially overlap, for example, a reduction in the numbers of the filter feeding crustaceans enables their food, the nanoplankton, to survive much better. When nutrients are scarce the motile species also become more important and as such reduce the loss of biomass as a result of sedimentation (Fig 3).



**Fig. 2**  
*The development of individual algal groups in Lake Lucerne. Green algae (chloro) and blue-green algae (cyano) are found here in spite of the generally accepted principles predicting their absence for low nutrient waters. GesProh: total phosphorus content during circulation.*



**Fig. 3**  
*Size classes of Phytoplankton.*  
*Changes in the trophic level affect the development of the size classes, partially as a result of the decoupling of algal consumers from the primary producers. Dwarf algae (black) become more common than the larger more economical algae (white) as a result of the reduced zooplankton activity.*

The fresh-water biologist is often faced with the same question as the climatologist as to whether there has already been a shift in climatic conditions. If only the trend is followed, one can conclude that nothing has changed compared to earlier years. If, however, we compare the oscillations which occur in the nutrient chain and which result in the clear-water period then we can see good evidence for the fact that nutrient addition has changed the activity of the biology.

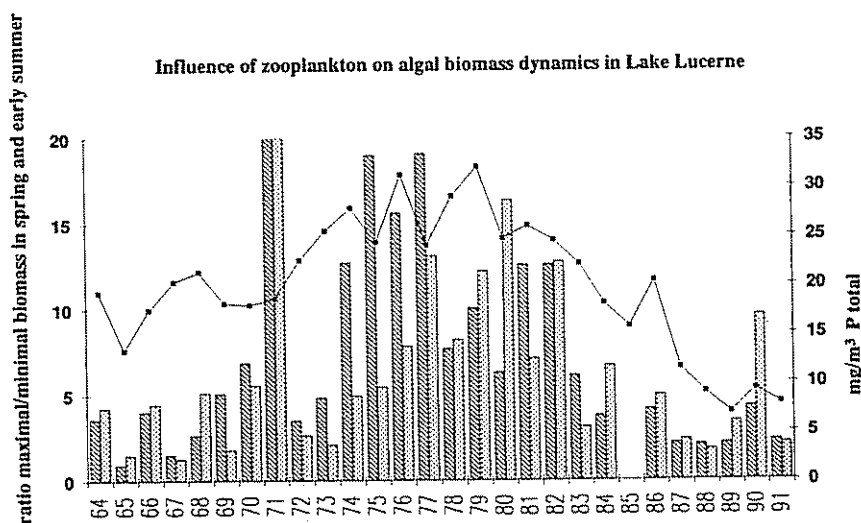
As a result of either larger or smaller interactions between the different trophic levels of the nutrient chain, larger or smaller variations can result e.g. in the form of clear-water periods. Even the predatory zooplankton are bound to these variations although they themselves are in no way directly influenced, but indirectly by the same regulators, the herbivorous zooplankton (Fig 4). It is impossible to describe all of the events which occur as a result of eutrophication or oligotrophication. These processes occur in phases. In the first phase those species which are already present will react. Those plankton species present at the moment the change occurs react according to their own ecological prerequisites. Shifts in the dominance structure might occur. As a direct response to the altered level of productivity, the thickness of the productive layer will change. In eutrophic lakes this can decrease down to a few meters

as a result of the shading by the uppermost algae, in oligotrophic lakes, this layer can increase to 20-30m. The low productivity levels and total biomass then remain at a constant level. With increasing levels of pollution the potential will be reached enabling either already present forms or those which get washed into the system to increase massively in numbers. At this point in time they usually lack a natural enemy. In the opposite case, reduction in the nutrient levels results in a much less dramatic replacement of the less

well suited species by more frugal species. The nutrient content is then so low that it prevents any massive population growth, which is also the reason why the less well adapted forms are not overrun. Since it is always the forms momentarily present adapted to some previous condition which react, then oligotrophication cannot be considered to reflect the mirror image of eutrophication. The real situation is more characteristic of a hysteresis.

### 3. The bountiful years are over - recession has also hit production in many lakes.

How does the plankton react to a wide-scale stoppage in nutrient supply? The zooplankton are well adapted to cope with restrictive conditions. This adaptation can be traced to the necessity to proliferate in oligotrophic waters during the pre-historic era. Without anthropogenic influences, many lakes would be extremely poor in nutrients. The implication of this as far as the plankton are concerned is that it reflects a return to their basic conditions for which they were once adapted. What adaptation mechanisms have developed for this? One such mechanism involves an exaggerated migratory tendency. During the day, they live in the colder deeper zones and during the night they come into the



**Fig. 4**  
*Changes in the nutrient content of the water affect primarily the dynamics of plankton and not their mean annual biomass. At higher nutrient levels the variations between April and August (spring maximum, clear-water period and summer maximum) increase dramatically. These variations are also an indication of the coupling within the nutrient chain.*

surface zones in order to feed. This behaviour reduces their loss which would otherwise result from predation by the fish which hunt visually and also enables them to survive longer in the colder deep water as a result of the food they have consumed.

Together with migration, staying together in a pack (swarming) increases the probability that males and females will meet at the same place (a precondition for the long-term survival of the population). The trigger for such swarming behaviour is the presence of a certain substance in their bodies. As soon as the predators appear, a fraction of this prey specific compound is released by the digestive system and the prey become dispersed in patches.

Many zooplankton have developed practical survival strategies based on the development of physiologically distinct survival structures (cysts). Induction of this differentiation is often connected to starvation conditions. Nu-

trient limitation is especially important at high temperatures since oxygen is rapidly exhausted and a large amount of energy is expended. These survival structures are able to germinate even after several months to years because they possess a protective shell which surrounds them. Many forms also enter a summer "dormancy" (at the time that nutrients are particularly low in oligotrophic lakes).

#### 4. Internal restoration measures: retardants or accelerators of oligotrophication?

Circulation assistance and oxygen diffusion in three Swiss lakes (Lake Hallwil, Lake Sempach and Lake Baldeg) have generally accelerated the healing process. When one examines the mean annual plankton biomass per square meter then no definite trend can be discerned [3]. This scientific analy-

sis is also supported by visual assessment of the lakes which show a very high growth of vegetation.

Here also, the response is not reflected by the total biomass maintained and degraded during the course of a year, but the number of individual classes of organisms. The variations during the course of a year have increased markedly. As in the case of eutrophication, this is indicative of shifts and a non-equilibrium status. How did this situation arise?

The aim of artificial circulation is to promote the revitalisation of the lake. Oxygen must reach the deepest depths of the lake. But this measure not only affects the depth of the circulating layers but also the time span of the circulation phase. Since circulation is the cheaper option than the alternative and usually subsequent oxygenation using pure oxygen, the attempt is nevertheless made to maintain the circulation phase as long as possible by means of large bubble aeration. The planktonic algae are thereby continuously and over a prolonged period carried from the surface down into the depths. Growth is therefore limited to the basic minimum since the light at such depths is insufficient for primary production. The nutrient reserves in the lake remain initially intact as a result of circulation. At the moment when the radiation intensity becomes so strong that stratification can no longer be prevented, it follows relatively suddenly.

The addition of oxygen to the sediment-water interface and the eddies promote the germination of the cysts. This germination can determine the subsequent course of events. Changes in the weather conditions help to bring about the downfall of the well-adapted species. The algae now present find everything in excess and the fast-growing nanoplankton multiply exponentially. Such a nutrient basis is available at just the right time in Lake Hallwil to serve the now plentiful zooplankton as a food source at an important phase in their growth (in Lake Sempach the spring maximum is almost non-existent). As a result of biological interactions phyto- and zooplankton undergo rapid maximum and minima. The potential for a high biomass is maintained for a long time as a consequence of the recycling of nutrients (from the

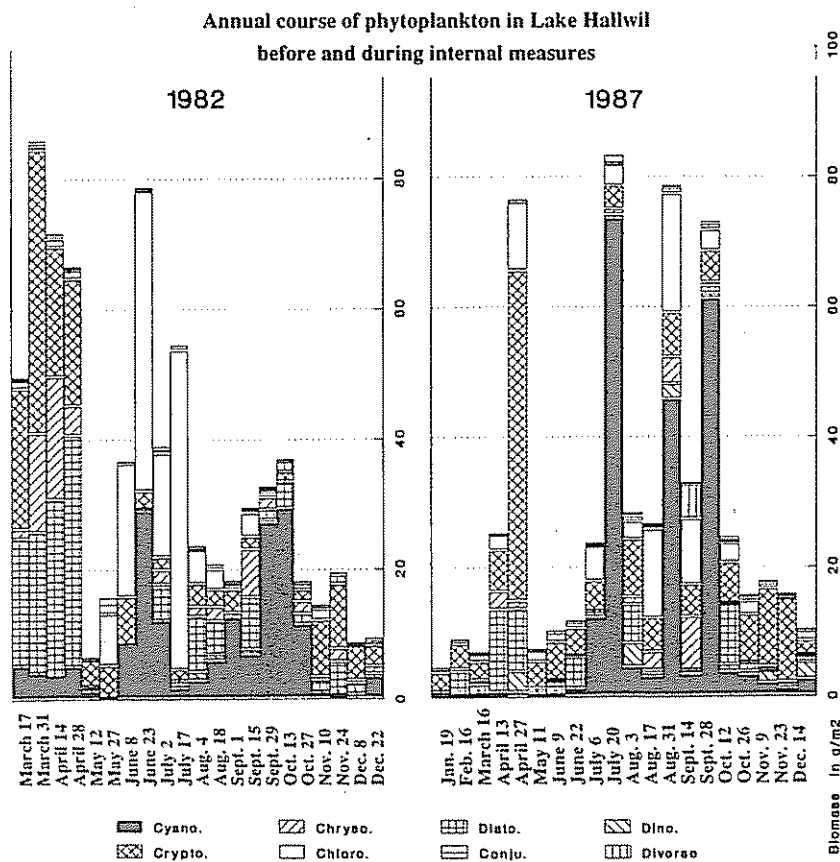


Fig. 5 Biomass of different algae classes found during the course of a year before and after introduction of internal lake oxygenation. As a result of the lake internal restoration measures in Lake Hallwil, the main vegetation periods in this lake have shifted. Instead of the earlier marked spring maximum, summer maxima appear more and more frequently as a result of the extended circulation period.

algae into the zooplankton and from their excretory products back into the phytoplankton). Since the inception of these internal lake restoration measures, the number of algal maxima and their consequences have changed. The consequence has been that events in the lake are quite hectic and several accentuated summer maxima have been observed (Fig. 5).

Sedimentation of the nutrient depends mostly on which suspended forms are dominant. Motile plankton, algae with swimming aids (gas vacuolated) and nanoplankton experience little loss by sinking as opposed to the larger non-motile plankton. Compaction of the small food particles also contributes to sedimentation within fecal pellets excreted by zooplankton. These then have a high sedimentation velocity as a consequence of their increased overall size (Fig. 6).

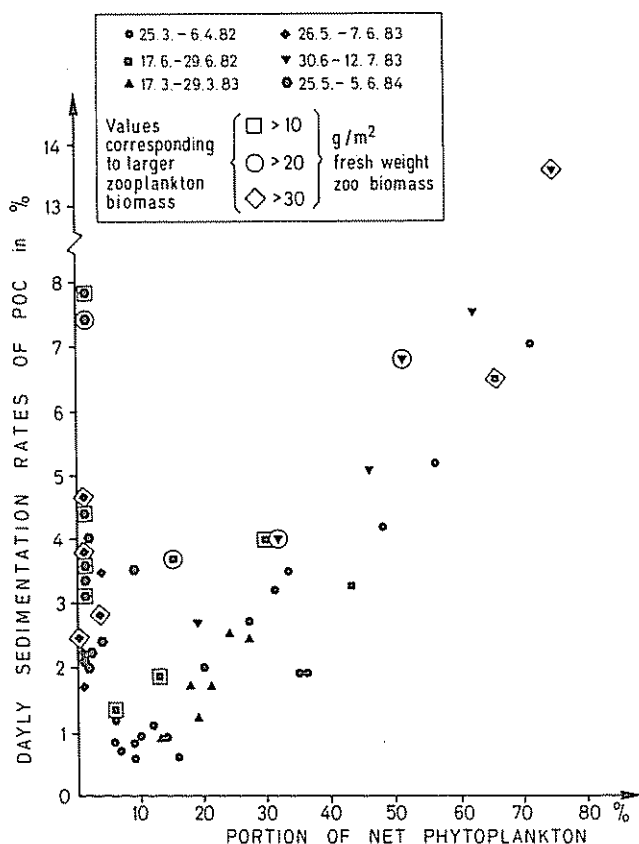
Both the hunting grounds of the fish and the potential space occupied by the zooplankton increase with the change in the oxygen content of the benthos. The zooplankton inhabit this area continuously. However, several forms lose their safe niches. For example, Cyclops and Chaoborus can survive for a long period of time under conditions with very low concentrations of oxygen. During the day they dive into the deeper water zone and remain in the partially oxygen-free sediment and as such can avoid being attacked by the fish. Since the introduction of the restoration measures for this lake, the life expectancy for these animals has decreased since the fish can now also hunt in the deeper water. As a result of this it is now possible to observe succession processes occurring amongst the zooplankton.

## 5. Summary

The reaction of the zooplankton to changes should not be examined primarily at the level of total biomass, but instead in the extent of interactions between different members of the nutrient chain. This is reflected by the broad variation in the species diversity and in their functional interaction. With increasing nutrient load, the extent of variations increases and shifts in the plankton composition appear to occur. In turn, these changes influence the sedimentation.

Biodiversity also changes: In eutrophic lakes different communities comprised of a few but dominant species follow one after another resulting in a large diversity of species over the course of a year. In oligotrophic lakes, a relatively large number of species are present at any particular time, but are more or less constant over the longer term.

Internal lake restoration measures significantly alter the ecology. The algal maxima are delayed into the second half of the year with the result that subsequent events are more hectic and individual zooplankton succumb more easily to the feeding pressure of the fish.



**Fig. 6**  
*Interrelationships between sedimentation and plankton composition. Both higher zooplankton biomass as well as higher content of the large algae (net plankton) enhance loss by sedimentation. As much as 10% (or more) of the suspended algae from the upper zone can be lost to the sediment per day.*

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# Biogeochemical processes at the sediment surface

Bernhard Wehrli, Andrea Ventling and Rudolf Müller

## 1. Internal lake restoration between success...

Looking at lakes containing an excess of nutrients often makes bathers think rather of pea soup than of the pleasures of bathing. Below the unappetizing algal broth, however, further problems lie hidden: in the 1970s, for instance, the deep water of Baldeggersee contained practically no oxygen during the summer. The total oxygen reserve below a depth of 10 m was consumed by the mineralization of dead algal biomass (Fig. 1). This limited the habitat of the fish to the upper few metres. For almost the last 10 years, Baldeggersee and Sempachersee have been artificially aerated. These lake-internal systems supply the deep water in summer with pure gaseous oxygen. Fine gas bubbles are injected into the water through various diffusers, causing a rising stream of bubbles. The gas bubbles dissolve rapidly and a layer of oxygen-rich water forms about 20 - 30 m above the lake bottom. The injection of 3 t O<sub>2</sub> per day guarantees achievement of the 4 mg O<sub>2</sub>/l

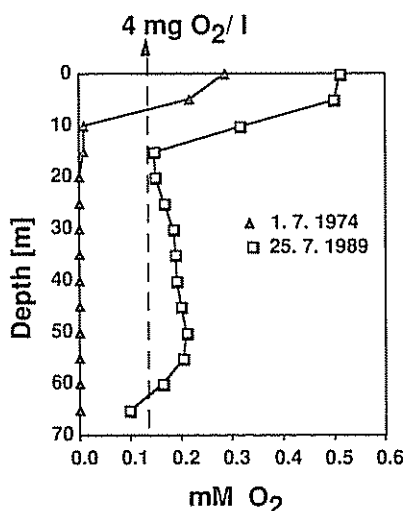


Fig. 1  
Depth profiles of oxygen concentration in the deepest part of eutrophic Baldeggersee. Since the commencement of internal artificial aeration in 1982, the water quality goal of 4 mg O<sub>2</sub>/l can normally be attained.

water quality goal. In winter, the injection of compressed air into the water in the form of coarse bubbles improves lake mixing, resulting in the supplementation of the lake oxygen reservoir by oxygen from the atmosphere.

As a result of the positive experience gained in Baldeggersee and Sempachersee, an aeration apparatus was installed in Hallwilersee in 1985/86. These carefully monitored internal lake restoration measures have proved that it is possible even in sheltered eutrophic lakes to guarantee aerobic conditions in the deep water.

## ... and only partly fulfilled hopes

Although improvement of oxygen conditions at the lake bottom was a central goal of the internal restoration measures, two hoped-for by-products of these measures were politically more significant even during the planning stage:

1. A decrease in the release of phosphorus from the sediments under the artificially-maintained aerobic conditions prevailing in the deep water.

2. The creation of a habitat in which fish could survive throughout the entire lake thanks to a sufficiency of oxygen at all depths.

These two expectations have been only partially fulfilled:

- Before the introduction of artificial aeration, the Baldeggersee sediments released 4.8 - 10 tonnes of phosphorus to the deep water each summer. Since its introduction, this range has been reduced to 2.2 - 7.4 tonnes [1]. The observed reduction in the internal phosphorus loading of Sempachersee was substantially less. Here, an average of 15.8 tonnes of phosphorus released before the introduction of artificial aeration compares with an average of 13.8 tonnes released over the period 1984-88 [2]. Thus, despite favourable oxygen conditions, about 70% of the phosphorus deposited by sedimentation was released again to the deep water. In modelling studies of EAWAG concerned

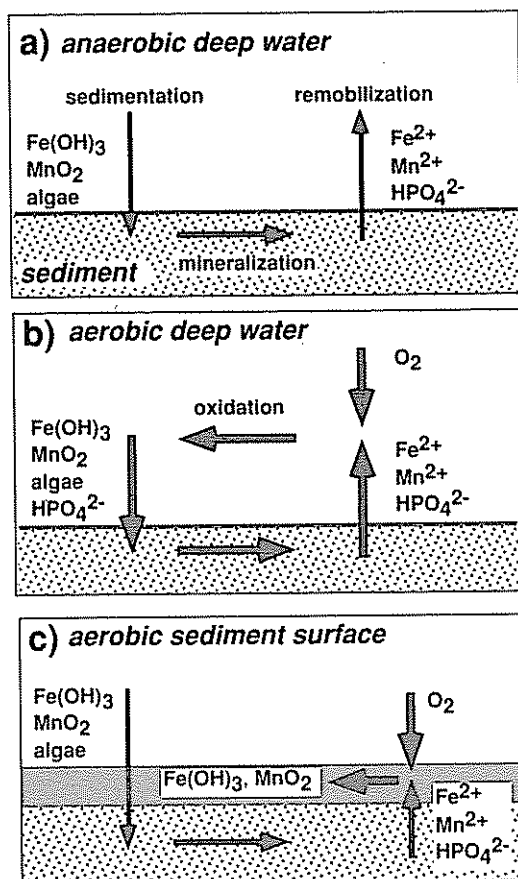
with the restoration of Baldeggersee and Hallwilersee [3], the authors initially assumed only about 1-5% phosphorus release into aerobic waters. This value proved to be too optimistic for modelling Sempachersee.

- With respect to fisheries, the internal restoration measures have also brought only partial success. It is true that in the meantime the entire lake volume is again inhabited by fish; however, the Sempachersee whitefish population cannot reproduce naturally. Whitefish eggs die on the sediment before hatching [4]. The artificial aeration has restored the lake in terms of a habitat for fish, but the sediment surface remains a "zone of death" for whitefish eggs. The whitefish population survives only thanks to intensive artificial stocking measures.

If we want to understand the reasons for these in part disappointing results, we must understand the microbiological, mineralogical and chemical transformation reactions which take place at the lake bottom. This multidisciplinary approach has been labelled "biogeochemistry". We will first look at the problem of the release of phosphorus from the sediments and then try to find out the reason for the whitefish egg mortality. As we will see, both these very different phenomena have a common cause.

## 2. The "slipping clutch" connecting the oxygen and phosphorus cycles

It has been known since the 1940s that enrichment of phosphorus, reduced iron(II) and reduced manganese(II) occur simultaneously in the deep waters of eutrophic lakes during summer stagnation as soon as the oxygen is totally depleted [5]. Microorganisms at the sediment surface use nitrate, sulphate, iron(III) oxide and manganese(III) oxide as oxidizing agents for the oxidation of degradable biomass when oxygen is lacking. If these oxidizing agents are also used up, fermentation and methanogenic bacteria take over, eventually releasing gaseous



**Fig. 2**

**The coupling between oxygen concentration in the deep water and phosphorus release from the sediments:**

- a) If oxygen is completely lacking in the deep water in summer (e.g. in Baldeggersee in 1974; see Fig. 1), the deep water becomes enriched with reduced substances such as dissolved iron(II) and manganese(II) ions. Iron hydroxide,  $\text{Fe(OH)}_3$ , and manganese dioxide,  $\text{MnO}_2$ , on to which phosphorus can be adsorbed, dissolve to a great extent. The degree of phosphorus retention by the sediments is low.
- b) If the deep water contains oxygen, either naturally or as a result of artificial aeration, a redox cycle can develop. Reduced iron and manganese ions are oxidized in the deep water. This causes a local increase in the rate of sedimentation of  $\text{Fe(OH)}_3$  and  $\text{MnO}_2$ . These minerals are rapidly reduced again at the sediment surface. Phosphorus undergoes transport along with these substances, but the amount of phosphorus retained in the sediments remains low.
- c) Not until oxygen penetrates into the sediment can an oxic layer develop, in which oxidized iron and manganese minerals become enriched. This gives rise to new phosphorus adsorption capacity.

methane. Since amorphous iron hydroxide,  $\text{Fe(OH)}_3$ , shows a very high phosphate adsorption capacity, the reductive dissolution of iron(III) also mobilizes phosphorus (Fig. 2a). If oxygen is present in the deep water, and if conditions are favourable, dissolved iron(II) and manganese(II) can undergo oxidation to solid iron hydroxide and manganese oxide,  $\text{MnO}_2$ , at the sediment surface. These minerals then become enriched in the transition zone between sediment and water, and dramatically increase the phosphorus retention capacity of the sediment (Fig. 2c). Under less favourable conditions - in productive lakes with little mixing above the lake bottom - the "clutch" connecting oxygen and phosphorus retention begins to slip: if the sediment surface becomes anaerobic, dissolved iron(II) and manganese(II) begin to be exported unhindered into the deep water. Since these elements do not undergo oxidation until they have reached the bulk water, their concentration in the vicinity of the sediment surface remains low. Under these conditions, an efficient final storage of the algal nutrient phosphate in the sediments does not occur (Fig. 2b). Instead, an intense redox cycle develops in the

deep water, resulting in the reduction of particulate iron oxide and manganese oxide in the upper few centimetres of the sediment. The dissolved ions  $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$  are transported into the aerobic deep water, where they are oxidized back to particulate  $\text{Fe(OH)}_3$  and  $\text{MnO}_2$ . In Sempachersee, the manganese cycle a few metres above the lake bottom is especially intense [6]. To continue the analogy with an engine transmission, with regard to phosphorus, such cycles (Fig. 2b) correspond to the gears being in neutral, since, although the phosphorus is retained within the cycle, phosphorus retention in the sediments is scarcely affected.

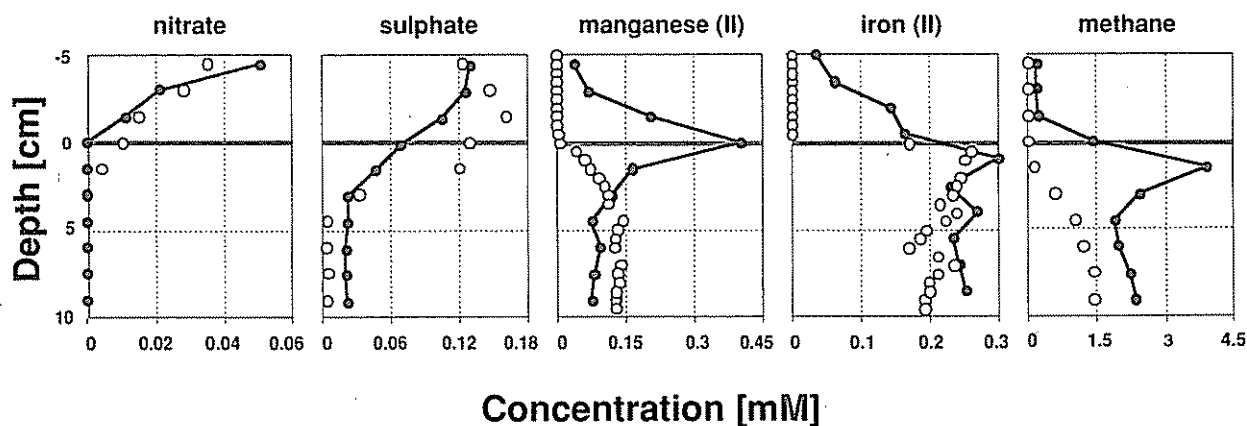
### 3. Chemical analysis in the cm range

In order to decide whether an aerobic sediment surface exists in artificially aerated lakes (Fig. 2c), it is necessary to conduct chemical analyses on a scale of cm or mm. We have employed dialysis samplers to carry out this type of fine-scale *in situ* sampling. This method has been improved by K. Hanselmann's research group at the University of Zurich [7], so that gradients of dissolved substances in the porewater at the sediment-water interface can be determined with a resolution of 5 - 15 mm. In this method, about

1 - 3 ml of pure water are brought into equilibrium with the sediment porewater across a dialysis membrane. The samplers consist of plexiglass plates about 80 cm long, in which holes or slits have been cut. They are mounted on a tetrahedrally shaped frame and exposed for about 2 - 3 weeks at the lake bottom. Employment of this method has allowed us to analyse the chemical traces left behind in the sediment porewater by biogeochemical processes.

A series of typical analyses conducted at the deepest point of Sempachersee, 86 m under the lake surface, is illustrated in Fig. 3. In general, concentration gradients at the end of spring turnover are substantially less than in summer. The gradients of methane and manganese are detectable down to a sediment depth of about 10 cm. It is thus the upper 10 cm of sediment which take part in an intense exchange of substances with the lake water. Sediment older than about 20 - 30 years has scarcely any contact any more with the lake water.

After spring turnover, nitrate penetrates into the sediment to a depth of about 2 cm. Looking at the methane profile, we can conclude that  $\text{CH}_4$  is oxidized in the sediment. Taken together with the very steep iron(II) concentration gradient, this points to the sediment surface having been aerobic at that point in time. An oxic layer



**Fig. 3**

*Dissolved substances in the porewater in the vicinity of the sediment-water interface. The profiles were measured in April (white circles) and July (black circles and solid line) in the deepest part of Sempachersee. The gradients show that the sediment was aerobic in April: while nitrate diffuses into the sediment, iron is oxidized at the surface. The oxidation of methane begins to occur at about 1.5 cm depth. In July, on the other hand, the sediment surface is anaerobic, since high concentrations of reduced iron(II), for instance, occur at the sediment-water interface.*

preventing the release of phosphorus was therefore able to form. Indeed, a significant degree of phosphorus release into the deep water of the lake is usually not observed until July.

After the first large sedimentation pulses of dead algal material, oxidative decomposition intensifies, and denitrification occurs only in the upper few millimetres of the sediments. The nitrate concentration at the sediment surface falls practically to zero. Since intense denitrification occurs as a rule only at low oxygen concentrations, the nitrate concentration gradient gives a first indication that oxygen may be depleted at the sediment surface at this point in time. The concentration gradients of manganese(II) and iron(II) confirm this suspicion. Since iron(II) reacts very rapidly with oxygen, concentrations exceeding 100  $\mu\text{mol/l}$  can only develop over a long period of time.

In July, the gradients of dissolved iron, manganese and methane continue across the sediment-water interface into the bulk water above the sediment. This points to a strong reduction in mixing over the lake bottom during this period. Since large amounts of carbonic acid and dissolved ions are released during the mineralization processes, the density of the water in the vicinity of the sediment increases. This results in stabilization of the water column above the sediments and consequently in a slowing down of the mixing processes. In deep lakes, this

process can lead to anaerobic conditions lasting for decades [8]. This process reduces the supply of dissolved oxidizing agents such as oxygen, nitrate and sulphate to the sediment surface. High rates of decomposition of organic material do not only give rise to oxygen depletion: by stabilizing the water column, they also hinder the transport of dissolved oxidizing agents to the places at which their consumption is highest. In spite of the introduction of 3 t of pure oxygen per day, anaerobic conditions during summer at the deepest point of Sempachersee extend over depths of millimetres to decimetres.

Under these conditions, oxidized phases of iron and manganese are not stable. As the gradients illustrated in Fig. 3 show, these minerals undergo rapid dissolution. Microorganisms which bind phosphorus in the form of polyphosphates also release these polyphosphates under anaerobic conditions [9].

With the help of X-ray spectroscopy (EXAFS), we were able to confirm that hardly any oxidized minerals accumulate on the surface of the Sempachersee sediment. In the upper 2 mm of sediment, only reduced manganese carbonate ( $\text{MnCO}_3$ ) was found. The proportion of oxidized manganese oxide ( $\text{MnO}_2$ ) accounts for 20% at most.

The "slipping clutch" situation, a partial decoupling of the oxygen and phosphorus cycles, can therefore be

seen to exist at the deepest point in Sempachersee. Because of the high rates of decomposition of dead algae, stagnant conditions occur which hinder the transport of  $\text{O}_2$  to the sediment surface. This renders impossible the formation of an oxic layer preventing the release of phosphorus.

#### 4. The sudden death of the whitefish eggs

In spite of the eutrophic conditions, the Sempachersee fishing yield has not diminished. The average catch in the years 1979-84 was 87 t of fish per year, of which whitefish accounted for up to 90%. These good yields are, however, only possible due to the artificial hatching and stocking measures of the professional fishermen.

The whitefish spawn around the middle of December at a preferred depth of 2 - 10 m. Using a diver-operated suction sampler, the egg density in Sempachersee could be determined and the fate of these naturally spawned eggs was investigated during three successive winters. Each winter, the egg density was observed to exceed 1000 eggs per  $\text{m}^2$  in the middle of December. In the incubator at 4°C, the eggs required about 10 weeks for 90% of the fry to hatch. In the lake, however, neither living eggs nor fry were found in the spawning area after the middle of February. Fig. 4a shows how the number of living eggs collapses within a few days. Pre-

dation accounts for only a small fraction of the losses; most of the dead eggs are infested with fungi. To test the hypothesis that toxic substances from the sediment (e.g. hydrogen sulphide or ammonia) damage the eggs, eggs from the incubators were exposed in the lake, on the one hand on a plastic sheet covering the sediment surface, and on the other hand directly on the sediment. The egg mortality rate in such experiments was, however, the same. Apparently, the sediment does not act as the source of toxic substances. The hypothesis remaining is that the oxygen supply to the eggs is insufficient.

### 5. Microelectrodes

In principle, measurements with microelectrodes should allow the determination of oxygen concentration gradients down to a spatial resolution of about 50  $\mu\text{m}$  [10]. We employed this method with a simple micro-manipulator to determine the oxygen conditions over and in sediment cores from the Sempachersee littoral zone (Fig. 4b). The analysis was conducted in the field in order to keep disturbances to a minimum. As has also been shown by *in situ* measurements conducted at the sediment-water interface, a diffusive boundary layer with a thickness varying from 0.2 mm to 2

mm (according to current speed and sediment topography) forms, in which a strong decrease in oxygen concentration is observed. Despite an oxygen concentration of approximately 7 mg/l in the bulk water overlying the sediment, the oxygen concentration falls to below 4 mg/l at the sediment surface. During the early stages of their development, fish eggs require oxygen concentrations of at least 3 mg/l. Before hatching, however, this critical oxygen concentration increases to 7-8 mg/l. As illustrated in Fig. 4b, during this phase it is very difficult for a whitefish egg in a eutrophic lake to satisfy its oxygen requirements. In addition, egg dispersion experiments with marked eggs have shown that during winter storms, when turbulence is high, eggs are often transported into deeper regions of the lake, where they tend to collect in depressions in the sediment. Current speeds tend to be lower there, thus further hindering the oxygen supply to the eggs.

### 6. Conclusions

Internal restoration measures in Swiss lowland lakes consist mainly of deep-water aeration.

Improving the oxygen supply to the sediments proves to be difficult. The somewhat enhanced degree of phosphorus retention in Baldeggensee

and the advance of benthic worms in Hallwilersee [11] does permit the assumption that the supply of oxygen to the sediment surface at medium depths in these lakes is better today than in earlier years, because the oxygen-rich water from the stream of bubbles forms a layer at these depths. In deeper regions, however, artificial aeration cannot prevent the occurrence of periodically anaerobic zones with a very low phosphorus retention capacity at the sediment surface.

Even in the littoral zone, oxygen depletion at the sediment-water interface occurs within the space of a few millimetres, because the concentration of dead algal biomass in the sediment is too high. The whitefish eggs, which are forced to occupy a habitat a few millimetres thick at the sediment surface, literally suffocate as a result of the hunger for oxygen exhibited by the microorganisms which live a millimetre beneath the eggs.

Oxygen will only penetrate into the sediment at higher concentrations if the sedimentation of dead biomass decreases. This requires a reduction in the external phosphorus loading.

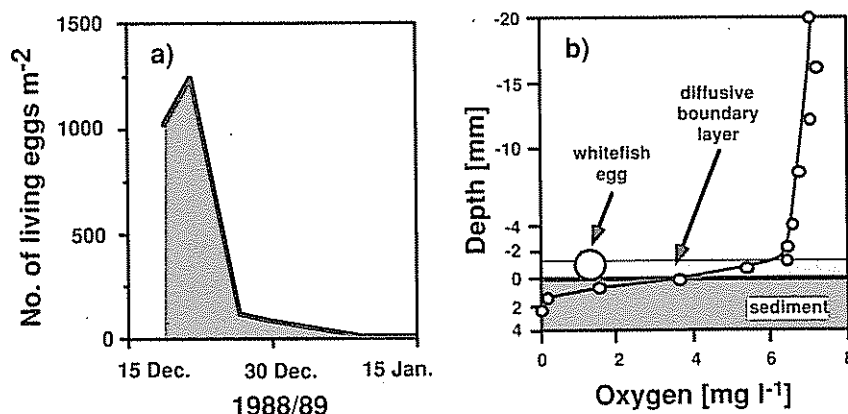


Fig. 4  
Whitefish egg mortality in Sempachersee.

- The number of live whitefish eggs collapses rapidly as soon as the oxygen requirement of the eggs increases.
- Whitefish eggs require an oxygen concentration of at least 7-8 mg/l during embryonic development. Microelectrode measurements show that this requirement is satisfied by the oxygen concentration in the overlying water. The eggs, however, are located in the diffusive boundary layer, where the oxygen concentration often falls short of the critical value.

# The benthic fauna push into the lower depths in Lake Hallwil

Fred Stössel

## 1. Life below 20 meters of depth?

Lake Hallwil is a highly eutrophic lake located in the Swiss plateau region. Since 1985 it has been the subject of a restoration programme involving artificial recirculation in winter and deep-water oxygenation in summer. The restoration project is the result of a collaboration between EAWAG and the Department of Water Protection in the Cantons of Aargau and Lucerne.

Situated on the north-south axis between two hills, the lake is largely protected from wind and as a consequence only circulates on average once every 10 years to the maximum depth of 46m. As a result of this, most of the lake is subject to complete deoxygenation during the summer months, due to stratification of the lake during this period. At the end of the summer stratification, oxygen remains unavailable below 25m and even at 20m depth in some portions of the lake. The oxygen profile in the lake during a one year period (1985) is shown in Fig. 1. This figure clearly shows the effects of inadequate recirculation of the lake during the previous winter months. The boundary of the anoxic zone, moved within 6 months from 35m depth to 22m depth. At the same time, the oxygen minimum which was found in the region of the thermocline (at 10m depth) also diffused upwards. In be-

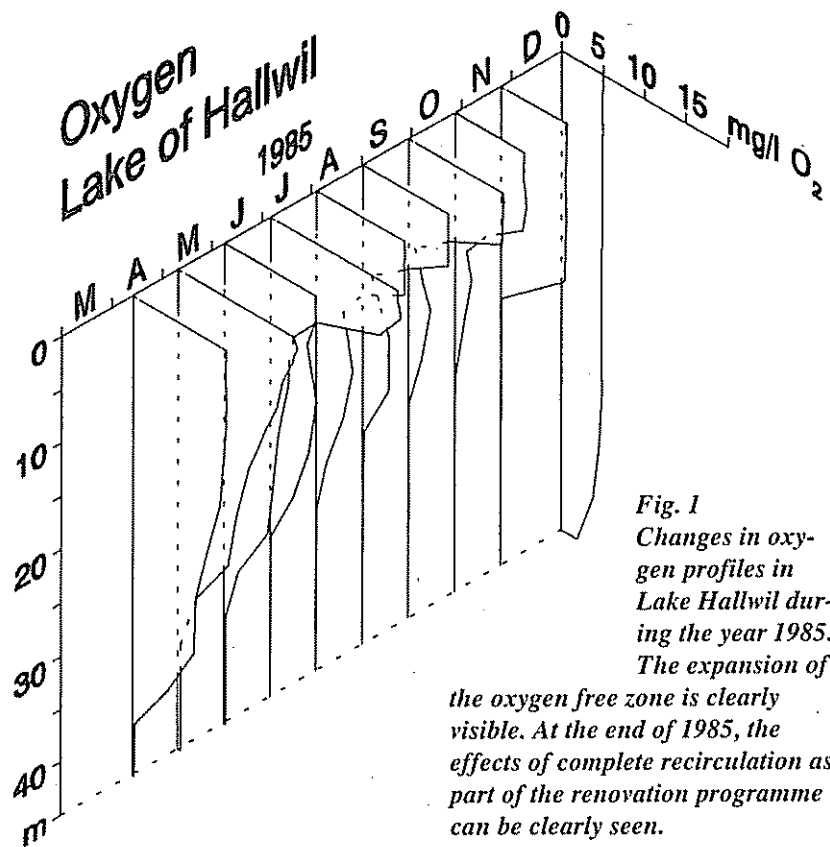


Fig. 1  
Changes in oxygen profiles in Lake Hallwil during the year 1985.  
The expansion of

the oxygen free zone is clearly visible. At the end of 1985, the effects of complete recirculation as part of the renovation programme can be clearly seen.

tween there was a small residual oxygen concentration which remained, but this was never sufficient to satisfy the requirements of the oxygen-sensitive animal life. Märki and Schmid [1] measured even lower values in October 1973 when the oxygen was already depleted below 10m depth. This precarious oxygen condition resulted in the situation that the dead planktonic material which sank during the summer season was no longer degraded

aerobically (using oxygen) and a black anoxic sludge formed. Under these conditions the organic matter was degraded by anaerobic bacteria which produced the toxic compound hydrogen sulfide as a product of their metabolism. This gaseous poison prevented the invertebrate animal life from inhabiting the benthos and restricted the habitat and breeding areas of the fish. Since the area of the lake below 20m depth constitutes over two-thirds

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of the total area, the result is that a large part of the lake habitat was no longer available to the invertebrates nor for the various species of fish which would have otherwise been present. In order to investigate the effect of the restoration project which began in 1985 on the invertebrate species, the first samples from the benthos were taken in the late spring of the same year so that an assessment of the initial conditions in the lake could be made.

## 2. What was investigated?

Analysis of the progress of restoration was carried out by EAWAG in conjunction with the Department of Water Protection of the Canton of Aargau. The latter were responsible for the monitoring of the chemical and physical parameters whilst EAWAG undertook the responsibility of monitoring the repopulation of the benthos by macro invertebrates.

The first results concerning the physical-chemical investigations were published by Stöckli and Schmid [2] whilst those concerning the biology were published by Stössel [3].

For the purposes of biological sampling, the lake was divided into four transects in the form of a cross, which met at the deepest part of the lake. Samples were taken on these transects at 1-2m, 5m, and thereafter at 5m intervals, using a small dredge net. Those invertebrate species found in the sludge within the net were carefully separated from the sludge, and their frequencies determined by microscopic examination of the samples. A more detailed description of the sampling procedure was described by Stössel [3].

## 3. Biological and ecological conditions necessary for repopulation.

In order to interpret the results which follow, a short description of the conditions necessary for resettlement by invertebrates might be useful. Resettlement of the benthic region of a lake is strictly limited by abiotic characteristics:

- Continuous darkness prevents any

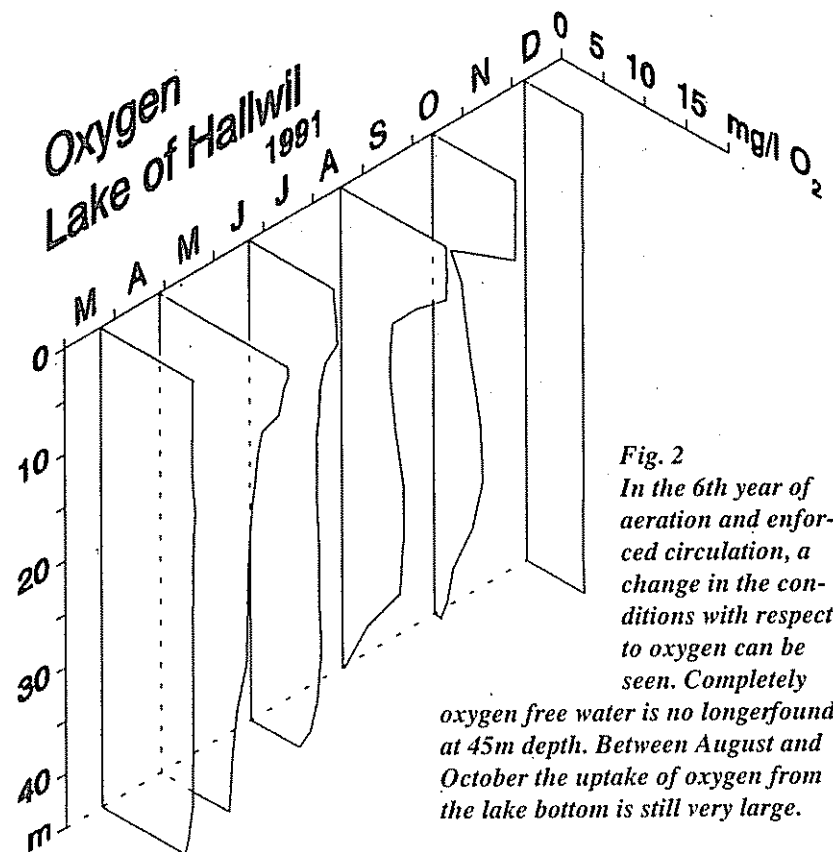


Fig. 2  
In the 6th year of aeration and enforced circulation, a change in the conditions with respect to oxygen can be seen. Completely

oxygen free water is no longer found at 45m depth. Between August and October the uptake of oxygen from the lake bottom is still very large.

plant growth such that only detritivorous and carnivorous invertebrates are able to inhabit this area.

- with increasing depth, there is an increasing amount of sludge on the lake bottom with the consequence that the habitat is very uniform.
- with increasing depth the pressure increases and the temperature decreases.

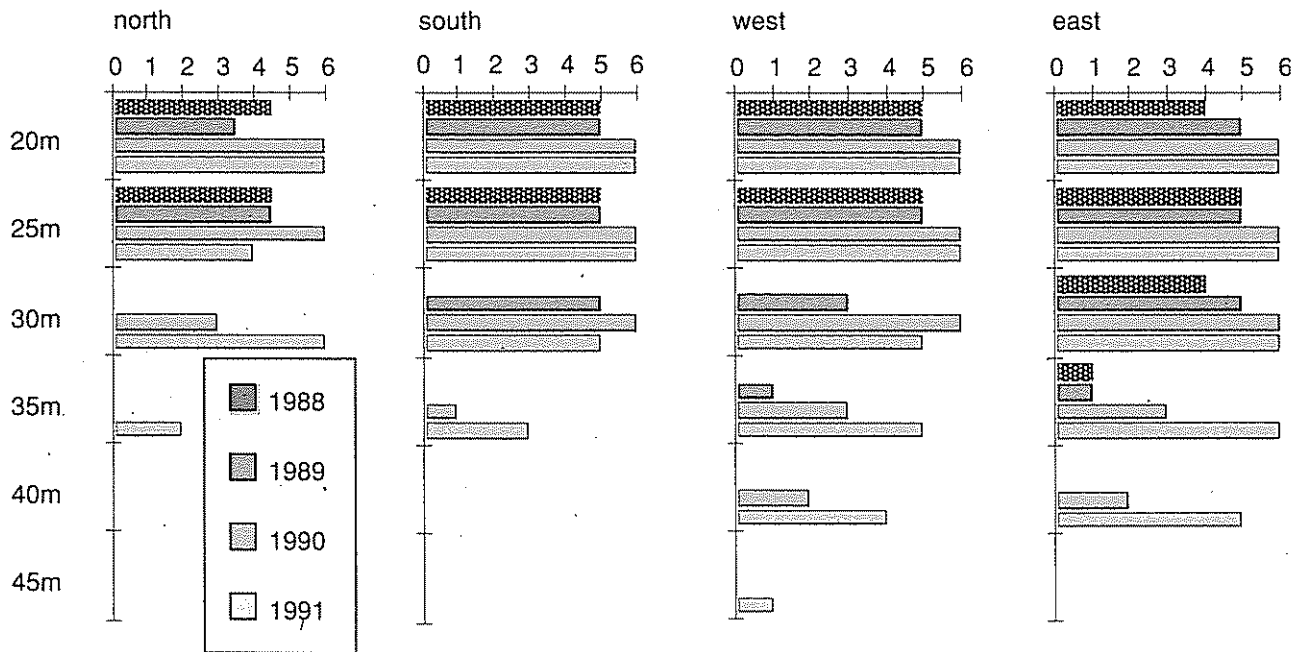
These living conditions impose very strict restrictions on the invertebrate species able to survive here. The true worms in the family Tubificidae can be considered to be pioneers in repopulating this region. They are able to survive well under the conditions described above because they possess a well adapted respiratory system. The front part of the worm is imbedded within the anaerobic sludge, whilst oxygen diffuses into the animal through the skin on the surface of the caudal part of the body and through the lower intestinal wall. The uptake of oxygen is helped by the haemoglobin containing blood which this animal possesses. Due to the high affinity of haemo-

globin for oxygen, the Tubificidae are able to remain alive at very low oxygen concentrations. Several other Tubificid species can survive periods of up to 4 weeks under anaerobic conditions (in the complete absence of oxygen) although under these conditions they are unable to feed or reproduce. Due to these special characteristics, it has been proposed that these animals were predestined for their pioneer role [4]. During their burrowing activity, these sludge worms loosen up the sediment and thereby assist in accelerating oxidation of the sediment (bioturbation). In addition to the true worms, there are several species of midge larvae (Chironomidae) and orb-shell cockles (Pisidium sp.) which are also capable of populating the lake bottom at this depth. Güntert [5] in his dissertation written in 1913, found 3 species from the family Tubificidae and one roundworm (Nematoda) species and the orb-shell cockle (Pisidium fossarium) were found at 46m depth. The first chironomid species was found at 40m depth.

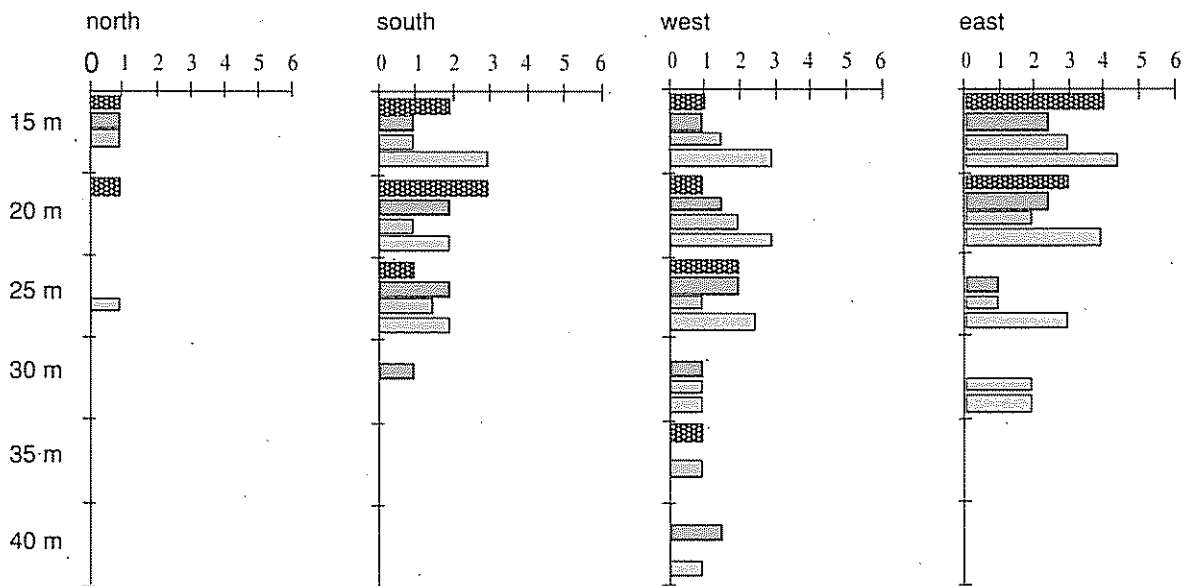
For repopulation in this habitat, two other biological parameters need to be considered, namely;

- length of reproductive cycle
- Migration velocity

- \* Detrivore: Consumer of dead animal and plant materia
- Carnivore: Meat eater



**Fig. 3**  
*The Oligochaets in Lake Hallwil. The intensity of the shading (see Fig. 4) indicates the year of sampling, and the length of the bars the frequency of the worms.*



**Fig. 4**  
*Development of the Chironomid population in Lake Hallwil. Clearly seen are the low frequencies of the midge larvae compared to those of the Oligochaets. At this stage it is not possible to discern a true repopulation effect due to the low frequencies of species found. However there are strong indications of a tendency for repopulation to deeper depths.*

With respect to the former, reproductive cycle times of up to 2 years have been measured for the Tubificidae, whilst only one generation per year was typical for the Chironomids. One factor responsible for this is the low summer temperatures (4-5°C) in the water in the lower fraction of the lake. The migration velocity of the Oligochaeta and the Pisidium are small

and a-directional. The chironomid larvae certainly move much faster and the eggs of the midge larvae which sink to the bottom of the lake can be transported over large distances. For these insect larvae or eggs, the conditions at the bottom of the lake must also be suitable, i.e. there must be sufficient oxygen available. Especially the latter require continuously suffi-

cient oxygen in order to ensure satisfactory development.

#### **4. Effects of the 7-year aeration**

In 1991, for the first time since the beginning of the restoration programme, there was sufficient oxygen in the lake over almost the entire year

down to a depth of 45m (Fig 2). As such, development of the Tubificids and their reproduction was possible. The development of the Oligochaests between 1988 and 1991 is shown in Fig. 3 for the depths below 20m. Results for the various transects are shown separately. Up until 1991, the Tubificids were only able to develop down to a depth of 35m at very low frequencies. As was expected, their development in the east and West transects were faster. These sampling areas were closest to the compressed air and oxygen diffusers. Here they were able to establish themselves at up to 40m depth and some were found at 45m depth. The first data for the late summer of 1992 have indicated a slight improvement in this situation. The sediment at 45m depth and at the deepest point at 46m depth was also inhabited albeit at low frequency.

In Fig. 4 the repopulation by the Chironomid species is shown. Here also, the north transect shows different characteristics compared to the others. The frequencies are so low that little can be said about the repopulation. The other transects however, show from year to year an increasing tendency for settlement in the deeper portions of the lake. Although the Chironomid larvae are more agile than the Tubificidae, they were nevertheless unable to penetrate below 30m except in one instance in Autumn 1990 where they were found at very low frequencies at 35m. The sampling carried out in 1992 have shown no sign that this situation has improved. This is an indication that the Chironomid species in Lake Hallwil are much more sensitive to the oxygen concentration than are the Tubificids.

In Table 1, the changes with respect to the diversity of species found below 20m in all of the 4 transects are shown. In 1985, with the exception of the temporarily anoxic living Chaborous larvae ("Büschelmücken"), and a larval stage of the Cyclops ("Ruderfusskrebs") no other invertebrates were found below 35m. By 1991, the oxygen condition had improved to such an extent that an additional 4 species were able to exist down to a depth of 25m. At 30 and 35m depths, it was the Tubificid and the Chironomids that were able to settle and at 45m a very small

**Table 1**

*An increase in the number of species is apparent between 1985 and 1991. As expected, the largest increase was found in the region up to 30m.*

Depth	1985	1991
[m]	Number of species	Number of species
20	8	12
25	4	8
30	3	7
35	2	4
40	2	4
45	0	3
46	0	2

number of Tubificids were also able to exist in addition to the anoxic living varieties already mentioned.

### 5. What's next?

Lake Hallwil is one of the few Swiss lakes which still retains to some extent its original shoreline, and as such this has helped the general recovery of the fish in this lake.

Under what circumstances can the lake be considered to have recovered with respect to repopulation by the benthic invertebrates? This question can only be answered when one considers the fact that the state of the lake, even after repopulation of the entire benthic region is such that it will be impossible to maintain this once the renovation measures are halted. This bleak outlook is the result of the geographical location of the lake, since this has predetermined that the lake will only be capable of turnover and complete recirculation once every ten years. As such, the condition of oxygen deficiency in certain regions of the benthos are inherently pre-programmed.

There remain in this case two possible solutions:

- Once the renovation programme has been completed the natural fate of the lake must be accepted and along with this the realisation that certain parts of the Benthos will never be populated.
- The alternative is that as a minimum the enforced recirculation of the lake continues to be operated during the winter months. How-

ever this will only be truly effective if by then the uppermost sediment layers have become reoxidised and that input of nutrients especially from the Lake Baldegg has been minimised. Given these preconditions this is a possible means by which the revitalised state of the lake achieved after this exhaustive external aeration programme can be maintained.



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# Effects of artificial aeration on trophic status and hypolimnetic oxygen concentration in lakes

René Gächter and Alfred Wüest

## 1. Water quality objectives

Lakes are important sources of drinking water. As "natural" habitats, they not only produce fish but also guarantee the survival and natural reproduction of all other organisms present in the unpolluted waters. They also serve as places of recreation.

Algal blooms are not only unpleasant, they may also impair the taste of drinking water or even cause fish kills. In any case, they drastically lower the oxygen concentration in the hypolimnion. For these reasons, lakes in Switzerland must satisfy the two following minimum water quality criteria:

- Unfavourable natural conditions excepted, lakes should be oligotrophic or at the most mesotrophic.
- Oxygen concentrations should never fall below  $4 \text{ g O}_2/\text{m}^3$  anywhere in the lake at any time (without artificial aeration).

In order to grow, algae require various nutrients. According to the limitation law, the growth of algae is limited by the nutrient in shortest supply compared to demand. In lakes, the production of algae is generally lim-

ited by the concentration of available phosphorus compounds, as illustrated in Fig. 1. In oligotrophic lakes, primary production increases in proportion to the P concentration. In eutrophic lakes, it reaches a plateau at about  $460 \text{ g C}/\text{m}^2 \text{ yr}$ . In mesotrophic lakes, primary production ranges between 150 and  $200 \text{ g C}/\text{m}^2 \text{ yr}$ . On average, production rates of this magnitude are attained at phosphorus concentrations approaching 20 to  $30 \text{ mg}/\text{m}^3$ . In individual lakes, however, the relationship can deviate markedly from the average relationship shown in Fig. 1.

## 2. What are naturally unfavourable conditions?

With respect to oxygen, conditions are considered to be unfavourable if the natural  $\text{O}_2$  supply is insufficient to prevent the hypolimnetic oxygen concentration from falling below  $4 \text{ g O}_2/\text{m}^3$  at a primary production rate of  $200 \text{ g C}/\text{m}^2 \text{ yr}$ . If we assume, as illustrated in Fig. 2, that:

- 90% of the assimilated organic carbon is respired in the epilimnion;
- 50% of the organic carbon settling to the hypolimnion is eventually permanently buried as refractory organic carbon in the sediment; and
- the other 50% is mineralized mainly during summer stagnation; then  $35 \text{ g O}_2/\text{m}^2$  are consumed in the hypolimnion during the summer stagnation period. Under the assumption that springtime mixing will result in an oxygen concentration of  $11 \text{ g O}_2/\text{m}^3$ , then up to  $7 \text{ g O}_2/\text{m}^3$  can be consumed during the summer without the oxygen concentration falling below the required concentration of  $4 \text{ g O}_2/\text{m}^3$ . A supply of  $35 \text{ g O}_2/\text{m}^2$ , however, requires an average hypolimnion depth of at least 5 m. Consequently, unfavourable conditions can be said to exist in lakes with a shallow hypolimnion.

Oxygen is not consumed in the

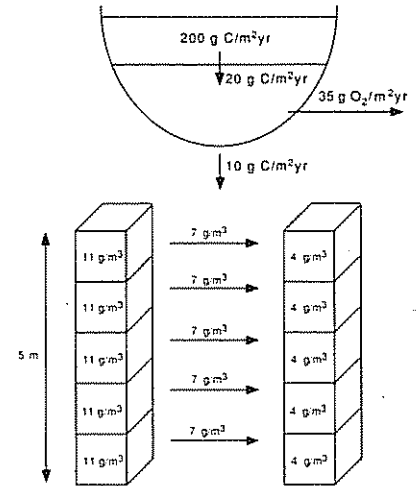


Fig. 2  
Schematic illustration of primary production and mineralization in a mesotrophic lake.

water column alone. Sediments consume even more. As a consequence, as illustrated in Fig. 3, the water quality goal for oxygen may not be attained even in deep mesotrophic lakes if the ratio of sediment surface to water volume is large in the layers close to the

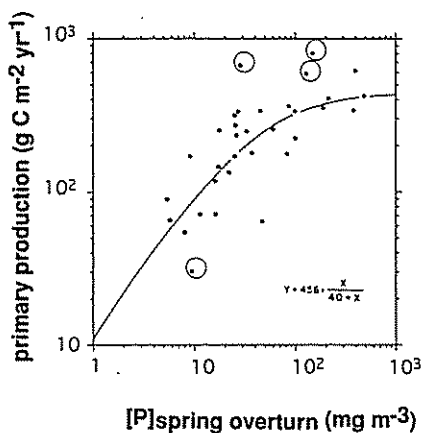


Fig. 1  
Annual primary production as a function of total phosphorus concentration at spring turnover (according to Fricker [8]).

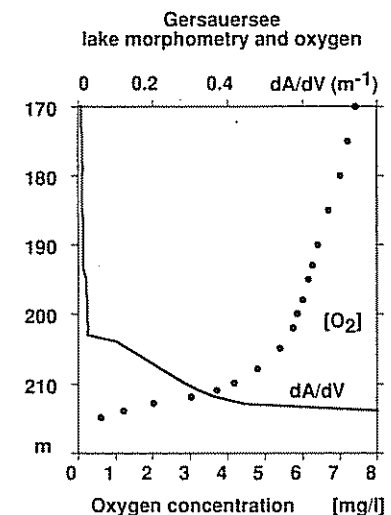


Fig. 3  
Ratio of sediment surface to water volume and oxygen concentration as functions of depth in Vierwaldstättersee (Lake Lucerne) (data supplied by H. Ambühl, EAWAG).

lake bottom, and if eddy diffusion is not sufficient to supply enough oxygen from the upper layers. Conditions are especially unfavourable if the hypolimnion is loaded with allochthonous oxygen-consuming substances (e.g. natural gas), or if mixing during winter is insufficient to bring oxygen concentrations back up to near saturation values by the end of spring turnover. Mixing may be limited by wind exposure or by the release of salts from the sediments [1].

### 3. Were all lakes originally aerobic under natural conditions?

In eutrophic lakes, recent sediments often show a laminated sequence of light and dark layers, whereas older deposits are light in colour and amorphous in structure. Since the time of Nipkov [2], these observations have been interpreted as follows. As a consequence of anoxic conditions at the sediment surface, black iron sulphide is formed in the sediment. During spring and early summer, a layer of light-coloured allochthonous minerals and autochthonously precipitated calcium carbonate is formed. Under anoxic conditions, there are no benthic macrofauna to disturb the sequence. Thus, under such conditions, this lamination is persistent. The uniformly grey sediment underlying the laminated deposits was deposited when the lakes were oligotrophic and their hypolimnia aerobic.

Based on observations of such layering, Züllig [3] concluded that the hypolimnia of many Swiss lakes must have become anoxic a long time before the construction of sewer systems and the introduction of intensive agriculture. For example, 6500 years ago the hypolimnion of Baldeggersee must have been partially anoxic for some time and the hypolimnion of Rotsee, a small lake near Lucerne, has been partially anoxic for 2000 years. The pigment content of 3000 yr old sediments in Soppensee exceeds that of recent sediments. Hallwilersee sediments deposited during the second half of the 18th century are black, although sediments with the same pigment concentrations deposited both earlier and later than this are light coloured and

non-laminated. Such observations suggest that the cause of anoxic conditions at the lake bottom may not necessarily be excessive primary production. It seems that even in Hallwilersee during its oligotrophic period, the hypolimnion exhibited a tendency towards partial anoxia due to insufficient mixing during overturn. Because the release of calcium bicarbonate from sediments increases with increasing primary production, mixing may have declined further with increasing eutrophication. Thus, eutrophication not only increases the demand of the sediments for oxygen, but may also inhibit its resupply.

### 4. What phosphorus concentrations are needed to attain the water quality objectives set?

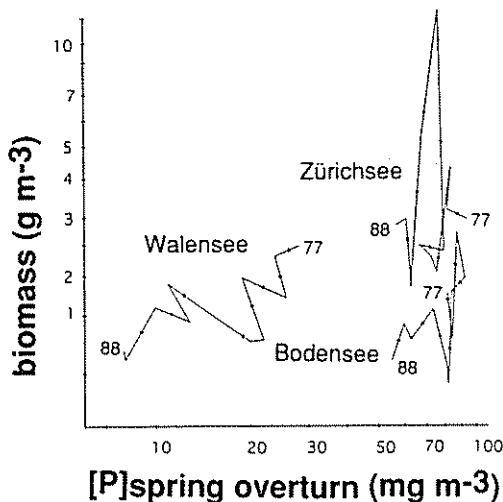
In most Swiss lakes, phosphorus concentrations have been decreasing since the seventies due to advanced wastewater treatment. People living in the catchment area of a lake judge water quality mainly on the basis of aesthetic criteria such as colour, transparency, odour, taste, and quality and quantity of plants living in the littoral zone. They may include in their assessment the quality of the lake for sport fishing as well as information distributed by the media. In the catchment areas of each of 11 lakes, 20 randomly selected inhabitants were called and asked for their subjective opinion on the quality of "their" lake. Answers allowed were "very good", "fair" and "unsatisfactory". The water quality of lakes with phosphorus concentrations less than 40 mg/m<sup>3</sup> was frequently described as "very good" (Table 1). Those lakes with phosphorus concentrations exceeding 100 mg/m<sup>3</sup> were mostly ranked "unsatisfactory", indicating that the people living in the catchment area are aware that despite the costly wastewater treatment the remaining P concentrations are still too high.

Scientists replace such qualitative aesthetic assessments by more objective measurements of phytoplankton biomass or primary production. If phosphorus concentrations and biological parameters such as chlorophyll concentration, phytoplankton biomass or

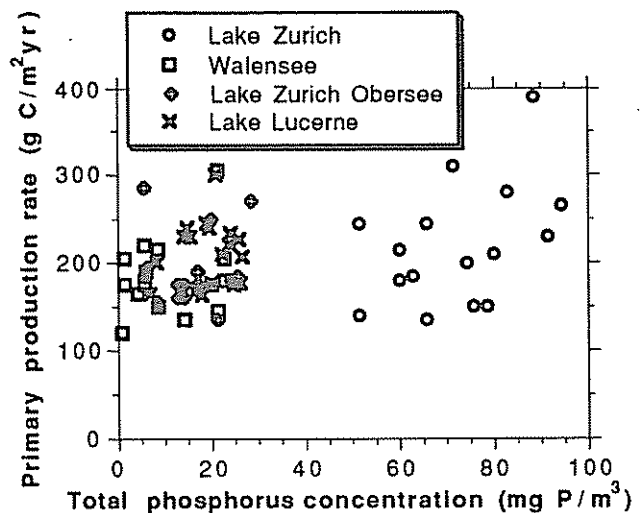
**Table 1**  
*Phosphorus concentration at spring turnover (mg/m<sup>3</sup>) in 11 Swiss lakes compared with a subjective assessment of their water quality by people living within the catchment area of the lake. Grades 1 to 3 denote "very good", "fair" and "unsatisfactory" respectively.*

Lake	Grade	Conc. [P] [mg/m <sup>3</sup> ]
Zürichsee (Lake Zürich)	1.05	35
Walensee	1.05	10
Vierwaldstättersee (Lake Lucerne)	1.10	10
Bodensee (Lake Constance)	1.15	40
Hallwilersee	1.35	120
Bielensee	1.35	45
Lac de Neuchâtel	1.55	70
Lac Léman (Lake Geneva)	1.85	60
Sempachersee	2.15	100
Zugersee	2.45	170
Baldeggersee	2.50	120

primary production are related, then on average, chlorophyll concentrations, biomass concentrations and primary production rates should increase with increasing phosphorus concentrations. Individual lakes, however, can deviate markedly from the average relationships depicted in Figs. 1, 4 and 5. In practice, environmental protection in the case of lakes always deals with individual lakes, and hence such knowledge about a hypothetical "average lake" is only of limited value. For example, concentrations of phytoplankton biomass are nearly equal in Walensee and Bodensee (Fig. 4) although their phosphorus concentrations differ by a factor of two to twenty. On the other hand, the phytoplankton biomass in Zürichsee exceeds that of Walensee by about a factor of three, although phosphorus concentrations are similar. In addition, the phytoplankton of the three lakes differs qualitatively. The phytoplankton of Walensee, Bodensee and Zürichsee is dominated by diatoms, dinoflagellates and blue-green algae, respectively. Fig. 4 demonstrates further that in individual lakes the biomass may vary by a factor of three to five in successive years, even though phosphorus concentrations may be similar. From this it can be concluded that an assessment of the



**Fig. 4**  
Average epilimnetic phytoplankton biomass as a function of phosphorus concentration at spring turnover (according to Stabel [9]).



**Fig. 5**  
Annual primary production rates in four Swiss lakes as a function of total phosphorus concentration at spring turnover.

success or failure of restoration measures necessitates the carrying out of precise observations over a period of several years.

As Fig. 5 indicates, the scatter in the annual primary production rates estimated from 12 to 24 measurements in four individual lakes is relatively large. As a consequence, again, a decrease in the phosphorus concentration of a lake must not necessarily result in an immediate decrease in primary production, if, for example, only two successive years are compared.

These examples demonstrate that no one particular phosphorus concentration can be set as a water quality goal valid for all lakes. Since we do not fully understand the reasons for lakes' individual behaviour, it is impossible to predict exactly the phosphorus concentration to aim for in any one particular lake. As a consequence, the exact phosphorus concentration at which all water quality goals will be achieved must be determined empirically for each individual lake.

### 5. Will wastewater treatment suffice?

The construction of advanced wastewater treatment plants may not suffice to reduce the phosphorus loading of a lake. For example, the loading

of Sempachersee with dissolved phosphorus originating from wastewater decreased from 7 t/yr in 1977 to 1 t/yr in 1988. At the same time, phosphorus runoff from agricultural land increased from 5 to 7 t/yr, diminishing the positive effect of wastewater purification. Today, about 80% of the Sempachersee phosphorus loading originates from soil. In Baldeggensee, soil contributes more than 70% of the phosphorus loading [4]. A phosphorus mass balance reveals that for many years, more phosphorus has been added to the soil as fertilizer than was removed with the crop. As a consequence, the phosphorus content of the soil, and probably also the phosphorus runoff, has increased. In order to avoid a further increase, the spreading of manure would have to be reduced by 30% within the catchment area of Sempachersee and by 50% within the catchment area of the nearby river Bünz [5].

### 6. Experiences with lake aeration

Sempachersee, Baldeggensee and Hallwilersee do not reach the quality goals either with respect to trophic status or with respect to oxygen. All these lakes are subjected to artificial aeration during winter to increase mixing. Because this artificially induced

mixing decreases the oxygen concentration at the lake surface, it enhances the transfer of oxygen from the atmosphere to the water.

In a well-mixed lake, the oxygen concentration ( $[O_2]$ ) approaches steady state. According to equation (1), the steady-state  $[O_2]$  depends on the oxygen concentration at saturation ( $[O_2]^s$ ), the net oxygen consumption rate  $J$  (biological production minus consumption), mean depth  $z$  and transfer velocity  $\alpha$ .

$$[O_2] = [O_2]^s - Jz/\alpha \quad (1)$$

$[O_2]$  increases with decreasing trophic status (decreasing  $J$ ), with decreasing average depth  $z$ , and with increasing wind exposure and wind velocity (increasing  $\alpha$ ). In artificially mixed Sempachersee, Baldeggensee and Hallwilersee,  $[O_2]$  reaches values between 8.5 and 10 g/m<sup>3</sup>. After winters with favourable meteorological conditions, such high values were also reached in Sempachersee even without artificial aeration, but never in Baldeggensee and Hallwilersee, which are more sheltered from the wind by hills. From this we can conclude that artificial mixing during winter has a beneficial effect on the lake oxygen conditions if natural mixing is not sufficient to yield a completely homogeneous water body.

In none of the three lakes is the

value of  $[O_2]$  attained at the end of spring turnover sufficiently high to prevent it from decreasing below  $4 \text{ g/m}^3$  before the end of the stagnation period. For this reason, 2 to 3 tonnes of gaseous oxygen per day are introduced into the hypolimnion in the form of fine bubbles. These bubbles dissolve before reaching the thermocline, and hence do not disturb the natural density stratification existing during sum-

mer.

In Fig. 6, oxygen concentrations in the lakes are compared before and after the introduction of artificial mixing and oxygenation. These measures have obviously resulted in a significant increase in hypolimnetic oxygen concentrations.

### 7. Effects of the artificial oxygen supply on the phosphorus cycling of lakes

As indicated in Fig. 7, the phosphorus content of Hallwilersee and Sempachersee decreased more rapidly after artificial mixing and oxygenation went into effect. In Baldeggersee,

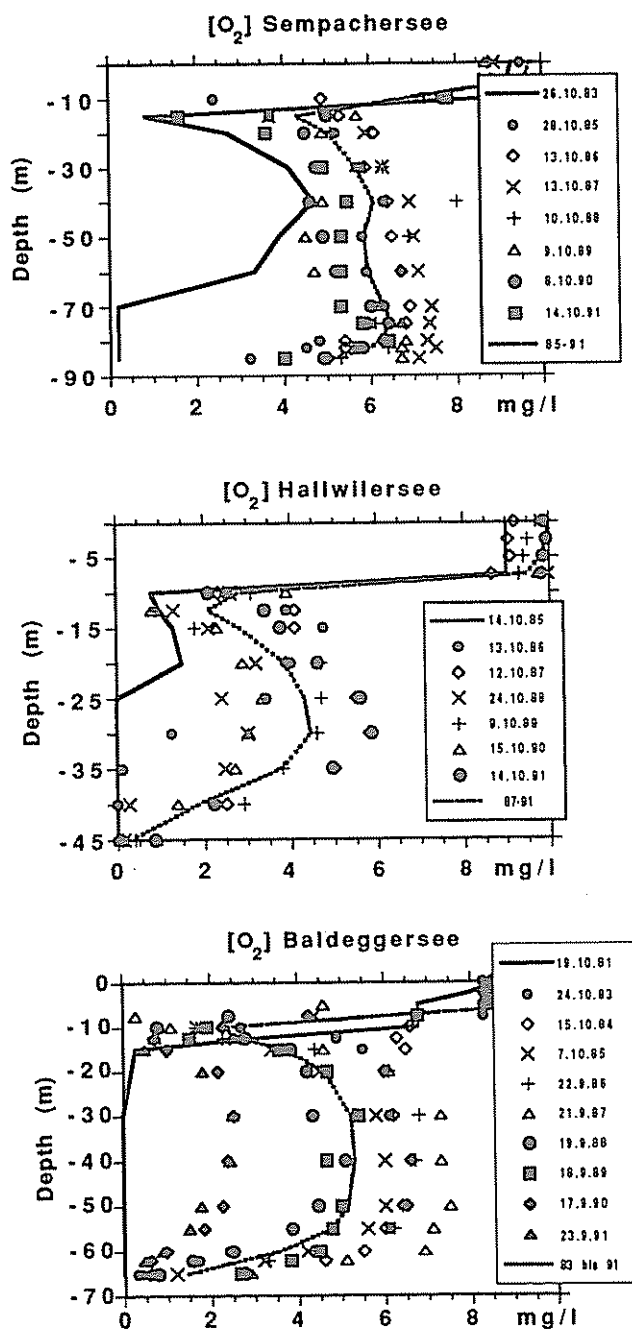


Fig. 6  
Autumn oxygen profiles in Sempachersee, Hallwilersee, and Baldeggersee.

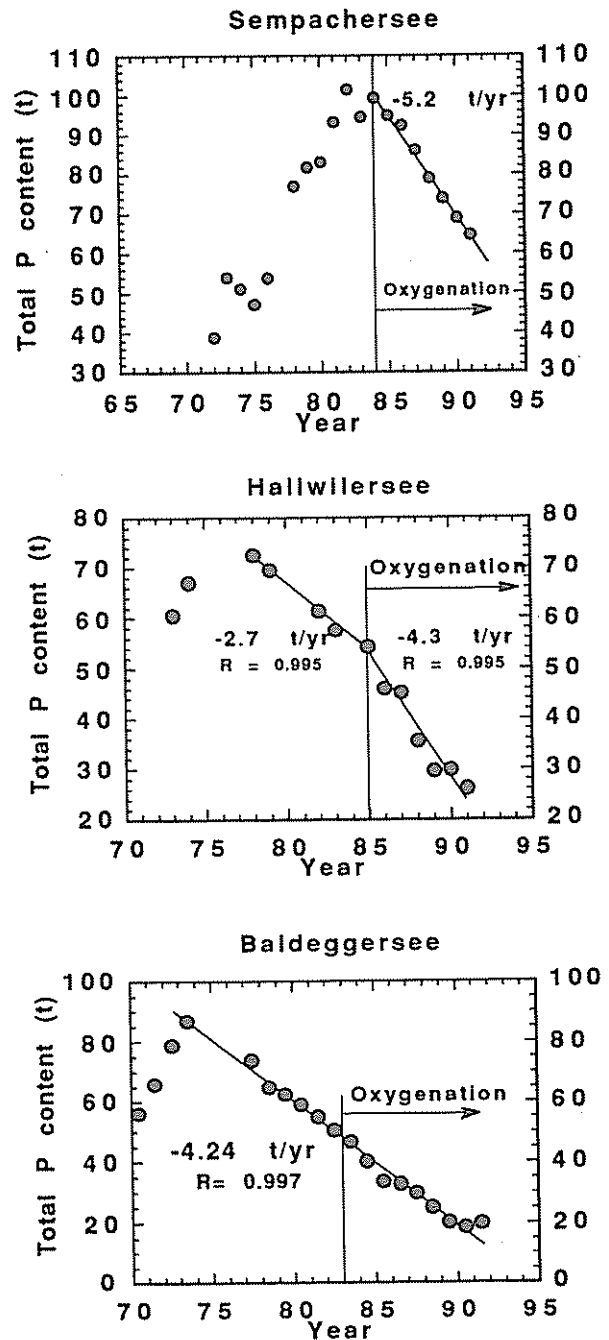
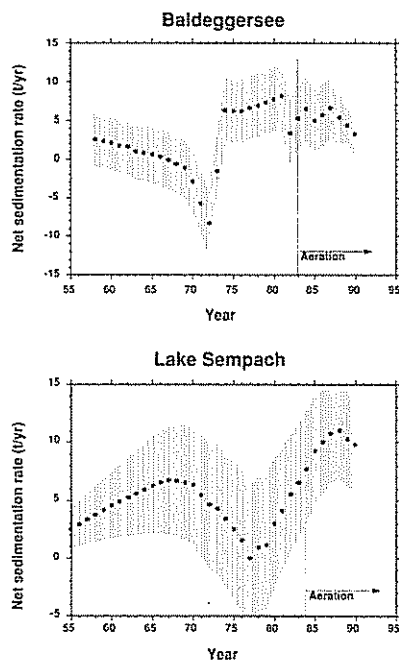


Fig. 7  
Variations in phosphorus content in Sempachersee, Hallwilersee, and Baldeggersee.

however, this was not the case. Increased oxygen concentrations may have increased net phosphorus sedimentation rates in Hallwilersee and Sempachersee. However, as can be seen from equation (2), the rate of change in the P content of a lake ( $dC/dt$ ) depends not only on the net sedimentation (S), but also on the input (I) and export (E) via the effluent.

$$dC/dt = I - E - S \quad (2)$$

If  $dC/dt$ , I and E are known, the net sedimentation S can be estimated. The relatively large uncertainty in the estimated net sedimentation (the shaded area in Fig. 8) results from a large uncertainty in the estimated input values I. According to Fig. 8, the net sedimentation in both lakes reached a minimum in the seventies and began to increase again several years before the internal measures went into operation. It is believed that - due to an increase in the trophic status - the release of phosphorus from the sediment underwent a continual increase before the minimum net sedimentation was attained, and decreased afterwards as easily mobilized phosphorus became



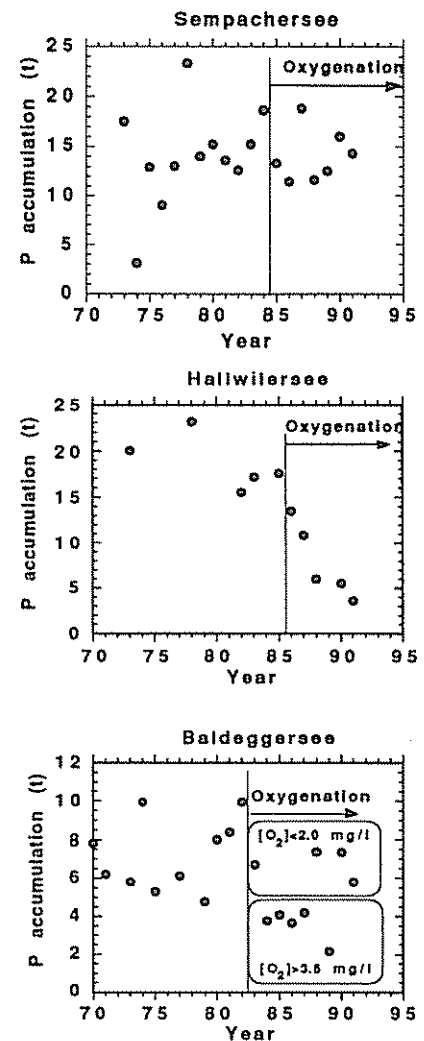
**Fig. 8**  
*Net sedimentation of phosphorus in Sempachersee und Baldeggensee estimated from mass balance calculations (eq. 2). The shaded area indicates the uncertainty in the estimates (mainly a result of the uncertainty in the phosphorus loading data).*

exhausted in the sediment. Because the increase in the net sedimentation did not coincide with the introduction of the artificial aeration measures, the data do not directly support the expected cause and effect relationship: "the more oxygen, the higher the net sedimentation".

The net amount of phosphorus sedimented out is the difference between the gross amount sedimented out and the amount released from the sediment at the sediment/water interface. Because phosphorus released from the sediment accumulates in the hypolimnion, the amount of phosphorus accumulated in the hypolimnion during summer stagnation is a measure of the release of phosphorus by the sediment. The data plotted in Fig. 9 suggest that the phosphorus content of the hypolimnion decreased in Hallwilersee and Baldeggensee at oxygen concentrations exceeding  $3.5 \text{ g/m}^3$  at the lake bottom. In Sempachersee, however, such an effect could not be observed. As shown in Fig. 6 in Baldeggensee and Hallwilersee, almost the entire hypolimnion was previously anoxic, whereas in Sempachersee the anoxic area was restricted to the deepest region of the lake and covered less than 30% of the sediment surface in the hypolimnion. In addition, as shown by Wehrli et al. [7], in this deepest region of the lake the sediment surface remained anoxic regardless of the increased oxygen concentration in the overlying water.

Hüttnersee and Türlensee are two other lakes that are artificially mixed during winter. The hypolimnion of Hüttnersee, which is also artificially aerated during summer, is now aerobic throughout the year, and the hypolimnion of Türlensee only becomes anoxic in late summer. After the internal restoration measures went into operation, hypolimnetic phosphorus concentrations decreased significantly in Hüttnersee, and continued to decrease in Türlensee. However, as shown in Fig. 10, epilimnetic phosphorus concentrations did not change significantly.

To sum up, as a consequence of increased hypolimnetic oxygen concentrations, less phosphorus accumulated in all lakes except Sempachersee. In Hallwilersee this may have acceler-



**Fig. 9**  
*Phosphorus accumulation during summer in the hypolimnia of Hallwilersee, Baldeggensee and Sempachersee before and after artificial mixing and oxygenation went into operation.*

ated the rate of recovery. However, in all other lakes, the increased hypolimnetic oxygen concentrations did not significantly affect the phosphorus content of the epilimnion and hence did not lower the primary production or affect the trophic status.

## 8. Summary and conclusions

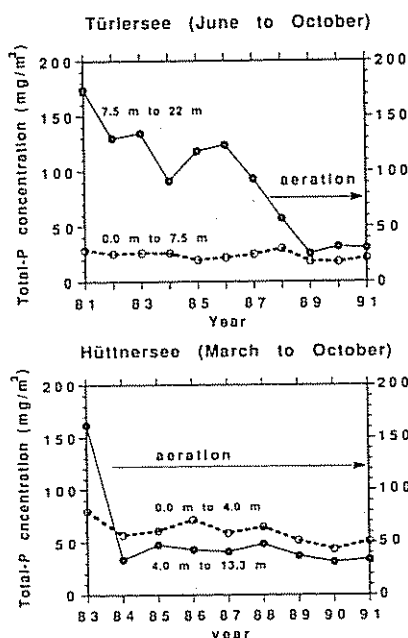
In all Swiss lakes, reductions in phosphorus loading have resulted in decreased phosphorus concentrations and hence in a reversal of eutrophication. However, the dependence of primary production, chlorophyll concentration or phytoplankton biomass on phosphorus concentration

seems to vary from lake to lake, and also from year to year within a single lake. For this reason it is very difficult, if not impossible

- to predict the resulting trophic status of a lake after its external phosphorus loading has been diminished, or
- to define exactly a phosphorus concentration that will guarantee the attainment of a particular objective such as:
  - 1) mesotrophy;
  - 2) hypo-limnetic oxygen concentrations of at least  $4 \text{ g O}_2/\text{m}^3$ ;
  - 3) no aesthetically unattractive phytoplankton blooms;
  - 4) no fish kills;
  - 5) the survival and unhindered natural propagation of all organisms which would be present in the lake if it were in an unpolluted condition;
  - 6) no bad odours; and
  - 7) an adequate drinking water quality.

Consequently, the desired phosphorus concentration must be empirically determined for each individual lake.

Based on sediment records, some



**Fig.10**  
Total phosphorus concentration in surface waters and hypolimnia of Hüttnersee (average March - October) and Türlensee (average June - October) (Data from W. Meyer, AGW Zürich).

lakes experienced anoxic conditions long before sewer systems were invented and fertilizers spread on agricultural land. Such lakes will most probably remain partially anoxic even after the introduction of optimal wastewater treatment and increased care in the use of manure in agriculture. If all the above criteria are satisfied except for the oxygen criterion, however, we see no reason to aerate these lakes artificially.

Artificial mixing during winter is a relatively inexpensive way of increasing the oxygen supply from the atmosphere to those lakes in which eutrophication has caused an accumulation of salts in the hypolimnion sufficient to impede natural mixing. As a beneficial side-effect, artificial mixing increases nutrient concentrations at the surface, and hence the export of nutrients from the lake.

An artificially increased oxygen concentration in the hypolimnion extends the habitat of those organisms that depend on oxygen and lowers the accumulation of phosphorus in the hypolimnion. However, it seems neither to lower the trophic status of lakes significantly nor to guarantee that the eggs of sensitive fish will successfully reach hatching [7].

Artificial mixing and oxygenation of the hypolimnion should therefore only be considered if

- the phosphorus loading of a lake has been lowered as far as possible and the phosphorus concentration has reached a new steady state;
- the water quality objectives mentioned above have still not been attained;
- the sediment record indicates that the lake was oxic at lower rates of phosphorus loading prevailing in the past, and
- artificial mixing and oxygenation are reasonable tools to use in overcoming remaining deficiencies in water quality.

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# Estimate of P-inputs to the Lake of Sempach from diffuse sources, and measures for their reduction

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With the aid of a model for material fluxes, the input of phosphorus to the Lake of Sempach from diffuse sources was estimated. According to this estimate 14.5 tons of phosphorus reach the lake annually from areas predominantly used for agricultural production. The most important pathways for phosphorus input are losses by surface runoff and soil erosion from grassland (45%) and arable land (41%). The largest surface-specific losses are from arable land. Dissolved phosphorus, which presents a problem for the lake, is predominantly from grassland runoff. These diffuse inputs of phosphorus could be reduced approximately by 50%, if a number of appropriate measures were taken.

## 1. Introduction

The total input of phosphorus to the Lake of Sempach is composed of the following loads: 'Streams', 'Sewage treatment plants', 'Rain overflow traps', and 'precipitation' (1). Phosphorus input via streams is separated into 'Untreated wastewater' and 'Diffuse sources' (Table 1).

During the past 30 years, the total phosphorus input to the lake has quadrupled. As a result of measures taken concerning sewage water, the amount of untreated wastewater has dropped by 85%. The contribution from diffuse sources, however, has multiplied to 16 tons annually. The reason for this increase is the intensification of agriculture (Fig. 1).

Hitherto, the contribution from diffuse sources has been estimated by a balance calculation. In other words, the known partial fluxes were subtracted from the total load, and the difference was attributed to agriculture. In the present study phosphorus

inputs from diffuse sources are estimated directly.

## 2. The model for fluxes of material with area-specific assumptions

In (2) a method to quantify nutrient inputs to surface waters from diffuse sources was presented. The model for material fluxes links the data for land use with coefficients for losses specific for different types of utilization. Each section of land within the catchment is characterized by the type of land use (grassland, arable land, forest, fallow or barren land, areas built on at low density), by inclination, and by drainage conditions. Coefficients for losses, which are assigned to each surface section, are taken from the literature or derived from our own field experiments.

The most important land use data in the Lake Sempach catchment are summarized in Fig. 2 and Table 2. Particular to this region is the high

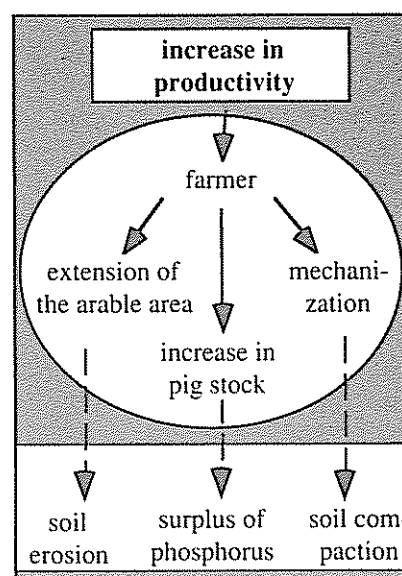


Fig. 1  
Some effects of intensive agriculture in the Lake of Sempach catchment.

proportion of drained plots (30% of the agricultural land) and the high stocking density. In this catchment, an annual load of approximately 270 tons of phosphorus results from farmyard manure (4). This would cover the phosphorus requirement of the area to 150%.

The following parameters were changed in the model for material fluxes used in (2):

Based on provisional results from a field trial in the Lake of Sempach catchment, the contribution of surface runoff to the total discharge is increased from 5% to 10%. This increase can be explained by the number of soils in the catchment which are influenced by down-slope water, groundwater and

Table 1:  
Input of phosphorus to the Lake of Sempach (according to (1)).

years of measurement	input of phosphorus (tons P <sub>tot</sub> y <sup>-1</sup> )			
	the whole	streams and remaining catchment area		
		total	untreated waste water	diffuse sources
1954	4.4	3.4	3.2	0.2
1966-67	10.3	9.2	7.1	2.1
1976-77	14.9	12.8	6.7	6.1
1984-86	14.6	12.5	1.4	11.1
1986-88	18.7	16.6	0.5	16.1

**Table 2:**  
*Partitioning of the agricultural area into grassland and arable land according to levels of inclination.*

land use (ha)	plane (0-5%)	slope (6-30%)	steep slope (over 30%)	total
grassland	1506	2511	8	4025
arable area	300	581	0	881

backwater (3). For the same reason, the contribution of drainage water to the total discharge is increased from 65% to 70%.

The content of phosphorus in the water running off from the surface of grassland is increased from 2 mg P l<sup>-1</sup> to 3 mg P l<sup>-1</sup>. This assumption is based on the provisional results from the same field trial.

The concentration in drainage water is assumed to be 0.1 mg P l<sup>-1</sup> instead of 0.06 mg P l<sup>-1</sup> (3).

Average soil erosion from arable land is increased from 2.5 t ha<sup>-1</sup> y<sup>-1</sup> to 7 t ha<sup>-1</sup> y<sup>-1</sup> (after 3,5). Based on (3) and our own observations, soil erosion from managed pasture and natural pasture located on slopes and steep hills of 1.5 t ha<sup>-1</sup> y<sup>-1</sup> and 0.5 t ha<sup>-1</sup> y<sup>-1</sup>, respectively, is included. Phosphorus content of the top soil is increased from 0.05% to 0.2% (3), and the enrichment factor is eliminated. Furthermore, the deposition factor for eroded soil material is reduced from 60% to 50% because the

density of drains in the Lake of Sempach catchment is 1.5 times smaller than the average for the Swiss Central Plateau (after (2)).

Because of the large numbers of animals and the high density of drains in the catchment, the assumptions for the direct inputs 'Fertilizer discharge alongside waters', 'Direct input from farms', and 'Fertilizer application to roads' are doubled.

### 3. Estimate of nutrient inputs

The results from the calculation of water fluxes are summarized in Table 3. The total discharge of water amounting to 39 million m<sup>3</sup> y<sup>-1</sup> is in agreement with the water balance of the lake between 1986 and 1988 (1).

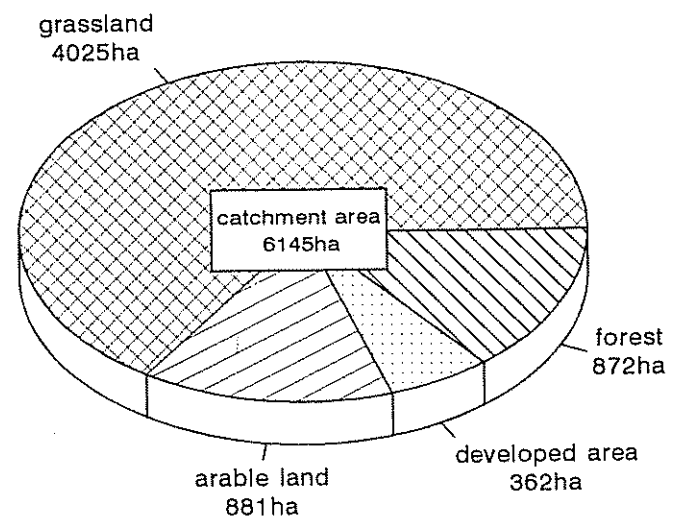
The model calculation reveals an input of phosphorus to the lake from diffuse sources of approximately 14.5 t P y<sup>-1</sup> (Table 4) which agrees with values derived from measurements (1).

With 86% of the total input, surface runoff and soil erosion are the most important input pathways for phosphorus to the Lake of Sempach. Other input pathways are of minor importance. The area-specific loss from arable land via surface runoff and soil erosion averages about 7 kg ha<sup>-1</sup>, and from grassland the average is approximately 1.6 kg ha<sup>-1</sup>. About 45% of the total diffuse phosphorus inputs are from grassland, and about 41% from arable land. In the case of arable land, 97% of the total phosphorus reaching the lake is bound to particles. In the case of grassland, 74% occur in soluble form which is more problematical for the lake. In the Lake of Sempach catchment a total of approximately 52% of the phosphorus is lost in particulate form. This is in good agreement with the measured value of 57% (1).

In addition, the estimate for nitrogen inputs to the Lake of Sempach are included in order to validate the model. The resulting 166 t N y<sup>-1</sup> agrees with the 170 t N y<sup>-1</sup> reported in (6). Approximately 89% of the nitrogen from diffuse sources reach the Lake of Sempach via drainage and leaching from the soil.

**Table 3:**  
*Water fluxes into groundwater and surface waters in the Lake of Sempach catchment.*

waterflows	(Mio m <sup>3</sup> y <sup>-1</sup> )	%
surface runoff from grassland	2	4
surface runoff from arable land	0.4	0.9
drainage water beneath grassland	5	14
drainage water beneath arable land	1	3
infiltration to the groundwater beneath forest	6	14
infiltration to the groundwater beneath grassland	19	48
infiltration to the groundwater beneath arable land	4	10
runoff from wasteland	<0.1	0.1
runoff from developed area	2	6
rainfall to surface waters (without lake)	<0.1	<0.1
total	39.4	100



**Fig. 2**  
*Land use in the Lake of Sempach catchment.*

#### 4. Natural background load

The natural background load includes the nutrient losses which would reach the surface waters in the absence of an anthropogenic influence in the region. In the Lake of Sempach catchment the soil would naturally be covered by forests. The natural background load thus represents the loss of nutrients from a closed forest. In the case of phosphorus the respective value is about 0.7-1.0 t P y<sup>-1</sup>. Consequently, the loss of phosphorus from diffuse sources due to present-day agricultural land use is approximately 15 times higher than the natural background load.

Table 4:  
Inputs of phosphorus from diffuse sources to the Lake of Sempach.

Input pathways (t P y <sup>-1</sup> )	P <sub>particulate</sub>	P <sub>total</sub>	%
nutrient losses by surface runoff from grassland		4.8	33
soil erosion on grassland	1.7	1.7	12
nutrient losses by surface runoff from arable land		0.2	1.3
soil erosion on arable land	5.8	5.8	40
nutrient losses by drainage beneath grassland		0.5	3.7
nutrient losses by drainage beneath arable land		0.1	0.8
leaching beneath forest		0.1	0.8
leaching beneath grassland		0.4	2.6
leaching beneath arable land		0.1	0.6
losses of waste land		<0.1	<0.1
losses of developed area		<0.1	0.2
atmospheric deposition to surface waters		<0.1	<0.1
pasture alongside waterways		<0.1	<0.1
application of fertilizer alongside waterways		<0.1	0.1
direct input from the farm		0.5	3.7
livestock traffic on roads		<0.1	<0.1
application of fertilizer to roads		0.2	1.2
<b>total</b>		<b>14.5</b>	<b>100</b>
P <sub>particulate</sub>	7.5		52

#### 5. Measures to reduce phosphorus inputs

In order to reduce phosphorous inputs from agriculture, measures must be taken in five main areas:

- 1) **The infiltration capacity of the soil in grassland must be maintained or even increased, in order to reduce surface runoff:**
  - adapted mechanization and optimized timing of cultivation
  - extensive farming where sensitive soils occur
  - a dense and possibly closed turf
- 2) **Fertilization must be optimized with respect to vegetation, site conditions, and timing:**
  - balanced nutrient budgets, i.e. a maximum of 2.5 large animal units per hectare
  - buffer zones alongside surface waters, drainage wells, and streets
  - no application of liquid manure to frozen soils and to soils covered with snow, and reduced application of liquid manure to wet soils and before heavy rainfalls

#### 3) Reduction of soil erosion in arable farming (9):

- cultivation adjusted to site-specific conditions and production of crops in suitable crop rotation
- reduction of the area of arable land
- consideration of measures to reduce soil erosion for all types of cultivation: seed rows, minimum soil management, contour cultivation, integrated weed management, etc.
- preservation and new establishment of hedge rows and lanes

#### 4) Improvement of water retention in the catchment:

- preservation of existing gullies and raising of inlet wells (sedimentation basins)
- building of small terraces and dams to reduce surface erosion

#### 5) Direct inputs must be reduced:

- special care when applying liquid manure
- tight storage containers and pipes

#### 6. Possible potential for further reductions

The estimate of the potential for reductions can be done in the same way as the estimate of nutrient inputs was carried out with the aid of the model for material fluxes. The parameters for surface runoff and soil erosion which are primarily influenced by agricultural measures are adjusted according to experimental data and cross-comparisons. It should be possible to reduce surface runoff from grassland by 25% and to reduce the concentration of phosphorus in surface runoff by 40%. Direct inputs from farms and roads could be cut in half. Based on the fact that soil productivity can only be maintained in the long run if soil erosion does not exceed 1 t ha<sup>-1</sup> y<sup>-1</sup>, this value is used as a maximum tolerable value for soil erosion from arable land.

Based on an input of phosphorus amounting to 14.5 t P y<sup>-1</sup>, the calculation reveals a potential for reduction of approximately 8 t y<sup>-1</sup> (Fig. 3). Relative to the total diffuse losses minus the natural background load, this reduction is equivalent to 60%.

The largest potential to reduce the

total load of phosphorus is associated with arable farming. In order to reduce the load of soluble phosphorus, measures focusing on grassland result in the most substantial reduction (Fig. 3).

## 7. Concluding remarks

The agreement between measured values and the values estimated by the model (water fluxes, phosphorus inputs, ratio between bound and soluble phosphorus) demonstrates that the model for material fluxes from (2) can be applied to smaller catchments. Because of the necessary assumptions,

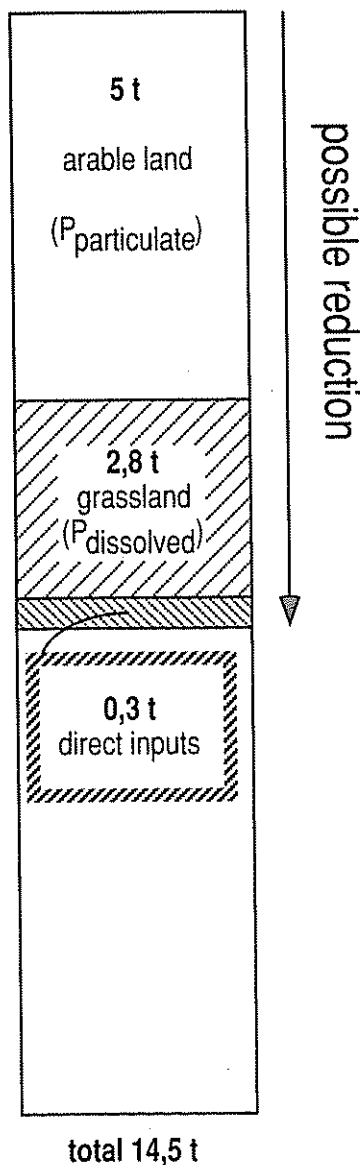


Fig. 3  
Estimated yearly reduction potential of phosphorus input through agricultural measures.

however, the estimate must be interpreted with caution. Furthermore, the variable soil conditions in the catchment have not been considered. For this reason, the calculation of loads from individual affluents is not possible. In this sense, the present contribution represents a study of plausibility.

The largest portions of phosphorus input to Lake of Sempach are from soil erosion and surface runoff. While arable land shows the highest area-specific loss of phosphorus, grassland contributes the most to the load of soluble phosphorus which causes problems to the lake.

According to (7), the contribution from agriculture should not exceed 2 t  $P y^{-1}$ , in order to reach the goal of restoring the Lake of Sempach (oligotrophication). The estimate reveals that this goal can only be achieved by additional measures (reduction of arable land, a maximum of two large animal units per hectare, etc.).

Measures to reduce phosphorus inputs from agriculture have long been known. Their realization, however, is problematical because most of these measures would lead to a loss of income for the farmers. The change in the law for agriculture (i.e. direct payment for ecological services) is a first step in the right direction. Because of the difficulties arising from the existing infrastructure, from restricted funds, and from the 'human' factor, most measures will only be realizable in the long run, and, eventually, technical measures, such as drying of liquid manure or low-phosphorus feed for pigs, might need to be considered in the short term. However, in the end, only by a change in the agricultural awareness and in society as a whole will the recovery of the Lake of Sempach be possible (8).

### Acknowledgement

We thank the Federal Office for Environment, Forest and Landscape for the financial and technical support. Also, we acknowledge all technical offices for supplying data.

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# Reflection in the Lake of Sempach

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Man's environment is the reflection of its inner life. The status of the Lake of Sempach reflects the feelings of the people who utilize the rural environment primarily for the production of physical nutrition. Thus the solution to the 'Environmental Problem Lake of Sempach' can not only be sought in the physical, external world but also in the psychological inner world of man.

## 1. The Lake of Sempach is ill!

As a result of nutrient inputs, mainly from sewage and from agriculture, the lake became overfertilized which led to the collapse of its regulatory system. Since then it has been aspirated artificially in order to keep it alive.

Due to agricultural land use, about 15 times more phosphorous reaches the lake as compared to the natural background load (5). In addition to the steps towards restoration already taken, measures targeting on agriculture should be realized. Depending on the desired reduction potential concerning nutrient inputs, measures at different levels must be taken (Fig. 1):

- At a **scientific** level: Measures such as actions taken by the farmers around farms and in the field lead to a relatively small reduction potential. These measures include: Reduction of surface runoff from grassland, proper fertilization with respect to crop, site conditions, and time, reduction of soil erosion from arable land, reduction of direct inputs, etc.

- At a **political** level: An intermediate reduction potential results if the measures at the scientific level are supplemented by measures such as those used in the various areas of realization. These measures include: subsidies for ecological services (agricultural policy), revision of the water protection law (legislation), etc.

- At the level of the **humanities**:

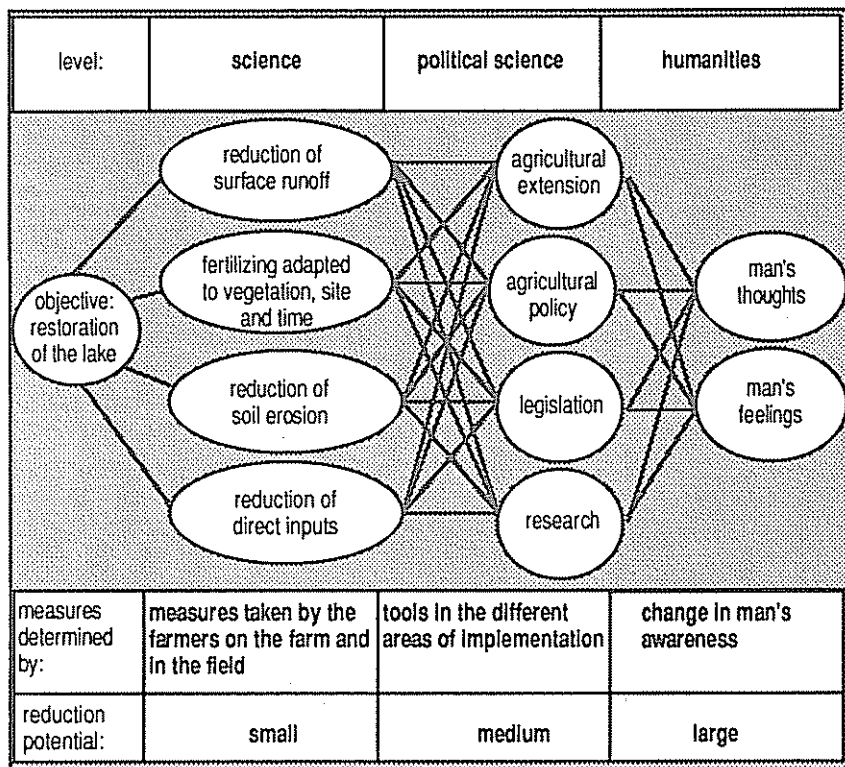


Fig. 1

Measures to restore the Lake of Sempach are necessary at various levels.

The potential for reduction is largest when measures are taken to directly changing man's awareness. These measures include: confrontation with the psychological and physical links between man and its environment (thoughts and feelings), adjustment of man's rhythm to that of the earth, etc.

In (5) it was shown that by taking measures at the first two levels the desired degree of reduction of nutrient inputs to the Lake of Sempach and recovery of the lake cannot be obtained. Hence it is the aim of this presentation to establish a link to the human level.

## 2. Inner life and the external world

All humans have an inner life and an external world. The term 'external world' will be used here as a synonym for 'environment'. A man's life is the

plane of interaction for inner life and external world (Fig. 2). Inner life and external world are linked with each other physically by the exchange of matter, water, air, and energy. A particular atom which could have been part of the external world yesterday is build into inner life today. The physical inner life is composed of body, food taken in, aspirated air, etc. The physical, external world is composed of the basics for life, i.e. soil, water, air, etc.

Inner life and external world are also linked psychologically to each other by the conscious and the subconscious. (Today, the subconscious is rather called the 'unconscious', because it does not need to be subordinated.)

The personal subconscious of each individual is rooted in the 'collective subconscious' of all life (2,3,4, and 7). Contrary to the subconscious, the con-

scious can think logically. On the other hand, the subconscious holds the entire life. Even when conscious is turned off during sleep, the subconscious keeps the heart beating, the lungs breathing, etc. Thus the psychological inner life is composed of personal thoughts, feelings, dreams, etc. The psychological external world is composed of collective thoughts, feelings, dreams, etc.

Interactions exist between the conscious and the subconscious. Thoughts as part of the conscious can act as orders for the subconscious which are executed by the later. The behaviour of a person becomes the reflection of his thoughts and feelings. To take full advantage of mental capabilities means to use the conscious, the subconscious and their interactions in favour of both inner life and external world.

In (6) the thermal death of feelings is described. Feelings can be a synonym for the subconscious. As the feelings for the external world become cooler, man begins to destroy it by polluting soil, water, and air, as well as by the extinction of animal and plant species. Because of the psychological and physical links existing between inner life and external world, every destruction concerning the external world is equivalent to a destruction of inner life. Inner life becomes the reflection of the external world.

On the other hand, the external world is also a reflection of inner life. Internal equals external (2). Every destruction of the environment reveals how internally ill man is. Illness of inner life emerged because man was no longer aware of himself internally. Illness of inner life has become illness of the external world; therefore, the pictures are very similar. Inner life and external world can be ill in a psychological or physical way (Fig. 2).

The status of surface waters reflects agricultural land utilization in the catchment (1). But, agriculture is also the reflection of agricultural policy, the later being the reflection of society, which itself is the reflection of all people. In this sense, the Lake of Sempach reflects man's thoughts and feelings that the utilization of rural land mainly serves to produce physical nutrition, and that psychological values are being forgotten.

### 3. Protection of inner life and external world

The realization that illness can be caused by the psyche led to the creation of the term 'psychosomatic illness'. But there is another side to this observation.

By taking advantage of mental capabilities, and, especially, by the power of the subconscious, one can heal the symptoms of illness of inner life (7). The subconscious has access to all information about life's functions under normal conditions. A positive attitude towards illness can thus be favourable for recovery. This was recognized by ancient cultures which is indicated by their term for medication 'remedium' which means 'back to the centre' (2). From our own centre, we derive the energy to protect ourselves from illness and to heal illness. It is where we find access to the subconscious.

Illness of inner life and external world produce the same symptoms. We can thus conclude that in analogy to the illness of inner life, illness of the external world can be healed through the utilization of mental capabilities. This means that the external world can only be restored if man changes its thoughts and feelings towards it. Consequently, illness of the external world

is also a psychosomatic illness. The body affected by the illness (= 'soma') is the earth.

The realization of the existence of a uniform principle for recovery points in the same direction. This principle acts in the form of the subconscious in all forms of life: in humans, in animals, in grass, in the wind, in the earth ... (7). This general principle for recovery acts in inner life as well as in the external world. Protection of inner life and the external world merge to form a circle (Fig. 2).

### 4. Outlook

Illness of the external world reflects illness of inner life. In the same way many medications are used to treat symptoms of inner life illness, often measures to protect the environment are used to treat the symptoms of external world illness. In both cases, medication is used to cover the symptoms of illness, thereby obscuring the view of the origin of the illness. But illness is an indication that the body has a problem. Environmental problems thus are only secondary questions with respect to survival. They are, in the first place, a sign of the illness of man's external world and inner life.

Nutrient fluxes are a reflection of

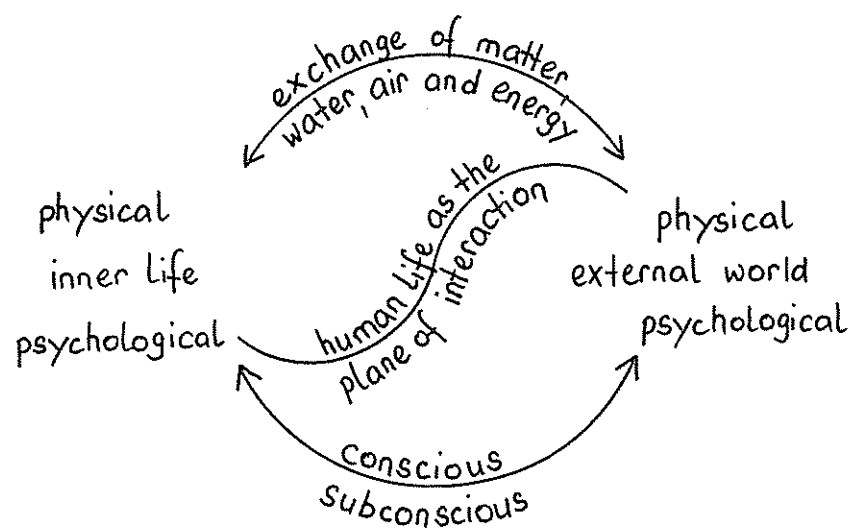


Fig. 2

Man's inner life and external world, as well as physical and psychological relationships.

man's way of life. Nutrient fluxes increase with increasing production and increasing rhythm of man's life. If a reduction in the nutrient fluxes in the external world is required, then the increase in the life rhythm must be broken down and adjusted to the natural rhythm of the earth. This means that the people must learn again to sense the earth's rhythm and to oscillate with the earth. To the same degree as man lives compatible with the external world, they will be compatible with inner life. Similar to the way psychotherapists invest in the treatment of an ill inner world, environmentalists are engaged in the healing of an ill external world. The two groups should collaborate more closely.

The solution for external world illness must be sought both in the physical external world and in the psychological inner life. The solution for the

external world problem called 'Deterioration of the Lake of Sempach' not only requires measures for reductions in external world agriculture, it also requires a change in the way each individual person thinks and feels about the soil, the water, and the air in the catchment, in Switzerland, in Europe, and on earth. This appears in the reflection of the Lake of Sempach.



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## Concluding remarks

Alexander J. B. Zehnder

### 1. The lake

Lakes are valuable components of our landscape and function as points of attraction for recreation and tourism. Lakes serve as a source of food, carry traffic and store water. The variety of uses they are put to, the fact that sewage, both treated and untreated, is introduced into them, and their role as receiving basins for substances eroded from agricultural land has led to their pollution and a consequent reduction in their water quality. In contrast to rivers, the water bodies of lakes do not undergo rapid renewal and consequently must deal with the pollution and enhanced nutrient input themselves. Many lakes are unable to cope with nutrients and other types of pollution. The result is eutrophication.

In Swiss lakes, eutrophication is brought about by an oversupply of phosphorus, mainly in the form of phosphate. An increase in the phosphorus input raises algal production, and in eutrophic lakes leads regularly to algal blooms. Decomposition of dead algae in the deep lake water or on the

lake bottom causes oxygen depletion and renders these parts of the lake uninhabitable for higher organisms.

Phosphorus in the upper layers of the lake is taken up by algae and incorporated into the biomass. Dead algae sink to the sediment, taking their bound phosphorus with them; most of this phosphorus is released into the water as phosphate during mineralization. Phosphates also form salts or are adsorbed onto particles. Both insoluble salts and particles sink to the lake bottom. These input processes enrich the sediment with phosphorus. Part of the annual phosphorus input is made available again by remineralization and recycling processes; part of the phosphorus remains in the sediment, however, and there undergoes continual enrichment.

### 2. Water protection measures

As early as the 1950s, water protection efforts were focused on keeping lakes and their inflows free from pollution. The reasons for this were

the occurrence of rather obnoxious algal blooms at the lake surface, and of oxygen depletion in the depths of the lake. Considerable financial investment in lake restoration has been made at federal, cantonal and community government levels in Switzerland over the last 30 years. The main emphasis has been on treating wastewater and, in many cases, keeping the treated wastewater away from the lakes altogether. Detergents containing phosphates were prohibited, leading to a reduction in lake phosphorus pollution. For 10 - 15 years now, the effect of the water protection measures introduced on Swiss lakes has been obvious. Phosphorus concentrations in the lake water are continually decreasing. The condition of some lakes today is very good. Many lakes, however, are still excessively polluted with phosphorus, especially those in agricultural areas. Artificial aeration can help in such cases, but artificial aeration cannot solve all problems and should only be employed temporarily to allow time for more thorough measures. In future, the major emphasis must be

on reducing the phosphorus input from agriculture. The necessary measures must not be enacted with only lake pollution in mind, however, but should be viewed within the context of a general strategy to combat environmental problems associated with agriculture (the pollution of surface waters and groundwater with nitrogen compounds is another example) and to facilitate nature conservancy.

### 3. Lake sediments as "contaminated sites"

Despite all restoration measures employed, much phosphorus still remains in the sediment. Lake sediments have become "contaminated sites", a source of stored pollution. This can only be dealt with by elimination or isolation. The success of lake restoration measures thus depends strongly on whether the phosphorus remains bound in the sediment, or even better, can be eliminated from the sediment and from the lake. An oxidized sediment layer of up to a few centimeters thick present during the whole year can prevent phosphorus from being remobilized. Such a layer acts to isolate the phosphorus from the lake. In the short term, artificial aeration can make possible the renewed settlement of the sediment surface with benthic organisms. However, a drastic reduction in phosphorus input and, with it, primary production (algal growth) is necessary if the sediment surface is to be brought back to an aerobic condition in the long term. Technical measures of eliminating phosphorus from the sediments do exist. One possibility is the removal of the phosphorus-rich sediment layers, analogous to the dredging of harbors; another possibil-

ity is the installation of a deep-water diversion system to remove phosphorus-rich water. For various reasons, however, both measures are difficult to carry out. The dredging of lakes is hardly feasible economically; in addition, there is no space to store the dredged sediment with its load of partly toxic substances. Deep-water diversion is both economically and technically feasible; carrying it out in practice, however, often founders on the resistance of those living below the lake, who have no great desire to have other people's dirt flowing past their own door. The question also arises of whether it is justifiable to burden the North Sea, the Mediterranean or the Black Sea with the pollution of inland waters. Treatment of the deep water after diversion could lead to acceptable solutions, but the relevant technology has yet to be developed.

### 4. The future

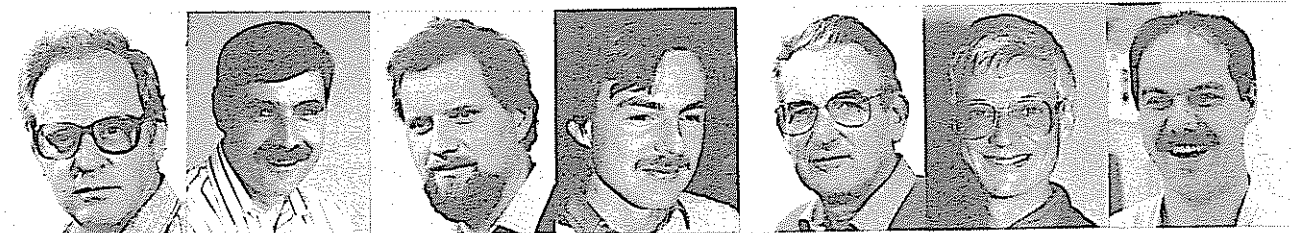
Until now we have concentrated mainly on eutrophication and its cause: phosphorus. The relative degree of success we have achieved with the various measures we have employed should act to spur us on, not only to continue with lake restoration, but also, in the sense of sustainable development, to bring the lakes into a condition which would allow future generations to satisfy their needs to as high a degree as possible. The new Swiss water protection law contains certain criteria for such a sustainable development. According to these criteria, lakes should, among other things

- guarantee the health of humans, plants and animals;
- guarantee the availability of drinking water and water for other uses;

- serve as a natural environment for indigenous plants and animals;
- be able to be used for fishing; and
- satisfy the aesthetic requirements of those seeking recreation.

Apart from an understanding of lakes on a physico-chemical level, some of these criteria also demand of us a sound insight into the relevant biological and ecological processes and interrelationships. In the future, we must devote more of our attention to these aspects. Modern developments in biology and ecology allow us to make quantitative predictions in these disciplines, too. If the lake is to fulfil its rôle as ecosystem, it is imperative that the shore areas and littoral also be protected.

As far as lakes are concerned, up until a short time ago we were concerned mainly with limiting and reducing damage. In lakes which are still polluted, these goals are still relevant. Nowadays, however, additional goals to strive for are those of foreseeing and avoiding potential damage and of dealing with the causes impairing the optimal functioning of the lake ecosystem.



*The speakers of the conference (from left to right): Heinz Ambühl, Dieter Imboden, Hans Rudolf Bürgi, Bernhard Wehrli, Fred Stössel, René Gächter, and Markus Braun.*

## News about EAWAG and its employees

### **New EAWAG focus of research**

The focus of research during the coming years is entitled: "Sustainable resource management - the example of water and anthropogenic sediments". It is comprised of:

- the formation, rehabilitation and use of anthropogenic sediments;
- pollution, protection and use of groundwater;
- the rôle of inland waters in the natural environment and as an object of economic use.

These topics and their mutual interactions are intended to yield a basis and suitable techniques for sustainable regional resource management.

### **Körper prize for European science**

Prof. Werner Stumm (director of EAWAG from 1970-1992) has been awarded the "Green Rosette of European Science" by the Körper foundation. His research on chemical processes at particle surfaces forms a prerequisite for understanding the behaviour of substances in the environment.

The "Förderpreis für die europäische Wissenschaft", a prize endowed with 1.25 million Deutschmarks, was awarded to a group of five researchers from Switzerland, France and Germany who work on groundwater pollution and who guarantee successful implementation of the research programme being supported: *Dr. Philippe Behra, Strasbourg; Prof. Wolfgang Kinzelbach, Kassel; Prof. Ludwig Luckner, Dresden; Prof. René Schwarzenbach and Prof. Laura Sigg*, both EAWAG. The scholars intend to use the prize money to extend their knowledge by developing mathematical models for the prediction of groundwater pollution and by testing the predictions on some frequently occurring problem substances.



*Visit by Dr. Philippe Roch, director of BUWAL (Bundesamt für Umwelt, Wald und Landschaft; Federal Office for the Environment, Forest and Landscape) on 6th of October 1992.*

*In his capacity as a new member of the EAWAG consultative commission, he was introduced to EAWAG and discussions were held concerning the future intensification of cooperation between EAWAG and BUWAL.*

### **Expansion of research area**

"Microbiology" is the new title for the former "Technical Biology" department. This change was introduced to more accurately describe the field of research undertaken in the department, including the new areas made possible by the addition of a molecular biology research group. As part of the changes, a rotating scheme has been adopted for the department head. Mario Snozzi heads now the department.

### **New group**

As of January 1993, a new group, "Human Ecology", has been set up by Carlo Jaeger, with the intention of encouraging interdisciplinary work among the humanities, the engineering sciences and the natural sciences

within and outside EAWAG. The group consists of 8 members, including two Ph.D. students.

### **"Nachdiplomstudium Siedlungswasserbau und Gewässerschutz"**

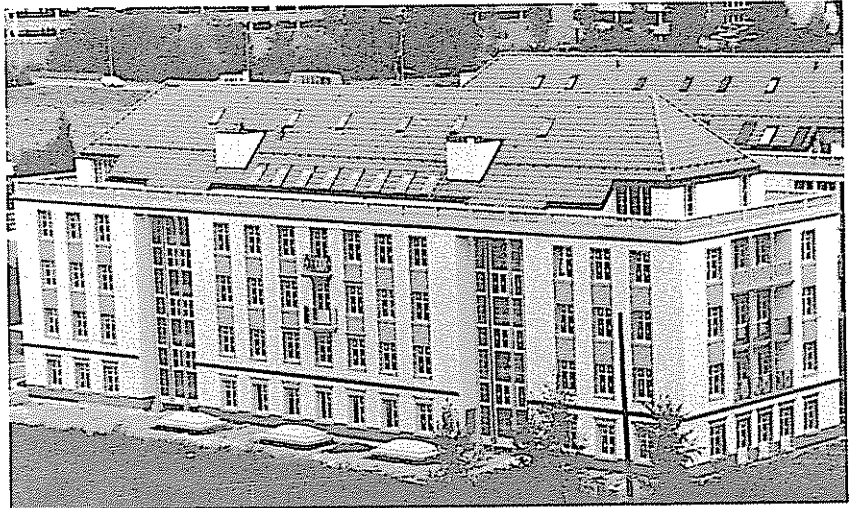
The "Nachdiplomstudium Siedlungswasserbau und Gewässerschutz" (NDS), a one-year postgraduate course in aquatic civil engineering and water pollution protection carried out by the Department of Civil Engineering of the Swiss Federal Institute of Technology (ETH), was offered for the first time in 1980 on the initiative of EAWAG. Since then, 154 male and 33 female students have been able to profit from this course, complementing their undergraduate studies with a course emphasizing either the engineering or scientific aspects of aquatic science.

Until recently, this course offered the only possibility of undergoing fur-

ther education in the fields of ecological interrelationships and technical methods in water pollution control at the Swiss Federal Institute of Technology. The introduction of new degree courses in environmental technology and environmental sciences has, however, led to a certain degree of overlap.

During the 1992/93 academic year, the NDS will be held for the last time along existing lines. A working group consisting of EAWAG and ETH employees under the direction of Willi Gujer supported by Dieter Diem was set up to work out a new concept for the NDS which would take into account the new state of affairs. On the one hand, the lectures forming part of the new degree courses should be made use of, on the other hand, opportunities should be created for working engineers and scientists to undergo further education.

other departments in didactically skilful presentations. The most modern multi-media methods were employed and imagination was found not to be lacking.

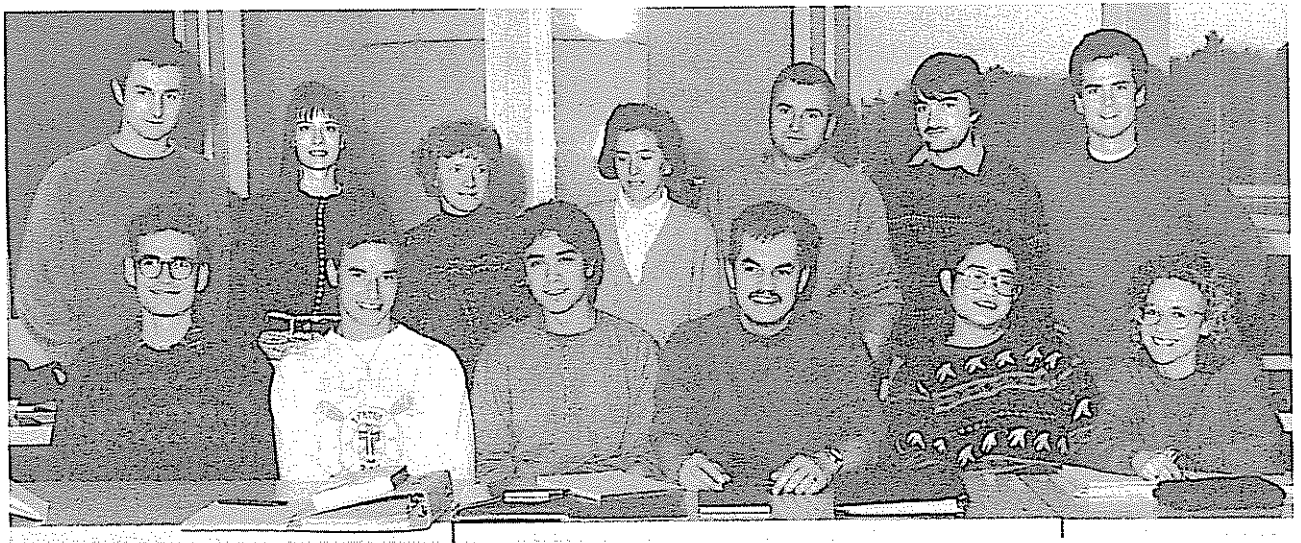


### **Series "We Introduce Ourselves"**

Every Friday afternoon from 11th September to the end of October, each EAWAG department took turns introducing itself to the members of the

### **Moving**

In March 1993, part of the staff will move to new offices in the Chriesbach Building, located near the main EAWAG building (see photo above). Some departments will move from the laboratory wing to the office wing of the main building. Please call in at the reception as before and Ms. Mohlberg will give you directions.



**The 12<sup>th</sup> postgraduate Course in Sanitary Engineering and Water Pollution Control**

**First row (from left to right): Younes Hassib, Martin Häfliger, Max Maurer, Michael Nay, Jianhua Lei, Ivana Vancarkova**

**Second row: Peter Hunziker, Ines Conrad, Christa Hayoz, Monika Kriens, Hans Lamp, Andreas Hurni, Agostino Clericetti**

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## Environmental Organic Chemistry

By René Schwarzenbach, Philip M. Gschwend, and Dieter Imboden

Since society's ever expanding utilization of materials, energy, and space is accompanied by an increasing flux of anthropogenic organic chemicals to the environment, the contamination of water, soil, and air with organic pollutants is and will be a major issue in environmental protection. For everyone who deals with the difficult and complex problems concerning the fate of organic chemicals released to the environment, the book 'Environmental Organic Chemistry' will be both teaching text and valuable reference.

This textbook yields insight into the molecular interactions and macroscopic transport phenomena determining the distribution, in space and time, of organic chemicals. The reader learns how to utilize the knowledge of the structure of organic molecules to deduce the physical properties and chemical reactivities of the respective compounds. The description of the equilibrium and kinetic aspects of phase transfer processes is followed by a discussion of chemical, photochemical, and biological transformation reactions in the environment. The final chapter gives a careful introduc-

tion into modeling concepts. Emphasis is placed on quantification of processes at each level. By considering each of the processes that act on chemicals one at a time, this book provides an understanding that is indispensable in mathematical modeling to evaluate organic compounds fate in the environment.

The various chapters or topics are divided into a more elementary and a more advanced part, thus making this book useful for beginners as well as for people with more expertise. For those who do not recall (or never had) basic chemistry, some important thermodynamic and kinetic concepts are explained on a basic level. References incorporated throughout the text and an extensive bibliography help people who want to study a particular topic in more depth. Besides serving as a textbook, this book should also be a useful source of information for risk and hazard assessment of man-made compounds in the environment.

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### Table of Contents

1. Introduction
  2. An introduction to environmental organic chemicals
  3. Background thermodynamics
  4. Vapor pressure
  5. Aqueous solubility and activity coefficient in water
  6. Air-water partitioning: the Henry's Law constant
  7. Organic solvent/water partitioning: the octanol/water partition constant
  8. Organic acids and bases: Acidity constant and partitioning behavior
  9. Diffusion
  10. The gas-liquid interface: Air-water exchange
  11. Sorption: Solid-aqueous solution exchange
  12. Chemical transformation reactions
  13. Photochemical transformation reactions
  14. Biological transformation reactions
  15. Modeling concepts
- Appendix  
Bibliographie

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