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Aquatic Sciences

Lake Lucerne, Switzerland, a long term study of 1961–1992

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ABSTRACT

Lake Lucerne, Switzerland, "Kreuztrichter"-basin, was investigated between 1961 and 1992. This time period offered a unique opportunity to study an eutrophication event lasting some ten years and the following recovery period as well as the limnological behavior of a deep pre-alpine lake. Results are presented as isopleths and long-term trends. Five year averages show clear patterns in the dynamics of ammonia or nitrite. Lake Lucerne (Kastanienbaum basin) is a monomictic lake, with only one complete overturn every six years. Other basins of Lake Lucerne such as the southernmost basin (Lake Uri), destratify each year, because of its wind-channel orientation.

Kreuztrichter Basin was physically stabilized for years by trophic-induced processes. As the lake recovered, the density gradient in the bottom water layer decreased and turnover frequency increases. The oxygen peak in summer was usually overridden by temperature effects. Nitrogen concentration increased steadily during the 30 year period. Data for N, P, Si and O_2 suggested the concept of compensation depth could be applied. The results were e.g. settling seston had no effect on nitrogen but caused a decrease in soluble phosphorus. In the most productive years silica use was more intense. The abyssal part of the wind-shielded Weggis-Vitznau basin is the most sensitive spot to the effects of nutrients in the lake. This paper is a summary of a more extensive report of the data (Bührer and Ambühl 1996).

Introduction

A long-term study is a kind of monograph that usually reports decades of work in a very condensed way, and thereby emphasizing the highlights. In 1960, today's "Kastanienbaum Limnological Research Center", originated as Professor Hans Bachmann's creation and heritage, and a gift of the Lucerne Society for Natural Sciences to EAWAG/ETH. Limnological activities started at the nearby, 111m deep, "Kreuztrichter" station at October, $1^{\text{st.}}$, 1960. Since then, monthly samples have been collected at several depths, concomitant with in situ measurements of temperature, specific conductance and dissolved oxygen. Water was analyzed for chem-

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ical parameters, for phyto- and zooplankton and during a long period, for bacteria. The laboratory expanded in 1964, which included an additional boat, with the sampling program enlarged to other sub-basins as far as lake Uri. After some years, the sampling program was reduced for technical reasons, and the additional stations eliminated, even though the closest station to the lab (Kreuztrichter "Cross Funnel") proved to be most remarkable. The 30 year study period covers an increase of nutrients in Lake Lucerne to it's maximum and the development back to very low contents. As phosphorus concentrations ended their steep decrease, monthly sampling was replaced in 1992 by the "Swiss Minimal Program" (sampling only in spring and autumn). Since 1992 collection of planktonic organisms was no longer coordinated strongly with the chemical and physical sampling.

Some special programs, such as primary production, plankton dynamics etc. are still going on (by other researchers).

Other Long Term Studies

Discussion of limnologists on the appropriate time period to study a lake has been ongoing across decades. Until the late 1950's, most limnological knowledge was founded on so-called case-studies; short-term (1–2 years) analysis of a lake using monthly sampling.

Lake typology reached it's peak with the conclusion of H.J. Elster (1958) and others that each lake is an individual and should be treated as such. It was obvious that a short glance at a lake, which lasts 1 year in a limnological sense, was insufficient for water protection purposes. Therefore many surveillance programs were started and most of these as monitoring programs by government agencies (CIPEL, Maggiore, Biwa, Tahoe, Great Lakes, IGKB).

Publications of long-term investigations of Swiss lakes exist for Lake Walensee and Lake Zurich (Zimmermann et al., 1993), Lake Constance (IGKB Reports) and Lake Geneva (CIPEL 1995). Many other Swiss lakes are sampled regularly by local authorities and data collected by federal authorities examples cf. (BUWAL Liechti 1995). Bürgi (1995) reported phytoplanktonic trends of Lake Lucerne.

Other long-term studies outside Switzerland are Lake Washington (Edmondson, W.T., 1991), on trend in Lake Michigan silica concentrations (Schelske, 1988), and Lake Tahoe and Castle Lake (Goldman, 1990).

The general conclusion of long term studies is Heraclitus' "panta rhei", i.e. lake chemistry and biology are relatively stable over the "short term" study of a few years (i.e. repeating patterns), whereas nothing is "stable" in longer periods. So-called "biological constants" change with time, because the underlying biocenosis is shifting towards new steady states. These facts not only inhibit a precise description of a lake, but provide the opportunity of parameter separation and therefore a base for new hypotheses.

The entire Lake of Lucerne consists of a chain of different sub-basins, separated by topography: lake Uri, Gersau, Vitznau and Kreuztrichter. Features of the sill at Brunnen (Fig. 1), separating lake Uri and the Gersau sub-basin are described in Aeschbach-Hertig et al. (1996) and in Bührer and Ambühl (1996). The deep lake back current, i.e. the flux of "high" density hypolimnetic water into Lake Uri (as

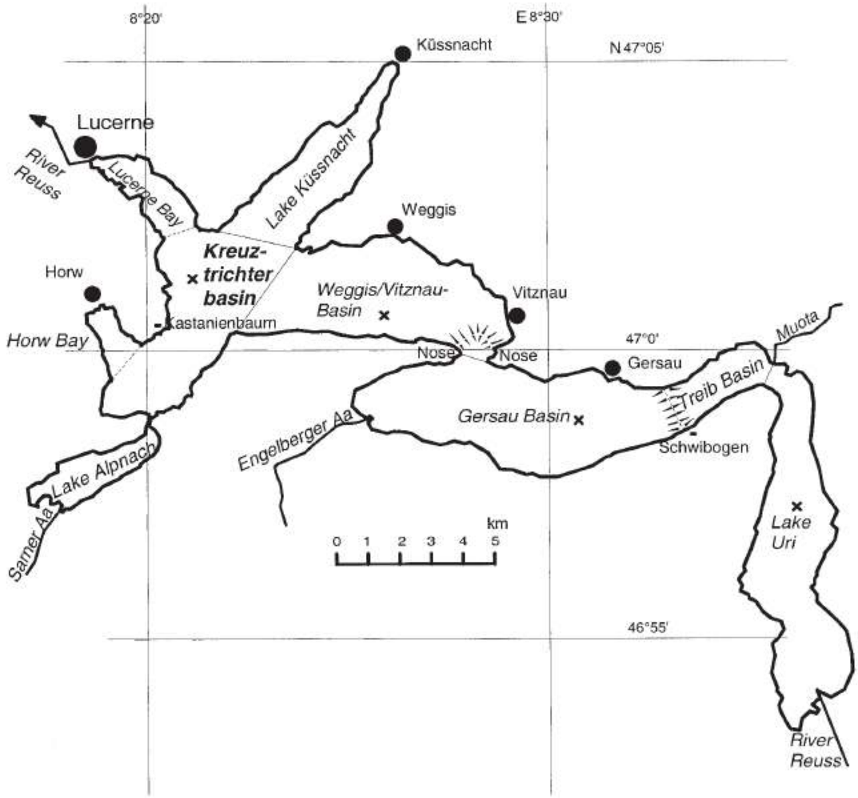

Figure 1. Map of Lake Lucerne, sampling sites (×) and names of basins

postulated by Wüest, 1987), was confirmed with SF_6 by Schlatter et al. (1997). The most distinct constriction is between the sub-basins of Gersau and of Vitznau, where the two so-called noses and a sub-lacustrine moraine form a narrow passageway. An almost fictitious line separates the sub-basins of Vitznau from Kreuztrichter; the sill is at a depth of 100 m. Lake Uri is in a rectilinear valley with steep slopes, that form a wind channel. Therefore frequent storms (Bise and Foehn) are very efficient for partial turnovers of the lake. Basin of Vitznau is wind-shielded by mountains, whereas Kreuztrichter is relatively open and surrounded by hills. An overview of the morphological, hypsographic, and hydrological features, together with a synoptic comparison of the physical/chemical properties of all sub-basins is given in Bührer and Ambühl (1996).

Methods

Remote measurements:

Temperature and conductivity were measured in situ with a sensor that could determine dissolved oxygen using a gold – zinc electrode pair (Ambühl, 1960). Oxygen readings were calibrated by the classical Winkler technique (Winkler, 1888). Temperature was measured by NTC-sensors (thermistors), via an amplified bridge network, to a precision of ±0.05 °C (Ambühl, 1960). Conductivity was measured with electrical alternate current between platinum coated platinum electrodes, with values read with a Wheatstone bridge (Ambühl, 1960) to ±0.5 µmhos cm^{-1}. The same type of instrument was used for the entire thirty year study period. Recalibration was done regularly (until 1974), but later on only when visibly necessary.

Water temperatures were measured usually in the morning between 9:00 and 11:00. Therefore diurnal cycles are disregarded. However, some 24-hour observations, taken in several student courses, did not show substantial temperature variations within a day and within the precision of readings of 0.05 °C.

As temperature, electrical conductance was measured by a remote sensor in a fine vertical grid. Therefore interpolations with time only were needed for plotting the isopleths. The series between March 1975 to March 1978 had to be corrected by a small additive value, due to calcite incrustations on the electrodes.

Chemistry:
Water was sampled using an enlarged Friedinger sampler (type EAWAG 5 L), a wide open cylindrical tube and closed with two plane covers by a messenger. Water samples were usually taken before noon. Water was transferred into Duran glass (boron silica) ground-neck bottles, chemicals added as needed, transported to the "Kastanienbaum" laboratory and filtered. Since 1970, samples have been directly transported to Dübendorf, Switzerland and sensitive parameters were analyzed on the same day. Chemical methods used are those of the limnological department (EAWAG 1996).

Oxygen:
The data base of oxygen values were from Winkler titrations. Vertical intervals were filled with remote estimates, Oxytester (Ambühl, 1960) readings. Therefore any subsequent interpolations of oxygen were needed for time only.

Nitrogen:
After the change from the salicylate method to the reduction method in 1985 the irregularities in nitrogen patterns disappeared. Values in the analysis gap (1986–1990) originated from student courses which were added to our regular data collection.

References for all methods used within the last 30 years would fill a paper in it's own, therefore only recently used methods are referred to in Table 1.

In order to provide a consistent data base, analytical methods were changed only when absolutely necessary (i.e., when clearly superior instruments or methods became available). Changes were done for silica and nitrogen compounds, but both, new and old methods ran parallel for a long time to provide a good correspondence.

Data Analysis:
It is not easy to condense thirty years into one graph. Slow changing (on a monthly scale) parameters, such as temperature or conductivity are plotted as isopleths. Other measures are presented as averaged year or as smoothed time series of

Table 1. Analytical methods

Parameter	Technique/Method	Reference
SRP	colorimetry (in 1960)	Ambühl and Schmid (1965) Schmid and Ambühl (1965) Vogler (1965)
particulate P	peroxodisulfate	Ebina et al. (1983)
dissolved P	ditto	
Ammonia	colorimetry after Bertholot reaction	DEV E5 (1983)
Nitrite	(azo-dye)	DEV D10 (1983)
Nitrate	From 1961 to 1985 salicylate method was used. After 1985: homogenous reduction and estimation as nitrite (azo-dye). In a revision of the survey-program nitrogen compounds were canceled in 1986 and revived in 1990. Values in the gap origin from student courses which were added to our data collection.	
$NO_2^- + NO_3^-$	reduction to NO_2^-	Downes (1978) modified by Stöckli 1985) and DEV D10 (1983)
particulate N	acid peroxodisulfate +	DEV D10 (1983)
DOC	IR-spectroscopy EAWAG	
TIC	same method after acidification with sulfuric acid	
Oxygen	Winkler 1888 modified by	Carpenter (1965)
Silica	Molybdate	

volume weighted average concentrations (Bührer and Ambühl, 1996). Data analysis was completed since 1978 by the FORTRAN program BEKA (Bührer, H., 1975, 1979), which migrated from mainframes in the last years to PC's and workstations. Smoothing of time series was done by a low pass Bessel filter (Bührer and Ambühl, 1996).

Results and Discussion

Temperature

Temperature-isopleths show a similar pattern as in other lakes, e.g. Constance: (Schmitz, 1967), Léman: (CIPEL 1995). Some long rainy (e.g. 1980, 87) periods cooled the surface, with the effect lasting more than a month (Fig. 2). A long-lasting inverse stratification was observed in the unusually cold winter 1962/63 (but without freezing the lake), when Lake Constance and nearly all other Swiss lakes froze. Therefore, Lake Lucerne should be considered a "warm" lake. Some other shorter or minor inverse stratifications were missed due to the sampling interval, e.g. the small harbor at the lab on lake Lucerne was covered several times with ice between surveys. According to Wetzel (1983) Lake Lucerne is situated (latitude and

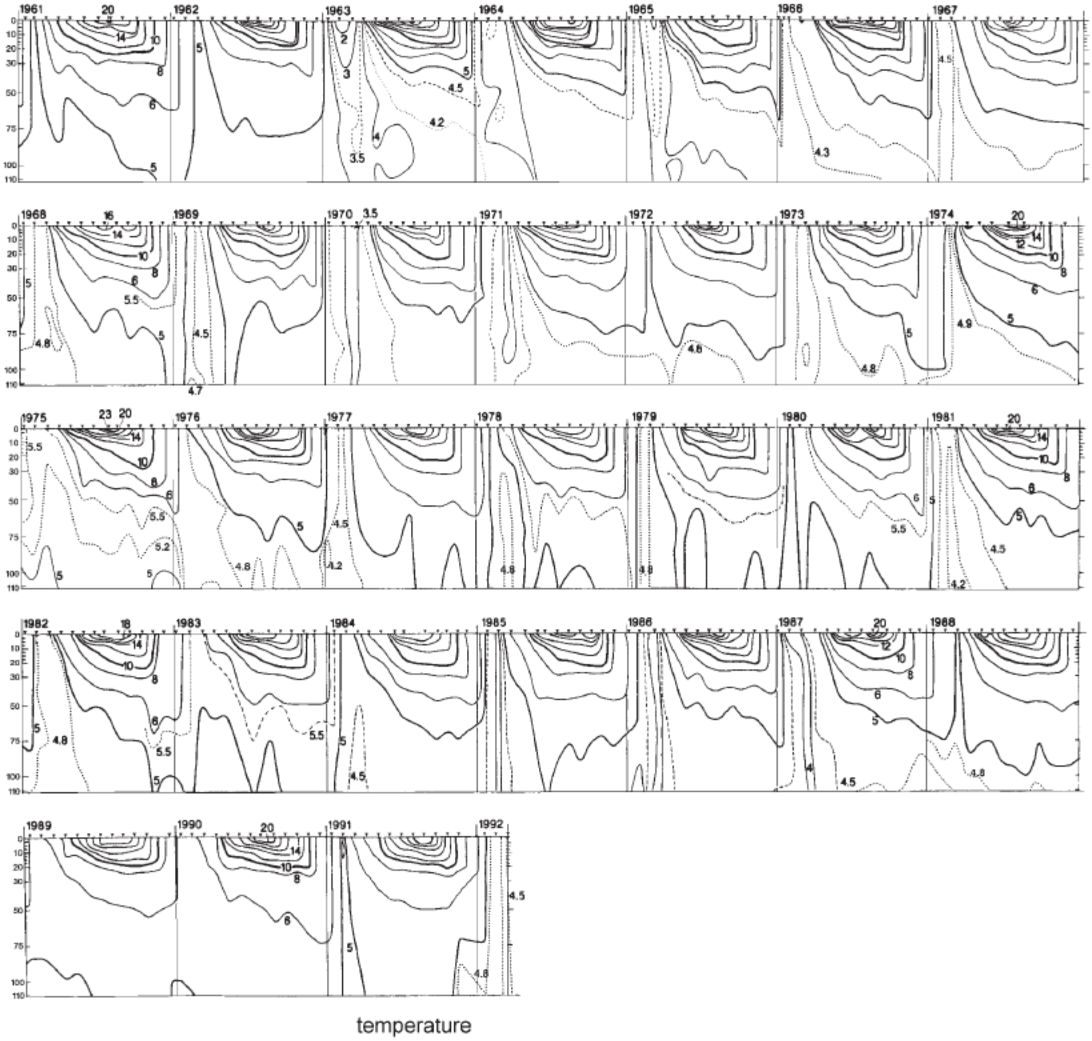

Figure 2. Temperature isopleths of Lake Lucerne at Kreuztrichter basin. Distance between lines above 6 °C are 2°, lower values were selected to optimize appearance of structure

altitude) in the center of dimictic lakes, and thus grouping it among warm lakes is an exception. Perhaps the "Foehn", the warm dropping storm, crossing the Alps, may be an explanation in Lake Lucerne typology.

If we assume that the only heat sources to the lake are sun and air, then temperature isopleths should penetrate monotonously with lake depth. The isopleths in Fig. 2 are uncorrected (unsmoothed) drawings of the monthly temperature readings, interpolated only in time. The "waves", as shown in Fig. 2, are the result of a scaling problem. For example, processes in the lake acting at a shorter time scales, such as algal growth (h), diurnal rhythms (d), or surface and internal seiches (min – h)

(Sarasin, 1900) can interfere with the idealized pattern of top down heat transport. Direct disturbances by interflow of rivers can be ignored for the Kreuztrichter basin because the nearest drainage area is relatively small with minimal discharge. The long-term temperature plot at the lake bottom is described best as a saw tooth curve, with one tooth lasting several years. Temperature decreases indicate turnover. Temperature increases are due to geothermal flux and energy from the decomposition of organic material (both in the same magnitude) and heat transport by vertical eddy diffusion. The local vertical temperature rise in the sediment-water boundary layer is caused by local processes and was observed irregularly because of the low sensitivity (0.05 °C) of the remote thermometer.

The hypolimnion of Lake Lucerne needs usually some years for the temperature increase from 4.2 °C to 4.8 °C, when the probability of a complete turnover increases towards certainty ($p > 0.8$).

Density differences between water at 3.95 °C (maximal density corrected for conductivity, Chen and Millero, 1986) and 4.5 °C are not sufficient to compensate the accumulation of solutes. Starting at winter 1962/63, Lake Lucerne required four years for the next turnover, occurring under oligotrophic conditions. Enhanced stabilization by trophic processes is known for Lake Zug (Wüest et al., 1995) and Lake Lugano (Wüest et al., 1992). We assume that heat loss during a cold winter lasts longer than heat gain from a hot summer because of the shielding effect of the thermocline. In the entire study 1961 – 1992, complete turnover was not observed, if turnover is defined as complete mixing. With a less restrictive definition, 8 "turnovers" were registered (see Fig. 2) and lasted usually less than a month. Inverse stratifications were observed only five times. This is less a question of the lake's physics but of the monthly sampling program.

Conductivity

Conductivity is caused mainly by the mobility of bicarbonate and calcium ions. Alkalinity is here regarded as the sum of bicarbonate, two times carbonate (calcite included) plus H^+ minus OH^-. As the sum of anions (alkalinity) must be balanced by cations (especially calcium), resulting in no electrical charge, alkalinity should be linearly correlated with conductance.

However, the correlation between alkalinity and conductivity was not as good as presumed.

During the study period there was a steady, slow change in the ratio between alkalinity and conductivity (Fig. 3). A general increase in nitrate, chloride and magnesium enhanced conductivity by 15–20 µmhos cm^{-1} (Fig. 4), but this ion-specific conductivity (CRC, 1986) stands only for a small shift and could not explain the drift. The cause of the drift is still unknown but may involve calcite nucleation processes (W. Stumm, personal communication, 1997). For example because alkalinity also includes particulate carbonates contrary to conductance, particle formation may explain the drift in the ratio.

Conductivity is affected in the Kreuztrichter basin by processes which are connected to algal dynamics, such as carbon assimilation, calcite precipitation, sedimentation and decomposition in the hypolimnion. The complex morphology of the

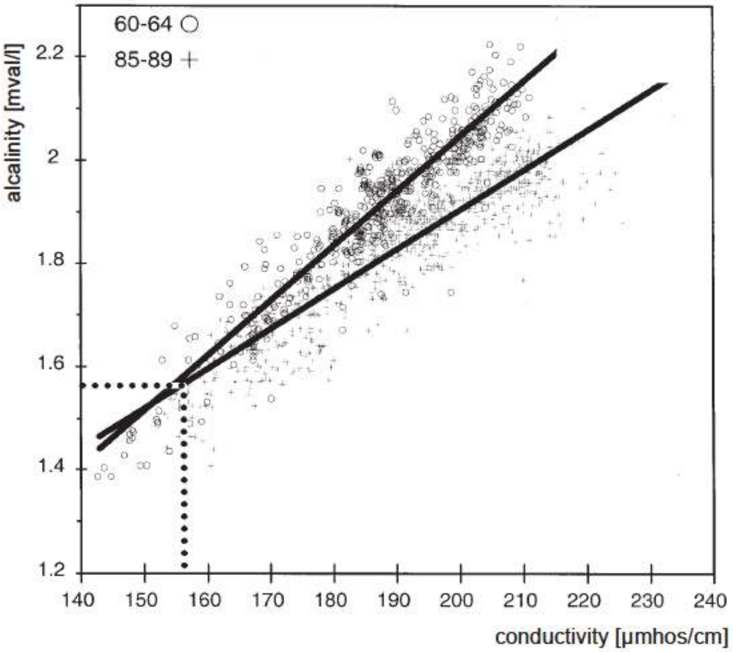

Figure 3. Correlation of alkalinity with conductivity. o Values from 1960–1964; + from 1985–1989. The gap between these two five year periods would show a continuous transition

basin, together with the geochemistry of the catchment area and/or snow melting cycles also influences conductance of Lake Lucerne.

The main water input, the River Reuss, enters the lake at the southern end (Lake Uri) with soft water. Rivers, running in the northern end of lake Uri (Muota) drain limestone catchments and rivers of the sub-basin of Gersau are hard water streams (Bloesch, 1994). The only natural outlet, the River Reuss, leaves the lake through the city of Lucerne at the west end of the lake. According to Imboden (1995), there is an underflow back current originating from Lake Alpnach (Fig. 1), that is loaded with sodium sulfate and continues to the sub-basin of Gersau. As with temperature, local disturbances of conductivity by in- and interflows of local streams play only a minor role and therefore can be neglected for Kreuztrichter station. Isolines (Fig. 4) show, besides long-term fluctuations, some shorter waves, that reflect internal seiches.

The depths of thermocline and chemocline indicated by conductivity should match in non ultraoligotrophic lakes, because self shading of phytoplankton and light extinction by water is preventing primary production in deep layers. Conductivity is reflecting mainly the presence of phytoplankton, and the vertical temperature/density structure is restricting the mixing to the epilimnion. But the chemocline of conductivity in Lake Lucerne reaches 10 m deeper than the thermocline. Compared to Lake Constance or to Greifensee (where the authors also worked for years) this is unusual. In these lakes the temperature and chemistry are stronger correlated. As light compensation depth was less or equal than the depth

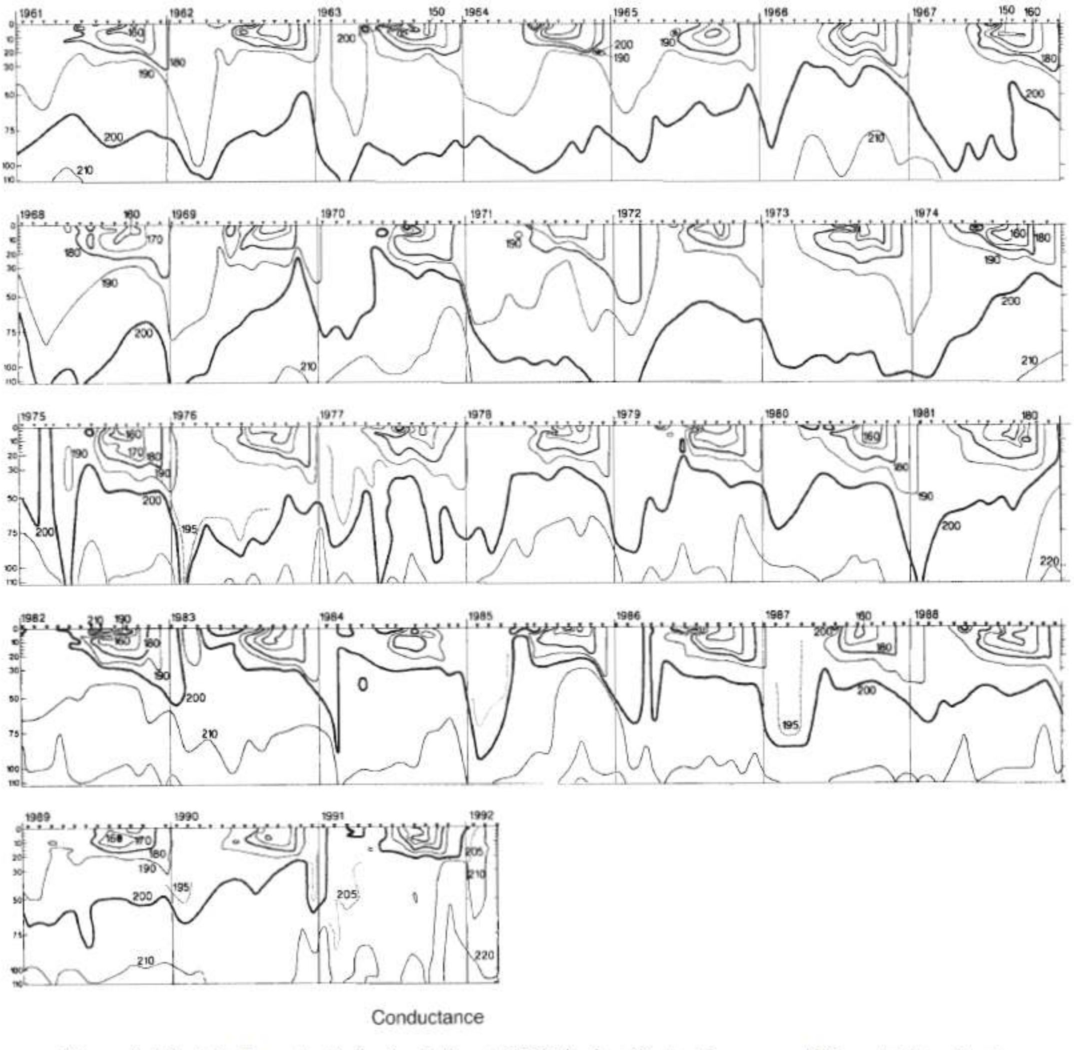

Figure 4. Electrical conductivity isopleths at 20 °C (k_{20}), of Lake Lucerne, at Kreuztrichter basin (1961–1992). Equidistant lines are 10 µmhos cm^{-1}; additional lines are dotted

of thermocline, there is another explanation needed, e.g. horizontal mixing with other sub-basins. In other words: this effect is still unclear.

The comparison of Fig. 2 and Fig. 4 shows some divergences between thermocline and chemocline: Soluble substances accumulated above the sediment for years (e.g. 1963–1966), until a complete turnover (sensu strictu) mixed them within the entire lake and started a new cycle in 1967.

In spring, conductivity depletion does not start at the surface but at a depth of 5–10 m. The inverse processes in autumn, i.e. cooling and replenishing conductivity by vertical eddy diffusion, are not synchronous. Differences in the density caused by increases in conductivity and temperature, respectively, may explain this discrepancy. Density changes caused by temperature are much stronger than those caused by conductivity (i.e. soluble compounds). Based on to conductivity measures complete overturns occurred on average every six years.

Long term fluctuations, shown by the 200 μmhos cm^{-1} line (as SI units: 20 mA V^{-1} m^{-1}) in Fig. 4, indicate a general increasing of mixing cycles over several years and also biogenic stabilization as described for Lake Zug (Imboden and Wüest, 1995). The development of the lake from 1960–80 showed an increasing, biologically induced, surplus stabilization by conductivity and suggested that "unfavorable conditions" had developed. "Unfavorable conditions" is a term mentioned in Swiss law. It defines an exception for natural eutrophic ponds, which never can meet the quality limit of more than 4 mg L^{-1} O_2 (anywhere and anytime), because they are at the end of the senescence of a lake. In these cases, it is generally accepted that there is no possible recovery. Nevertheless, even these unfavorable conditions in Lake Lucerne have been attenuated since 1983. The same statement is valid also for Vitznau Basin. Therefore caution should be used in referring to "unfavorable conditions". The term should not be used as a pretext for not even attempting a restoration.

Oxygen

Deepest oxygen samples were collected one meter above ground (110 m depth), based on echo soundings. However, for long-term trends and similar calculations, we used values at 100m to avoid the steeper gradient of the bottom boundary layer. At beginning of our survey, an increase of nutrients had started already (Fig. 6). Maximum nutrient (phosphorus) concentration was reached in 1974–76. Coupled phenomena, such as higher oxygen production in the epilimnion or faster oxygen consumption in the hypolimnion, were not evident relative to weather influences. Epilimnetic oxygen concentrations should show a maximum in summer reflecting plankton development (Bürgi, 1995; Fig. 11). Due to the lowered solubility of oxygen at higher temperatures, the summer maximum was never observed (Fig. 5). A second oxygen maximum appears only as percentage of the oxygen saturation (Mortimer, 1981).

At higher trophic conditions, Lake Lucerne not even reached a mesotrophic state, a metalimnetic oxygen depletion zone is evident (in 1966, 1967, 1971 and 1974) using the 8 mg L^{-1} line as reference (Fig. 5). For the 1984–88 period, the 9 mg L^{-1} line shows a similar pattern, but it's depth increased from 20 m to 30 m. In essence, these minima are too deep and too late, and can not be explained by old methane sources nor by vast sediment surfaces in the corresponding depths (Imboden, in "Large Lakes" Tilzer, 1990). After 1989, these oxygen minima disappear. The lowest oxygen concentrations in Kreuztrichter Basin (2 mg L^{-1}) were attained at a depth of 110 m in 1976.

Hypolimnion is oxygenated not only by internal eddies, but also during turnovers by advection. Approximately every third year, however, partial turnover was sufficient to oxygenate hypolimnetic water for the oxygen demand of the following summers. The longest period without oxygen regeneration (8 years) coincides with the period of highest trophic state.

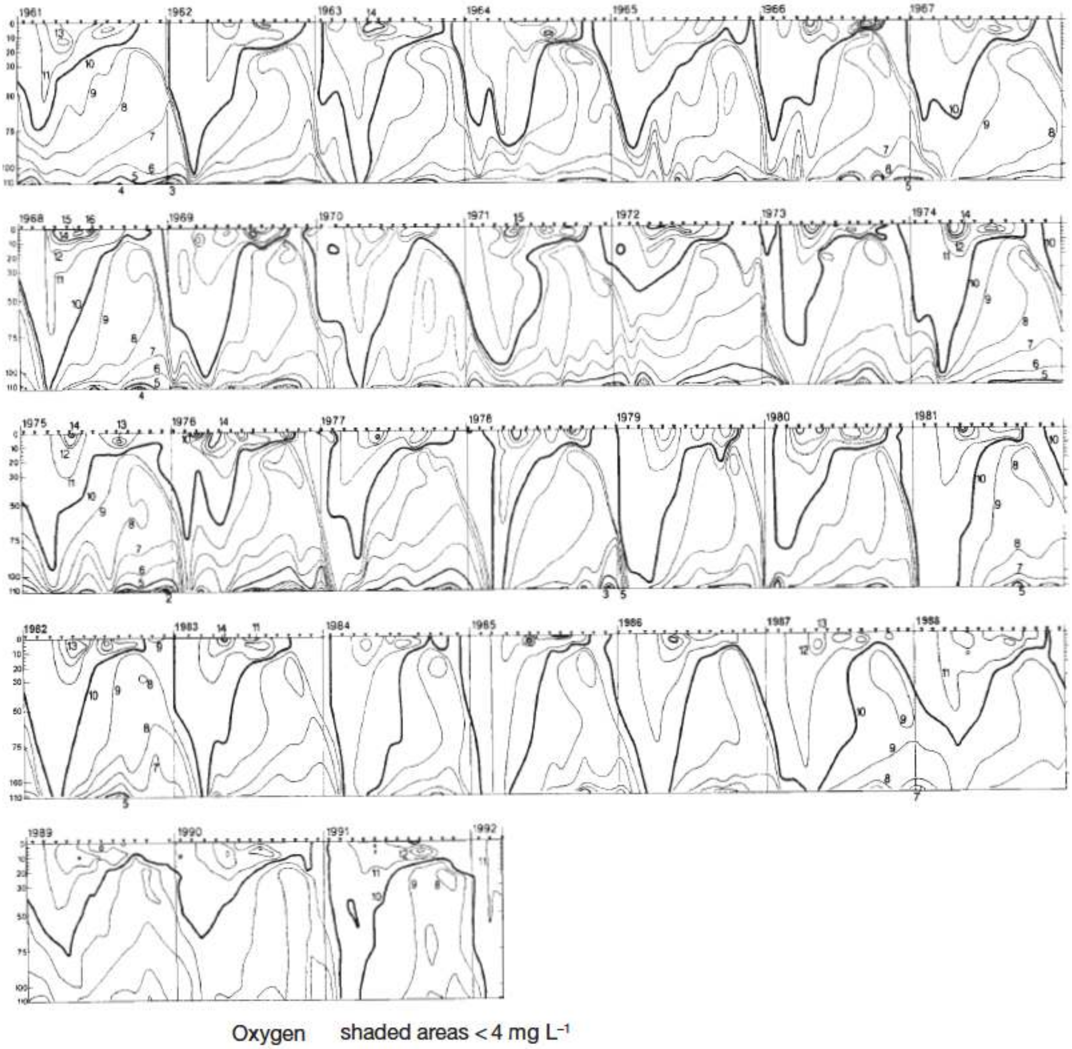

Figure 5. Dissolved oxygen isopleths of Lake Lucerne, Kreuztrichter basin (1961–1992). Equidistance 1 mg L^{-1}. Shaded areas are less than 4 mg L^{-1} O_2

Several short time oxygen maxima (1972–1976) above the metalimnion are correlated with particulate phosphorus and are reflected in population peaks of the cyanobacterium *Oscillatoria(Planktothrix) rubescens* (Bürgi, 1995). In addition, the depth and strata stability minimizes oxygen loss to the atmosphere.

The highest oxygen peaks developed at the lake surface, although the probability of recording these peaks is poor, because they can develop and disappear within one week.

A mixed layer (vertical isolines) was slightly apparent in autumn only, suggesting that the destroying process (mixing) was less efficient than the forming process (building the oxygen gradient by primary production). So the concept of the epilimnion as a mixed layer is sustained only in autumn for Lake Lucerne.

Phosphorus

In 1960 the lowest possible limit of detection was 10 µg L^{-1} P. Analytical methods for P were improved in 1960 (Ambühl and Schmid, 1965). Phosphorus concentrations increased until 1978 and then decreased significantly. Each point in Fig. 7 represents the volume weighted average of 12 SRP estimates (SRP = soluble reactive phosphorus). The decrease in SRP is due to water protection efforts in the catchment

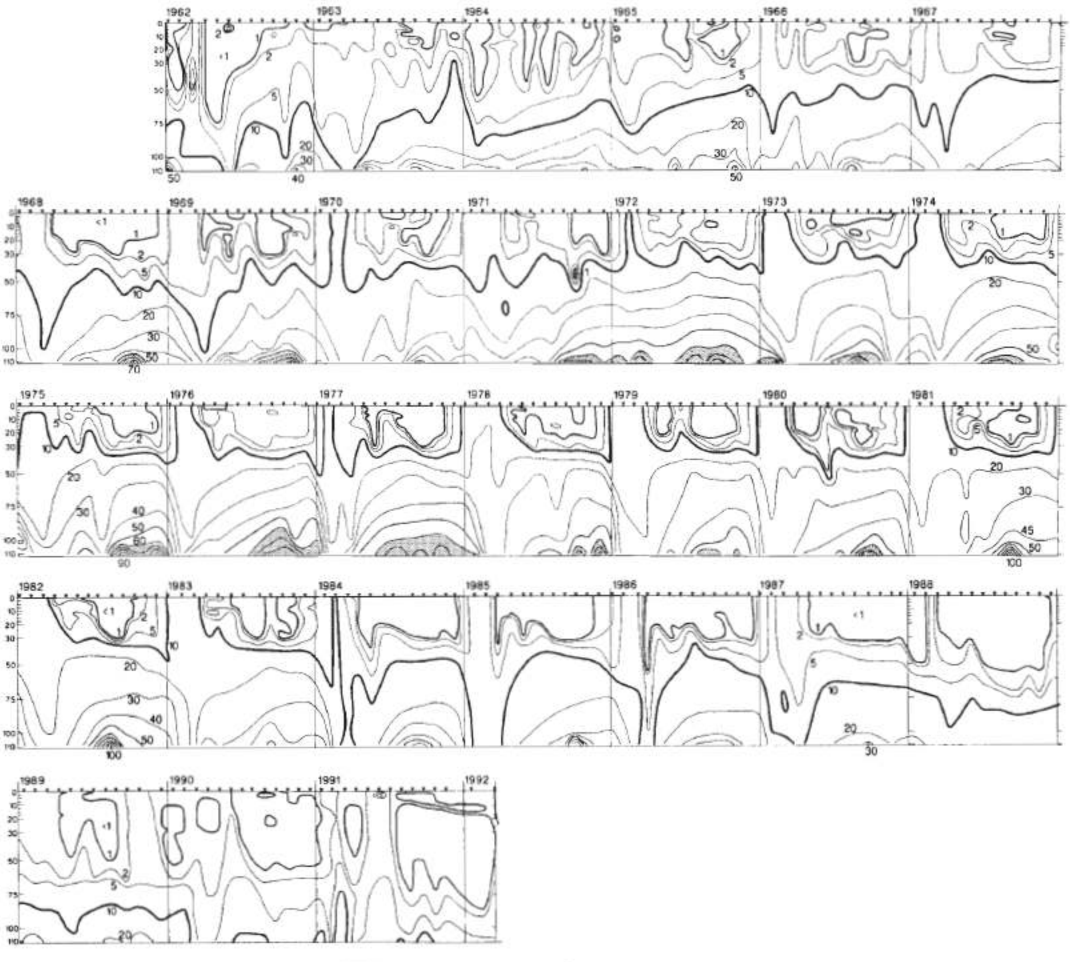

Figure 6. Phosphorus isopleths of Lake Lucerne, Kreuztrichter basin (1961–1992). Equidistance 10 µg L^{-1}. Further values 1, 2 and 5 µg L^{-1}. Shaded areas: P-contents greater than 60 µg L^{-1}

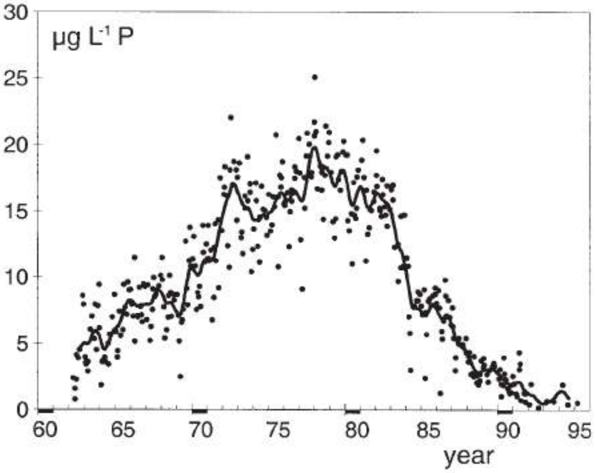

Figure 7. Volume weighted average SRP concentrations in Kreuztrichter basin (1962–1995)

(i.e. house drainage connections, new sewage treatment facilities) and also due to adsorption of phosphorus by inorganic suspended solids in the river Reuss (Ambühl, 1975; Bloesch, 1994). In the last years particulate phosphorus dominated the composition of total phosphorus; i.e. SRP was almost completely assimilated by plankton (Fig. 6).

The characteristics of phosphorus dynamics changed over time: phosphorus depletion was first observed in autumn 1963, and that depletion pattern was repeated in following years, especially 1965 and 1969. In the second half of 1968 an hypolimnetic enrichment started; probably supported by sediment release. Maximum phosphorus concentrations were reached in 1975. Periodic decreases of phosphorus occured in spring and autumn up to 1983, although the average concentration was higher for this time period. Since 1983/84, midsummer replenishment stopped and both decreases (spring and autumn) merged, forming one depletion zone. At the end 1991/92 the depletion zone extended to 75 m. This pattern began in 1983 at 50 m depth, and suggests a long term dynamic process of phosphorus deficiency (monotrophication, IGKB Report 2000). No distinct chemocline was discernible after 1990 due to very low phosphate concentrations. The highest concentrations in Lake Lucerne were low, compared with phosphorus maxima in Greifensee (600 µg L^{-1} P) or Lake Constance (100 µg L^{-1} P IGKB, 1994). Having returned to low SRP-levels, lake Lucerne is now prone to a system change. No longer are there several limiting factors, as during oligotrophic times, but only one and namely phosphorus. Therefore we expect a selective pressure on planktonic communities because the N/P ratio has climbed above 100 (w/w). The appropriate term for this kind of composition would be dystrophic with the medical meaning of a wrong composition of nutrients. As this term is already occupied in limnology for "brown water"-lakes, a different term is needed. Furthermore there is a tendency to stabilize a "natural" ratio of 7 to 1. Lower ratios are compensated readily by cyanobacteria; higher values enhance nitrogen losses to atmosphere (Höhener, 1990).

As oligotrophy reflects a natural situation where several factors are limiting growth of algae in different ways (e.g. Sommer, 1989), we propose the term "monotrophic" for lakes, in which primary production is limited by only one constituent. The difference between a natural shortage of nutrients and a man-made lack of only one nutrient (i.e. phosphorus) is obvious. The natural scheme progresses from one need to the next, as the seasons and phytoplankton composition change. The natural scheme usually starts in winter under low light and no vertical separation of the lake's water body. For a short period in spring, when nutrient limitations are absent, the limits are only given in plankton inherent parameters, such as maximum growth rate (Kremer and Nixon, 1978). However, soon (in late spring and summer) phosphorus, silica and also nitrogen (in autumn) are limiting the growth. In contrast to the present situation of Lake Lucerne (1995), limitation by nitrogen ended in 1971 and limitation by silica is still not back to the old values of 1960. We hypothesize a connection with an almost permanent limitation in phosphorus.

Nitrate

Nitrate is the main form of nitrogen in Lake Lucerne (Fig. 8). Changes in nitrogen are clearly shown using the 400 µg L^{-1} line (Fig. 8). High concentrations first appeared in 1963. The last time when bottom concentrations were less than 400 µg was in 1966. In contrast the nitrate concentration barely dropped to 400 µg L^{-1} at maximum epilimnetic depletion in 1991, and the 600µg L^{-1} isoline is similar to the 350 µg L^{-1} isoline of 1962. In general nitrogen concentrations doubled from 1962–1992 (Fig. 9). A lake is a dynamic system, thus if a compound doubles, the yearly inputs also had to double (or even more, if internal losses are enhanced) to reach a steady state.

The depth of the chemocline of nitrate matches with the depth of the chemocline of the conductivity (Fig. 3) (in contrast to phosphorus chemoclines), suggesting no additional uptake of nitrate by settling seston (also in contrast to phosphorus).

Sediment embedding of nitrogen is not as substantial than it is for phosphorus, and nitrogen losses by denitrification are low (Höhener, 1990), therefore only one nitrogen depletion is found in the hypolimnion of the lake in 1974 (Fig. 8). This single nitrogen loss (i.e. sum of nitrate-nitrogen, nitrite-nitrogen and ammonia-nitrogen) was 5% only (estimation error: 2.5%).

Up to 1973, nitrogen was limiting to algal growth for various length of time in autumn. The last year that nitrate-nitrogen was less than 50 µg L^{-1} for longer than a month was in 1971. At similar concentrations, there was a bloom of the cyanobacterium *Anabaena sp.* in Kreuztrichter and Vitznau basins in summer 1968; an event which was not repeated in subsequent years.

Silica

Silica is a very dynamic lake parameter, mainly driven by changes in diatom abundances. The diatom frustules development occurs in the epilimnion, then they sink

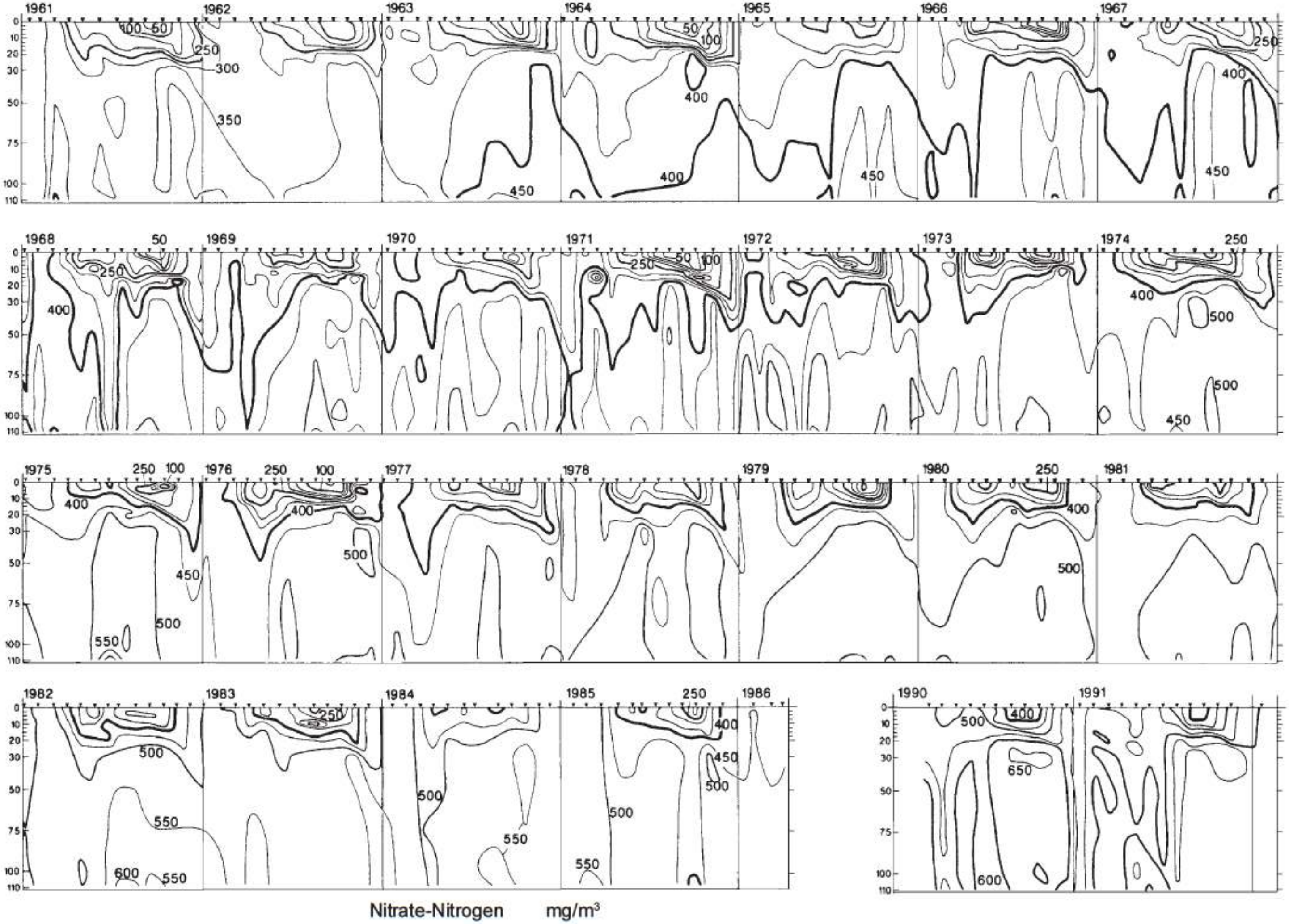

Figure 8. Nitrate-nitrogen isopleths of Lake Lucerne, Kreuztrichter basin (1961–1986) and (1990–1992). Distance between isolines are 50 µg L^{-1} N

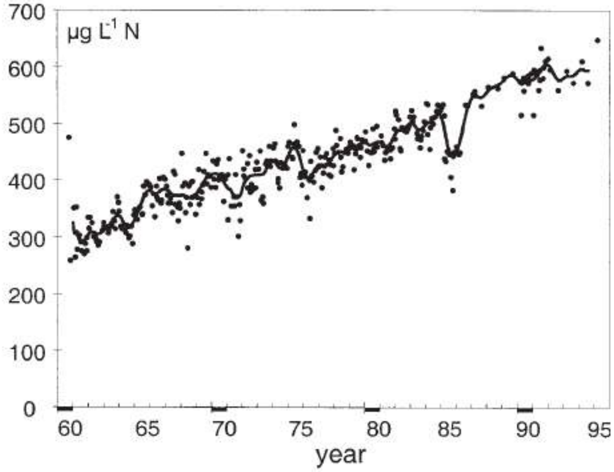

Figure 9. Volume weighted average Nitrate-N concentrations in Lake Lucerne, Kreuztrichter basin (1961–1995)

and release, upon death silica in the hypolimnion and the sediment. It has been known for almost a century that high diatom production is correlated with high silica depletion (Richter, 1903).

Primary and secondary str<uctures of silica of bacillariophyte frustules are still unclear. The sum formula of $SiO_2 \times nH_2O$ is usually reported as "opal like" structure. More convincing are SiO_2-gel like macro structures, where crystallization is inhibited by organic substances, as reported by Werner 1977.

Silica isopleths (Fig. 10) look similar, but not identical, to those of phosphorus and other nutrients. Vertical silica depletion reached 20 m in depth at the trophic peak, whereas before and after this period the maximum depletion depth was only 15 m (Fig. 10). Compensation depth, i.e. depth where silica concentrations are uniform over time, is about 30 m.

Silica dynamics are complex: Even during the most efficient turnovers (except 1984), silica still showed concentration gradients.

We assume that "abyssal" sediment is a constant source of silica even in winter. Furthermore, data show that mixing is not intense enough to eliminate this gradient. The highly variable trend curves for silica concentrations were not correlated to phosphorus, to temperature, or conductivity. Even a multiple plot of phosphorus, space and time, combined with weather and climate was insufficient for predictions of silica concentrations. Average concentrations show no clear long-term trends. There are clear seasonal patterns in silica concentrations, but the yearly repetitions are inconsistent.

Averaged Year

Lake chemistry data are subject to time cycles of days to seasons within a year. For condensing data we can smooth cycles to emphasize long-term trends, or keep cycles

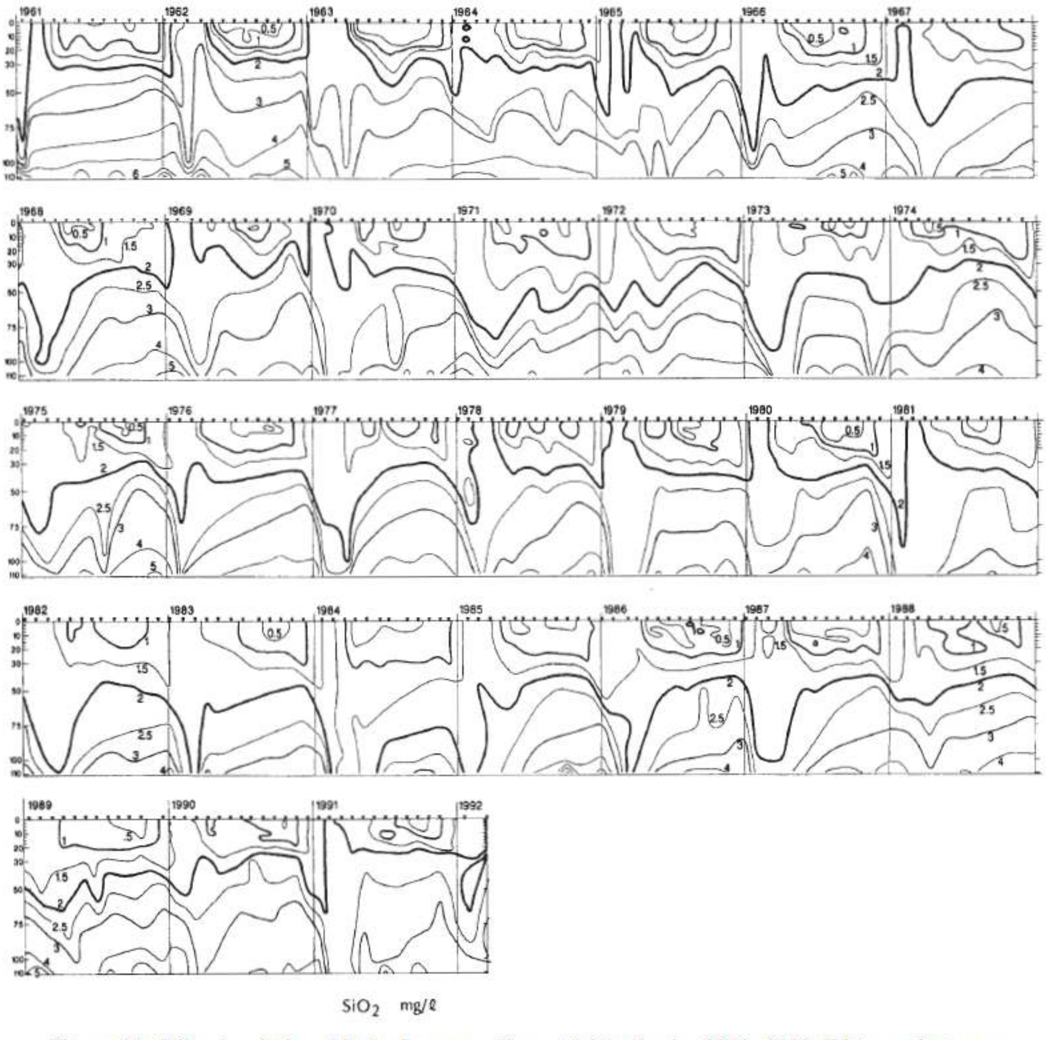

Figure 10. Silica isopleths of Lake Lucerne, Kreuztrichter basin, 1961–1992. Distance between isolines are 0.5 mg L^{-1} SiO_2

to present results within "weather corrected" years. The algorithm used is described in Bührer and Ambühl (1996). It was unavoidable that gradients blur vertically as well as in time; hence these values should not serve for gradients. However, derived values are an excellent base for use in prediction models, especially for calculation of vertical eddy diffusion coefficients (Li, 1970). Smoothing seasonal patterns also allows presentation of highly transient parameters such as particulate phosphorus, nitrite, or a comparison of different trophic states of Lake Lucerne. We chose two periods, one at maximum trophy (1974–1978) and the other at the start of low phosphorus concentrations (1984–1988). An average of all 31 years was not useful, even when corrected for trends, because annual patterns also varied greatly with time.

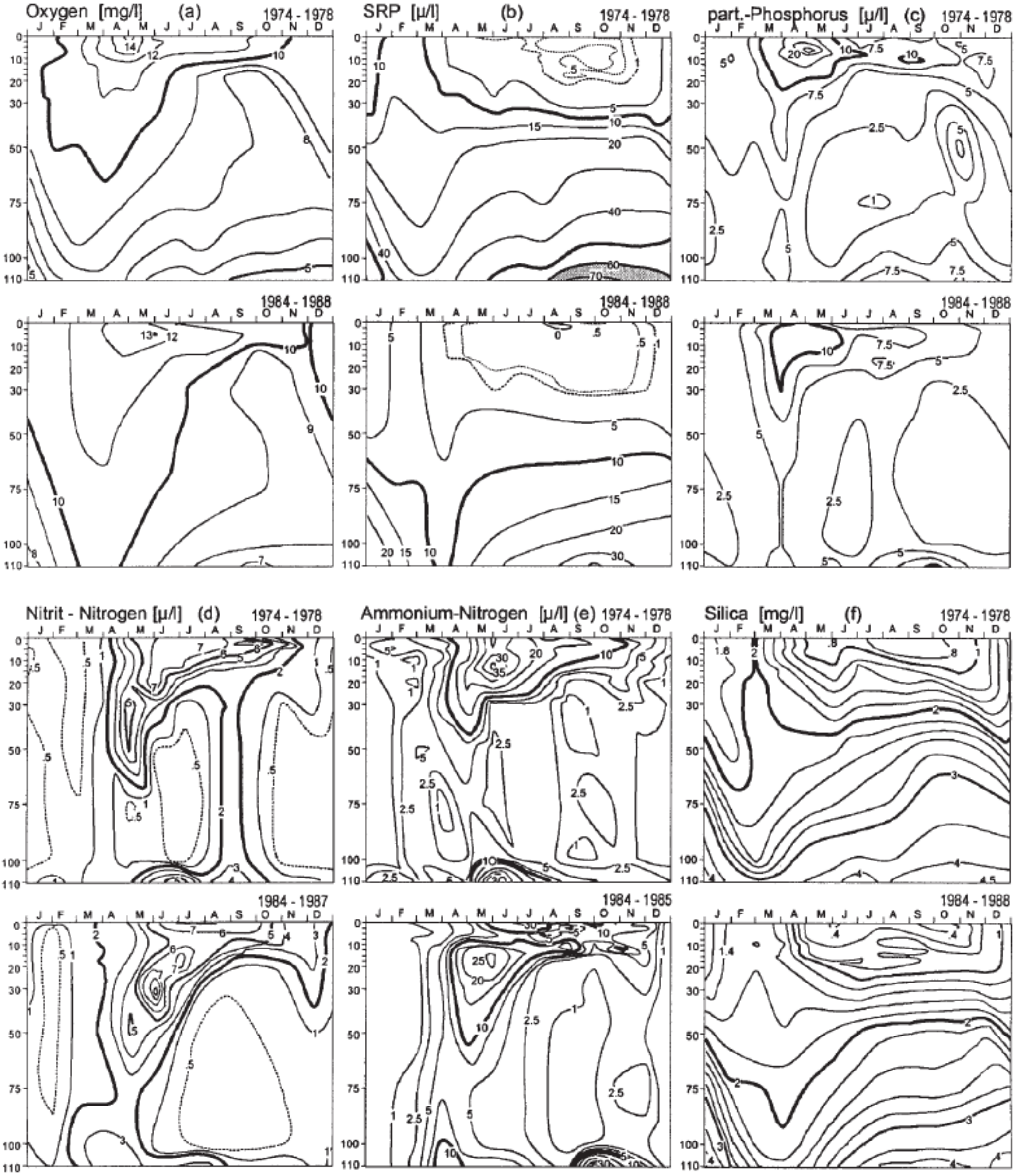

Figure 11. Five year average values (1974–1978 and 1984–1988) of selected parameters: Dissolved oxygen, SRP, particulate P, Nitrite, Ammonia, Silica

In Switzerland, lake oxygen concentration is used as a goal for general lake quality.

For monitoring the respective criteria, instant measurements are useful (e.g. see Fig. 5). Differences between two time periods may be more insightful: The oxygen results show that deep water never reached surface saturation and dropped to less than 5 mg L^{-1} (from 1974 to 78) whereas the better mixing period of 1984–88 indicated an average turnover of more than 10 mg L^{-1} and 7 mg L^{-1} in autumn (Fig. 11). Below the surface, there is only one oxygen peak in spring that remained until 1988. Plankton counts (Bürgi 1996) show a mid-summer peak that was not reflected in oxygen because of low gas solubility at higher temperatures.

The SRP results show the decrease of this limiting nutrient (minima were reached after 1988) (Fig. 11). E.g., the 30 µg L^{-1} isopleth was replaced by a 10 µg L^{-1} isopleth, and the 5 µg L^{-1} isopleth (showing the time – depth range of nutrient depletion in 1975) by a 1 µg L^{-1} isopleth. The fast recovery of bottom concentrations in 1984–88 is unusual, probably because of phosphorus release by sediments. This process was reduced after 1988 (cf. Fig. 7).

In the actual data, particulate phosphorus peaked on 26. April, 1978 at 5 m (36 µg L^{-1}). Summer peaks were low of long duration. The hill in the autumn mixing front at 50 m in (Fig. 11c), is influenced by a single value (41 µg L^{-1}) on 24. Oct., 1974. During 1984–88, the highest single concentration was on 10. March, 1986, partially suppressed by smoothing. Usually maximums were reached at the end of April with a distinct lower maximum in summer in mid August. However, because plankton peaks may be of short duration, they are easily missed in our four week interval sampling program. Furthermore, analytical variation is high, because of the particle distribution (e.g. patchiness). Average particulate phosphorus concentrations were less later than in the first period. Oxygen production per particulate phosphorous diminished during the year, indicating a closer coupling of production of oxygen with the carbon-cycle than with phosphorous.

According to the laws of thermodynamics reduced compounds, e.g. nitrite, should be found only in the water above the sediment. Figure 11 shows that nitrite and ammonia are better correlated with plankton biomass than with oxygen deficiency, therefore we suggest, that reduced compounds were formed mainly by the microbial cycle. Very low levels of oxygen in which chemical processes produce ammonia or nitrite were never reached at Kreuztrichter station.

Trophic state did not have a large effect on the annual distribution of silica in the lake; Silica concentration patterns over time are similar to the phosphorus peaks and to P-limited times (monotrophy). The almost linear climbing of isolines in the hypolimnion after turnover, continued in 1974–78 until September did not reflect any effect of the mid-summer diatom population. In 1984–88 the depletion of silica in epilimnion was lower than in 1974–78 and was invariant for four months (summer/autumn) in 25–60 m depth, indicating a very extended steady state of uptake, settling, release and diffusion.

Further Lake Basins

The entire Lake Lucerne consists of a chain of different basins (Fig. 1). The basins along thalweg are Lake Uri, basin of Gersau, basin of Vitznau and at the end the main station Kreuztrichter basin. The samples cover only the period of 1965–73, therefore the highest dynamics of eutrophication were not recorded. In the present paper, oxygen is used as an example (Fig. 12.). Oxygen concentrations of less than 4 mg L^{-1} in Vitznau basin, and less than 1mg L^{-1} in Gersau basin were recorded. True minima are even lower because samples were taken 3–4 m above the sediment at Gersau. Mixing was deepest in Lake Uri. The greatest oxygen peaks are of same magnitude in all basins. Differences between years correlate with algal growth. Oxygen consumption in the hypolimnion in the 214 m deep Gersau basin is low; therefore isolines run almost horizontal. Hypolimnetic oxygen decrease rate is highest in spring in all sub-basins. As a whole Lake Lucerne is monomictic; autumn turnover is directly followed by spring overturn without being interrupted by winter stratification. Oxygen peak in the hypolimnion is delayed by a month of winter heat mixing. Apparently easily degradable compounds are oxidized before an oxygen maximum can be reached. Oxygen never exceeded 14 mg L^{-1} in Lake Lucerne, therefore the use of the term "mesotroph" is an exaggeration, and "oligo-mesotrophic" may be more realistic. The long-term trend since the highest trophic state (1974–78) indicates a decrease in oxygen dynamics along the thalweg. The decrease started in Lake Uri and already has reached the Kreuztrichter and even the Vitznau sub-basin. The most sensitive location in the lake is the abyssal part of Vitznau sub-basin, which has recovered. In 1992, the oxygen concentrations at a depth of 148m were 9.23 mg L^{-1} in spring (March, 17.): and 7.25 mg L^{-1} in autumn (Sept. 1st.). This represents a remarkable difference to the values shown in Fig. 12.

Conclusions and Summary

The limnology of Lake Lucerne was investigated between 1961 and 1992. The data base accumulated some 156 000 records of monthly samples, not including supplemental CTD or light readings. Although it is a tremendous compilation on Lake Lucerne, it is still incomplete. E.g., the data from special investigations (Ph.D. theses or the complete plankton series) were not included in this report. The initial goal of the investigation in 1961 was to gain some knowledge on the actual trophic status of the lake. Later on it shifted to a survey of changes of trophic state and lastly with long-term monitoring.

Temperature stratifies the lake in summer in the classical way; separating the water body into an epi-, meta- and hypolimnion. Stratification disappears in autumn and winter. Complete homothermy is rare. It is usually preceded by a rise of hypolimnic temperature to more than 4.8 °C, which requires an average of four years. Inverse stratifications in winter occur rarely. There is no general trend of temperature for the entire period, but there was a general cooling of the lake in shorter 10 year intervals.

Electrical **conductivity** reflects photosynthesis in the euphotic zone and the decay of organic matter in the hypolimnion. Conductivity is a good indicator of turnover. Homogeneity of temperature tells only that the lake may turn, homogenous conductivity shows that it does or did. On average, an almost complete overturn occurs

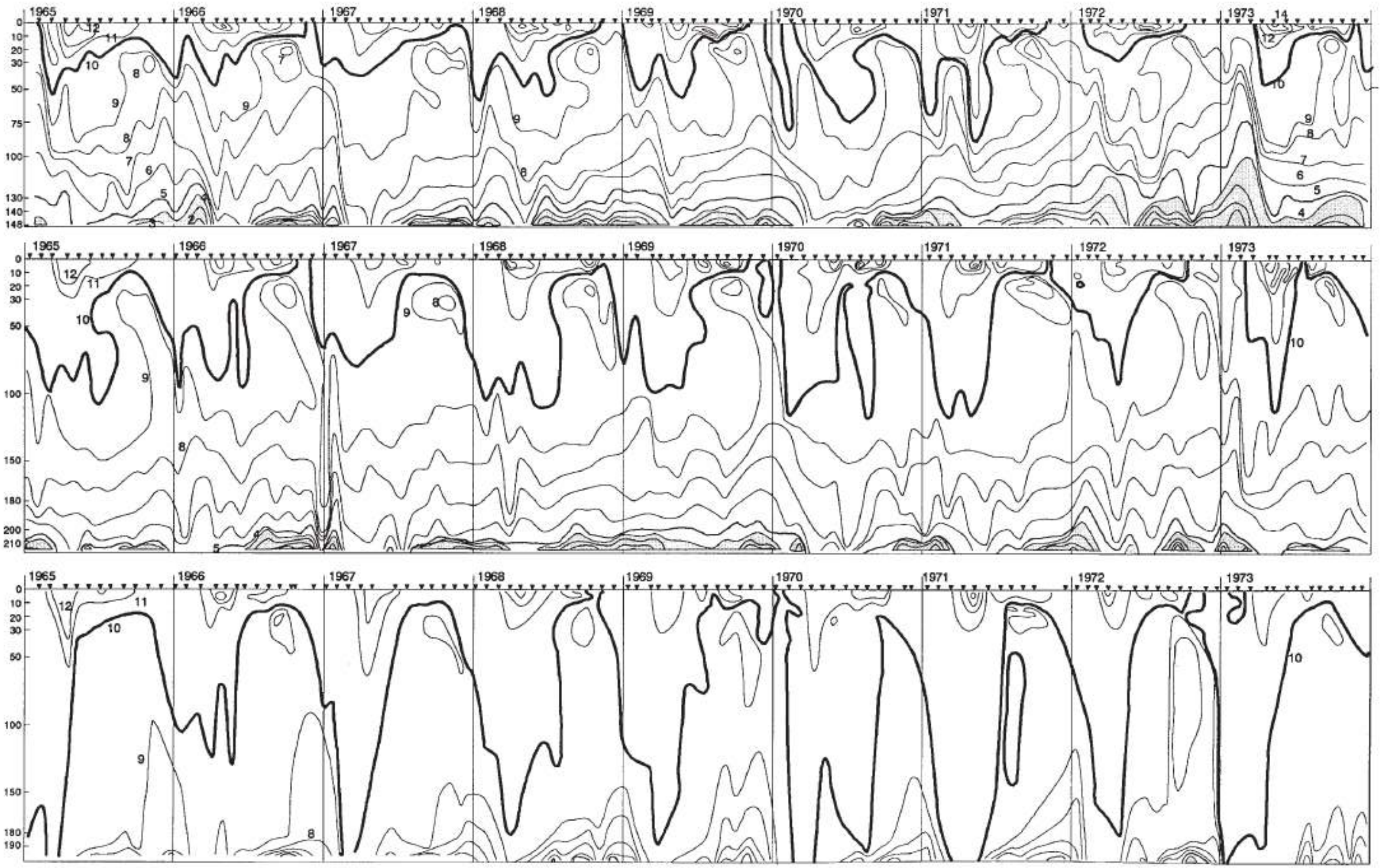

Figure 12. Dissolved oxygen in Lake Lucerne, Vitznau basin (above), Gersau basin (middle) and Lake Uri (below) from 1965 to 1973. Equidistance 1 mg L^{-1}. Shaded areas indicate concentrations of < 4 mg L^{-1} O_2

every sixth year. During the entire period there was a steady, and slow change in the ratio between alkalinity and conductivity; the cause is still unknown. (Hypothesis: calcite nucleation processes).

Oxygen concentration showed epilimnetic gross production and hypolimnetic consumption combined with mixing by incomplete turnover. Approximately each third year, a turnover reduced hypolimnetic depletion sufficiently until the following summer. Minima were reached in the hypolimnion during the eutrophication in 1977. Oxygen dynamics have slowed since 1988. Summer peaks that should reflect plankton development in summer, were suppressed by effects of temperature. Metalimnetic oxygen depression was present until 1974. Differences in oxygen content between the depths of 50 and 100 m have decreased since 1975.

Phosphate: SRP (soluble reactive phosphorous) concentration in 1961 was 5 µg L^{-1}, reached 20 µg L^{-1} in 1978 and decreased to1 µg L^{-1} in 1992. Typical patterns of uptake in the epi- and metalimnion as well as release in the hypolimnion were observed during the study period. The SRP chemocline dropped from 50 m (1983) to deeper than 75 m (1990). Later a SRP chemocline was not observed due to very low concentrations. The lake is now phosphorous limited, i.e. monotroph, but not oligotroph. This means that multicomponent nutrient limitation (oligotrophy) was not re-established. The consequences are a total change of system for the biocenoses.

The patterns for total phosphorous are similar to those of SRP, although also including the peaks of the cyanobacterium *Oscillatoria (Planktothrix) rubescens.*

Nitrate: **Nitrogen** content doubled during the last 30 years and appears to still be rising. Annual nitrogen consumption reached a maximum in the 1970's. Nitrogen limited the algal growth in autumn until 1976 (<50 µg L^{-1} NO_3-N). Other nitrogen components such as ammonia or nitrite, are metabolized much faster and can be illustrated only as trends. As nitrate-nitrogen was the main constituent of total nitrogen, they showed similar patterns. Contrary to phosphorus, there was no uptake of nitrogen by settling seston.

The annual **silica** dynamics was mainly caused by diatoms. During the trophic peak (1978), vertical silica depletion reached 20 m (being 15 m before and after this peak). Average concentrations show no clear long-term trends. Seasonal fluctuations also are inconsistent over time. Silica fixation in sediments seems to be incomplete.

For illustrating seasonal variations, five years averages were presented as isopleths. These kind of plots are ideal for parameters with fast transformations such as particulate phosphorus, ammonia, nitrite, particulate nitrogen and chlorophyll. A synoptic comparison of other sub-basins of Lake Lucerne showed different behaviors, (e.g. regular turnover in wind exposed lake Uri) or sensitivity to nutrients as in Vitznau sub-basin.

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