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Restoration of a shallow, ground-water fed urban lake using a combination of internal management strategies: a case study

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with 7 figures and 3 tables

Abstract: The shallow urban lake 'Alte Donau' is almost exclusively influenced by subsurface nutrient input. Recently the lake has shifted from the clear water macrophyte dominated stable state to conditions characterised by high turbidity because of cyanoprokaryote dominance. Causes and consequences of these long-term changes and conditions during the bloom phase are analysed. Based on intensive investigations and several pilot experiments management strategies are developed. Finally, internal rehabilitation methods using a combination of $FeCl_3$ and $Ca(NO_3)_2$ for phosphorus flocculation and sediment oxidation (Riplox-technique) are applied. As a consequence of the restoration measures average concentrations of total phosphorus decreased from 62.4 µg l^{-1} to 23 µg l^{-1}, average chlorophyll-a levels declined from 42.6 to 12.7 µg l^{-1} and mean transparency increased from 0.5 to 1.7 m. Biomanipulation and macrophyte re-colonisation are discussed as additional restoration measures necessary for further improvement.

Introduction

Accelerated eutrophication is one of the main problems related to anthropogenic usage of fresh-waters (HARPER 1992, HENDERSON-SELLERS & MARKLAND 1987). Stresses posed to recreational urban lakes are often most severe (RYDING & RAST 1989). Because nutrient concentrations, especially phosphorus, are usually low in ground water, inputs directly to a lake have generally not been considered an important nutrient source. However, subsurface flow in combination with nutrient regeneration from the bottom sediments, considered as diffuse internal loads by RYDING & RAST (1989), can be the main and most important nutrient sources in shallow lakes when superficial in and outflows are absent. In addition, septic tanks may be a common problem in intense populated urban areas (CARLILE 1985). Once nutrients enter a lake, they can be recycled many times between the sediment, aquatic plants and the water column. Wind-induced mixing of bottom sediments, or anoxic conditions at the sediment-water interface will favour nutrient regeneration. In such circumstances merely limiting exter-

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nal nutrient inputs to very low levels may be insufficient to improve the water quality conditions of nutrient enriched, shallow lakes.

Here we report a case study from an urban lake within the city-limits of Vienna, Austria that is mainly influenced by subsurface nutrient inputs. Long-term changes, restoration measures, the resulting changes and additional management strategies are described.

Site description

Regulation of the River Danube at Vienna in 1875 resulted in the isolation of parts of the main river channel. The remaining backwater, known as 'Alte Donau', became almost entirely dependent on subsurface seepage (Fig. 1, Table 1). The lake soon developed into a famous recreational resort and has progressively been engulfed by the city.

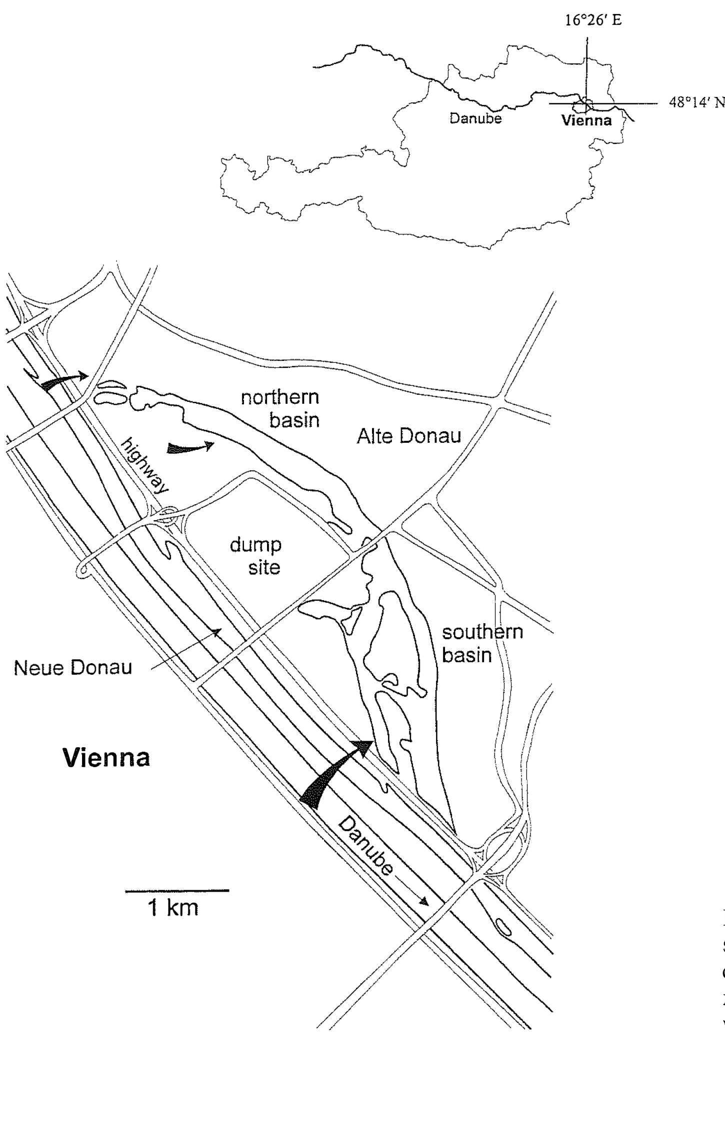

Fig. 1. Location of the study site. Arrows indicate direction and approximate amount of groundwater flow.

Table 1. Morphometric data for Alte Donau.

Altitude	157 m a.s.l.
Area	1.583 km^2
Volume	3.697 x 10^6 m^2
Maximum depth	6.8 m
Mean depth	2.33 m
Mean theoret. retention time	~190 days

Until fairly recently, the water was clear with high Secchi-disk transparencies, frequently down to the bottom. Large areas were covered with submerged macrophytes substantially influencing nutrient dynamics (LÖFFLER 1988, SCHIEMER et al. 1992).

Over the years organic rich sediments have accumulated in several areas on top of the fluvial deposits as a result of internal processes. Parts of these sediments became anoxic because of respiration and reduced water exchange (LÖFFLER 1988).

First symptoms of severe deterioration of water quality were detected during routine monitoring by the municipality in 1992 (MA 15, Institute of Environmental Medicine). By early 1993 the lake had shifted to a new stable equilibrium (Fig. 2) characterised by the dominance of phytoplankton (SCHEFFER et al. 1993, DONABAUM et al. 1998), and was now classified as eutrophic (GÄTZ & KREILL 1992).

Long-term changes: causes and consequences

The causes for the dramatic change were manifold. Annual average concentrations of total phosphorus in the water increased by about 50% from 35 to 70 $\mu g\ l^{-1}$ during the period 1987 to 1994 (Table 2). Similarly, levels of total nitrogen raised marginally, but left the N:P ratios virtually unchanged. Release of nutrients from anoxic sediments was quite important in certain areas (DOKULIL et al. 1994).

Table 2. Annual average concentrations of total phosphorus (TP) and chlorophyll-a (chl-a) in $\mu g\ l^{-1}$ for 'Alte Donau' and for the period 1987 to 1997. 1987: calculated from LÖFFLER (1988); 1988-1990: unpublished data from the MA 15; 1991-1992: according to BMLF (1994).

Year	TP [$\mu g\ l^{-1}$]	Chl-a [$\mu g\ l^{-1}$]	Chl-a/TP [%]
1987	35.09	5.25	14.96
1988	66.12	16.62	25.14
1989	110.40	15.20	13.77
1990	42.40	15.00	35.38
1991	47.06	20.25	43.03
1992	41.35	22.40	54.17
1993	54.16	43.11	79.60
1994	70.00	41.00	58.57
1995	27.30	11.97	43.85
1996	19.08	12.55	65.78
1997	28.40	13.10	46.13

However, chemical data from the ground water discharging to the system (VRANA 1994) indicated a large input of inorganic phosphorus (166-323 µg PO_4-P l^{-1}), ammonia (0.6-45 mg NH_4-N l^{-1}), nitrate (38-487 µg NO_3-N l^{-1}) and organic nitrogen (4.09-10.40 mg N_{org} l^{-1}). These dissolved nutrients are partly liberated from an old waste disposal site because oxygen concentrations in the ground water are low (0-2.4 mg O_2 l^{-1}).

Stabilisation and elevation of the water level has been identified as one of the triggering factors for the shift from macrophyte dominated clear water to turbid conditions because of high phytoplankton biomass (DONABAUM et al. 1998). Additionally, the hydrological regime has been modified through nearby activities (MA45-IWHW-BOKU 1998).

Annual fluctuations of the water level were as high as 1.70 m between 1958 and 1980. Both the amplitudes and the mean level varied largely between years. The highest mean water level during these years was observed in 1970 (156.7 m above sea level) which is 50 cm above the average for that period. Two years later the level had dropped to 155.6 m a.s.l. or 60 cm below the long-term average. Since 1980, amplitudes never exceeded 80 cm, the differences between yearly means were within 50 cm and the long term average was 28 cm higher than previously (Fig. 3).

These changes were primarily caused by the construction of the flood-water diversion canal 'Neue Donau' and, more recently, by a hydroelectric dam completed on the River Danube. Because of the altered flow direction of the groundwater, the water-level fluctuations were reduced by about 50% and volume oscillations changed from 1:3 to 1:1.4 (MA45-IWHW-BOKU 1998). Accordingly, the renewal of the lake water due to groundwater exchange increased from 1.4 to 1.9 times per year. This corresponds to a decrease of the average retention

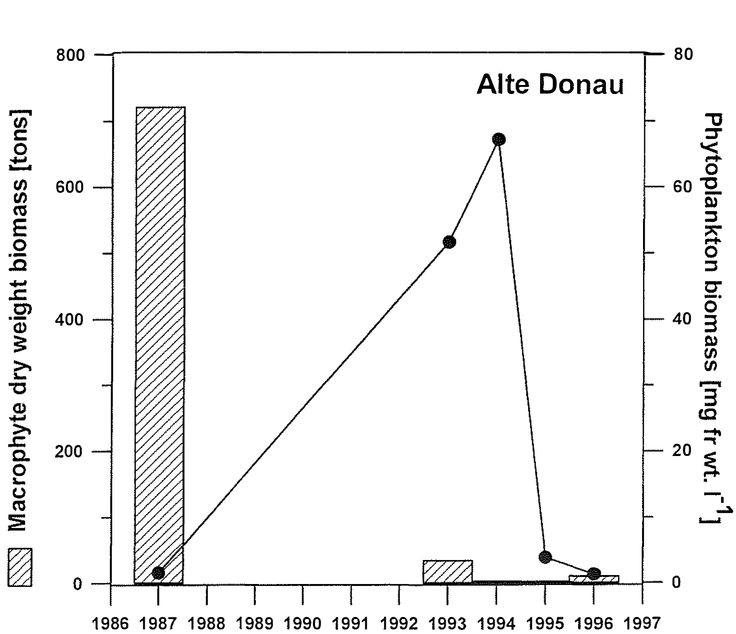

Fig. 2. Long-term changes of total macrophyte biomass in tons dry weight (?) and phytoplankton fresh weight biomass per litre (?)

time from 260 to 190 days. Alteration was largest in the southern basin where it changed from 970 days previously to 180 days at present.

Reduced illumination of the water column as a consequence of the elevated water level (on average 37 cm during 1987-1993), reinforced macrophyte management and the reduced dynamic in combination with increased levels of phosphorus were the decisive factors responsible for the dramatic decline of the submerged vegetation and hence for the shift to a new equilibrium characterised by dominance of phytoplankton (Fig. 2 and 4).

The significant reduction in visibility and the red-brown coloration of the water then observed was a result of the mass appearance of the filamentous cyanoprokaryotes *Oscillatoria redekei* VAN GOOR and *Cylindrospermopsis raciborskii* SEENAYYA ET SUBBA RAJU (DOKULIL et al. 1993, 1995).

Conditions of water and sediment during the phytoplankton bloom phase

Chemical data during the bloom phase are summarised in Tables 2 and 3. The development of the phosphorus-chlorophyll relationship during the investigation period is shown in Fig. 4.

Massive algal blooms of filamentous cyanoprokaryotes (= cyanobacteria) occurred in 1993 and 1994. By May 1993 the phytoplankton was dominated by these species adapted to low light conditions and low phosphate supply which are able to fix atmospheric nitrogen through heterocyst activity. During spring 1994 diatoms (*Synedra acus* (W. SMITH) LANGE-BERTALOT), chrysophytes (*Dinobryon* sp.) and chlorophytes (*Tetraedron minimum* (A. BR.) HANSG., *Scenedesmus quadricauda* (TURP.) BRÉB, *Scenedesmus acuminatus* (LAG.) CHOD. were important. The filamentous algae became more prominent again during April and early May, but disappeared at the end of May (DOKULIL & MAYER 1996). Afterwards green algae

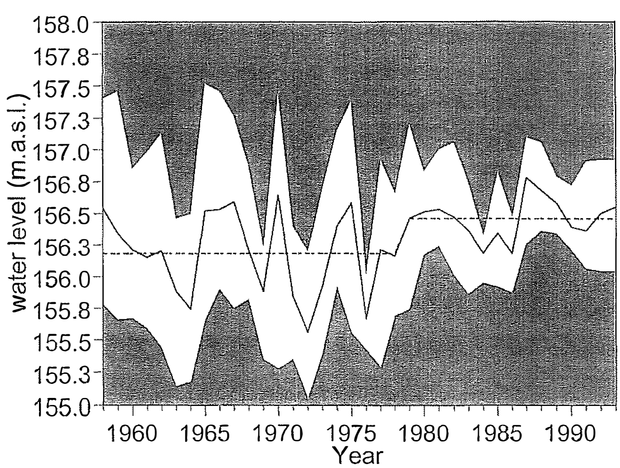

Fig. 3. Changes of water level as meters above Adriatic sea level (m a.s.l.) in 'Alte Donau' for the period 1958–1993. Th solid line indicates the annual averages, the dashes lines are mean values over longer periods and the white area shows annual ranges (minimum–maximum).

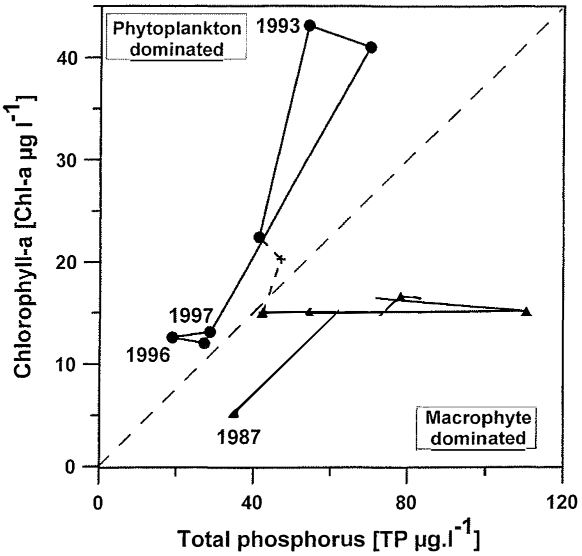

Fig. 4. Annual average total phosphorus [TP µg l^{-1}] versus chlorophyll-a [Chl-a µg l^{-1}] concentrations in 'Alte Donau' for the period 1987-1996. The dashed diagonal line separates the period when macrophytes dominated from the years when phytoplankton dominated. Years of transition are connected by a hatched line.

such as *Scenedesmus* spp. and *Tetraedron* gained importance. By the end of July *C. raciborskii* increased again exponentially and became the dominant algal species. Growth was promoted by exceptional high water-temperatures during the summer and early autumn months. The bloom lasted therefore until the end of October (Fig. 5). Zooplankton populations were dominated by small sized crustaceans and rotifers (SALBRECHTER 2000).

Average phosphorus concentrations in the sediment were 1.16 mg TP g^{-1} sediment dry weight (range 0.66-1.16) in 1993 and 0.76 (range 0.42-1.15) in 1994. Similarly, nitrogen concentrations in the sediment were lower in 1994 (average 5.9 mg TN mg dry weight^{-1}; 3.53-0.12) when compared to 1993 values (7.74; 2.43-19.32). Anoxic conditions were common at the sediment-water interface during the summer seasons of 1993 and 1994. Nutrient release rates from the sediment were therefore a significant contribution to the high nutrient concentrations in the system (DOKULIL et al. 1994).

Table 3. Annual average nutrient concentrations before and after restoration.

	1993 (mg l^{-1})	1994 (mg l^{-1})	1995 (mg l^{-1})	1996 (mg l^{-1})	1997 (mg l^{-1})
Total phosphorus [TP]	0.055	0.070	0.027	0.019	0.028
Total dissolved phosphorus [TDP]	0.013	0.021	0.007	0.004	0.007
Particulate phosphorus [TP–TDP]	0.042	0.049	0.020	0.015	0.022
Soluble reactive phosphorus [SRP]	-	0.003	0.002	0.0009	0.002
Total nitrogen [TN]	1.69	1.75	1.88	0.940	0.632
Total dissolved nitrogen [TDN]	-	0.93	1.63	0.747	0.425
Particulate nitrogen [TN–TDN]	-	0.83	0.25	0.155	0.206
TN : TP	31	25	70	52	23

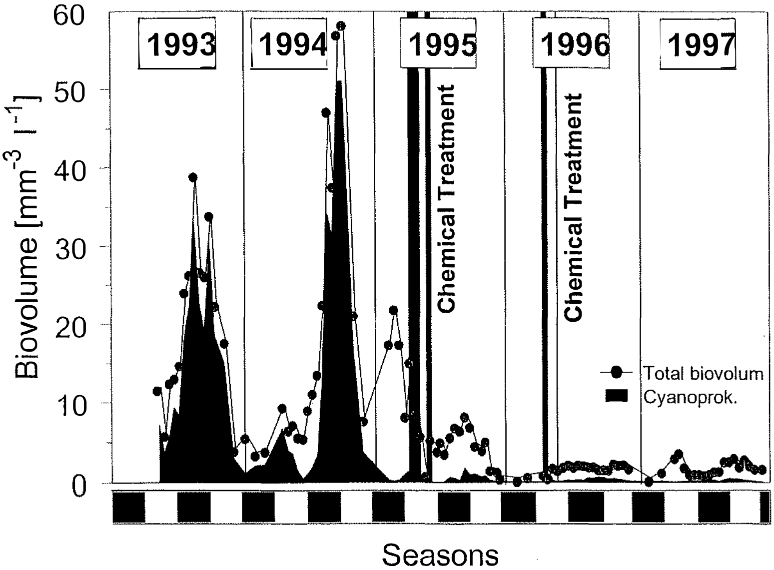

Fig. 5. Seasonal periodicity of total phytoplankton biovolume and cyanoprokaryote fraction both in $mm^{-3}\ l^{-1}$ for the years 1993–1997 in 'Alte Donau'. Dark vertical bars indicate the periods when chemicals were applied to the lake in 1995 and 1996.

Restoration measures: Pilot projects, decision and application

The unsightliness, the potential toxicity of the water bloom and public awareness urged the municipality to launch a detailed scientific investigation (DOKULIL et al. 1993, 1995). As an immediate measure, about half of the water volume was drained and replaced by water of better quality from the high-water bypass 'Neue Donau'. (DOKULIL & GASSER 1994) As a result, algal composition and algal concentration improved during the first six months of 1994 (DOKULIL et al. 1995). In addition, several pilot experiments were set up during 1994 to evaluate the most appropriate restoration technique (DOKULIL 1994, 1995). Based on the results from these trials, the data from the continuing investigation and an experimental dredging in a side-arm of the lake, the RIPLOX-technique was chosen as management (RIPL & FEIBICKE 1992, RIPL 1994, WOLTER 1994, MA45 1995). This method flocculates phosphorus compounds in the water column and binds them in the sediment. In a second step, nitrate is added to the sediment to enhance remineralisation.

The two-step procedure, timing and the amounts of the chemicals used in 'Alte Donau' are shown in Fig. 6 and explained in the following paragraph.

1. Input of $FeCl_3$-solution

This step flocculates phosphorus and adds iron (Fe^{3+}) to the sediment thus preventing P-release. Because the solution is very acidie, powdered lime is added as a buffering agent. Intro-

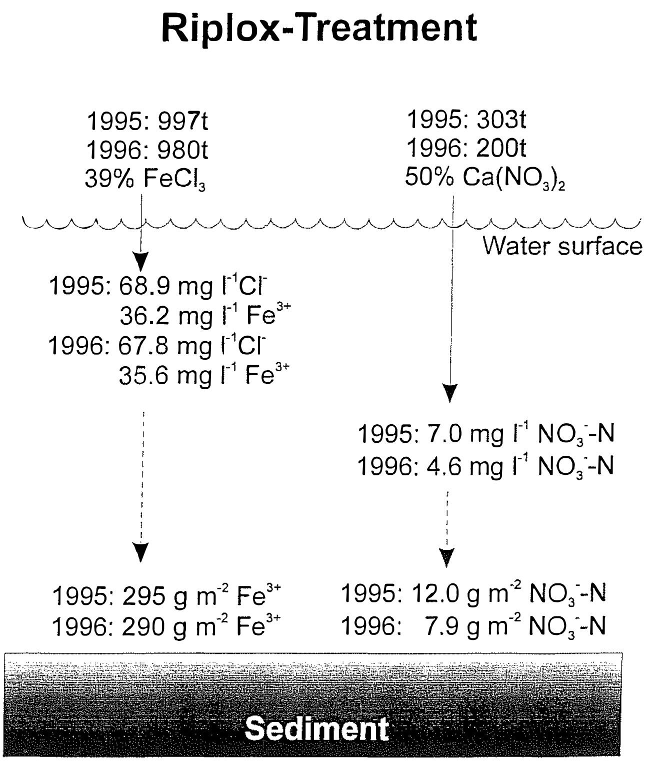

Fig. 6. Summary of the restoration treatment using the Riplox-technique. For more details refer to the text.

duction of this solution into the water results in chemical flocculation and mechanical sedimentation of particles which then settle from the water column.

Between 3 April and 5 May 1995 997 tons of a 39% $FeCl_3$ solution were introduced to the lake. Buffering was achieved through addition of 1,150 tons of powdered lime. The resulting average concentrations in the water column were 69.9 mg l^{-1} chloride and 36.2 mg l^{-1} iron, corresponding to 295 g Fe^{3+} m^{-2} of sediment.

This procedure was repeated between 1 April and 14 May 1996, this time adding some 980 t of $FeCl_3$ and 770 t powdered lime (average concentrations: 67.8 mg l^{-1} Cl and 35.6 mg l^{-1}Fe).

2. Input of $Ca(NO_3)_2$ solution

Calcium-nitrate is injected and distributed near to the sediment to enhance anaerobic denitrification. This reaction reduces nitrate to N which escapes to the atmosphere and turns organic substances into water and CO_2. As a consequence microbial oxygen demand is largely reduced and therefore anoxic periods in the sediment become more unlikely.

Between 22 May and 6 June 1995 303 tons of a 50% solution of $Ca(NO_3)_2$ was added to the system corresponding to 10.0 mg l^{-1} of calcium and 7.0 mg l^{-1} of nitrate. In the following year, 200 tons were added from 20-23 May which is 6.6 mg l^{-1} calcium and 4.6 mg l^{-1} nitrate on average.

Changes as a result of restoration measures

As a result of the chemical treatment, the values for most of the variables changed significantly towards better quality. Annual mean Secchi-depth significantly increased in 1996 and 1997 to 1.7 and 1.5 m respectively and total suspended solids were drastically reduced (Fig. 7, upper panels). Concentrations of the main nutritive elements decreased considerably (Table 3). Average total phosphorus concentrations declined from 62.4 $\mu g\ l^{-1}$ before the treatment to 23 $\mu g\ l^{-1}$ after, with much smaller variance (Fig. 7, lower left panel). Total dissolved and particulate phosphorus were about halved (Table 3). Concentrations of nitrogen fractions were drastically reduced since 1995. Values for total and dissolved nitrogen were down to one third from the levels before the restoration process. The particulate fraction was even lower. The ratio of total nitrogen to total phosphorus changed accordingly (Table 3). As a consequence of these changes, average chlorophyll-a levels, as a measure of phytoplankton biomass, declined from 42.6 to 12.7 $\mu g\ l^{-1}$ (Fig. 7, lower right panel), which is somewhat lower than the mean for 1988 (Table 2 and Fig. 4). All these results are now in agreement with water-quality legislation for recreational waters (ÖNORM M6230 1980).

The filamentous cyanoprokaryote *Cylindrospermopsis* became undetectable in the samples. Species composition of the phytoplankton shifted to diatom-dominated in winter and spring, and prevalent green-algae in summer and fall. Seasonal dynamics of biovolume returned to bimodal in 1997 with a pronounced spring peak (3.6 $mm^3\ l^{-1}$) and a smaller but longer lasting maximum in autumn (Fig. 5). Species of small Cyanoprokaryotes appeared in greater biomass during the summer of 1997 but never exceeded 18%. Primary production, bacterial enzymatic activities and bacterial biomass were reduced by about 25%. The quantity of zooplankton declined by 30-50% but small sized species are still dominant indicating a severe feeding pressure from a large stock of planktivorous fish (SALBRECHTER 2000). Submerged macrophytes were starting to increase again in abundance and biomass (Fig. 3). However, their capacity to store phosphorus, still remained low (15 kg in 1997) when compared to the 900 kg of 1987.

Conclusions

As indicated by the changes observed in the lake, the restoration of 'Alte Donau' using a combination of phosphorus flocculation and nitrate addition to the sediment (RIPLOX-technique) has been successful. Secchi-depth has considerably increased while average annual phosphorus concentration came down to 27% of those from 1993 and are about halve of 1987. With values of >1.5 m and <30 $\mu g\ l^{-1}$ respectively both parameters are now in agreement with conditions outlined in ÖNORM M6230 (1980) for recreational waters. Nutrient levels indicate mesotrophic conditions.

Phytoplankton composition has been altered in the desired direction. The dominant filamentous cyanoprokaryotes have disappeared but were partly replaced by small sized species in 1997. Phytoplankton biomass has drastically declined (Fig. 5). Chloropyll-a levels have declined by 70% and are now lower than 1987 (Table 2). However, values are still in the eutrophic range and are hence too high (Fig. 4). A further reduction in biomass is desirable.

As a result of better light conditions due to the restoration measures, species composition of macrophytes has changed and their biomass has started to increase again (Fig. 3). Phosphorus storage in the submerged plants was 7x greater in 1996 when compared to the previous year. However, macrophytes are still absent in large areas of the lake. Pre-eutrophication conditions

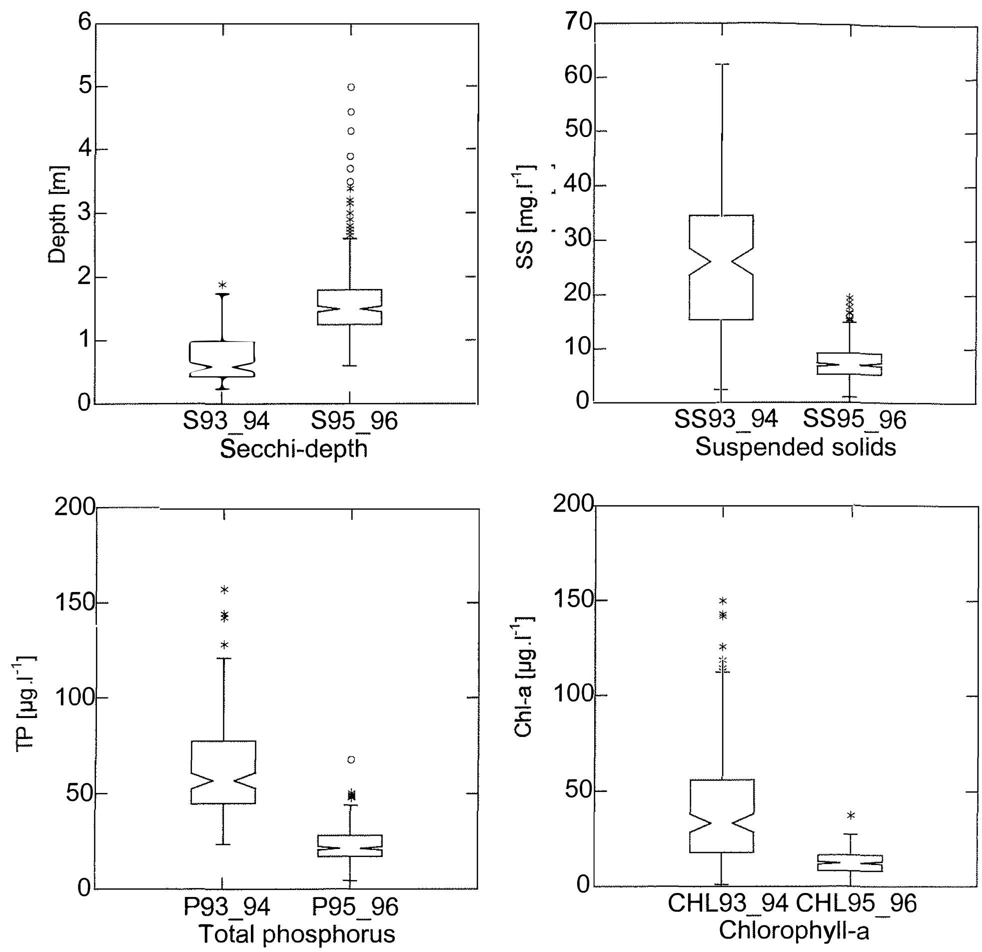

Fig. 7. Notched box-whisker plots for Secchi-depth (upper left), suspended solids (upper right), total phosphorus (lower left), and chlorophyll-a (lower right panel) for the years preceding the restoration (1993/94) and the restoration phase (1995/96). Boxes are notched at the median, return to full width at lower and upper confidence interval and include 50% of the values.

with high submerged macrophyte biomass could not be re-established because of the differing respons of plant biomass to nutrient concentrations during the eutrophication and recovery phase (Fig. 4).

This hysteresis effect is caused by alternative stable states (SCHEFFER et al. 1993, 1997) and is most commonly caused by a shift in energy transfer from the classical food-chain to more decomposition-orientated processes. The sustainability of P-precipitation in the open water may thus be seriously questioned. Initially, P-concentrations and biomass of cyanoprokaryotes remain low. Soon after populations re-establish in the productive zone (TILLE-BACKHAUS et al. 1990). Such a situation needs additional management strategies such as biological control through biomanipulation.

Further rehabilitation techniques

As a consequence of the conclusions drawn from the results so far, further restoration measures have to be implemented. Biomanipulation techniques presently being are tested. Removal of herbivorous fish as well as stocking large numbers of carnivorous fish are used in large natural and artificial exclosures to alter the structure of the zooplankton assemblage. The re-establishment and long-term stabilisation of large stands of submerged macrophytes is seen as an indispensable pre-requisite for all further measures. To achieve better re-colonisation material from different species has been planted with some success by scuba divers (PALL et al. 1998). The main problem associated with this technique is the feeding activity of aquatic birds.

We believe that sustainable long term stabilisation of the lake restoration will only be achieved through a combination of different internal management practices.

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