Strategy and current status of combating eutrophication in two Berlin lakes for safeguarding drinking water resources

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Abstract After reduction of the external phosphorus load by phosphorus elimination plants, Lake Tegel and Schlachtensee in Berlin underwent a significant trophic improvement. The phosphorus elimination plants work by precipitation/coagulation/flocculation – sedimentation – post precipitation – filtration. The external load was reduced by one to two orders of magnitude down to 10–20 $\mu g\,P\,L^{-1}$.The inlake phosphorus concentration followed. The development of algae and cyanobacteria was reduced substantially below a threshold value of about 50 $\mu g\,P\,L^{-1}$, clearly due to phosphorus limitation. In Lake Tegel, the external load reduction of the main inflow was counteracted partially by the external load of the second main inflow by the River Havel and the internal load. This has to be managed further in future.

Keywords Lake restoration; phosphorus elimination; water resource management

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Introduction

Water bodies in densely populated areas are used intensively for different purposes, particularly as recipients for treated sewage, stormwater from the separate system and overflow of the combined sewer system, and further for recreation and water supply. These uses are conflicting, as wastewater recipients tend to have high nutrient loads leading to eutrophication, which threatens use for recreation and water supply. Therefore, many efforts have been made in past decades to reduce the external loads (Marsden, 1989; Sas, 1989), sometimes in combination with internal measures to suppress the internal nutrient cycle (Cooke *et al.*, 1993).

Lake Tegel is an outstanding example of intensive multiple usage of an urban lake: as a waterway for shipping, as a recreational area, as a recipient of wastewater, but also as one of the city's major reservoirs for drinking water. The Tegel waterworks – one of largest in the city of Berlin – are located near the surface water system of Lake Tegel. Discharging wells are drilled in short distances around this lake near the bank to abstract water, which is gained from bank filtrate, groundwater, and its artificial recharge with water from the lake. Nonetheless, it has been possible to maintain the supply without further treatment except aeration and rapid sand filtration, and the microbiological quality is so good that no disinfection of the drinking water is required. Schlachtensee was used as a source for bank-filtrate in the southwest of the city until 1995, when demand declined due to reduced per capita water usage, and it remains a major recreational area.

However, in the 1970s, heavy eutrophication was a threat to the usage of Lake Tegel and Schlachtensee as important drinking water resources. Concerns particularly included the potential breakthrough of organic metabolites from heavy phytoplankton blooms, e.g. taste and odour substances and substrate for bacterial regrowth. To maintain this close-to-natural water treatment without a need for disinfection, a concept for the restoration of

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these lakes was developed aimed at a drastic and quick reduction of the external phosphorus loads. The Vollenweider (1979) model for loading by area provided the basis for calculation of the acceptable input to reach mesotrophic lake conditions with a mean P concentration in the lake of around 30 $\mu g\,L^{-1}$. Assuming a water retention time of around 200 days in Schlachtensee and 80 days in Lake Tegel (Klein, 1990), the Vollenweider model indicated that a P load per area of 0.45 (Schlachtensee) – 1.5 (Lake Tegel) $g\,m^{-2}\,yr^{-1}$ should not be exceeded, which corresponds to a total load of 200 $kg\,P\,yr^{-1}$ for Schlachtensee and 4,600 $kg\,P\,yr^{-1}$ for Lake Tegel (Schauser and Chorus, 2006). At the time, however, their loading amounted to 1 to 3 $t\,P\,yr^{-1}$ and 100–200 $t\,yr^{-1}$.

After a wastewater treatment plant with simultaneous precipitation had gone into operation in Schönerlinde (Figure 1), loading to Lake Tegel declined to values around 50 $t\,P\,yr^{-1}$. However, in the face of a goal of roughly 1 $t\,yr^{-1}$, this was still 1 to 2 orders of magnitude too high. Schlachtensee is fed by the highly eutrophic Havel River. Thus for both lakes, sufficient reduction of the external phosphorus loads could be achieved only by constructing phosphorus elimination plants to treat the inlets immediately before their entrance into the lakes. A similar technology already had been installed successfully at Wahnbachtalsperre in 1977 (Sas, 1989; Heinzmann and Sarfert, 1990; Heinzmann *et al.*, 1991).

Method

Thus, since 1981 and 1985, respectively, surface water has been treated by the phosphorus elimination plants (PEP) at Beelitzhof (Heinzmann and Sarfert, 1990) and Tegel (Heinzmann *et al.*, 1991), which apply a four-step process: precipitation/ coagulation/flocculation – sedimentation – post precipitation – filtration. The PEPs reduce the total phosphorus concentration at the lakes' inlets by 1–2 orders of magnitude, i.e. from 0.3–0.5 $mg\,L^{-1}$ at Schlachtensee and at Lake Tegel from up to 5 $mg\,L^{-1}$ down to 8–20 $\mu g\,P\,L^{-1}$.

The surface water treatment process is similar for both lakes and is described below using the example of the PEP at Tegel. The scheme of the process is shown in Figure 2.

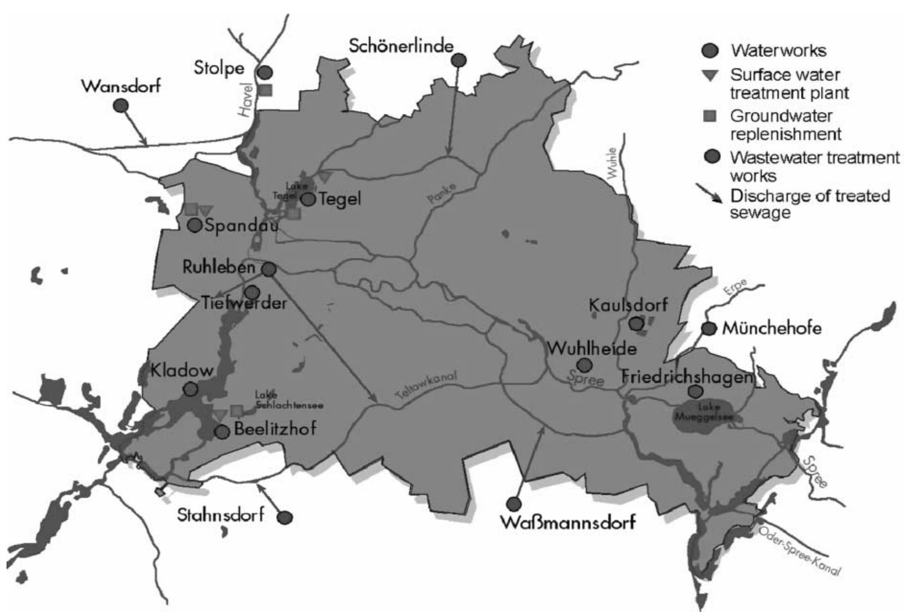

Figure 1 Map of water bodies, waterworks and treatment plants in the Berlin region

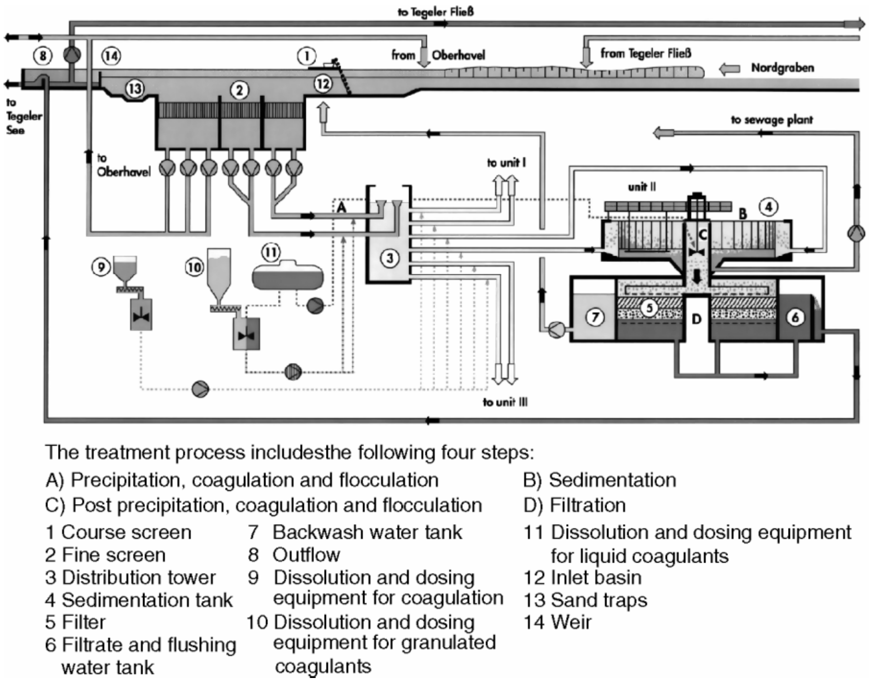

Figure 2 Scheme of the surface water treatment process in Tegel (Berlin) (Heinzmann *et al.*, 1991)

Mechanical pre-purification comprises coarse screening (25 mm mesh size) and sedimentation of sand and larger particles in the inlet basin. Further, the water flows through a fine screen (8 mm mesh size) to the raw water pumps. From here, it is pumped to the distribution tower. The coagulants are directly dosed into the two pipes (pipe flocculation). To support rapid and complete mixing, the coagulants are dosed through nozzles at four points at which the two pipes are narrowed from 1 m to 0.7 m and then again extended to 1 m. On the way to the distribution tower, micro flocks build up. After the distribution of the water to six pipes (diameter 1.2 m), a coagulant aid is added to support the macro flocculation process. Two pipes lead to each of the three sedimentation tanks in which the macro flocks settle. The sludge is removed into sludge traps by scrapers. The treated water flows down to six filters, which are situated under the sedimentation tanks. Additionally, there is the possibility for a second dosage step (post precipitation) in the clear water outflow tank before the filters. In the filters, the particles and flocks are removed in a double-layer system with a filtration velocity of approximately 6 $m\,h^{-1}$. The upper layer consists of 600 mm pumice gravel with a diameter of 2.5–3.1 mm. Under this layer, a 1,300 mm sand layer (diameter 0.71–1.25 mm) is arranged. Approximately every 24 hours, the filters have to be backwashed. The treatment costs including capital cost are approximately 0.15 € per m^3 treated surface water (Heinzmann and Sarfert, 1990; Heinzmann *et al.*, 1991).

Result and discussion

Both lakes were flushed approximately twice a year with water leaving these plants with only 8–10 μg/L of total P at Schlachtensee and around 20 μg/L at Lake Tegel. Both responded to the dramatic reduction in external phosphorus loading with an immediate decline in total phosphorus concentration, which followed a nearly exponential pattern during the first years (Figure 3). However, in Lake Tegel, this recovery slowed down at levels around 100 $\mu g\,L^{-1}$, just enough to start slightly reducing phytoplankton maxima.

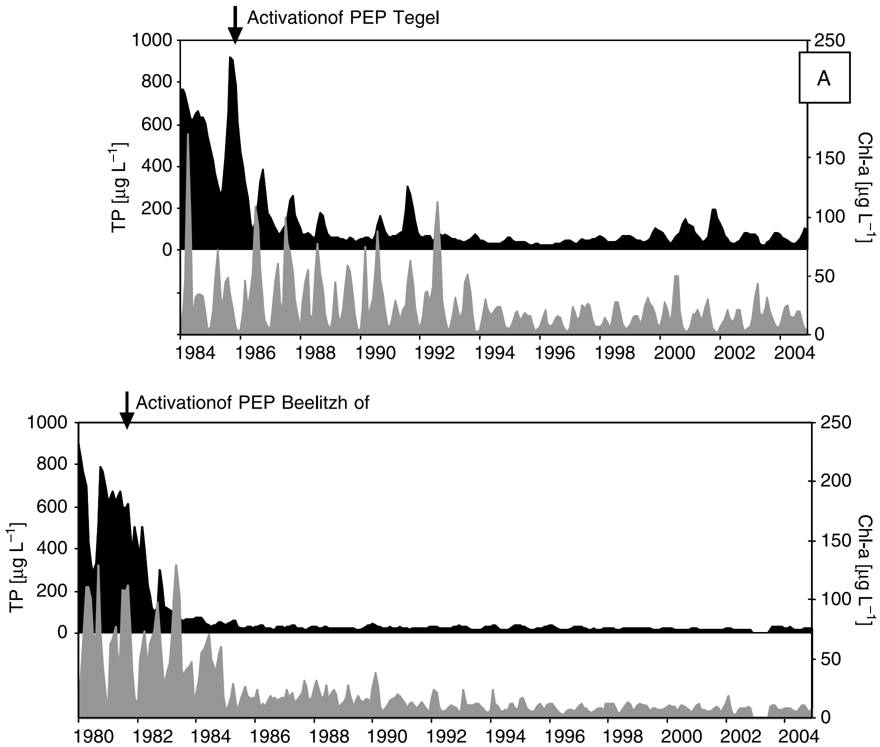

Figure 3 Total phosphorus (black) and chlorophyll-a (grey) concentrations [A] in Lake Tegel (1984–2004) and [B] in Schlachtensee (1980–2004) [monthly mean values, $\mu g\,L^{-1}$ in 1 m depth]. Note: No data for Schlachtensee from December 2002 – June 2003

Only in 1993, eight years after the measure was begun, did total phosphorus decline further, and phytoplankton started showing a pronounced response. In Schlachtensee, the phosphorus concentration continued to decline further, leading to pronounced reduction of the biomass for the first time in 1985, already four years after restoration was begun.

In both lakes, seasonal patterns indicate substantial ‘internal loading’ through the release of sediment-bound phosphorus. This is related to the temperature and the nitrate concentrations above the sediment (Schauser *et al.*, 2006). The two important release processes of P in the sediments are mineralization of organically bound P and desorption of inorganically bound P. Mineralization is the primary process and highly temperature dependent. It involves the reduction of electron acceptors. Because hypolimnetic oxygen concentrations are limited during thermal stratification in summer, following the redox chain nitrate is the next important electron acceptor. If the nitrate-oxygen is consumed, first iron and then sulfate are reduced. This leads to the precipitation of iron sulfide, with the consequence of desorption and then release of previously iron-bound phosphorus. For Lake Tegel, after 1992, elevated nitrate concentrations from treated, nitrified sewage helped to keep the sediments oxidized and thus reduced release. As the EU legal requirements of sewage denitrification needed to be met, denitrification was introduced and this nitrate is no longer available since the late 1990s. However, for Lake Tegel, there is no clear relationship between the nitrate concentration and P concentration in the deep water layer: even under aerobic conditions, when nitrate is still available, P release occurs. It seems that P release from the sediment in Lake Tegel is mainly temperature controlled and that the aerobic P sorption capacity is rather low. In contrast, for Schlachtensee, a threshold of about 0.5 mg NO_3-N L^{-1} seems to exist: Whenever the nitrate concentrations above the sediment decline beneath this value, an increase of the P concentration in the hypolimnion was observed. On the other hand, there was no or only little P release under anaerobic conditions. This indicates that, in contrast to Lake Tegel, aerobic sorption capacity for P in Schlachtensee is sufficient to suppress P release under aerobic conditions.

However, in Schlachtensee, both the total P content of the sediments and the fraction of redox sensitively-bound phosphorus (BD-P) are much lower than in Lake Tegel (Figure 4). Therefore, the total amount of redox sensitively-bound phosphorus that can migrate from the sediments into the hypolimnion is about an order of magnitude lower than in Lake Tegel, and this corresponds to hypolimnetic phosphorus maxima, which are also an order of magnitude lower. This may be one reason for Schlachtensee's more rapid recovery. A further factor is the withdrawal of the hypolimnion, which was conducted for several weeks in late summer starting in 1980 until 1996. Especially in the first years, it supported the reduction of the P content in Schlachtensee (Schauser and Chorus, 2006).

For Lake Tegel, the difficulty in accounting for the source of phosphorus remaining was in differentiating between internal loading and import from the Havel River. The Havel River flows past the mouth of Lake Tegel and is highly loaded with nutrients. Mean annual phosphorus concentrations range between 100 and 160 $\mu g\,L^{-1}$ (1990–2002) (Figure 5). Depending on water budgets, some inflow of river water into the lake is likely. Estimations by mass balance calculations and modelling indicate that around 30%

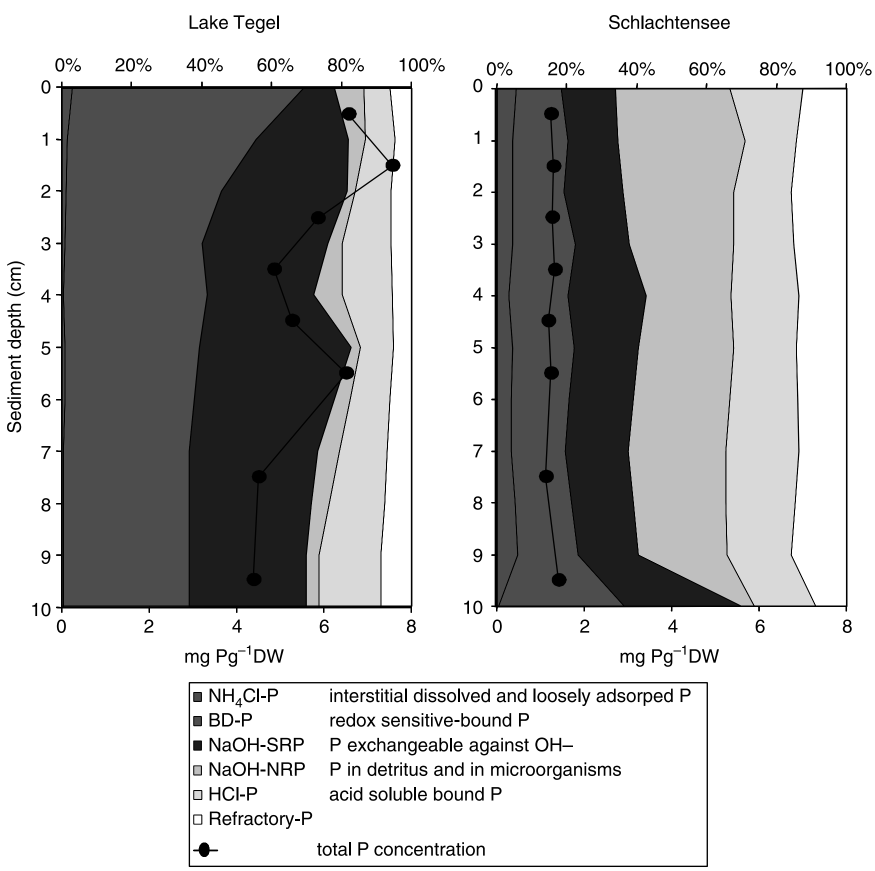

Figure 4 Distribution of the phosphorus fractions and total phosphorus concentration in the sediment of Lake Tegel and Schlachtensee

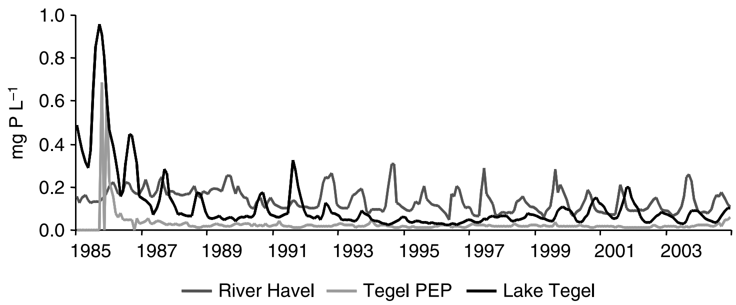

Figure 5 Mean monthly phosphorus concentrations of the River Havel, the outlet of the phosphorus elimination plant and Lake Tegel [mg P L^{-1}]

to 40% of the inflow of the lake may be Havel water (Ripl *et al.*, 1993; Lindenschmidt and Fröhlich, 2000). A numerical modelling showed that the share of Havel water depends largely on the River Havel runoff, the discharge of the Tegel PEP and the abstraction of the Tegel waterworks for groundwater enrichment (Schauser and Chorus, 2004) This was of special importance in the years 1997 to 2001, when the throughput of treated water in the phosphorus elimination plant was reduced to around 1.5 m^3/s, as compared to a more or less constant level of 3 m^3/s during earlier years. Particularly in these years, total P concentrations in the lake follow those in the Havel River, suggesting this to be a major source. Since 2002, this problem is being addressed by maintaining a higher throughput of 2.2 m^3/s during the critical summer months.

Lake Tegel's and Schlachtensee's phytoplankton biomass (shown here as concentrations of chlorophyll-a) responded to reduced phosphorus concentrations in the lake with a pronounced threshold pattern (Figure 6). At levels above 100 $\mu g\,L^{-1}$ total P, there was no reaction of annual mean values, and summer maxima were only slightly reduced (compare Figure 3). In contrast, an exponential relationship between annual means of total P concentration and annual means of chlorophyll-a became apparent in the range between 20–60 $\mu g\,L^{-1}$ total P. These results demonstrate that for effective control of mass developments of algae and – potentially toxic – cyanobacteria, it is necessary to

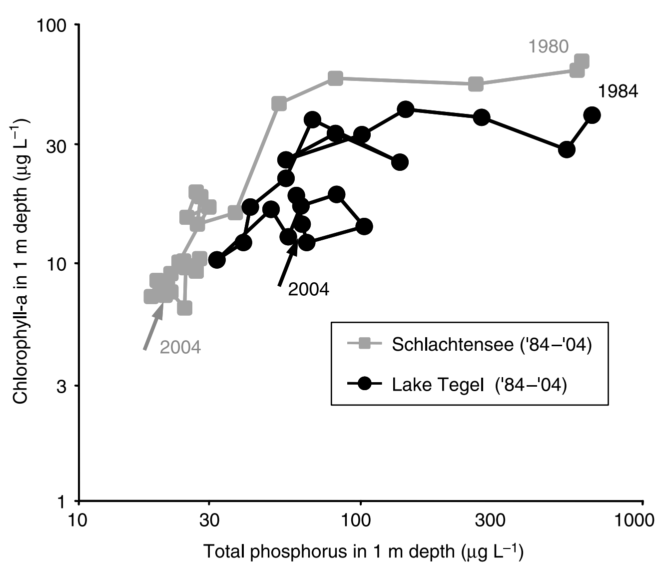

Figure 6 Relationship between total phosphorus and chlorophyll-a in Lake Tegel and Schlachtensee [$\mu g\,L^{-1}$ in 1 m depth]

reduce total phosphorus concentrations well below 50 $\mu g\,L^{-1}$. In Schlachtensee, 20 $\mu g\,L^{-1}$ proved effective to keep the cyanobacterial populations at very minor levels. The Vollenweider model (1976) indicates that Schlachtensee has reached a new steady state condition with an annual mean P concentration around 20 $\mu g\,L^{-1}$, thus the effect of internal loading is no longer significant.

Conclusion

In both Berlin lakes, the external P load reduction was followed by a drastic improvement of trophic state. This is contrary to other lakes, where the external load was reduced more gradually over many years, and therefore the P concentration decline in the lake, as well as the phytoplankton reaction, was slow and less pronounced. In some lakes, where the P reduction was not high enough to limit the phytoplankton development, only a small or no response in trophic state was observed (Sas, 1989). However, like in the Berlin lakes, in most lakes a decline in phytoplankton biomass was accompanied by a shift in community structure (Jeppesen *et al.*, 2005).

In Schlachtensee, it was possible to suppress the external load rapidly and sufficiently so that the lake could reach a new steady state with P concentrations around 20 $\mu g\,L^{-1}$. To sustain this improvement, the Beelitzhof PEP has to remain in operation, as the large-scale situation is unlikely to reduce external loading to natural background levels. For Lake Tegel, meanwhile, the external load by the River Havel is more important than the load from the Tegel PEP. This, together with the internal load, leads to pronounced annual variations of the P and chlorophyll-a concentrations. In addition to continued operation of the Tegel PEP, further management measures are important:

- to reduce the Havel inflow, the through flow of the PEP has to be kept above a minimum level of at least 2.2 m^3/s
- the temperature at the lake bottom has to be kept low by supporting the stratification stability, and
- increasing the aerobic P-sorption capacity of the sediment with more oxidized iron emerges as an option to explore in more detail

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