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The significance of sedimentation and sediments to phytoplankton growth in drinking-water reservoirs

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In the mesotrophic–eutrophic Saidenbach Reservoir in Saxony, the nanoplankton and cyanobacteria have increased at the expense of diatom dominance, due to a doubling of the external phosphorus load in the last 15 years. However, the phosphorus sedimentation flux is still very high (up to 80% of the input), corresponding to more than 2 g m^2 d^{-1} in terms of dry weight. There is a strong correlation between the abundance of diatoms in the euphotic zone and their sedimentation flux (with a delay of about 2 weeks). Only about 25% of the deposited material could be clearly attributed to plankton biomass; the remainder resulted from flocculation and precipitation processes or directly from the inflow of clay minerals. The ash content of the deposited material was high (73%). Thus the sedimentation flux can be considered to operate as an internal water-treatment/oligotrophication process within the lake.

The neighbouring Neunzehnhain Reservoir still has a very clear water with a transparency up to 18 m depth. Though the sediment was not much lower than Saidenbach sediment in total phosphorus and total numbers of bacteria, sulphide was always absent and the ratio of Fe^{2+} to Fe^{3+} was very low in the upper (0 – 5 cm) layer. Thus the external and internal phosphorus loads do not attain the critical level necessary to induce a "phosphorus – phytoplankton" feedback loop.

Introduction

Saidenbach Reservoir is situated in the Erzgebirge Hills, Saxony, and has been in operation since 1933. It is one of the principal sources of drinking-water for the municipality of Chemnitz. Its full water level is at 439 m, the catchment has an area of 76 km^2 and is mainly used for agriculture. The area of the reservoir is 1.46 km^2 and its volume is 22.4 million m^3, with a mean depth of 15 m and maximum depth 45 m. The catchment of the neighbouring oligotrophic Neunzehnhain Reservoir has an area of 12.8 km^2 and is covered by forest (mainly spruce, *Picea*). Its area is 0.29 km^2 and the volume is 2.5 million m^3, with a mean depth of 10.3 m and maximum depth 33 m.

Saidenbach Reservoir is longitudinally separated, with a pre-reservoir and underwater pre-reservoirs arranged in series in the inflow area. These not only serve as traps for suspended solids but also for phosphorus (Figs 1 – 3). Although design criteria for pre-reservoirs, concerning their capacity to immobilize phosphorus, have been described by Uhlmann & Benndorf (1980) and Benndorf & Pütz (1987 a,b), the quantitative aspects of the processes governing the retention, immobilization and sedimentation of phosphorus in process reservoirs arranged in series are still largely unknown. Phosphorus retention may range between 20% (Stimpfig *pers. comm.*) and more than 50% if different pre-reservoirs are compared. These also have to cope with suspended solids, the load of which is a reflection of the intensity of erosion processes in the catchment (Fig. 4).

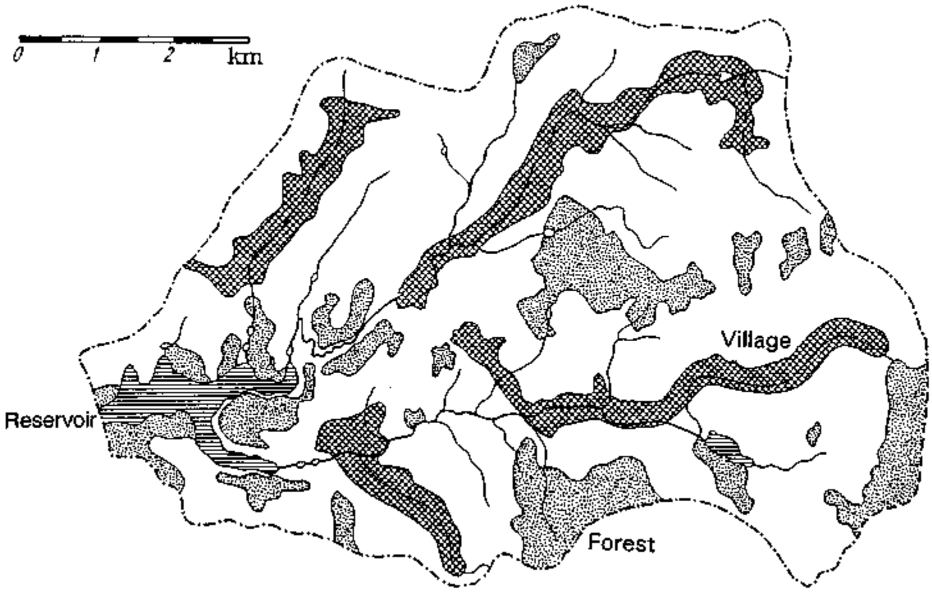


Figure 1. Saidenbach Reservoir (horizontal shading) and its catchment area, showing forest (stippled) and villages (cross-hatched).

In the following account the processes governing the sedimentation of phytoplankton biomass and phosphorus, as factors which decrease the residence time of P-compounds in the euphotic layer, will be dealt with in some detail. The chemical analyses of water and sediments referred to here were performed as described in "Ausgewählte Methoden" (1986); the sediment trap was developed by Horn & Horn (1990).

Phytoplankton growth and sedimentation

One of the principal processes which govern the sedimentation of phosphorus in mesotrophic to eutrophic drinking-water reservoirs like Saidenbach is the incorporation of phosphate by diatoms. These have a high sinking velocity and thus decrease the residence time of phosphorus in the euphotic zone. Investigations on Saidenbach also dealt with the question: to what extent are the seasonal changes in the abundance of phytoplankton followed by corresponding changes in the sedimentation flux, in terms of phytoplankton biomass and phosphorus, or suspended matter? As is evident from Figure 5, there was a surprisingly close correlation between the "biovolume" of the phytoplankton, and its sedimentation flux, with a phase shift of about 2 weeks between the two maxima. On the other hand, the sedimentation flux of suspended solids in general was not clearly correlated with the phytoplankton sedimentation. This is in accordance with the low proportion (about 25%) of the deposited material which clearly can be attributed to the phytoplankton biomass. This is also comparable to the low proportion (less than 26%) in the deposited material recorded by Hamilton-Taylor *et al.* (1984) from Lake Windermere in England. In Saidenbach the phosphorus load has doubled in the last 15 years. As a result, dissolved silica was depleted at the end of the diatom growth period. This was the trigger for a substantially increased abundance of cyanobacteria like *Aphanizomenon* and green algae, with a high proportion of nanoplanktonic forms. This resulted in an oxygen minimum in the metalimnion and at the surfaces of the corresponding sediment layers, and in a longer residence time for phosphorus in the euphotic zone. The minimum Secchi depth, which in the past has been 4.9 m, is now 3.8 m.

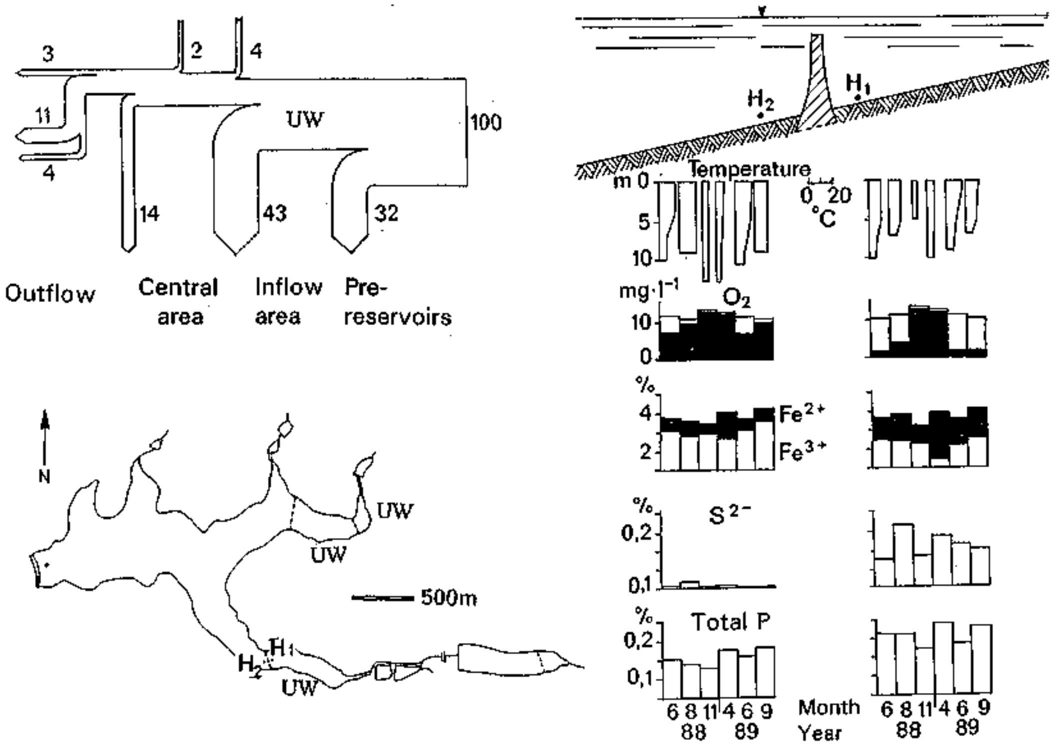


Figure 2. Some general features of Saidenbach Reservoir. Bottom left: plan view showing positions of one large and six small above-ground pre-reservoirs, and three under-water pre-reservoirs (UW). Above left: approximate proportions (numbers, %) of total phosphorus sedimentation in the longitudinal axis of the reservoir (after Hofmann 1972 and Petersohn 1987), although the phosphorus flux in the outflow (shown as 3+11+4=18%) may attain about 25% according to more recent calculations. Right: some properties of the water-body and sediments above (H1) and below (H2) the dam of the Haselbach underwater pre-reservoir. Variations in water level are evident from the temperature (°C)/depth (m) diagrams. Oxygen concentrations (mg l^{-1}) refer to the water layer 1m above the bottom. The white portion of the columns denotes the oxygen deficit below saturation.

Phosphorus sedimentation

The sedimentation flux of particulate matter (including phosphorus) seems to be the most important loss process with regard to phytoplankton growth in Saidenbach. In lakes and reservoirs with a short residence time for water, there is a comparatively low proportion of phytoplankton biomass in the total sedimentary flux. This has been observed in lakes in Austria and Switzerland, and also in Lake Windermere. As the allochthonous suspended solids (see Fig. 4) normally have a high concentration of iron or aluminium in catchments with igneous rock, they may operate as adsorbents, flocculants and precipitants, and thus play a significant role in the nutrient balance. The sedimentation flux in Saidenbach was, on average, about 2.33 g m^2 d^{-1} (as dry weight) and this may be considered to be a significant internal oligotrophication/water-treatment process within the lake. The deposition of the particulate matter, and thus phosphorus sedimentation, attains a particularly high level in the inflow area of the lake.

In most of the lakes mentioned above, the phosphorus sedimentation flux attains a high level (Bloesch & Sturm 1986; Gächter *et al.* 1989; Kleiner & Stabel 1989). This likewise has been observed in reservoirs (Porcalova 1989).

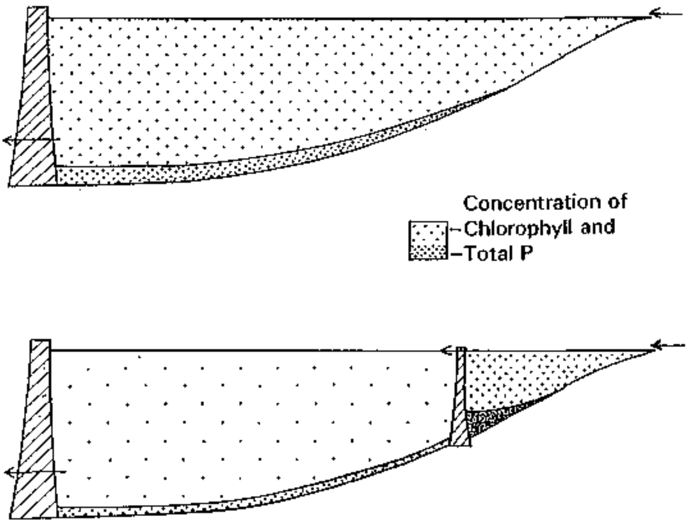


Figure 3. Diagrammatic representation of the effect of pre-reservoirs, showing an increase in phytoplankton growth and sedimentation, and a decreased loading of the adjacent main reservoir. The relevant processes of phosphorus and nitrogen elimination are: incorporation of N and P into biomass; absorption/binding of P to Fe, Ca and Al; formation of $MgNH_4PO_4$; nitrification/denitrification.

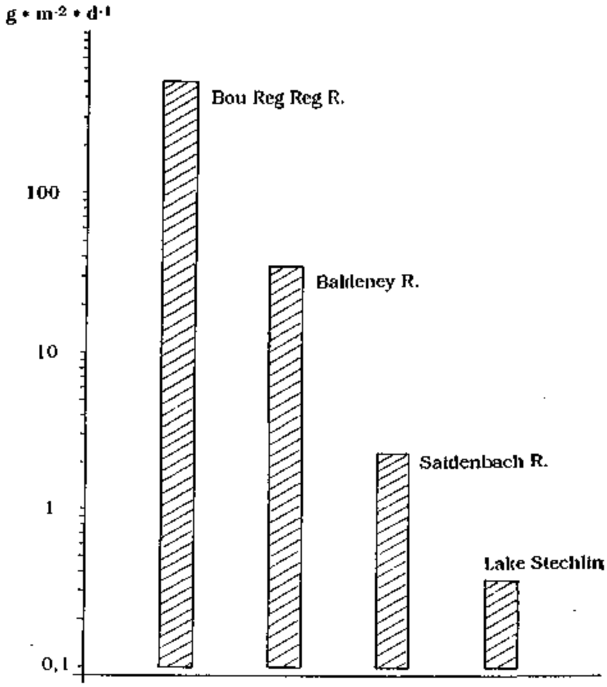


Figure 4. Comparison of the deposition rates of suspended solids (g dry wt m^{-2} d^{-1}) in three reservoirs and one lake with different intensities of erosion in their catchments. Bou Regreg is a large drinking-water reservoir in Moroc (Abouzaid *et al.* 1984). Baldeney Reservoir is an impoundment of the River Ruhr in a densly populated and highly industrialized area (Imhoff 1990), and Lake Stechlin is a deep oligotrophic lake of glacial origin with a small catchment area (data from Proft, *pers comm.*).

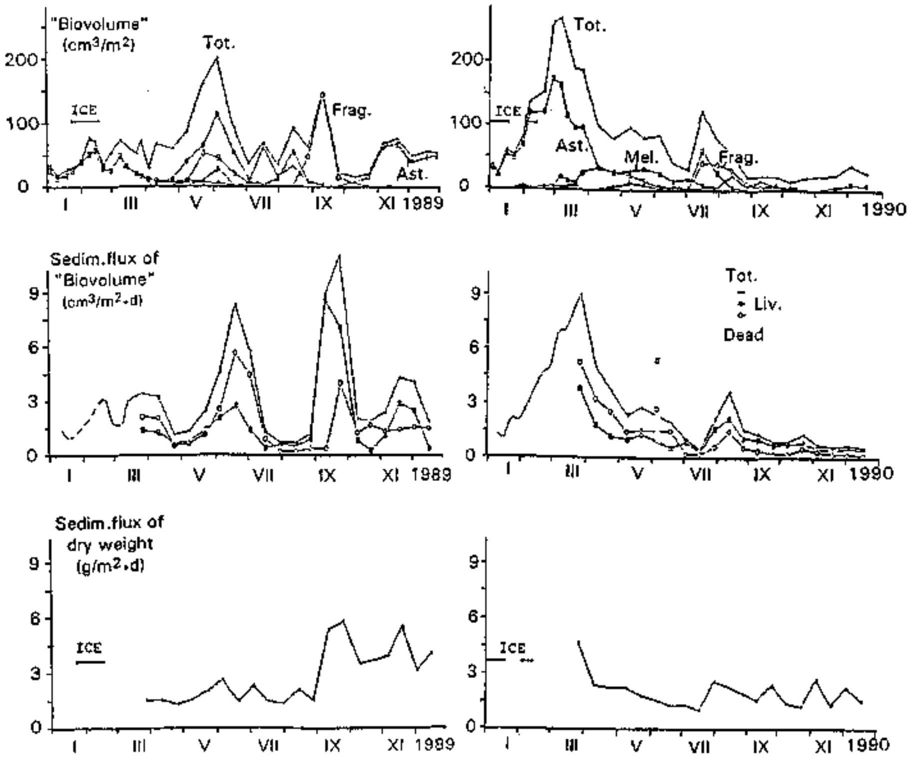


Figure 5. Seasonal variations of biomass (cm^3 m^{-2}), sedimentation flux (cm^3 m^{-2} d^{-1}) and total sedimentation flux (g dry wt m^{-2} d^{-1}) in Saidenbach Reservoir. —•—, total phytoplankton; □, *Asterionella*; ○, *Fragilaria*; ■, *Melosira*.

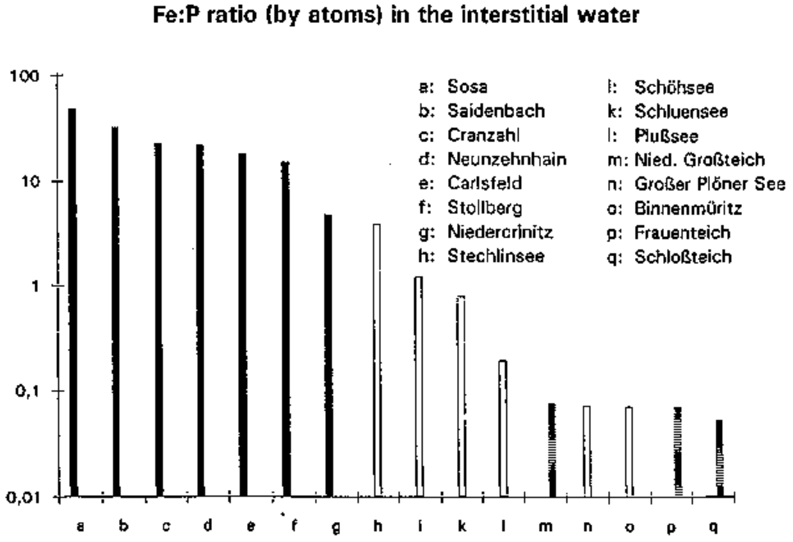


Figure 6. The atomic ratio of iron to phosphorus in the interstitial water of bottom sediments in different types of water-bodies: ■, reservoirs; □, lakes; ▤, carp ponds. The numerical data were drawn from Rühle (1971) and Guderitz (unpublished).

Sediments of reservoirs normally have a significantly higher iron content than sediments of lakes with a long water-residence time. In most of the drinking-water reservoirs presented in Figure 6, the atomic Fe:P ratio is essentially higher than 20:1, whereas it is below 1:10 in hypertrophic carp ponds and some eutrophic lakes. Furthermore, a substantial part of the iron is bound to sulphide in these conditions and thus is not available for the immobilization of phosphorus. In Saidenbach the (inorganic) sulphur concentration of the sediment was 0.38%. This is an indication of a comparatively high sulphide content, but as the iron concentration averages about 4% its major part is still available to bind phosphate.

Both Saidenbach and Neunzehnhain reservoirs have very high nitrate concentrations in the hypolimnion. The concentration of nitrate-nitrogen was nearly always higher than 4.5 mg l^{-1}. This means that the equivalent nitrate oxygen concentration was higher than that of molecular oxygen. Laboratory experiments with sediment cores showed that this nitrate assists in the immobilization of phosphate (Hupfer & Uhlmann 1991). Its velocity of diffusion from the water into the sediment is very high. As it is normally available in excess, there is only a low risk that an overshoot in phosphorus release occurs due to nitrate depletion. The immobilization of phosphate by the addition of nitrate was reversed by the presence of antibiotics. This indicates that microbial processes play an important role in the immobilization of phosphate, in addition to the chemical binding and adsorption which was described fifty years ago (Mortimer 1941). The existence of the oxidised barrier layer of the sediment – water interface, with its high content of trivalent iron, thus also depends upon the flux of nitrate oxygen.

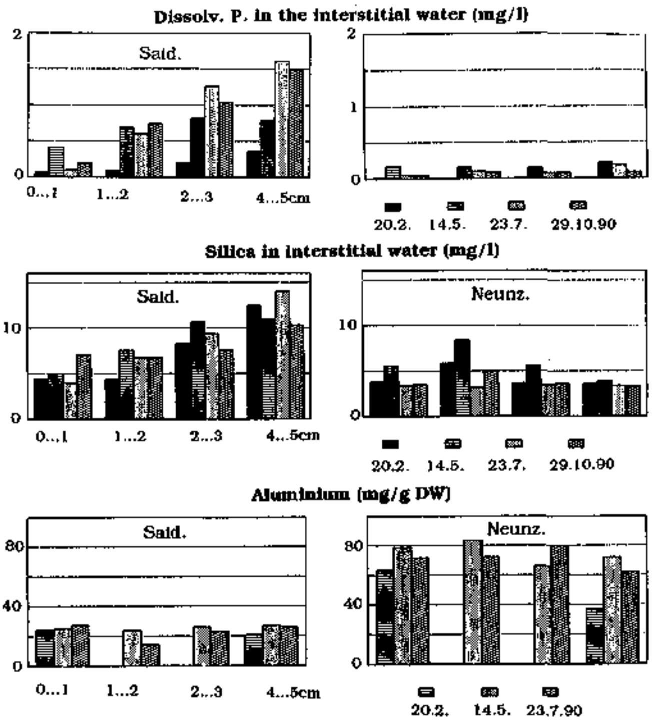


Figure 7. Comparison of dissolved reactive phosphorus (mg l^{-1}) and silica (mg l^{-1}) in the interstitial water of surface sediments and aluminium (mg g^{-1} dry wt) in the sediments of Saidenbach and Neunzehnhain reservoirs. The adjoining columns denote sampling dates in 1990 (20 February, 14 May, 23 July, 29 October) and each set represents samples taken at 0–1, 1–2, 2–3 and 4–5 cm depth in the sediments.

Figure 7 illustrates some differences between the Saidenbach and Neunzehnhain reservoirs. The concentration of dissolved phosphate in Neunzehnhain is obviously below the critical level which would be necessary to initiate a self-maintaining cycle of phosphorus release, phytoplankton growth, and sedimentation of phosphorus, together with reducing power (biomass). The vertical gradient of silica concentration in the interstitial water of Saidenbach corresponds to its growth-limiting role with regard to *Fragilaria crotonensis.*

The aluminium content of Neunzehnhain sediment was surprisingly high (Fig. 7) and obviously the result of acid atmospheric deposition. At times, the concentration of aluminium hydroxide flocs in the water-body was so high that these could be observed by the naked eye. In contrast the dissolution of aluminium from the soil is much less significant in the Saidenbach catchment, where the addition of lime for agriculture has been practised over many decades.

The impact of acid depositions originating from combustion processes is indicated by sulphate concentrations in the tributaries, which are much greater than would be expected from the natural geochemical conditions. This anthropogenic increase in sulphate was observed 35 years ago, but the effects only now become clearly evident. The significance of sulphate reduction is apparent from Figure 2, where the sampling points H1 and H2 refer to locations above and below the dam of the Haselbach underwater pre-reservoir. A longitudinal profile is presented on the right-hand part of the text-figure. The variations in water level are evident from the temperature profiles. At the bottom of the pre-reservoir there was a lower oxygen concentration and higher iron and sulphide concentrations, but nevertheless the sediment has a high phosphorus content, indicating that the pre-reservoir acts as a phosphorus trap.

Table 1. *Aspects of the phosphorus budget for Saidenbach Reservoir (downstream from the pre-reservoirs) in 1989 and 1990.*

A. Annual mass flow (kg year^{-1}), load per unit area (g m^{-2} year^{-1}) and mean epilimnion concentrations (mg m^{-3}) of total phosphorus and dissolved reactive phosphorus.

	Total P			Dissolved reactive P		
Year	Mass flow	Load	Concn	Mass flow	Load	Concn
1989	2725.52	2.161	24.4	1027.6	0.815	5.54
1990	1535.95	1.197	20.5	528.6	0.412	3.81

B. Rates of sedimentation (cm day^{-1}) of total phosphorus (TP), dissolved reactive phosphorus (DRP) and particulate phosphorus (Part. P). calculated from the Vollenweider model (after Benndorf 1979) and measured with a sediment trap.

	Calculated		Measured	
Year	DRP	TP	Part. P	TP
1989	32.4	16.3	101	48
1990	24.5	10.8	79	45

C. Average total phosphorus load (g m^{2} year^{-1}) to the reservoir (1) and above the sediment trap at 39 m depth (2), sedimentation flux (3) and (4) the flux expressed as a percentage of the load at 39 m (i.e. [(3)/(2)] × 100).

Year	(1)	(2)	(3)	(4)
1989	2.161	5.842	3.470	59.4
1990	1.197	3.246	2.929	90.2

D. Annual mass balance of total phosphorus, showing: (1) initial concentration (kg per total reservoir volume), (2) mass flow (kg year^{-1}), (3) loss in the outflow (kg year^{-1}), (4) theoretical initial concentration for the following year (kg per total reservoir volume), (5) elimination of TP from the water (kg per total reservoir volume) and (6) percentage eliminated (i.e. [(5)/(2)] × 100).

Year	(1)	(2)	(3)	(4)	(5)	(6)
1989	706.7	2726	854	2578	2081	76.4
1990	496.7	1536	460	1572	1182	77.0
1991	389.8	–	–	–	–	–

In Table 1, data on phosphorus sedimentation in Saidenbach are presented against a background of phosphorus mass-flow and concentration. The velocity of sedimentation measured by a sediment trap was still much higher than that expected from former calculations (12.1 cm d^{-1} for dissolved reactive phosphorus, Benndorf 1979). Data for the sinking velocity of total and particulate phosphorus have been compiled in Figure 8; the seasonal variations were lower than expected. The mass balance calculation (Table 1D) is for two succeeding years with very different hydrological conditions. Nevertheless the total phosphorus sedimentation fluxes were similar and comparable to data for sub-alpine lakes. In Saidenbach, phosphorus elimination was 76% in 1989 and 77% in 1990, corresponding to the levels measured in former years and confirming the significant role of phosphorus sedimentation in this material's balance sheet. This effect is amplified by the hypolimnetic outflow, which is a sink for dissolved reactive phosphorus. A very high phosphorus retention capacity has also been recorded for several lakes elsewhere, such as Lake Biwa (Tezuka 1986).

The sinking velocity of phosphorus in Saidenbach (Fig. 8) is equivalent to 280 – 370 m per year. As P-carriers, mineral particles with a high sorption/binding capacity are still much more important than phytoplankton biomass. If the numerical value of the phosphorus sedimentation flux is divided by the sediment flux in terms of dry weight, we obtain 0.3% P. This is equal to the concentration actually measured in the upper layers of the bottom sediment of Saidenbach (Fig. 9).

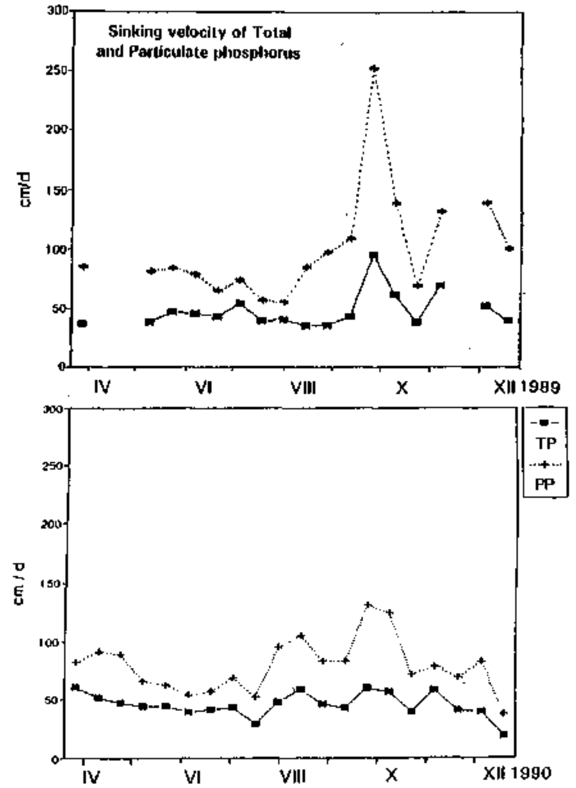


Figure 8. Seasonal variations of phosphorus sedimentation (cm d^{-1}) in Saidenbach Reservoir, in 1989 and 1990. ■, total phosphorus; +, particulate phosphorus.

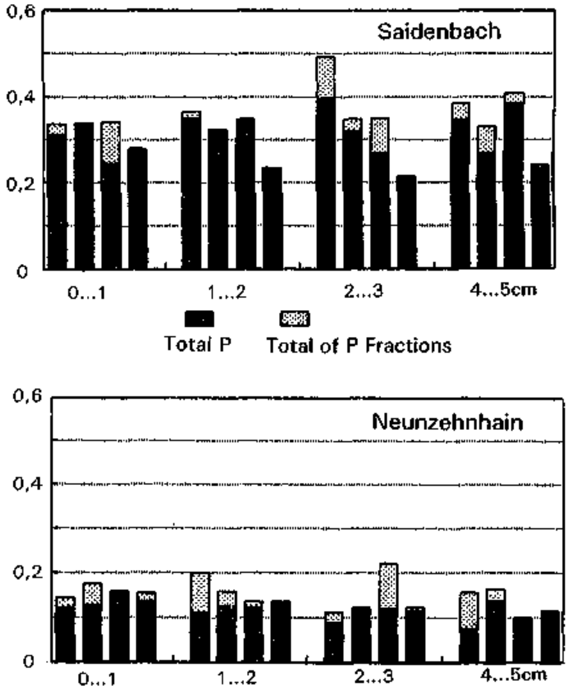


Figure 9. Total phosphorus (percent dry wt) of the surface sediments of Saidenbach and Neunzehnhain reservoirs. The four adjoining colums denote sampling dates in 1990 (as in Fig. 7) and each set represents samples taken at 0–1, 1–2, 2–3 and 4-5 cm depth in the sediments. (Fractionation after Uhlmann *et al.* 1990)

Sediment composition

The significant role of the bottom sediment as a store of phosphorus may be illustrated by a comparison with the concentrations in the interstitial water and in the hypolimnion water (Fig. 10). The concentration gradient between sediment and hypolimnetic water covers more than five orders of magnitude. This indicates that the mobilization of only a very small proportion of the sediment phosphorus would be equivalent to a very strong P-load surge. Though all three levels of phosphorus are lower in the oligotrophic Neunzehnhain than they are in Saidenbach (Fig. 10), the concentration of phosphorus in the sediment of Neunzehnhain is also still so high that a very slight mobilization of phosphorus would be an abundant source of eutrophication. Such a mobilization, however, does not occur in this type of reservoir, and the dissolved reactive phosphorus concentration was always very low in the water of Neunzehnhain. Figure 10 indicates that the phosphorus concentration in the sediment of Saidenbach was higher than in Neunzehnhain by a factor of 2. On the other hand, the phytoplankton biomass was, on average, higher by about two orders of magnitude.

Surprisingly, there was no significant difference between the numbers of bacteria per ml of dry weight or of fresh sediment in the two reservoirs. Likewise the activity of esterases (fluorescein diacetate) was not significantly different (Fig. 11). This underlines the finding of Hupfer (1990) that the results obtained with fluorescein diacetate are closely related to microbial biomass. However, they can not be used as a measure of potential *in situ* activity. The latter is better indicated by the loss in breaking strength of cellulose fibres, the activity of

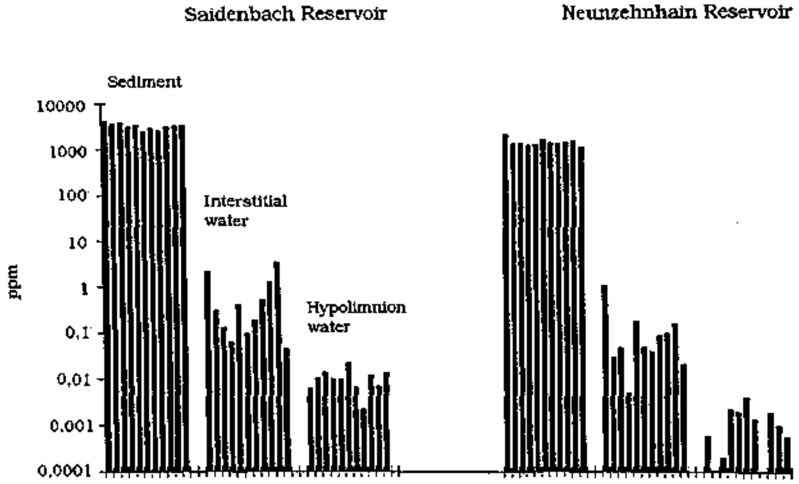


Figure 10. The gradient of phosphorus concentrations (parts per million) between water and sediment in the mesotrophic–eutrophic Saidenback Reservoir and the oligotrophic Neunzehnhain Reservoir. The columns show corresponding results for eleven samples of sediment (0–5 cm), interstitial water and hypolimnion water, respectively.

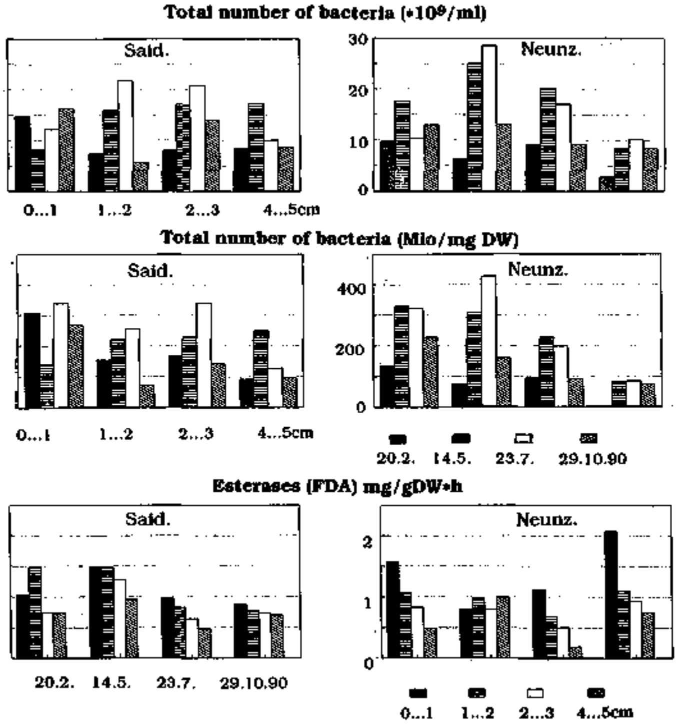
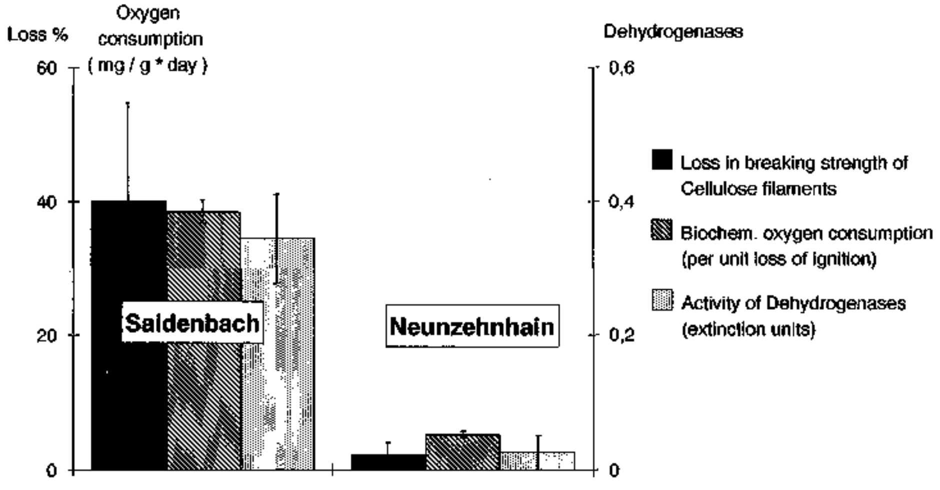


Figure 11. Total numbers of bacteria (x10^9 ml^{-1} and 10^6 mg dry wt^{-1}), and microbial cleavage of fluoresceine diacetate (mg g^{-1} dry wt h^{-1}) in samples from the surface sediments of Saidenbach and Neunzehnhain reservoirs. The four adjoining columns denote sampling dates in 1990, (as in Fig. 7) and each set represents samples taken at 0–1, 1–2, 2–3 and 4–5 cm depth in the sediments.



Data from E. RÜHLE (unpublished)

Figure 12. A comparison of some criteria for *in vitro* microbial activity of the surface sediments of Saidenbach and Neunzehnhain reservoirs (after E. Rühle, unpublished), showing: ■, the loss (%) in breaking strength of cellulose filaments; ▨, biochemical oxygen demand (per unit loss of ignition, mg g^{-1} d^{-1}); □, activity of dehydrogenases (extinction units)

dehydrogenases, and the biochemical oxygen demand of the sediment (Fig. 12). Obviously the majority of bacteria in Neunzehnhain sediment are in a dormant form; their activity seems to be both substrate- and transport-limited. These bacteria probably play a significant role in the immmobilization of phosphorus. This is indicated by the comparatively high proportion of NaOH-soluble non-reactive phosphorus in the sediments of both reservoirs (see also Hupfer & Uhlmann 1991). As in activated-sludge samples from sewage treatment plants with biological phosphorus elimination, this fraction may contain microbial polyphosphates (see Uhlmann *et al.* 1990), and it is supposed that the situation is similar in seston particles and in bottom sediments with similarly very high concentrations of bacteria. (Unfortunately, direct detection of polyphosphates in the sediment samples by means of NMR was impossible because of interference caused by iron). In Neunzehnhain, there is obviously no stimulus for the bacteria to mobilize their phosphorus reserves due to the lack of suitable substrates.

Conclusions

A longitudinal separation of a reservoir into cells arranged in series may significantly contribute to the immobilization of phosphorus in the first cells. There are two types of P-carriers: (1) biomass, either living or dead, or in an altered form as faecal matter or detritus, and (2) mineral particles with a high binding capacity for phosphorus. The influx of iron compounds is relevant to the inactivation of both phosphate and sulphide. Due to the high flushing rate, the Fe:P ratio is normally overstochiometric. Other important chemicals which are essential to the lake's internal water-treatment process are aluminium and nitrate. In catchment areas with limestone dominance, phosphorus sedimentation is governed by adsorption or chemical binding to calcium carbonate. Acid atmospheric depositions rich in sulphur influence the phosphorus balance of the well-buffered mesotrophic to eutrophic Saidenbach and the oligotrophic Neunzehnhain reservoirs in different ways (Fig. 13). Whereas

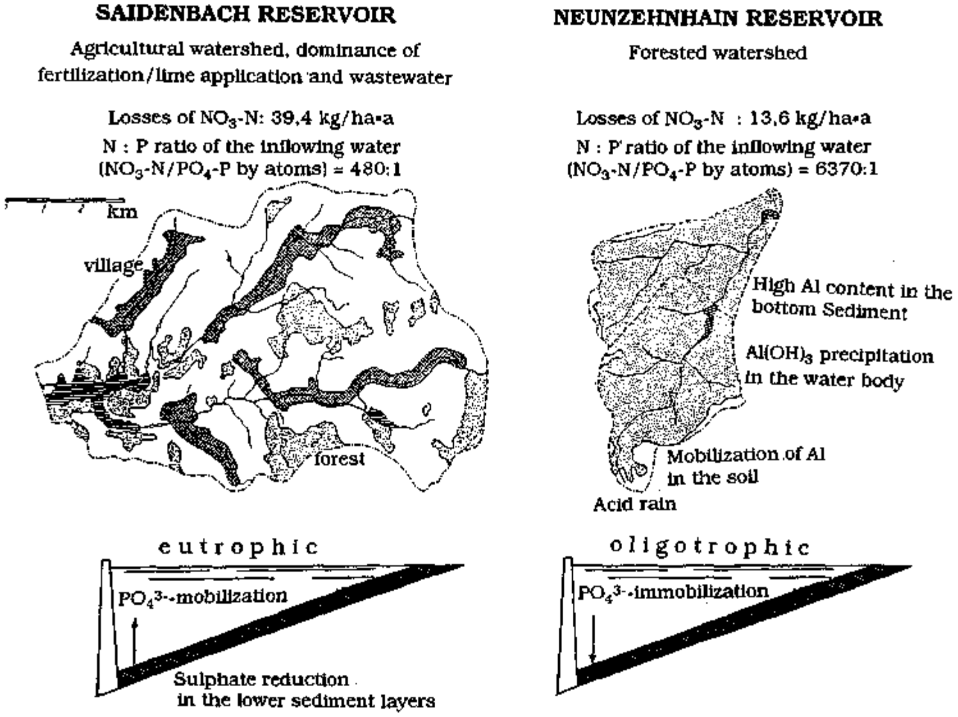


Figure 13. Summary of the effects of atmospheric deposition and land-use on two drinking-water reservoirs of different trophic character.

the natural sulphate concentration of surface waters in the central Erzgebirge hills should be very low, due to the character of the rocks, it is now available in excess as a component which promotes the mobilization of phosphate in sediments. On the other hand, sulphide formation is negligible in Neunzehnhain sediment due to the lack of "reducing power"(H-donors). On the contrary, the acid rainwater promotes the mobilization of aluminium in the poorly-buffered soils, and this results in the formation of aluminium hydroxide in the reservoir. This is equivalent to a high potential of phosphate inactivation. The phosphorus load to the reservoir is far below the level which would be necessary to trigger self-maintaining cycles of phytoplankton growth and phosphate regeneration.

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