RESERVOIR PROTECTION BY IN-RIVER NUTRIENT REDUCTION

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ABSTRACT

If in the catchment area of a reservoir the portion of phosphorus compounds from diffuse sources prevails, phosphorus input can be reduced by chemical treatment of the main tributary. This scheme has been applied by Wahnbachtalsperrenverband for the oligotrophication of Wahnbach Reservoir (volume 40,000,000 m^3). At the point where River Wahnbach flows into the reservoir the incoming water taken from the pre-reservoir which serves as a reserve basin is treated by precipitation, flocculation with iron-III-salts at pH 6.4, and filtration. With this the total P-concentration is reduced by 99 percent to 4 µg/l P as an average. Turbidity also is reduced to a residual of 0.05 FTU and dissolved organic carbon is reduced by 60 percent. This is achieved by energy-input controlled direct filtration (Wahnbach system) developed by Wahnbachtalsperrenverband. The treatment process includes precipitation of dissolved phosphates, destabilization of colloids and suspensoids, agglomeration of formed microfloc to large, well filtrable flocs and three layers filtration with maximum 15 m/h filtration velocity. The maximum throughput of the plant amounts to 18,000 m^3/h. The 3 years' run of the plant shows, that by drastically reducing the annual average P-concentration from 100 µg/l to 4 µg/l the eutrophic Wahnbach Reservoir is transformed from the eutrophic to the oligotrophic-mesotrophic status. The annual average concentration of all tributaries including precipitation was reduced in 1979 for the first time to 16 µg/l, distinctly lower than the tolerable annual average concentration of 20 µg/l. At present, the dominating phosphorus load comes in via small marginal tributaries of the reservoir. This input will be reduced by further special measures.

INTRODUCTION

The origins of phosphorus in the catchment area of a reservoir are varied and detailed examinations have to be carried out to determine the most important phosphorus sources. One differentiates here between 'point' and 'diffuse' phosphorus sources. If diffuse phosphorus sources dominate in a catchment area, then there are only a few methods of reducing loading (Bernhardt, 1978).

One of these methods entails treating the whole of the inflowing main tributary using chemical processes to control the phosphorus input. This chemical treatment has been used on the Wahnbach Reservoir in the Federal German Republic for 3 years (Bernhardt, Clasen, and Schell, 1971; Bernhardt and Schell, 1979). It can be applied to those reservoirs which have only one or two tributaries or a gathering channel from a neighboring catchment area and in which phosphorus is a minimum factor.

EUTROPHICATION OF THE WAHNBACH RESERVOIR

Increased phosphorus input has gradually eutrophied the Wahnbach Reservoir (40,000,000 m^3 content) since impounding began in 1957. This eutrophication process made it more and more difficult to treat the raw water taken from the reservoir for drinking water. At the end of the 1960's and beginning of the 1970's, masses of blue-green algae *Oscillatoria rubescens* appeared. This not only colored the water but the *Oscillatoria* broke through the filter. Using a special flocculation process with a double dose of flocculant combined with a dose of polyelectrolyte, we generally mastered this calamity (Bernhardt and Clasen, 1973).

Sometimes the mass development of large diatoms such as *Melosira italica* or *Melosira islandica* caused shorter filter-run times because the rapid sand filter became blocked after 4 or 5 hours. Later, the small blue-green algae, e.g., *Coelosphaerium naegelianum* grew in increasing quantities and despite a 90 to 99 percent reduction could not be totally eliminated from the water because they were present in too large a concentration (20,000 to 200,000 cells/ml in the raw water). This was unsatisfactory for obtaining drinking water from the Wahnbach Reservoir.

Difficulties particularly arose every autumn during drinking water treatment as a result of algal organic compounds (Bernhardt and Wilhelms, 1978). They also disturbed the flocculation and disinfection and were partly precursors for the development of trihalomethane (Bernhardt and Hoyer, 1979). All these factors compelled the Wahnbach Reservoir Association to take steps to reduce the high input of phosphorus compounds into the reservoir from its catchment area so that the amount of bioproductivity in the reservoir would become tolerable again.

THE CONCEPTION OF THE OLIGOTROPHICATION OF THE WAHNBACH RESERVOIR

Experiments carried out over a period of several years showed that phosphorus compounds in the reservoir are the limiting factor (Figure 1). Every year orthophosphate was depleted in the reservoir down to a concentration of 10 µg/l owing to bioproductivity. However, concentrations of nitrogen and carbon hardly decreased at all. This meant that it was sufficient to reduce the phosphorus in the lake only so that algal development would be controlled.

Detailed studies on the origin of the phosphorus compounds from the catchment area of the Wahnbach Reservoir showed that more than 50 percent originated from diffuse sources. Only a small part of them came from locatable point sources (Bernhardt, et al. 1978). For this reason the Wahnbach Reservoir Association decided to erect a plant to decrease the phosphorus content in the main tributary flowing into the reservoir; this tributary transports 90 percent of the annual reservoir influent and approximately 90 percent of the phosphorus entering the reservoir. Figure 2 shows the site of this plant. After flowing into the pre-reservoir which serves as a floodwater retention basin, the water is pumped into the phosphorus elimination plant (PEP) and treated by precipitation, flocculation, and filtration which aims at reducing the total phosphorus content to 10 µg l P. The water treated in this way then flows through a channel directly into the main reservoir. The construction of the phosphorus elimination plant (PEP) was completed at the end of 1977 and the plant has been in operation now for 3 years.

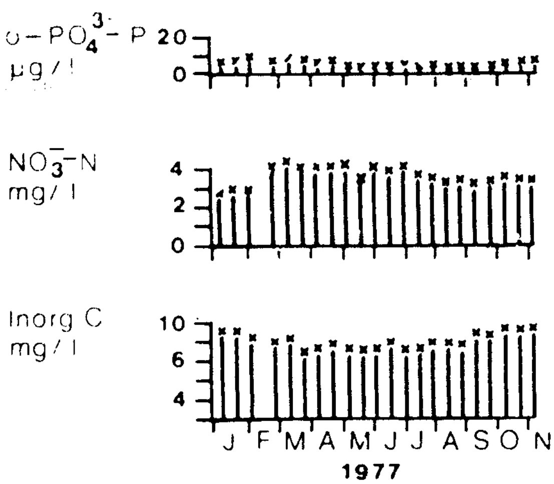

Figure 1 — Conc of O-PO -P, NO -N and inorganic C calculated as mean values over the mixing depths in the Wahnbach Reservoir (April-Sept 0-10 m depth, at other times all depths)

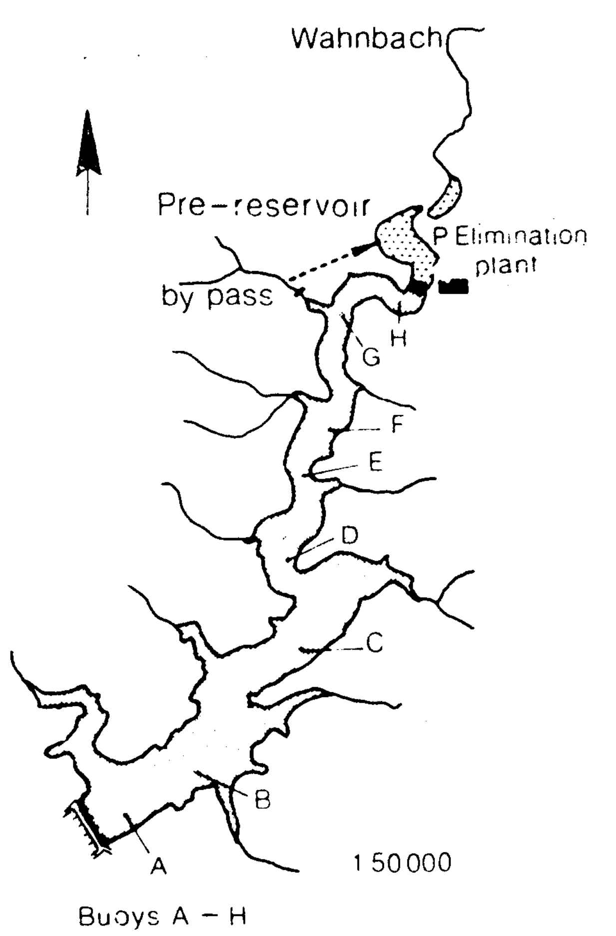

Figure 2 — P-Elimination plant on the Wahnbach Reservoir.

RESULTS OF PHOSPHORUS ELIMINATION AS REGARDS THE EXTENT OF NUTRIENT LOADING OF THE WAHNBACH RESERVOIR

Figure 3 shows the amount of phosphorus fed into the reservoir during 1977-1979 subdivided into individual nutrient sources. The black columns show the quantities of phosphorus (in monthly values) which the River Wahnbach transported into the reservoir before the phosphorus elimination plant was in operation. The columns marked with diagonal lines show the total phosphorus freight which was retained in the elimination plant after the plant was operating. This quantity of phosphorus would have been fed into the reservoir during 1978/79 if the plant had not been operating. The black columns in November 1977, May and June 1978 and March and December 1979 show the quantities of phosphorus which could not be treated owing to high water peaks (pre-reservoir overflow). The dotted columns are the quantities of P which were transported into the main reservoir based on the concentration of P still present in the plant outflow (5µg l P)

Before the plant began operating, most of the phosphorus was transported into the reservoir by the River Wahnbach. The quantities of phosphorus which reached the reservoir via lateral inflowing tributaries and precipitation were insignificant. After the plant was put into operation, it happened that more phosphorus was transported into the reservoir via these lateral tributaries (white columns) than had been transported by the main tributary. Thus the phosphorus loading of the reservoir caused by the lateral streams became decisively important.

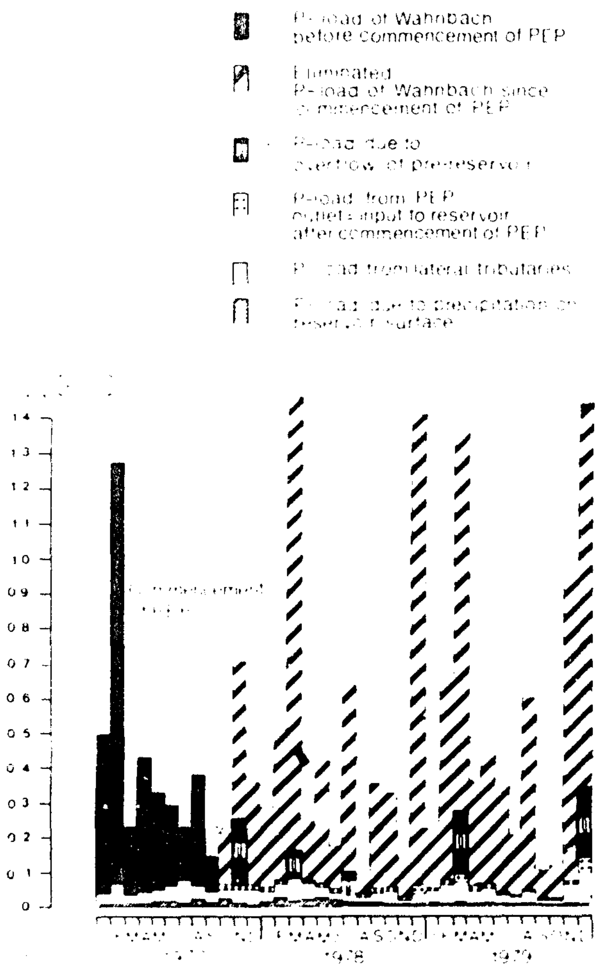

Figure 3 — Phosphorus load of Wahnbach Reservoir from different sources before and after commencement of phosphorus elimination plant.

THE AIM OF PHOSPHORUS REMOVAL AT THE MAIN TRIBUTARY

When the pilot plant for removing phosphorus was installed on the main tributary of the Wahnbach Reservoir, it was not precisely known how far the P-concentration in the main tributary had to be lowered to achieve a tolerable water quality in the reservoir. At that time one could only rely on Sawyer (1966), who had found out from practical experience that water quality caused no problems in those lakes in which the spring overturn P-concentration was below 10 to 15 μg/l P. To ensure that this concentration was attained in the Wahnbach Reservoir, it was decided to reduce the P-concentration in the main tributary to 10 μg/l P. Today we know that this concentration in the main reservoir tributary is still too high if the reservoir is to become oligotrophic to mesotrophic. If one applies Vollenweider's formula (1976) for estimating the tolerable P_{tot}-concentration in all the reservoir inflows $[\overline{PT}]_{i,c}$ onsidering the average P_{tot}-concentration in a reservoir $[\overline{PT}]_{\lambda} = 10$ μ/l calculated over a period of 1 year,

$$[\overline{PT}]_{i,c} = 10\,(1 + \sqrt{T_w}\,)$$

one then obtains for $[\overline{PT}]_{i,c} \approx 20$ μ/l if the retention time of the water in the reservoir $T_w = 1$ year.

Three years of operating the plant have shown that the P_{tot}-concentration of an average of 100 μg/l in the Wahnbach (60-180 μg/l P_{tot}) has been reduced to an average of 4 μg/l P_{tot} in the plant's outflow. This means that the P_{tot}-concentration of all the inflows into the reservoir including precipitation was reduced to 16-20 μg/l P_{tot}. This figure corresponds to the calculated P_{tot}-concentration of all the inflows.

PRINCIPLE OF THE PHOSPHORUS ELIMINATION PLANT

The phosphorus elimination plant (Figure 4) is designed for a maximal flow of 5 m³/sec. Thus the fivefold amount of the long time average flow of the River Wahnbach (1 m³/sec) can be treated. Together with the storage capacity of the pre-reservoir which serves as a water retaining basin with a capacity of 500,000 m³, up to 8 m³/sec can be treated, at least for a limited period.

The phosphorus elimination plant should meet the following requirements:

1. It should run for several weeks on full capacity.
2. Rapid variation of flow capacity between 3,000 and 18,000 m³/h.
3. Operation for a few hours with intervals of several days, frequent switching on and off without decreasing quality of filtrate.
4. No drop of efficiency at water temperatures of 0 °C (winter running).
5. Treatment of water with high turbidity (up to 100 mg/l content of solids (105°C) without shortening the duration of filter runs to less than 10 hours at the maximal filtration rate of 16 m/h.
6. Decrease of the total phosphorus content to values ≦5 μg/l.
7. Treatment should be arranged in such a way that ≧ 99 percent of the plankton occurring during the summer months (max. 400,000 cells/ml) can be eliminated from the water. Algal cells which break through the filter cause high concentrations of undissolved and dissolved organically bound phosphorus compounds in the filtrate. This means an undesired phosphorus load in the reservoir.
8. Removing 99 percent of inorganic turbidity flushed into the reservoir after the erosion of arable land which is rich in phosphates.

9. Flocculation is carried out with 4-10 mg/l Fe^{+3}. The total iron concentration in the effluent should not exceed 50 µg/l Fe.

10. The plant should be constructed as compactly as possible to be economically and technically worthwhile. The filter area is 1,100 m^2. With a throughput of 4.5 m^3/sec one has a filter velocity of 16 m/h.

To achieve all this we developed the energy-input controlled direct filtration called 'Wahnbach System' with the following steps (Figure 4):

1. Precipitation of the o-phosphate ions present in the water by adding iron-III-ions in the acid pH zone (pH 6.0-7.0, average pH 6.4).

2. Destabilization of the colloids and suspensoids in the raw water to which the precipitated iron phosphate products also belong. This is done by adding iron-III-ions as a flocculation agent.

3. Agglomeration by means of transport. The microflocs unite in a subsequent agglomeration step and form larger, partly visible flocs. By adding a cationic polyelectrolyte they are made suitable for filtering. The type of cationic polyelectrolyte used changes according to the time of the year.

Required for both destabilization and agglomeration, the amount of special energy-input is adapted to the quality of the raw water and the throughput. The filter of the phosphorus elimination plant consists of three layers of various granulations and densities:

1. Upper layer — 30 cm active carbon, granulation 3-5 mm, effective grain size 3.9 mm.

2. Middle layer — 125 cm hydro anthracite, granulation 1.5-2.5 mm, effective grain size 1.7 mm.

3. Bottom layer — 50 cm quartz sand, granulation 0.7-1.2 mm, effective grain size 0.9 mm.

EFFICIENCY OF THE PHOSPHORUS ELIMINATION PLANT

The quality of the filtrate is illustrated by Table 1. The average and the minimum and maximum values and the average elimination are shown. About 95 to 99 percent of the phosphorus compounds are eliminated. The total phosphorus concentrations in the filtrate amount to 4 µg/l 1 on a 2-year average. They are 60 percent less than the P-concentration we aimed at achieving.

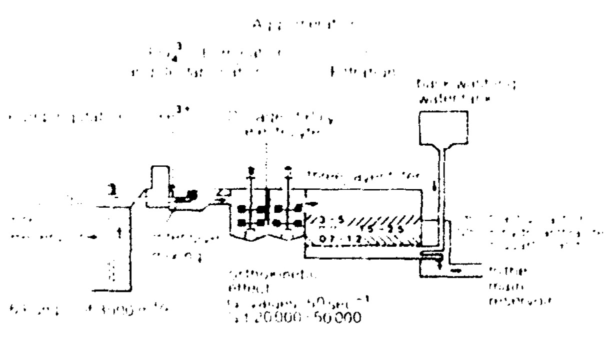

Figure 4. — Principle of the direct-filtration with controlled energy input, 'Wahnbach System'

The decrease of soluble organic compounds varies depending on the sum parameter chosen for characterization. We have 58 percent elimination of dissolved organic carbon because there is only 25 percent elimination of the organic compounds with a molecular weight of $<$1000 and 70 to 80 percent elimination of the organic compounds with a molecular weight $>$1000. More than 99 percent of the algae, expressed as chlorophyll, are eliminated during development periods. The decrease in turbidity is always higher than 99 percent. The very low remaining turbidity of $<$0.1 FTU, the small remaining concentrations of bacteria, algae, and iron ($<$30 µg/l) show that the quality of the filtrate is practically that of drinking water.

The decrease in P-input has caused a considerable decrease in the P-concentration in the Wahnbach Reservoir. As a consequence, there is less algal growth resulting in an increase in the Secchi depth as can be seen from Figure 5. The years 1969 and 1970 were chosen for comparison with the conditions after the commencement of phosphorus elimination as their hydrological conditions were similar. Not only Secchi depth increased, but there was also a considerable change in the composition of algal flora (Figure 6). Various species of tiny blue-green algae, e.g., *Coelosphaerium* and *Aphanothece*, completely disappeared after the plant went into operation. *Chlorella* which used to grow in large quantities is now present only in small amounts. In the spring diatoms such as *Asterionella formosa* and *Melosira* dominate.

ESTIMATION OF THE INFLUENCE OF P-ELIMINATION ON THE TROPHIC GRADE OF WAHNBACH RESERVOIR

If one tries to classify the Wahnbach Reservoir using the data from the OECD-Cooperative Program for Monitoring of Inland Waters (Vollenweider and Kerekes, in prep.), this reservoir would be with a probability of more than 50 percent mesotrophic in 1979 (Tables 2 and 3). During years of extensive *Oscillatoria* growth (e.g., 1969) with annual average chlorophyll concentrations of 25 µg/l, the reservoir was clearly eutrophic.

If one uses the total phosphorus concentration (annual average figures) instead of the average chlorophyll concentration, then the Wahnbach Reservoir would be with a probability of more than 50 percent oligotrophic.

If one applies the registered Secchi depths for classifying the reservoir, then the reservoir would be classed as oligotrophic or mesotrophic. The reservoir should be mesotrophic to eutrophic during the years 1969 and 1970 (Figure 5).

One should not forget that the data in Table 2 is based on the statistical evaluation of a large amount of data (Vollenweider and Kerekes, in prep.; Vollenweider, 1979). It is worth noting that the OECD cooperative program showed, for example, that the chlorophyll concentrations that actually occurred fluctuate to a far greater extent than the annual average values. This means that far higher concentrations of chlorophyll can occur for short periods of time in a mesotrophic lake. In 1979 peak concentrations of chlorophyll in the Wahnbach Reservoir were, however, only 10 µg/l.

Table 1 Elimination of several substances by the phosphorus elimination plant (1.10.1977-31.5.1980)

Parameter	N	PEP-Inflow min.--max x · s	N	PEP-Outflow min.--max. x · s	Elimination %
Coliforms bacteria 100 ml	560	0 68,000 5,979 · 8,818	479	0 171 8 · 15	99.87
Colony-count (22°C) colonies ml	560	285 290,000 12,504 · 20,530	479	0 17,100 263 · 1,338	97.90
Chlorophyll μg l	433	1.0 204.3 25.15 · 27.69	360	0.1 17.3 1.28 · 1.81	94.9
Turbidity FTU	515	0.6 48.7 10.4 · 5.25	515	0.01 0.8 0.06 · 0.09	99.3
COD mg l	107	3.7 22.3 11.13 · 4.52	97	0.1 6.3 2.56 · 1.12	77.0
Spectral absorption coefficient 254 nm m⁻¹	561	3.4 20.8 8.14 · 2.86	482	0.3 4.7 2.40 · 0.68	70.5
DOC mg l	563	0.9 7.3 2.37 · 0.83	484	0.4 2.2 1.00 · 0.30	57.8
Total P mg m⁻³	569	27 480 116.5 · 49.2	485	1 13 4.3 · 1.7	96.3

Table 2 Preliminary classification of trophic state (OECD-Cooperative Program). The geometric mean (based on log 10 transformation) was calculated after removing values or x 2 SD

		Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorus	x	8.0	26.7	84.4
mg m	x · 1 SD	4.85 - 13.3	14.5 - 49.0	48 - 189
	x · 2 SD	2.9 - 22.1	7.9 - 90.8	16.8 - 424
	Range	3.0 - 17.7	10.9 - 95.6	16.2 - 386
Chlorophyll *a*	x	1.7	4.7	14.3
(annual mean values)	x · 1 SD	0.8 - 3.4	3.0 - 7.4	6.7 - 31
mg m	x · 2 SD	0.4 - 7.1	1.9 - 11.6	3.1 - 66
	Range	0.3 - 4.5	3.0 - 11.0	2.7 - 78
Transparency	x	9.9	4.2	2.45
Secchi depth	x · 1 SD	5.9 - 16.5	2.4 - 7.4	1.5 - 4.0
m	x · 2 SD	3.6 - 27.5	1.4 - 13.0	0.9 - 6.7
	Range	5.4 - 28.3	1.5 - 8.1	0.8 - 7.0

x = geometric mean, SD = standard deviation (shortened from (10, 11))

SUMMARY

The phosphorus elimination plant developed by the Wahnbach Reservoir Association has been in operation at the point where the River Wahnbach flows into the reservoir since the end of 1977. Its operation has produced very clear water in the main reservoir and an average total phosphorus concentration of below 10 μg·l. This value was only exceeded for short periods of time, particularly when the inflow was higher than the retention capacity of the pre-reservoir and the efficiency of the plant.

The decrease in total phosphorus resulted in a shift in the algal species from blue-green algae to green algae and then to diatoms. This shift in species was typical of the change in the trophic state from eutrophic to oligotrophic-mesotrophic. Whereas blue-green algae have disappeared almost completely from the reservoir, the population of green algae has been reduced to such an extent that they have no dominating influence compared with diatoms. The clear decrease in the phosphorus input into the reservoir has caused a change in the trophic state of the lake which was eutrophic.

Table 3 — Classification of trophic state of the Wahnbach Reservoir (annual mean values (x)).

		Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorus mg m³				
1969	without PEP		[illegible]	
1970			26	
1977			16	
1978	PEP in operation	9		
1979		6		
Chlorophyll a mg m³				
1969				25
1970				11
1977			7	
1978			8	
1979			5	
Transparency m Secchi depth				
1969				3
1970				3
1977		5		
1978		6		
1979		6		

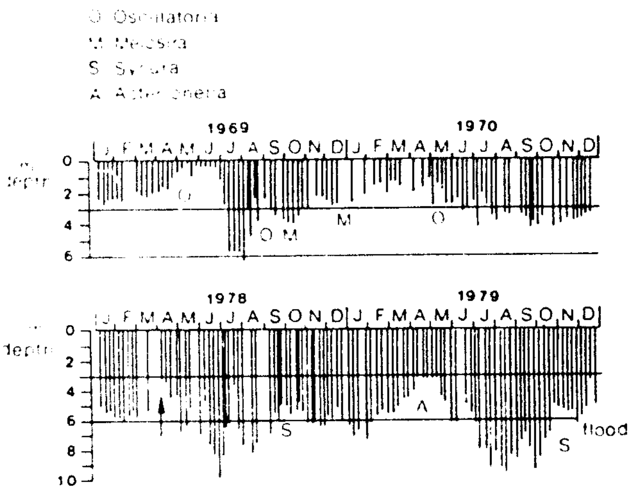

Figure 5 — Secchi-depths in the Wahnbach Reservoir before (1969/70) and after (1978/79) the begin of operation of the plant

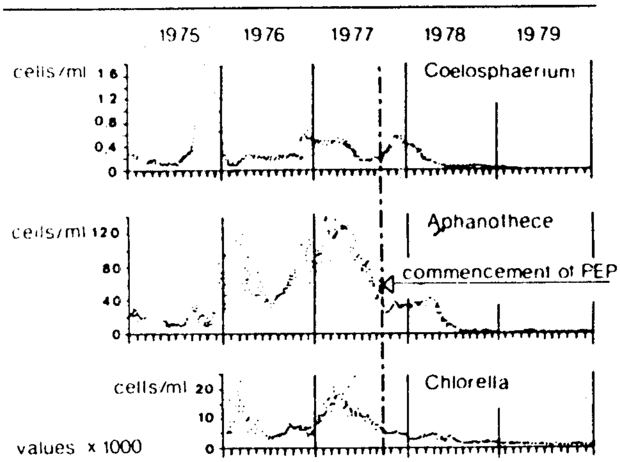

Figure 6. — Change in the occurrence of species of green and blue-green algae after the plant began to operate (values x 1000).

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