Experience with integrated water quality management in the Wahnbach Watershed

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Abstract This paper describes how integrated water quality management has been developed for Wahnbach reservoir and the experience which has been gained with this multi-barrier system. Different measures in the catchment area, where co-operation with farmers was most important, are combined with the operation of a phosphorus elimination plant, in which the main tributary is treated, and with aeration and biomanipulation in the reservoir. All measures together have led to the present oligotrophic state and the excellent hygienic condition of the reservoir.

Keywords Eutrophication; microbiological impacts; watershed management

Introduction
The watershed of Wahnbach reservoir, a drinking water reservoir in Western Germany consists mainly of agricultural land while forest amounts to only 25%. The structure of human settlements is dominated by hamlets. There are only two larger villages. The total population amounts to 15,000 inhabitants in an area of about 70 km². These conditions imply a high nutrient load and a considerable microbiological impact.

The consequence of the high nutrient input became visible a few years after the Wahnbach reservoir was built. Heavy blooms, mainly consisting of cyanobacteria, occurred in the reservoir and impaired the drinking water treatment process. These problems were not only related to the occurrence of high numbers of plankton organisms which clogged or passed filters, but also to the lack of oxygen which was caused by plankton decaying close to the sediment. The latter mentioned impact also led to the release of manganese from the sediment which could be removed in the treatment plant only with great difficulties.

During the following years many efforts were made to change these unfavourable conditions. These activities, comprising measures in the catchment area of the reservoir, at the mouth of its main tributary and in the reservoir itself finally led to a multi-barrier system, which enables integrated management of water quality.

Measures at the mouth of the main tributary

Reduction of the phosphorus input by means of a phosphorus elimination plant (PEP)
As phosphorus turned out to be the key element of eutrophication a comprehensive investigation programme about the phosphorus sources was launched. The results of this programme revealed that only 30 to 40% of the TP load originated from sewage, while the source of the greater part was agriculture. This led to the development of a phosphorus elimination plant, which went into operation in 1977 (Bernhardt and Clasen, 1988).

Beneficial effects of the PEP. In this plant the phosphorus concentration of the main tributary (90% of the total water load to the reservoir) is reduced to 3 to 5 µg/l TP only. While the discharge of the main tributary amounts to about 1,000 L/sec the maximal capacity of the
The plant is 5,000 L/sec. Because the discharge may rise to 20,000 L/sec spills of non-treated water may occur during flood events. Therefore the mean input concentration of TP amounts to 10 to 25 µg/l TP. This amount has been calculated by considering all sources which comprise the treated and non-treated water of the main tributary, the minor lateral tributaries and precipitation.

Occasionally the capacity of the PEP is surpassed by floods. During such events, which occur 0 to 5 times per year, untreated water enters the reservoir. The effect of such events on the average P concentration is not very great. The concentration of total P may increase, but this will last for only a few days. Only during such occasions can SRP be detected in reservoir water. Generally the concentration of SRP is under the detection limit of 1µg/L P. The annual mean of the $P_{tot}$ concentration amounts to 8 µg/l only.

Originally the exclusive purpose of the PEP was to reduce the phosphorus input and by this means to reduce the number of plankton algae in the reservoir. This aim has fully been reached. It took, however, several years to establish a new biotic system in the reservoir. The composition of the algal flora in the reservoir has remarkably changed, most obvious being the strong decrease of cyanobacteria (Clasen, 1991).

From Figure 1 one can see that the potential TP input concentration shows a rise from the mid 1960s to the mid 1980s. After that time this concentration declined and obviously has attained the original level. There are several reasons for this decline. The banning of P from detergents has certainly contributed to this. Another reason is that great efforts have been made to reduce the TP input from agricultural areas.

Other benefits of operating the PEP are the elimination of humic substances and the elimination of bacteria. This means that the PEP does not only reduce the phosphorus load. Its function has extended and it can be regarded now as a multifunctional pre-treatment step relieving the drinking water treatment plant.

Due to the operation of the PEP the concentration of organic substances in the raw water of the treatment plant is oscillating at a low level, roughly between one and two mg/L DOC. The original DOC concentration in the raw water of the PEP may occasionally rise to

![Figure 1](https://iwaponline.com/wst/article-pdf/46/6-7/303/42543/303.pdf)

**Figure 1** Comparison between the potential P concentration (red line) and the actual P concentration (black line) of the water flowing to Wahnbach reservoir.
>10 mg/l DOC. The number of bacteria is also considerably reduced by the PEP. An evaluation of daily measurements over a period of 15 years showed that the median of CFU counts amounts to about 3,000 CFU/mL in the raw water and to about 400 CFU/ml in the treated water of the PEP. Within the reservoir the plate counts do not change very much so that the CFU counts in the raw water of the drinking water treatment plant are almost as high as the CFU counts in the filtered water of the PEP. The CFU counts rarely exceed 200 CFU/mL in the raw water and 10 CFU/mL in the filtered water of the treatment plant prior to disinfection. In the time period mentioned above, only four cases occurred when one single coliform CFU was detected in 100 mL after filtration and prior to disinfection. After disinfection coliform bacteria or *E. coli* were never detected. In the PEP the median counts are 2,000 CFU/100 mL in the raw water and 15 CFU/100 ml in the treated water (Clasen, 2001).

**Measures in the catchment area**

**Protective zones laid down by legislation**

*Protective zones.* In Germany it is possible to lay down protective zones in catchment areas of water sources by legislation. This option has been applied to the catchment area of Wahnbach reservoir and also to the catchment areas of most other German drinking water reservoirs. The settlement of protective zones implies the restriction of several kinds of human activity. The extent of these restrictions depends on the distance from the surface waters. Whereas there are only few restrictions in regions far away from streams, they are most stringent in land strips along the tributaries. In general the restrictions concern e.g. the size of fuel tanks (only allowed above ground, the maximal volume being 10 m$^3$ for house heating and 5 m$^3$ for agricultural diesel engines), the building of edifices (only allowed within settled areas) and the application of pesticides and animal wastes. The strictest restrictions apply to a 100 m broad land strip along the shore of the reservoir. With the exception of the employees of the reservoir owner only a limited number of fishermen are allowed to enter this zone.

*Protective forest.* The strip along the shore is covered with forest, which has been established in a specific manner and which is called “protective forest”. The ideas about the design of a protective forest have changed in the course of time. Deciduous trees have always been regarded as beneficial, because their leaf litter does not acidify the streams and because their roots stabilize the stream banks more efficiently than the roots of the native coniferous trees do. On the other hand it was assumed that deciduous trees produce much more leaf litter than coniferous trees. The dead leaves are supposed to impair the water quality of the lake, where they could be transported by wind action. Therefore, as a compromise, it was recommended to grow coniferous trees in a narrow strip along the shore with the aim to control the leaf litter drift from the deciduous trees growing behind them. In the meantime investigations have shown that on a yearly basis coniferous trees do not produce less leaf litter than deciduous trees. Therefore they are no longer regarded to be beneficial for protective forests. The modern concept is to grow only deciduous trees in the protective forest but, in order to prevent too much leaf litter being blown into the reservoir, to plant bushes and smaller trees close to the shore. Following this idea the height of the trees and bushes should gradually rise from the shoreline to big trees growing at some distance.

**Co-operative measures in the watershed and their results**

Substances and organisms are transported into the reservoir primarily by surface and subsurface (interflow, groundwater) waters. The size, the land use and the geomorphological, pedological, meteorological and hydrogeological conditions of the catchment are most
important for the input and have to be considered while planning or undertaking measures to protect the water quality of the reservoir.

The input results especially from the following sources:
- Agriculture and forest
- Human settlements
- Industry
- Streets and transport of water polluting substances
- Recreation areas

One has to separate diffuse and point inputs. Measures to avoid or reduce inputs to surface waters were primarily carried out in agriculture and waste water treatment.

**Agricultural measures**

*Planning of fertilizing*
- nutrient analysis in soils and organic fertilizers
- depot fertilizing of ammonia
- computer aided planning of fertilizing
- site related slurry management
- enlargement of storage capacities for organic fertilizers

The farmers plan for each field the amount and times of fertilization. The basis for the fertilization plans are the nutrient concentrations of the soils. The number of fields with soil analysis has increased from 10 in 1989 to 200 in 2000. A very important measure is site related slurry management (Krämer, 2000a,b,c). The times and the amounts of slurry application are restricted on water sensitive fields according to the morphological, hydrological and pedological conditions. By the enlargement of the storage capacities for organic fertilizers the farmers can avoid application during hydrologically bad periods (water saturated, snow covered or frozen fields; low plant nutrient uptake).

*Protection from erosion*
- crop rotation on arable land (no mono-cultures)
- use of undersown crops
- use of intercrops
- area exchange, change of utilisation

As the catchment has an intensive morphological structure, erosion and surface runoff are main paths for the input to surface waters. Therefore a continuous covering of the fields by vegetation is a very important measure of water protection. On arable grounds mono-cultures were banned and the percentage of fields with undersown crops or intercrops was increased to 80%.

*Weed control*
- mechanical weed control
- application of alternative chemical pesticides

To reduce the amount of pesticide application, mechanical weed control was enforced. If possible, the farmers use different pesticides for the same crops to reduce the concentration of special active ingredients.

*Agricultural equipment*
- application of organic fertilizer by techniques that guarantee an exact dosage and diffusion and an application near to ground level
- application of pesticides with a high precision of dosage and diffusion
- tools to store silage of grass in foils on the fields

The technical equipment of the farmers was improved by modern machines and tools.
Point inputs
- fencing of surface waters and establishment of watering-places and cattle bridges
- farm drainage to sewage treatment plants

To avoid animals crossing or drinking in surface waters, 30 km of fences and 220 watering places were built along the surface waters. The sewage of the farms is led to treatment plants or into the slurry depots.

The practical application of theses rules was managed in the scope of a regional co-operation between agriculture and water resources management (Krämer and Schmidt, 1999; Krämer, 2000d). The latter financed measures to go beyond the usual agricultural practice and the lawful requirements. The employment of a water protection advisor, who is responsible for the practical application while considering the economic interests of the farmers has improved the acceptance of the necessary measures for water protection.

Human settlements, industry and deponies
In regard to the impacts from settlements and factories the following measures are mainly applied:
- connection with the public sewage treatment (in single cases small on-site sewage treatment devices)
- demarcation of settlement and business areas with consideration of the demands of water protection
- trickling of precipitation through the biological active soil layer
- reduced application of pesticides on hard surfaces
- observing the use of deponies and illegal waste

Streets and transport of water polluting substances
Speed limits and safety devices along embankments shall reduce the risk of accidents. The transport of water polluting substances is restricted to local supply and dangerous streets beside surface waters are closed for these transports. Transports crossing the catchment are strictly forbidden.

Recreation areas
The water protected area is observed by the waterworks concerning recreation activities near surface waters and around the reservoir.

Internal measures
Aeration
Aeration has long been applied in reservoirs and lakes as an internal measure to improve water quality. At Wahnbach reservoir an aeration system was developed which does not destroy summer stratification. The advantage of such a system is that the raw water, which is taken from the hypolimnion, is kept cool and low in plankton organisms in summer. From the 1960s the hypolimnetic aeration has been in operation every summer for many years. The main benefit of this device is the replenishment of oxygen in the hypolimnion and the oxidation of manganese released from the sediment. After the phosphorus elimination plant went into operation the time period in which it was necessary to run this device decreased from year to year. At present hypolimnetic aeration of Wahnbach reservoir is no longer regarded as beneficial. Although manganese release from the sediment at the end of the stratification period occurs even in recent years, it is by far not as pronounced as originally and can now be controlled by choosing the appropriate raw water intake level and by chemical oxidation. Aeration with freely ascending air is now used to advance the overturn as soon as the thermal stratification has become obsolete.
Biomanipulation

The composition of the plankton of a lake is to a great amount influenced by the structure of the fish population. In the first years of its existence Wahnbach reservoir was stocked with plankton feeding White fish (*Coregonus lavaretus*). The idea behind this measure was to indirectly harvest plankton by catching this species.

In the meantime the progress of limnological research has led to a completely different view. According to the present knowledge the population of plankton feeding fish should be kept very low if a plankton structure is wanted which is beneficial for drinking water treatment. This technical process is mainly impaired by phytoplankton and small zooplankton, whereas big zooplankton can easily be retained by filtration. If a lake is stocked with great numbers of piscivorous fish the number of plankton feeding fish which eat big zooplankton will be kept low. Consequently the number of big zooplankton organisms will increase. These will clarify the water by consuming phytoplankton and out-competing small zooplankton organisms like rotifers which cause problems in the treatment process. Measures to improve water quality by changing the composition of the fish population are commonly called biomanipulation.

At Wahnbach reservoir efforts have been made to increase the number of piscivorous fish by stocking the lake with pike and perch-pike. The results of a comparative research program which was run by the ATT (association of drinking water reservoirs) has shown that the effects of biomanipulation are clearly visible at Wahnbach reservoir, but a further improvement of the plankton composition should be possible (Grosse, Clasen, Hoehn *et al.*, 1998). Probably the efforts to control plankton feeding fish have not yet been fully successful, because perch and perch-pike are not the ideal fish predators in the case of Wahnbach reservoir. At present an attempt is being made to establish a population of lake trout (*Salmo trutta lacustris*) in the reservoir, which presumably are more appropriate to control the White fish population.

Results

The water quality management in the Wahnbach watershed has resulted in great improvements of water quality. Figure 2 shows that the number and concentration levels of pesticides have been clearly reduced. The phosphorus load has also been reduced to a remarkable extent, but is still at such a high level, that it is necessary to treat the water of the main tributary in a phosphorus elimination plant. This guarantees the oligotrophic state of Wahnbach reservoir.

The main goal of water quality management in the Wahnbach watershed was originally to reduce the input of phosphorus. Meanwhile additional factors (pesticides and microbiological agents) have gained much importance. Both the operation of the phosphorus elimination plant and the measures taken during the cooperation with farmers have led to a considerable decrease of the bacterial and pesticide load.

Figure 2 Decrease of pesticides in the main tributary of Wahnbach reservoir
In-lake measures like aeration and biomanipulation are also contributing to the good water quality of Wahnbach reservoir. However, the importance of aeration has decreased in the course of years. Biomanipulation has only been partly successful and can probably be improved in future.

**Conclusions**

The good quality of Wahnbach reservoir water guarantees that any disturbance which might affect the drinking water process is practically excluded and that the safety level of water supply from this reservoir is extremely high. Risks for human health are almost excluded considering the fact that the microbiological standards are met already after filtration and prior to disinfection. The excellent conditions in Wahnbach reservoir have been achieved with a bundle of measures in the catchment area, at the mouth of the main tributary and in the reservoir itself. Only the combination of all these measures has led to the present beneficial situation. Much effort, to a great extent based on the results of extensive research projects, was necessary to achieve this. This success was only possible because the original antagonisms between agricultural and water management interests could be overcome, leading to the present fruitful co-operation.

**References**


