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The importance of pre-reservoirs for the control of eutrophication of reservoirs

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ABSTRACT

Pre-reservoirs are small reservoirs, with a water-retention time of a few days, that reduce the phosphorus input in main reservoirs. The process of phosphorus removal involves the biochemical conversion from the dissolved to the particulate form (mainly phytoplankton) and the sedimentation of this particulate matter. The input variables are light, orthophosphate concentration, temperature of the inflowing water and discharge. The phytoplankton activity plays the most important role among the various processes. The maximization of orthophosphate elimination depends on adequate design, construction and operation of pre-reservoirs. A simple calculation procedure for the removal rates of orthophosphate-P has been developed. The efficiency of pre-reservoirs is limited, because the light intensity and the temperature during the winter period are low; on the other hand, discharge is often high in March and April (snowmelt). Although pre-reservoirs are an important tool for reservoir water-quality management, but they cannot substitute remedial action in the catchment area.

KEYWORDS

Design of pre-reservoirs; eutrophication; model calculation; nitrogen-elimination; orthophosphate-elimination; phytoplankton; pre-reservoirs; reservoirs; retention time; water-quality management.

INTRODUCTION

The dense population of Germany requires a highly efficient management of water ressources. The available discharge in the several regions shows large seasonal fluctuations. Therefore, a high water-utilization ratio had to be ensured by dam construction in the river basins in the German hill regions.

An important field of the uses from reservoirs in Germany is the drinking water supply. About seventy reservoirs with a total storage capacity of nearly 1100 Mio m^3 are used for it. Due to the geography and socio-economic conditions in Saxony, practically all of the catchment areas for these reservoirs are suffering from anthropogenic influences. Consequently, there are quite severe water-quality problems in several reservoirs. The water quality of a reservoir reflects the physical and geochemical structure of the watershed and is primarily affected by nutrients from both diffuse and point sources.

The objectives of the water quality management of reservoirs involve:

- protection of water quality against deterioration
- improvement of water quality as required to comply with the standards for the uses.

As far as eutrophication of these reservoirs is concerned, the objectives can be achieved by two main strategies:

1 Control of external loading
- sewage treatment plants including P-removal;
- diversion of sewage from the catchment area;
- proclamation of the catchment area as drinking water protective area with control of agriculture etc.;
- *construction of pre-reservoirs.*

2 Control of internal mechanisms
- hypolimnion aeration;
- artificial destratification;
- P-precipitation;
- sediment dredging;
- control of the internal ecosystem structure („Biomanipulation“).

The ability of pre-reservoirs to remove nutrients became known during numerous investigations on various existing pre-reservoirs in Germany (Klapper 1957; Beuschold 1966; Wilhelmus et al. 1978; Fischer 1980) and was later confirmed by investigations in Denmark (Nyholm et al. 1978) and in the former Czechoslovakia (Fiala and Vasata 1982).

MODE OF OPERATION

Pre-reservoirs are comparatively small reservoirs with an average water retention time of a few days. They are normally situated immediately above the larger main reservoirs whose inflowing water quality it is their purpose to improve (Benndorf and Pütz 1987). This improvement of the water quality is the result of a number of physicochemical and biochemical processes within the pre-reservoirs (Fig.1). The first stage in the process of nutrient removal in pre-reservoirs involves the biochemical conversion from the dissolved to the particulate form (mainly phytoplankton). The second stage is the sedimentation of phytoplankton and other particulate matters within the pre-reservoir or in the shallow inlet sections of the main reservoir. This sedimentation process is enhanced by the presence of natural precipitants and flocculants. In this context, it must be stressed that geochemical conditions in the drainage area can affect nutrient removal by influencing the nature and intensity of the processes involved, which are listet in Fig.1. Chemical binding or adsorption of the orthophosphate in solution can take place largely in the inflowing waters, but the uptake of orthophosphate by the algae is more important in the pre-reservoirs than the competing chemical or physicochemical processes, particularly in the ph range of 6.0 - 8.0. The greater the deviation of the pH from this range, the more likely it is that the orthophosphate will combine with iron, aluminium and manganese (at $pH < 6$) or calcium (at $pH > 8$) (Vollenweider 1976).

The sedimentation process is not only enhanced by precipitants and flocculants, but also by an appropriate plankton structure within the pre-reservoir. It is favourable, if the phytoplankton consists of algae having a high sedimentation velocity (above all diatoms), but blue-green algae are highly undesired. Mass developments of zoo-plankton, especially of effective filter feeders such as Daphnia, must be avoided because of the high grazing losses of phytoplankton and the resultant high intensity of the nutrient remineralization. Both the desired phytoplankton structure and the absence of planktonic crustaceans can be achieved by an optimal water retention time within the pre-reservoir, which allows diatoms and other fast-growing algae to grow but flushes away slow-growing blue-greens and zooplankters. The critical retention time amounts to nearly 2 days in the months of summer, about 4 to 8 days in spring and autumn as well as more than 20 days in the months of winter. Furthermore, the absence of effective filter feeders is supported by an appropriate structure of the fish community. No predatory fish species should be present in pre-reservoirs in order to guarantee the maximum possible biomass of small zoo-planktonfeeding fish (Nyholm et al. 1978;Benndorf et al. 1983).

Taking into consideration all these processes, some important demands can be set up for the optimal management of pre-reservoirs:
- the design of the size of a pre-reservoir should aim at an optimum retention time (and not simply at a long retention time).

- the mean depth of a pre-reservoir should not exceed considerably the depth of the euphotic zone (z_{eu}, in the most pre-reservoirs about 3 m) because of the dominance of photoautotrophic mechanisms governing the phosphate removal. Phosphate elimination decreases exponentially with increasing depth (Uhlmann and Benndorf 1980).
- if the maximum depth of the pre-reservoir exceeds the mixing depth z_{mix} as well as z_{eu} - which applies at least at times to almost all existing pre-reservoirs - a strong vertical orthophosphate stratification results. This stratification exhibits high concentrations in the deep water layers and the and the lowest concentrations near the surface. Therefore, surface release is an urgent need in the management of pre-reservoirs.
- the bottom sediment is to be removed in time intervals of 5 - 10 years (after emptying the pre-reservoir through bottom outlet).
- optimal management of pre-reservoirs in the sense of this paper primarily aims at the realization of the maximum possible P-removal. This is in almost all cases identical with the maximum possible N-removal. The only exception refers to denitrification, the maximization of which cannot be achieved by the same management strategy as used for a maximum P-removal.

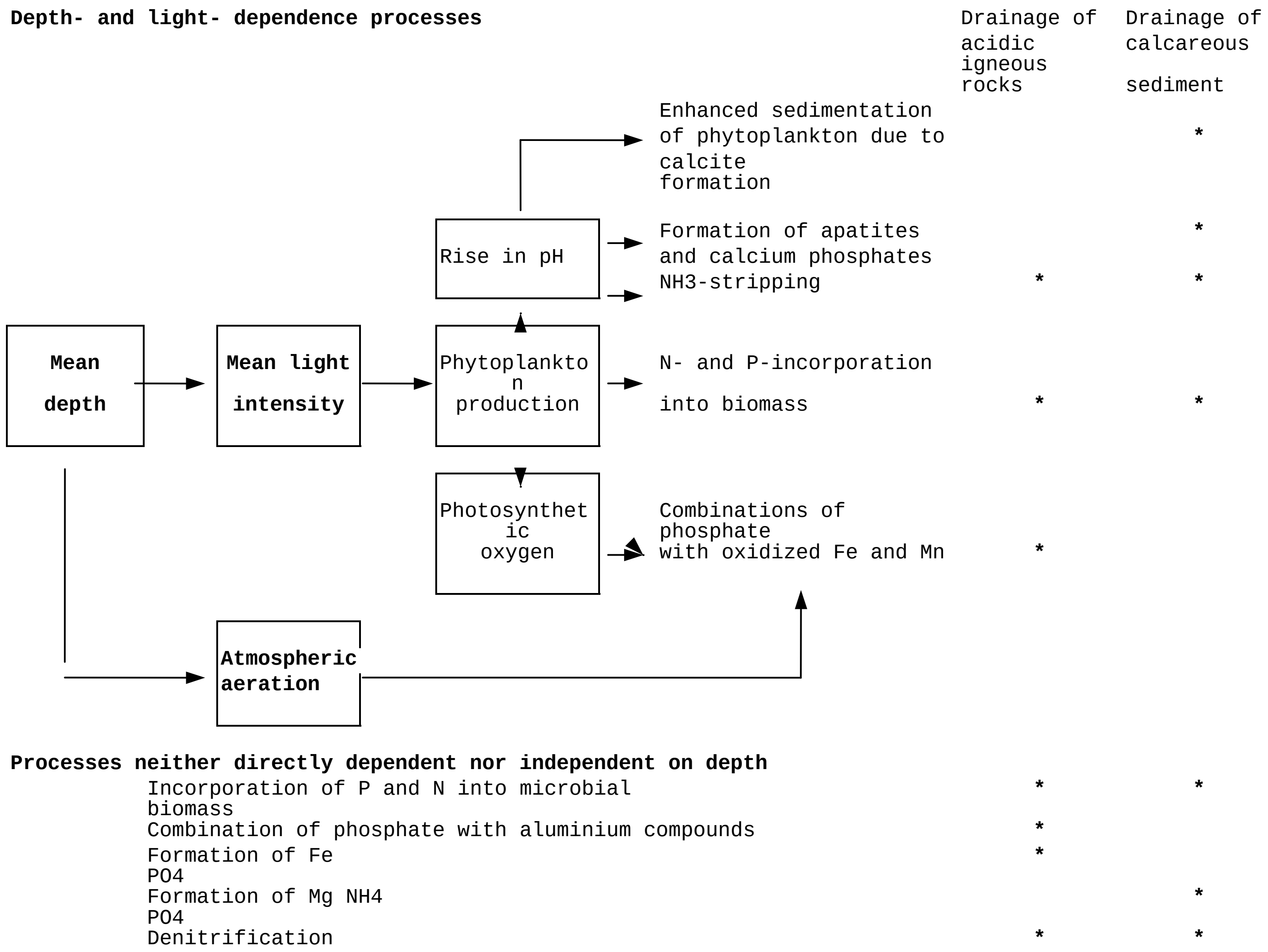

Fig. 1. Processes governing the phosphorus and nitrogen elimination in pre-reservoires, see Benndorf and Pütz (1987), slightly altred.

CALCULATION OF PHOSPHORUS ELIMINATION RATES

A procedure for calculating and predicting the removal rates of orthophosphate-P in pre-reservoirs has been developed (Benndorf et al. 1975) and was further refined by a subdivision between lightly loaded and heavily loaded pre-reservoirs (Benndorf and Pütz 1987). This procedure has been successfully as a standard practice for water quality management of the reservoirs in Germany. It can be used for calculating the removal rates of P in pre-reservoirs for a given volume of reaction space, but also to find the optimal volume for a desired removal rate, that means the procedure can be carried out as predictions for planned pre-reservoirs as well as for existing pre- reservoirs (Pütz 1995).

There are several input variables as shown below:
Meteorological variables
Light
In connection with the underwater light climate in the pre-reservoir the following definitions apply: the euphotic zone depth (z_{eu}) is considered to be 3 m, the mean light intensity (MI) in the euphotic layer amounts to 20 % of the photosynthetically active radiation (400-700 nm) at the surface. Only this euphotic layer is assumed to be the "reaction space" for the P-elimination process. The seasonal variation of MI decreases with decreasing geographical latitude and has to be re-estimated for each geographical location.

Temperature
The mean monthly water temperatures MT in the "reaction space" are calculated on the basis of multi-year monthly averages of the inflow temperature (MT_z) according to $MT = MT_z + a$ ($0°C < a < 2°C$, depending on season and retention time).

Hydrological variables
Discharge
The discharge determines the retention time of the inflowing water in the "reaction space". The probabilistic character of the hydrological processes is considered by means of the discharge duration curve for the individual months.

Hydrochemical variables
Concentration of orthophosphate-phosphorus
For the calculation, the concentration of orthophosphate-P in the affluent is employed. This value should be established as a separate monthly average for the entire 12 months, taking into consideration the discharge duration curve and the discharge-orthophosphate relationship.

The complete calculation procedure for P-elimination in a pre-reservoir is described by Benndorf and Pütz (1987).
The subdivision between lightly-loaded and heavily-loaded pre-reservoirs allows an estimation of the maximum possible areal elimination rate for orthophosphate-P on the basis of an empirical relationship between areal rate and mean depth. Heavily-loaded pre-reservoirs require very large areas, and are, therefore, uneconomic. The majority of the pre-reservoirs of Saxonian drinking-water reservoirs are lightly loaded.

ESTIMATION OF THE NITROGEN ELIMINATION RATES

A simple calculation procedure of the nitrogen elimination similar to that of the orthophosphate elimination can hardly be developed because of the much more complicated nature or the nitrogen metabolism in waters. There are two possibilities to predict the elimination rate of the inorganic nitrogen, namely:
- the construction of a rather sophisticated ecological model involving all essential processes which control the nitrogen metabolism within the pre-reservoir;
- the construction of a simple empirical approach which results from the generalization of field observations (Pütz 1995).

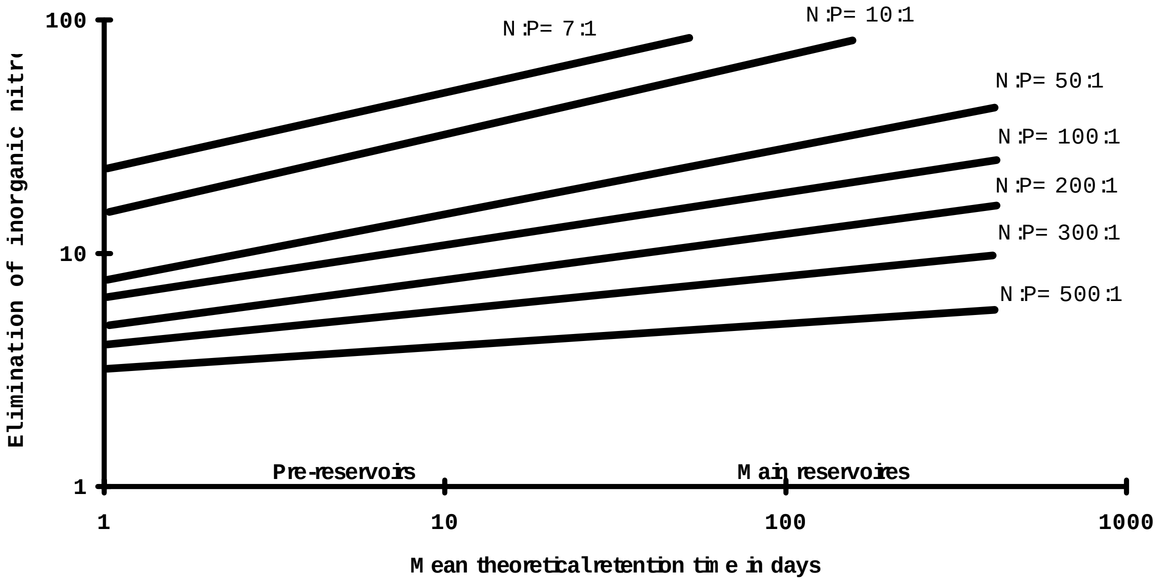

Fig. 2 Empirical estimation of the removal of inorganic nitrogen by reservoires in dependence on

The development of a sophisticated ecological model is expensive. Therefore, the second way showing sufficient results, is demonstrated in Fig. 2. This plot makes it possible to estimate roughly the removal rate of the inorganic nitrogen as a function of the mean retention time and of the N:P mass ratio.

DESIGN OF A PRE-RESERVOIR

Experiments in the Hydraulic Laboratory of the Technical University of Dresden (Benndorf et al. 1975) have helped to establish some important construction principles for pre-reservoires that secure a sufficient utilization of the "reaction space" (Fig. 3).

The sedimentation of suspended solids in the inflowing water near the inlet prevents the rapid decrease of the "reaction space". A sill (with the crown about 0,70 m below water surface) separates this "sedimentation space" from the rest of the pre-reservoir. If the length : width ratio of the pre-reservoir is less than 2 : 1, the installation of a spillway improves a steady throughflow. The water is released over the spillway (overflow) and the bottom outlet is closed (Fig. 3).

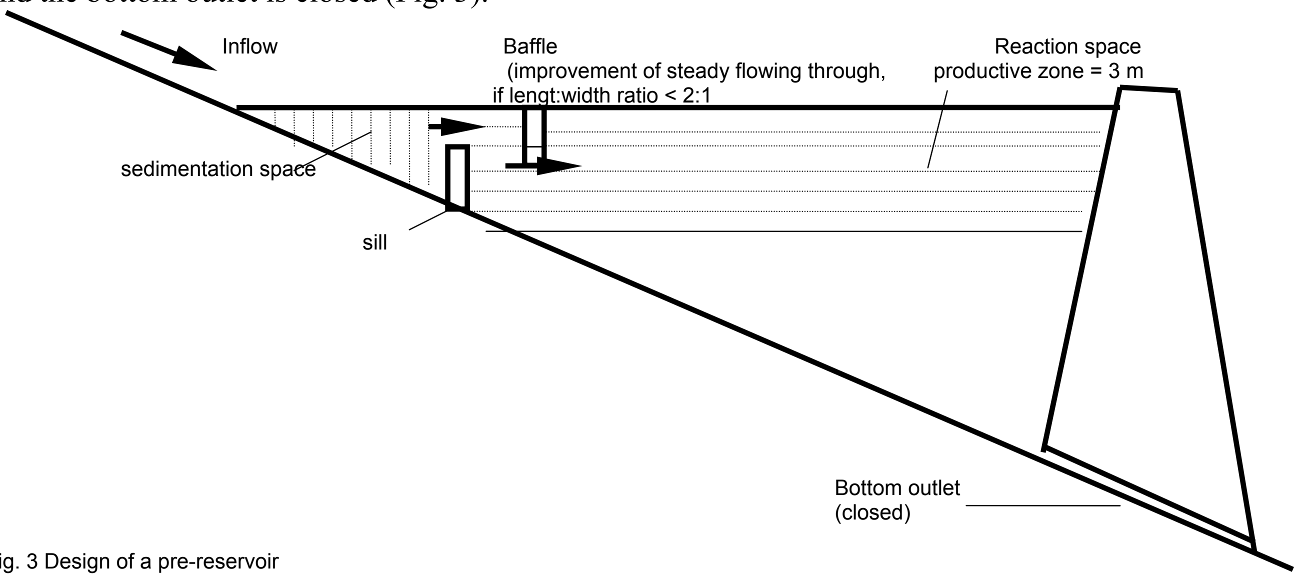

Fig. 3 Design of a pre-reservoir

VALIDATION OF CALCULATED ELIMINATION RATES

Annual mean elimination rates calculated with the pre-reservoir model described above were checked by means of a comparison between observed and calculated P-elimination rates in 15 pre-reservoirs two different investigation periods (1963-1972 (Benndorf et al. 1975) and 1974-1982 (Benndorf and Pütz 1987a)). The results showed a considerable degree of accuracy. Another comparison between calculated and observed annual P-removal rates in 11 Saxonian pre-reservoirs (commissioned after 1972, investigation period 1991-1996) shows a good fit (Table 1). The observed mean elimination rates for total phosphorus are relatively high in a number of cases, though lower than for orthophosphate-phosphorus.

Table 1 Calculated and observed annual P-elimination of Saxonian pre-reservoirs in the period 1991-1996

Main-reservoir	Pre-reservoir	Retention- time d	Elimin. o-PO_4 calculation %	Elimin. o-PO_4 observed %	Elimin. P_{tot} observed %
Lichtenberg	Dittersbach	2,0	22	45	34
Eibenstock	Schönheide	3,0	36	40	25
Gottleuba	Gottleuba	3,7	43	34	24
Lichtenberg	Lichtenberg	4,5	48	44	30
Eibenstock	Rohrbach	5,0	50	42	22
Saidenbach	Forchheim	6,0	55	57	35
Eibenstock	Rähmerbach	6,3	56	56	40
Eibenstock	Weißbach	7,0	57	60	42
Eibenstock	Geidenbach	7,0	57	64	44
Dröda	Ramoldsreuth	10,0	60	53	41
Dröda	Bobenneuk.	12,0	61	62	46

A CASE STUDY

The water quality management of the largest (drinking water) reservoir in Saxony, the Eibenstock-dam (75 million m^3, five pre-reservoirs), demonstrates the importance but also the limits of pre-reservoirs. The objective of water quality set for the main reservoir was to achieve mesotrophic to oligotrophic conditions in a recovery process. Productivity is limited by the nutrient phosphorus and the necessary P-load reduction was to be achieved by the implementation of a masterplan including:

- sewage diversion out of the watershed;
- conctruction or upgrading of sewage treatment plants;
- additional measures by agriculture
- five pre-reservoirs.

The design of these five pre-reservoirs was based on calculations from the pre-reservoir model described above Benndorf et al. (1975) and Benndorf and Pütz (1987 and 1987a). Figure 4 shows their actual P-elimination performance and its limitations.

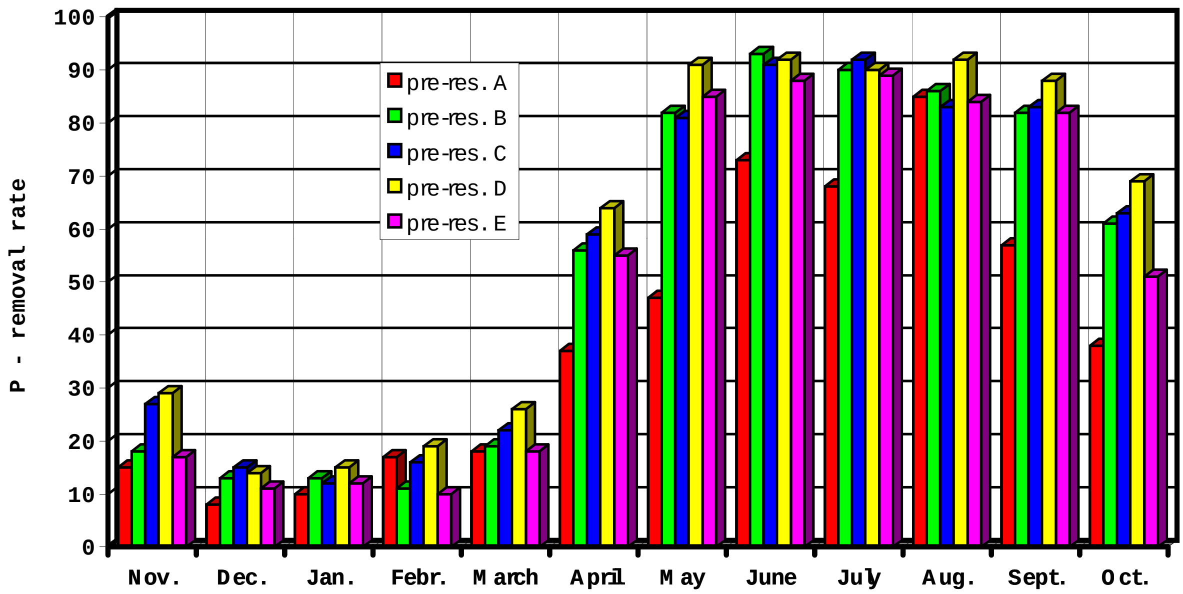

Fig. 4 P-removal rate of the pre-reservoirs of the Eibenstock dam (orthophosphate-P)

Nearly 60 % of the P-input from the tributaries occurs in the period November-April, nearly 40 % in the period May-October, but the removal rates in the first period are substantially lower than in the second period. Therefore, the P-input into the main reservoir during the winter and spring period is relatively high. Consequently the integral implementation of the entire water-quality masterplan is necessary.

CONCLUSION

- The phytoplankton activity plays the most important role among the various processes governing the phosphate elimination in pre-reservoires;
- The maximization of orthophosphate-P elimination depends on adequate design, construction and operation of pre-reservoirs:
  - a relatively low mean depth;
  - a relatively large reaction space, (upper 3 m zone), in relationship to the total volume with a mean retention time of a few days;
  - a constant storage level as a consequence of surface release;
  - an optimum size.
- A simple calculation procedure for the monthly mean removal rates of orthophosphate-P in pre-reservoirs has been developed on the basis of laboratory experiments, the results of which were combined with the probabilistic distribution of the water throughflow;
- The efficiency of the pre-reservoirs is limited, becaus the light-intensity and the temperature in the winter - period are low, on the other hand first of all in March and April, the discharge is often high in result of thaw.
- Also pre-reservoirs are an important tool for reservoir water-quality management, they can be no substitute for remedial action in the catchment area.

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