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A SUBMERGED FLEXIBLE CURTAIN IN THE RESERVOIR TO REDUCE THE NUTRIENT

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ABSTRACT

Pre-dams of optimum size normally located upstream of reservoirs have proven effective in phosphorus load reduction due to sedimentation of allochthonous and autochthonous seston. In order to achieve similar effects, model and in-situ experiments were carried out with an overstreamed submerged flexible curtain (SFC, 160m long, 6m deep) installed perpendicular to the flow direction in the mouth region of the main tributary of the Saidenbach Reservoir (Saxony, Germany). Before the installation of the SFC, the inlet normally formed a hydraulic short circuit between mouth and main basin of the reservoir along the upper metalimnetic layers during summer stratification. Therefore, the retention time of the inflowing water was too short (1.7 days on an average) to allow soluble reactive phosphorus (SRP) elimination higher than approximately 20% in the mouth region.

The flow through regime changed after the SFC was built-in. The average retention time increased to about five days and sedimentation was favoured in the volume separated. The SRP elimination varied between 40% and 60% in the summer months. It is conclusive from the results of a research project that flexible curtains of sufficient depth may be cost-effective substitutes for conventional pre-dams of eutrophic lakes or reservoirs.

Keywords: Flexible curtain, flow through regime, phosphorus elimination, pre-dam effects, thermal stratification.

RESUME

Les petites digues de taille optimale construites généralement à l'amont des barrages ont montré leur efficacité dans la réduction les nutriments, spécialement le phosphore (*Bendorf* and *Pütz*, 1987a,b). Le temps de rétention de l'eau entrante enrichie avec des nutriments est prolongé et la croissance des algues est favorisée. Les nutriments solubles particulièrement le phosphore réactif soluble (PRS) sont incorporés dans la biomasse des algues et éliminés par sédimentation. La P-adsorption aux particules minérales et la sédimentation subséquente peuvent également jouer un rôle. En plus, une réduction des germes a été observée dans les digues (*Nienhuser* 1996; *Goldyn*, 1994). L'efficacité de ces processus dépend du temps de rétention de l'eau (Hoffmann 1968). Afin de réaliser des effets similaires, des expériences modèles et in situ ont été effectuées avec un rideau submergé flexible (RSF, 160m de long et 6m de profondeur) installé de façon perpendiculaire au sens d'écoulement dans l'embouchure du réservoir principal de Saidenbach (Saxony, Allemagne). Le RSF doit interrompre le court circuit hydraulique entre le tributaire et le bassin principal du réservoir. Il doit aussi augmenter la période de rétention de l'eau entrante dans l'embouchure et favoriser des effets semblables tels qu'ils sont observés dans les digues conventionnelles. Durant la stratification d'été et avant l'installation du rideau submergé flexible (RSF), l'admission formait un court circuit hydraulique entre l'embouchure et le bassin principal du réservoir le long des couches métalimétiques supérieures. Par conséquent, le temps de rétention de l'eau affluente était trop court (1,7 jour en moyenne) permettant une élimination approximative du phosphore réactif soluble (PRS) de 20% dans l'embouchure. Le régime du courant a changé après l'installation du rideau submergé flexible (RSF). Le temps de rétention moyen a augmenté jusqu'à environ 5 jours et la sédimentation a été favorisée dans le volume séparé. Durant les mois d'été l'élimination du phosphore réactif soluble (PRS) variait entre 40 et 60%.

Mots clés : Eutrophisation, phosphore, digue conventionnel, rideau submergé, temps de rétention.

INTRODUCTION

Appropriately dimensioned pre-dams effectively eliminate nutrients, especially phosphorus (*Benndorf* and *Pütz*, 1987a, b). The retention time of the incoming water enriched with nutrients is extended and the growth of algae is promoted. Dissolved nutrients - particularly SRP - are incorporated in the algae-biomass and eliminated by sedimentation. P-adsorption at mineral particles and subsequent sedimentation may also play a certain role. Additionally, reduction of germs was observed in pre-dams (*Nienhüser* 1996; *Goldyn*, 1994). The effectiveness of these processes depends on the water retention time (*Hoffmann*, 1968). The main aim of a research project (*Paul* et *al.*, 1998) carried out in the Haselbach underwater pre-dam (UWHA) of the Saidenbach Reservoir (Saxony, Germany) was to prove whether similar SRP-elimination effects could be achieved by a submerged overflowable flexible curtain (SFC) installed across the direction of flow in the mouth region of a reservoir or lake. The SFC reached from several centimetres below the surface down to the depth beneath the thermocline. The SFC ought to interrupt the hydraulic short circuit between tributary and main basin of the reservoir, increase the retention time of the incoming water in the mouth region and promote similar effects as they are observed in pre-dams. Provided the proof succeeds, a SFC offers an advantageous alternative for a conservative pre-dam to be built as well as it can considerably enhance the effects of an existing under-dimensioned and ineffective pre-dam. In the last years, reports on manipulations of the flow-through regimes of reservoirs in Japan and USA with underflown flexible curtains were published (*Goldyn*, 1994). The goals of these experiments were to control the development of phytoplankton and to keep the temperature of discharging water as low as possible to protect the fish stock in the downstream river, respectively.

INFLUENCE OF THE SFC ON THE FLOW-THROUGH CONDITIONS

From the observed development of the thermal and chemical stratification in the Haselbach underwater pre-dam the following conclusions about typical flow-through patterns could be derived:

- Before the installation of the SFC, the inlet water was usually flowing in the boundary layer between epilimnion and metalimnion from the mouth over the underwater dam into the main basin of the reservoir within a short time (hydraulic short circuit, Figure 1a).
- After the SFC was installed, the longitudinal spreading of the discharge along the upper metalimnetic layers was stopped by the curtain in periods with warm weather and relatively high inflow temperatures. Overflow over the SFC was forced (Figure 1b). Water exchange below the thermocline and behind the curtain in the volume beneath the top of the underwater wall was very low. Consequently, oxygen depletion was found.
- In periods with cold weather and low tributary temperatures, the depth of inflow increased. Finally, underflow of the SFC was stated and the small previously stagnating volume between curtain and underwater wall was quickly displaced over the top of the dam into the main basin of the reservoir (Figure 1c).

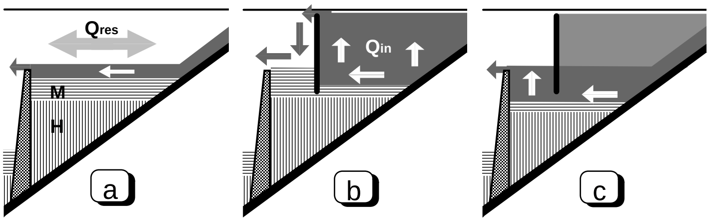

Figure 1: Schematic representations of flow-through regimes in the UWHA typical for summer stagnation periods before (a) and after the installation of the curtain (b: overflow over the curtain, c: underflow below the curtain).

NUTRIENT ELIMINATION

Theoretical bases

The P-elimination in pre-dams is essentially based on the SRP-incorporation in plankton biomass and is a function of the retention time of water. *Benndorf* and *Pütz* (1987 a,b) developed a procedure for the estimation of the theoretical SRP-elimination in dependence on the volume and the SRP-load entering a pre-dam. A theoretical SRP-elimination of more than 70% can be expected, if the relative retention time t_{rel} becomes greater than one. As shown in equation 1, t_{rel} is the ratio between the theoretical retention time t_R in the so-called reaction space V_R (volume of the euphotic zone, in pre-dams typically considered as the volume of the upper 3 m – layer) and the critical retention time t_{crit}:

$$t_{rel} = t_R / t_{crit} \qquad (1)$$

with:

$t_R = V_R / Q_{in}$

$t_{crit} = 24{,}7(1+2/P_M)\,(1+21/I_M)/T_M$

and

t_{rel} relative retention time,
t_R theoretical retention time in the reaction space [d],
t_{crit} critical retention time [d],
V_R volume of the euphotic layer of the pre-dam [m^3] (reaction space),
Q_{in} average monthly discharge [m^3/d]
P_M average SRP concentration in the inflow [µg P/l],
I_M monthly average of the photosynthetically active radiation in the reaction space [$J/cm^2/d$]
T_M monthly average of the temperature in the reaction space [°C]

Considering the SRP-elimination, the most important optimization-parameter is therefore the volume of the euphotic layer of a pre-dam. SRP-elimination rates of up to 90% can be reached in optimally dimensioned pre-dams in summer, especially if fast settling diatoms dominate the population of phytoplankton. In the cold and radiation-poor seasons, the biologically caused SRP-elimination is low due to the low primary production.
In too small pre-dams the relative retention time is too low. In over-dimensioned pre-dams (retention time t_R too high) the SRP-elimination is also restricted due to mass developments of algae growing and depositing slowly (such like flagellates or cyanobacteria) as well as of zooplankton and rotatoria remobilising phosphorus by grazing.
While in a conventional, always overflowing pre-dam the in- and outflowing SRP-load and therefore the SRP-elimination can be determined experimentally quite easily, this problem proves difficult in the pre-dam formed by a submerged wall in the main basin of a reservoir. The water and matter budget in the Haselbach underwater pre-dam is influenced by the inflow Q_{in} with the concentration c_{in} and, additionally, by wind-driven return-currents Q_{res} from the main basin over the top of the SFC with the concentration c_{res}. As mentioned before, a certain underflow Q_u below the curtain with a concentration c_u has to be considered as well sometimes.
The return-current-factor $q = Q_{res}/Q_{in}$ and the under-current-factor $x = Q_u/Q_{in}$ are considered to be constant during the calculation-period. If this is sufficiently long (a multiple of the theoretical retention time) the relative SRP-elimination E (%) can be estimated after equation 2.

$$E = 100\{1-[(1+q)c_0 + x(c_u - c_0)]/(c_{in} + qc_{res})\} \qquad (2)$$

C_0: initial concentration

An increase of the return-current and/or under-current causes a decrease of the SRP-elimination. Due to the increased flow caused by the return-current Q_{res}, the theoretical retention time t_{RTW} in the reaction-space V_R (the volume separated by the SFC) decreases. Equation 3 is now valid instead of equation 1:

$$t_{RTW} = V_R/(Q_{in} + Q_{res}) = t_R/(1 + q) \qquad (3)$$

The SRP-elimination

Similar to pre-dams, the achieved SRP-elimination is the most important criterion for the effectiveness of the flexible curtain. The monthly elimination rates E_{obs} calculated according to equation 2 in dependence on monthly averages of the measured concentrations c_{in}, c_o and c_u and the estimated factors q and x are represented in Figure 2.

Because the SRP-elimination strongly depends on discharge variability, the effect of the SFC cannot be assessed by a simple comparison of the monthly E_{obs} observed in the years 1995 - 1997 with those determined in the Haselbach underwater pre-dam in 1994 before its installation. For that reason, the E_{obs} were compared with SRP-elimination rates estimated with the procedure described by (*Benndorf* and *Pütz*, 1987 a,b) under the assumptions that (i) the SFC was not installed (E_{oTW}, q estimated like 1994) and (ii) with the SFC installed (E_{mTW}), see Figure 2. It must be mentioned that the influence of the return-current Q_{res} on retention time and SRP-load could but underflow could not be considered.

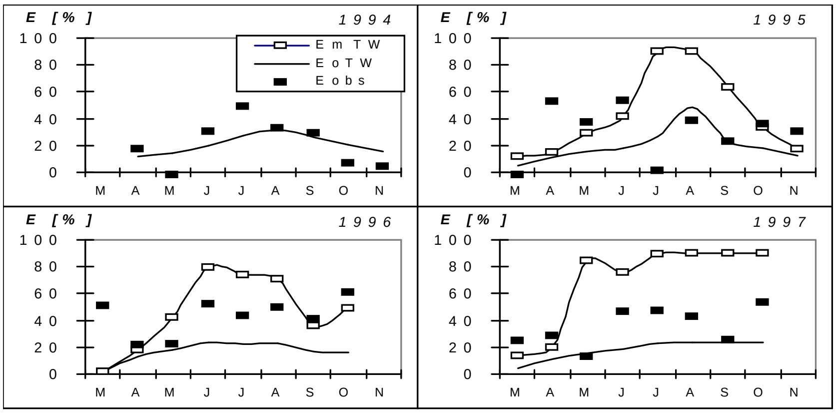

Figure 2: Observed SRP-elimination E_{obs} (determined with equation 2) compared with those estimated according to the procedure given by *Benndorf* and *Pütz* (1987a) assuming the SFC was not (E_{oTW}) and was (E_{mTW}) installed, respectively.

A satisfactory conformance between E_{obs} and E_{oTW} can be stated for 1994. The higher E_{obs} in June and July (when distinctive thermal stratification was observed) were probably caused by an underestimation of Q_{res}. However, relatively low SRP-elimination-rates were estimated for 1994 despite optimum weather conditions (relatively warm and high irradiation). After the installation of the SFC, E_{obs} was clearly higher than E_{oTW} mainly due to the reduction of the wind-driven return-current. In months with strong underflow beneath the SFC (factor x > 0.5), E_{obs} was strongly restricted (particularly in September 1995, 1996, 1997, and in July 1996). In May 1994, 1996 and 1997, low E_{obs} values but high total phosphorus elimination rates (not depicted) were found. In these months marked phytoplankton mass-developments were observed in the upstream Forchheim pre-dam and very low SRP-concentrations in the inflow and, consequently, E_{obs} in the Haselbach underwater pre-dam were found. It was different to 1995, when the Forchheim pre-dam was completely emptied.

The months July and August 1995 were characterized by very low discharges, long retention times and outstandingly high water temperatures. The internal P-turnover in the Haselbach underwater pre-dam probably was high and E_{obs} low, therefore. However, even under optimum conditions (low return-and underflow, high irradiation; August 1996, June until August 1997) E_{obs} was always lower than E_{mTW}. The most important reason for that is the much lower trophic state of the Haselbach underwater pre-dam than normally found in pre-dams, which is attributed to the already high SRP-elimination in the upstream Forchheim pre-dam and the general decrease of P-loading after 1990.

CONCLUSIONS

The results of the research project show that flexible curtains represent a cost-effective alternative for conventional pre-dams. Particularly in drinking water reservoirs, they can considerably improve the effect of an upstream pre-dam and, therefore, enhance the water quality and the stability of raw water supply. Optimally dimensioned flexible curtains cause negligible operating costs and upkeep. The durability of coated film materials available nowadays allows full functionality over many years. The dimensioning of a flexible curtain can be conducted by means of the procedure developed by (*Benndorf* and *Pütz*, 1987a, b) for pre-dams. The depth to which the curtain should reach depends on the temperature stratification. The deeper it expands to the hypolimnion, the less is the risk of underflow. If there is no stable and long-lasting thermocline at the place where the curtain has to be installed, it must reach down to the bottom.

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