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Trap efficiency of a forebay in a low mountain range

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ABSTRACT: For storage reservoirs, a sustainable management of sediments is necessary that fulfils economic and ecological requirements. The process of silting reduces the storage volume and, thus, diminishes the functional capability. Hence for barrages, the aim is to allow great amounts of sediments to pass through the dam or to prevent the sediment deposition by collecting the materials by means of sedimentation. It is essential to achieve high trap efficiency for a forebay. This function is especially of great importance for drinking water reservoirs in order to provide a good water quality. In the course of time, the trap efficiency decreases due to the deposition of sediment in the reservoir. For the economic life-time of a forebay, it is essential to know to what extend the decreased reservoir storage capacity influences the trap efficiency. The following work deals with an analysis of trap efficiency of the forebay of a reservoir in the low mountain range of the region Harz in Germany. For this purpose, Churchill's Method is applied. The changes in trap efficiency since the commissioning of the forebay are modelled. During the last 73 years, about 10% of the forebay volume has already silted up. On the basis of the model calibrated to the measured values, a forecast is made regarding the forebay's settling properties during the next decades.

Keywords: Forebay, Trap efficiency, Sedimentation

1 INTRODUCTION

Solids enter the storage reservoir via the inflows in reservoirs and forebays. There, the solids settle more or less completely and, thus, contribute to a reduction of the storage capacity. This effect causes a decrease in the storage volume and, thus, reduces the trap efficiency of the reservoir since the retention time of the water in the storage reservoir is more and more reduced.

Smaller sedimentary basins are built in front of large dams to prevent the latter from silting up. In these basins, the sediments introduced with the inflow are supposed to settle. Since the sediments are also frequently polluted with harmful substances, a trapping of the sediments in the forebay prevents the harmful substances from entering the barrage. In view of that fact, the trap efficiency of forebays is important for the latter's dimensioning and maintenance.

This article examines the trap efficiency of a forebay in the low mountain range of the Harz region situated in the geographical centre of Germany. It deals with the question which effects the deposited sediment has on the forebay's settling properties and at which point in time the forebay volume will have reduced itself to such a degree that the forebay will have to be evacuated in order to guarantee a certain extent of retention.

It is to be examined, in particular, whether it will become necessary to evacuate the forebay as a result of the altered settling properties after it has been in operation for more than 70 years. Which effects will the sediments have on the settling properties of the forebay if they remain where they are during the next 70 years?

2 INVESTIGATION AREA

The investigated forebay of a large drinking water reservoir is supposed to reduce or, if possible, prevent solids, in particular fine particles and nutrients, from entering the barrage. Owing to this, a good raw water quality is to be guaranteed for the abstraction of drinking water from the barrage.

The dam structure of the forebay consists of a dam body with a loam core. The dam is about 20 m higher than the original ground level and the crest is about 200 m long.

The main data of the forebay is as follows:

Length of the forebay	500 m
Annual discharge	$32.4 \cdot 10^6$ m³/a
Catchment area	38.3 km²
Water volume V_1 1931	699,600 m³
Water volume V_2 2004	634,600 m³
Sediment volume since 1931	65,000 m³
Flooded area	128,500 m²
Mean retention time	7.1 d

With regard to the forebay's trap efficiency, it is known that a sediment volume of about 65,000 m³ has settled since the time of the forebay's commissioning. The sediment quantity was estimated on the basis of differential data from the original topographical survey in 1931 and the recording of the present condition by means of an aerial laser scan survey.

High trap efficiency is essential for the forebay. Otherwise, problems with the drinking water purification could arise in the subsequent barrage.

3 MODELLING TRAP EFFICIENCY

The article by Verstraeten and Poesen (Verstraeten, Poesen, 2000) gives a good review of the currently available empirical and theoretical models for estimating the trap efficiency of water reservoirs.

From the existing models, amongst others according to Borland & Miller (Borland and Miller 1958) Brown (Brown, 1943), Brune (Brune, 1953), Churchill (Churchill, 1948) and Camp (Camp, 1945), the method according to Churchill was chosen for the issue on hand.

3.1 *Churchill's Method*

The model developed by Churchill in 1948 estimates the trap efficiency of a reservoir by means of a sedimentation index *SEDI*. With the Churchill Method, in contrast to other models, the y-axis of the plotted empirical curve is related to the percentage rate of the sediments passing through the reservoir

$$S_A = 100 - TE \quad [\%] \tag{1}$$

with *TE* standing for trap efficiency.

The method is based on data measured by the Tennessee Valley Authority regarding the trap efficiency of the dam system in the Tennessee Valley in the USA. In particular, the data related to the Hales Bar Dam and the Wilson Dam was applied. The sediment examined in the Tennessee Valley is classified as fine and is, therefore, mainly transported in suspension.

The curve determined empirically according to Churchill is given in Figure 1. The values for the sedimentation index *SEDI* are shown on the x-axis. In this context, the sedimentation index is described as the relation between the retention time t [s] and the mean flow velocity v [m/s]:

$$SEDI = \frac{t}{v} \tag{2}$$

It is also possible to present the sedimentation index in another way

$$t = \frac{V}{Q}, \; v = \frac{Q}{A} \text{ and } A = \frac{V}{L}$$

result in:

$$SEDI = \frac{V \cdot A}{Q^2} = \frac{V}{Q^2} \cdot \frac{V}{L} = \frac{(V/Q)^2}{L} \tag{3}$$

with V = storage volume [m³] Q = inflow [m³/s], A = mean perfused cross-section of the forebay [m²] L = length of the reservoir (flow path) [m] and *SEDI* = sedimentation index [s²/m].

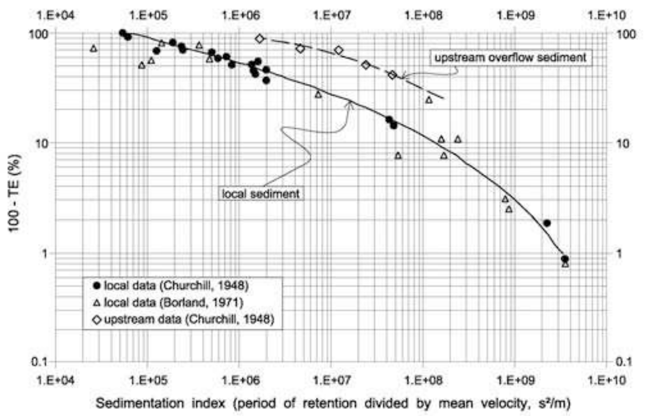

Figure 1. Trap efficiency (TE) related to sedimentation index (Churchill, 1948)

The Churchill curve for the local sediment in Figure 1 is represented by the following equation

$$S_A = 1600 \cdot [SEDI \cdot g]^{-0,2} - 12 \tag{4}$$

with S_A = percentage of the sediment quantity in the discharge [%] and *SEDI* = sedimentation index [s²/m].

The non-dimensional retardation factor R is difined as

$$R = 100 - \left(1600 \cdot [SEDI \cdot g]^{-0,2} - 12\right) \tag{5}$$

with R = sediment retained [%], $SEDI$ [s^2/m] and g = gravitational acceleration [m/s^2].

Since Churchill has carried out his investigations in the area of the Tennessee Valley in which the dams are set up in a row, he had to make a further differentiation. Thus, he differentiates between local and fine sediment. The local sediment comes from that part of the river's course which does not feature any reservoir. In the first storage reservoir, the retention is going to be exceptionally high (lower Churchill curve) since the coarse material can quickly settle there. After that, only finer sediment is passed with less sedimentation velocity to the dams at the downstream face so that the percentage of sediments in the discharge increases (upper Churchill curve). In this context, only the lower curve according to (4) is of any importance.

Owing to the sedimentation index and the taking into consideration of the retention duration and the flow velocity in the reservoir, Churchill's Method is able to describe the hydraulic conditions more precisely than other methods and, thus, is most suitable to estimate the trap efficiency in the present case.

Studies conducted by Borland (Borland, 1971) were able to confirm that Churchill's empirical approach would also deliver plausible results in case of reservoirs and sedimentary basins falling temporarily dry. In addition to this, the theory may easily be applied to smaller reservoirs as well.

3.2 *Application of the Method*

In order to apply the empirical model according to Churchill, the sedimentation index has to be calculated. In the present case, it is recommendable to express the equation (5) in a different form

$$R = 100 - \left(1600 \cdot \sqrt[5]{\frac{v}{g \cdot t}} - 12\right) \tag{6}$$

It can be recorded: the longer the retention time t in the forebay, the larger the factor R. That means, the longer the sediment particle can remain in the forebay, the higher the probability that the sediments settle and the higher the retardation factor R.

Moreover, the factor R is going to be smaller in case of an increasing flow velocity v within the forebay. That means, if the inflow increases in relation to the forebay volume V, the sediments will have less time to sediment.

In order to be able to make a statement about the forebay's trap efficiency in case of different discharges, the water inflow has to be linked with the respective bed load Q_{bl}. For this purpose, measured data has to be used. Oftentimes, a linear relationship

$$c_F = k \cdot Q \tag{7a}$$

is used as a basis, in this context, with c_F total solid in kg/m³. It follows

$$Q_{bl} = k \cdot Q^2 \tag{7b}$$

where Q_{bl} results in kg/s. For the present case, it is known that about 65,000 m³ of sediment has settled in the forebay between 1931 and 2004. A random sample taken during a flood showed a solid concentration of about 0,530 kg/m³ solid at an inflow of about Q = 33 m³/s for the inflow to the forebay. According to this pair of values, k would result in about 0,016 pursuant to equation (7).

In order to convert the settled solids into a volume, it is assumed that the grain density corresponds to a value of 2650 kg/m³ as is common in the region. The density of the materials settled at the forebay's base is estimated with 1325 kg/m³.

If approach (7) is combined with the daily inflow to the forebay, the changes in the forebay volume may be calculated depending on the sedimentation rate. In this context, the relationship (7b) may be calibrated in such a way that it results exactly in the measured value of 65,000 m³ of sediment for the period between 1931 and 2004.

If this approach is used, the following calculation formula applies to interval t_1,

$$R_1 = 100 - \left(1600 \cdot \sqrt[5]{\frac{Q_1^2 \cdot L}{g \cdot V_0^{\,2}}} - 12\right) \tag{8}$$

$$FF_1 = \frac{R_1}{100\%} \cdot k \cdot Q_1 \cdot \Delta t \qquad \Delta V_1 = \frac{FF_1}{\rho} \tag{9}$$

and to interval t_{n+1}

$$R_{n+1} = \left[100 - \left(1600 \cdot \sqrt[5]{\frac{Q_{n+1}^2 \cdot L}{g \cdot \left(V_0 - \sum_{i=1}^{n} \Delta V_i\right)^2}} - 12\right)\right] \tag{10}$$

$$FF_{n+1} = \frac{R_{n+1}}{100\%} \cdot k \cdot Q_{n+1} \cdot \Delta t \qquad \Delta V_{n+1} = \frac{FF_{n+1}}{\rho} \tag{11}$$

with FF = the mass of sediment retained in the forebay during one time step Δt.

As a whole, the following has to apply for the period between 1931 and 2004 for m time steps:

$$\sum_{i=1}^{m} \Delta V = 65{,}000\ m^3 \tag{12}$$

Figure 2 shows the measured daily discharge of the river for the years 1931 to 2004.

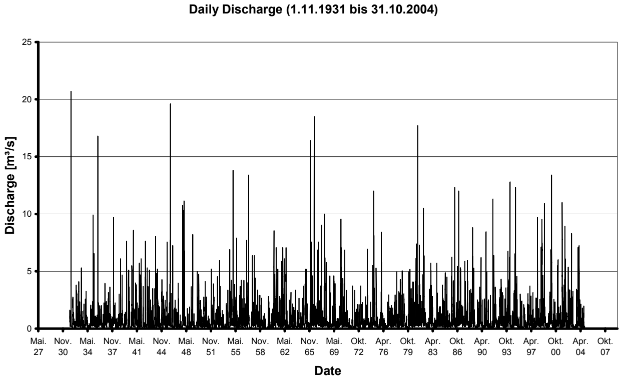

Figure 2. Daily measured discharge upstream of the forebay

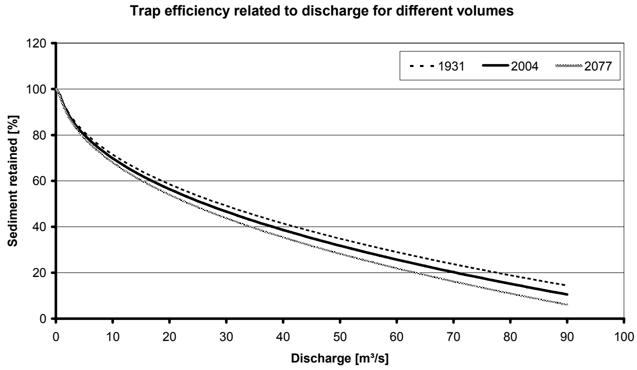

Figure 3. Computed trap efficiency for 1931, 2004, 2077 for the forebay

Since the hydrograph of the inflow in Figure 2 has a resolution of one day, the time step Δt = 1d was chosen. The solution of the system of equations (8), (9), (10), (11) and (12) is

$$Q_{bl} = 0.014 \cdot Q \tag{13}$$

with Q_{bl} = discharge of bed load [kg/s] and Q = discharge of the river [m³/s].

Afterwards, the calculation for the period between 2005 and 2077 is carried out on the basis of the same discharge hydrograph from 1931 to 2004 according to Figure 2. In this context, however, the volume of the forebay is reduced by 65,000 m³ (in comparison to 1931) resulting in a volume of 634,600 m³ which is applied as the storage volume V for 2004.

According to the result, a new sedimentation volume of 64,424 m³ will settle in the forebay during the next 73 years while the conditions and assumptions remain the same. Thus, the trap efficiency is diminished by 576 m³ or 8.86 % in the period from 2004-2077 as compared to the period from 1931-2004.

According to relation (8), the retention R of the forebay in its original condition in 1931, in 2004 and in 2077 may be calculated and compared depending on the inflow Q.

The result of this calculation is presented in Figure 3. It can be noted for the years 1931, 2004 and 2077 that recognisable differences in the retention R of the forebay can only be found in case of larger discharges (Q > 20 m³/s). In case of a medium inflow or even smaller inflows in the forebay, however, no noticeable changes have to be expected for the retention capacity in the future.

4 SUMMARY AND OUTLOOK

By means of the mean daily discharge value of the past 73 years, it was possible to model the forebay's trap efficiency for the period from its commissioning to today. In this connection, the inflow /bed load ratio was calibrated in such a way that it resulted in a sediment volume of 65,000 m³ measured up to today.

Based on today's condition of the forebay and the assumption that the forebay's future inflow behaviour remains the same as in the past 73 years, the modelling with identical assumptions shows that the forebay's trap efficiency will not change noticeably during the next 73 years in case of normal discharge. Only in case of higher discharges (Q > 20 m³/s), the retardation factor R is reduced by a few percent.

All in all, it can be said that, in case of constant boundary conditions and with a high probability, the trap efficiency of the investigated forebay will not significantly change in the future.

A further step to improve the forecast's accuracy would be a comparison with other methods as described in section (3).

In order to make even more detailed statements, precise measurements of the bed load at the inflow and outflow of the forebay would be necessary. By means of these data, the established model could be tested. In this context, other methods could be called upon for comparison as well.

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