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Hybrid modeling of sediment management during drawdown of Räterichsboden reservoir

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ABSTRACT: The Swiss utility Kraftwerke Oberhasli AG (KWO) currently implements "KWO plus", an upgrading program involving a large number of economical and ecological improvements of their hydropower schemes. A major project, the modification of the Handeck 2 power plant intake, requires total emptying of the Räterichsboden reservoir having an active volume of 25 million m^3. In order to define the most efficient and ecological emptying process for these circumstances, KWO commissioned a hybrid modelling program of the sediment remobilisation processes during the planned reservoir drawdown. Hydraulic model tests were conducted at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) by means of a 1:35 scaled Froude model. Numerical simulations of sediment transport were performed by the Laboratory of Hydraulic Constructions (LCH) using the software FLOW-3D. A good agreement between both models was found for total values of the sediment concentration and its variation in time. Both the physical and the numerical model were validated by prototype data obtained during an annual functional test of the bottom outlet. These measurements were conducted at three downstream positions in the Aare River. The involved solution procedures provide the (1) sediment flux during pressure flushing, (2) influence of outlet gate opening height and opening velocity on sediment concentration, and (3) time-dependent distribution of sediment concentration along the Aare River.

1 INTRODUCTION

1.1 *Background and project context*

The Swiss utility Kraftwerke Oberhasli AG (KWO) currently implements "KWO plus", an upgrading program involving a large number of economical and ecological improvements of their hydropower schemes. One major project involves upgrading the Handeck 2 and Handeck 3 power plants by enhancing the installed capacity from 145 to 230 MW, resulting in an increase in intake discharge from 42.5 to 65.5 m^3/s.

In order to install preventive measures against vortices, the intake structure has to be modified. Also, because of the limited hydraulic capacity of the existing pressure tunnel with an inner diameter of 3.0 m, a second, parallel pressure tunnel with an inner diameter of 4.1 m will be constructed. Even if the power plant will remain in service for most of the construction time of the parallel headrace tunnel, the Handeck 2 intake will be out of service during the construction of the diversion between the two tunnels and the joint right before the surge chamber. For both constructive measures, i.e. the anti-vortex cover and the connections between the existing headrace tunnel and the new parallel tunnel, it is necessary to empty the Räterichsboden reservoir. All engineering works are to be completed in the period from mid 2012 to mid 2014.

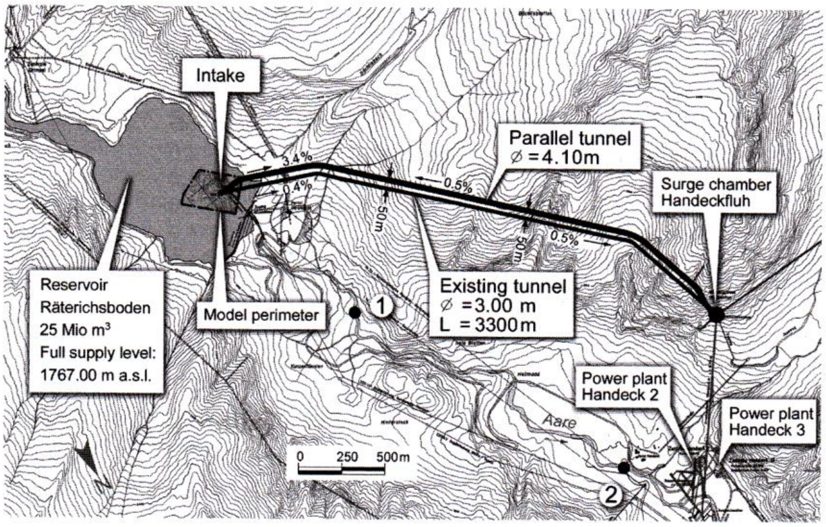

Figure 1. General arrangement of the hydropower plant including in-situ measurement sections no. 1 and 2 in the Aare river during flushing operation according to Table 1.

Using the bottom outlet for reservoir emptying, a certain sediment flushing is unavoidable during the process, with all its environmental impacts. During the last periodic yearly tests of the bottom outlet gate, recordings of sediment concentrations have been made. Also, in 1991 the Räterichsboden reservoir was totally emptied because of exceptional maintenance works. Sediment load and turbidity were registered downstream. Boillat et al. (2010) investigated the sediment flow out of the Grimsel reservoir, through the Aare reaches as well as inside the Räterichsboden reservoir by turbidity currents.

In the frame of elaborating documents for the environmental impact assessment, the question arose whether there are ways to reduce sediment concentration during the reservoir drawdown, for which two processes can be distinguished in general: (i) pressure flushing and (ii) free-flow flushing. Flushing under pressure is to release water through the bottom outlets by keeping the reservoir water level high. Free-flow flushing means releasing water by emptying the reservoir and also routing inflowing water from upstream through the reservoir by providing riverine conditions (Morris & Fan 1998).

This paper focuses on the study of the pressure flushing process, which was examined by (i) physical modelling, and (ii) numerical modelling. Both processes have been validated by measurements taken during the annual gate functional test in September 2010.

1.2 *Description of hydropower plant*

Both the Handeck 2 and the Handeck 3 power plants are fed by a common catchment area of about 52 km². Since the direct catchment area of the Räterichsboden reservoir comprises just about 9.5 km², most of the annual water volumes are conveyed through a subsidiary adduction tunnel from the Mattenalpsee reservoir (about 2 million m³), which is also fed, to smaller parts, by various other water intakes. The Räterichsboden reservoir has a storage volume of about 25 million m³, while annual inflow adds up to about 129 million m³. The average monthly inflow rates lie between 11 m³/s in July and less than 0.3 m³/s in the winter months.

The Handeck 2 and the later built Handeck 3 plant dispose of a common intake structure at the Räterichsbodensee reservoir. While the current structure is designed for an operating flow of $Q_d = 42.5$ m³/s, the Handeck 2 upgrading provides for an intake of $Q_d = 65.5$ m³. Model test showed that the installation of anti-vortex devices will be necessary.

Figure 1 depicts the general arrangement of the existing plant; Figure 2 shows the existing structure for the power and the bottom outlet intakes.

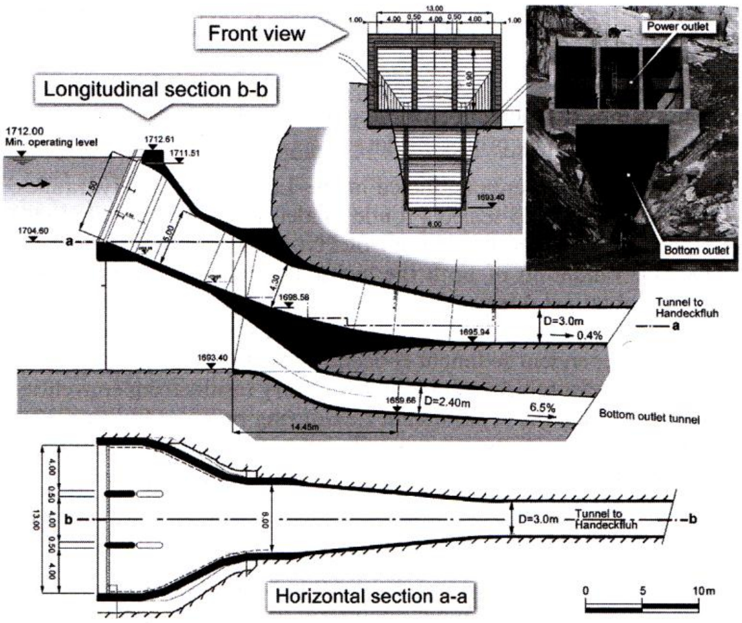

Figure 2. Intake structure of HPP Handeck 2 and 3 with power intake and bottom outlet.

1.3 *Planned procedure based on experience from reservoir drawdown in 1991*

The planned reservoir emptying should mostly be based on the experiences obtained during a similar operation in 1991, which had been rigorously monitored by limnologists. Foremost, the lowering of the water level will be obtained by turbining, until the lower edge of the intake structure will be reached (1704.60 m a. s. l.). Below a critical water level, machine power output will be limited to avoid vortex formation. Subsequently, the bottom outlet will be opened and pressure flushing begins. Finally, free-flow flushing and erosion occurs, until the lake bottom and a constant slope of the flushing funnel are reached.

In a concept phase, KWO had also studied alternative measures as well as pre- and post-flushing operations. These studies led to the conclusion that reservoir dredging or pumping was not a viable alternative to desilt the vicinity of the intake structure because of the harsh climatic conditions during the emptying period in winter, the lack of landfill sites, and the low flows in the nearby tributaries. Experiences of KWO showed that costly damages occurred while turbining sediment-laden water at the Innertkirchen plants, even if sediment concentrations were comparably low (around 1–1.5 g/l).

2 METHODS

For the reasons mentioned, a reservoir drawdown with subsequent flushing process is required. It is planned to start the flushing gradually with water of low sediment concentration. These preflushing operations allow the invertebrates in the downstream Aare river to enter into interstices in the riverbed where they find better shelter from the main flushing surge wave. Also, fish have the possibility to find suitable places where they can better withstand the increasing current and sediment load (Staub 2002). Moreover, post-flushing procedures are planned, in order to eliminate fine sediment deposits in the reaches downstream of the reservoir.

Clarifications had to be made to check whether the flushing process itself could be positively influenced and made as ecologically sound as possible. In order to define the most efficient and ecological emptying process for these circumstances, KWO commissioned a hybrid modelling program of the sediment remobilisation processes during the planned reservoir emptying consisting of:

1. Hydraulic model tests,
2. Numerical simulations of sediment erosion and transport process,
3. Validation of both models by prototype data.

The hydraulic model tests were conducted at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) in a 1:35 scaled Froude model. Numerical simulations of sediment transport were performed by the Laboratory of Hydraulic Constructions (LCH) using the software FLOW-3D. Validation of both the hydraulic and the numerical model was done with prototype data obtained during an annual functional test of the bottom outlet. Measurements of sediment concentration were conducted at three downstream positions in the Aare River. The time-dependent sediment concentration was obtained by correlating continuous turbidity-sensor measurement data with laboratory results from conventional samples.

These procedures provide the (1) sediment flux during pressure flushing, (2) influence of outlet gate opening height and opening velocity on sediment concentration, and (3) time-dependent distribution of sediment concentration along the Aare River.

2.1 *Hydraulic model tests (VAW)*

KWO commissioned VAW in April 2009 with a physical model investigation on the designed hydraulic scheme. The model tests comprised the analysis of vortex formation at the intake structure and possible counter measures as well as the mobilisation and the transport of sediments through the bottom outlet.

The perimeter of the model around the intake structure reproduced a section of about 300 × 200 m of the Räterichsboden reservoir including the terrain topography and about 70 m of the tunnel system (cf. Figure 3). The model scale of 1:35 complies with common limit values of surface tension and viscosity of a Froude model for the investigation of vortex formation by intakes (Möller et al. 2010).

The bottom outlet is situated directly below the intake structure (Figure 2). The possible mobilisation of the deposited sediment will be tested in a subsequent project phase. The sediments in the Räterichsboden reservoir are very fine, thus having cohesive effects due to a considerable share of the sediment size below the silt limit (Figure 4). A transformation of the given sediment to the hydraulic model is therefore not possible for a scale of 1:35. In the frame of a preliminary sensitivity study VAW has tested several types of sediment material and size distribution in the model such as medium sand, quartz sand and plastic granular material. The results obtained regarding sediment release through the bottom outlet and cone formation in the reservoir were similar. The finest sediment (fine sand with $d_m = 0.17$ mm) was finally chosen for the main flushing experiments in view of the fact that the model only allows a qualitative prediction of the sediment movements. The initial sediment elevation

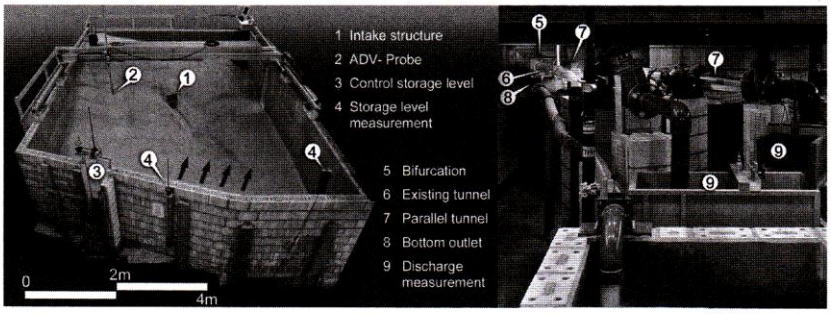

Figure 3. Hydraulic model at VAW. Left: view into the tank with partial reservoir topography; right: modelled tunnel system.

was defined as a constant surface all over the reservoir at 1704.60 m a. s. l. starting from the lower part of the power intake (see Figure 2). According to VAW's experience gathered with other projects on reservoir sedimentation, a funnel in the close-up range of the bottom outlet is expected to be formed and only a small amount of sediment would consequently be activated. This is in agreement with the findings of Meshkati et al. (2009) who analysed the effect of the water level and flow velocity in pressurized flushing operations. Sinniger et al. (2000) used an on-site bathymetric survey before and after pressure flushing operations at the Luzzone reservoir and observed similar flushing cone development.

2.2 *Numerical simulation (LCH)*

Numerical simulations of sediment transport were performed by the Laboratory of Hydraulic Constructions (LCH) using the software FLOW-3D. The numerical simulation was run by activating the sediment scour model in the program. The geometry of the Räterichsboden Reservoir (xyz file), intake gallery, bottom outlet and dam were inserted into FLOW-3D as a stereo lithography (stl) file created beforehand in several software packages. The geometry is based on the one realized at VAW. Figure 5 shows the created stl files for the reservoir and its outlets.

The water surface level was always held constant for the simulated scenarios. Sediment elevation was equal to the VAW model tests. The total number of cells in the computational space while modelling the reservoir reached some 2.1 million. The computational cells had a finer size (1 cm) around and in front of the intake and became coarser for the other regions with less importance in x-flow, y-flow and in z-vertical direction. With the intention of saving time and space for the result files, the meshing defined only the part of the reservoir directly concerned by the flushing process. Model simulation time was about 210 seconds corresponding to about 20 minutes at prototype scale. The output file size for each scenario was about 17 GB. In accordance with the hydraulic model (fine sand) the average diameter of the sediment was introduced as $d_m = 0.17$ mm with a density of 2707 kg/m^3 and 32.4° as angle of repose in all the computed scenarios. The boundary conditions were defined as follows: symmetry in $Y_{min, max}$

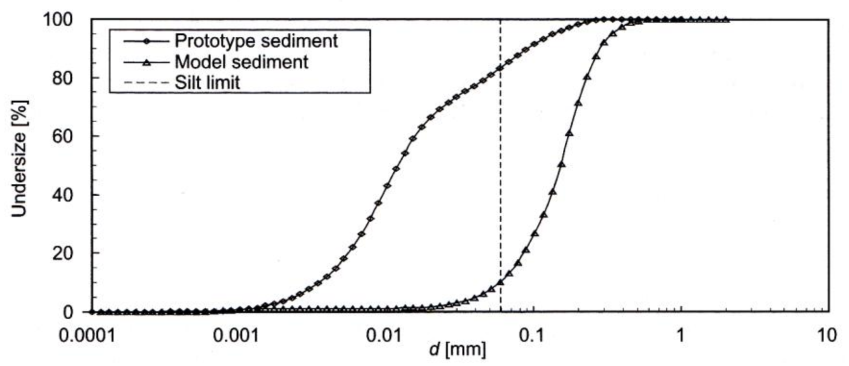

Figure 4. Particle size distribution from laser scattering of prototype and model sediment (fine sand).

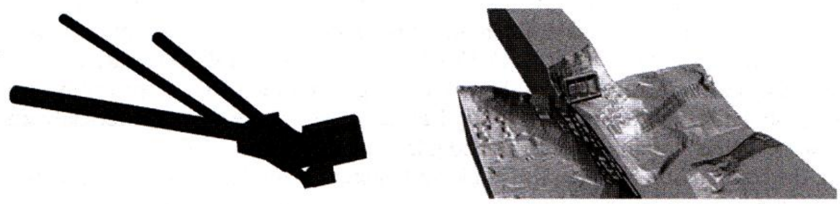

Figure 5. Intake structure and topography in numerical model, perspective of tunnel system (left); view of Räterichsboden reservoir (right).

Table 1. Measurement sections in the Aare river.

No.	Section name	Flow distance from bottom outlet
1	Bogenbrücke, Wanderweg	0.8 km
2	Gelmerbahnbrücke	3.1 km
3	Strassenbrücke Rotlaui	8.0 km

and $Z_{min, max}$. The symmetric boundary condition implies no flux in any property across the boundary and no shear. The boundary condition at X_{max} is defined as constant reservoir water surface level during flushing allowing water to flow in uniformly for mass conservation; at X_{min} a volume flow rate was defined as discharge through the bottom outlet.

2.3 *Model validation by prototype data (KWO)*

Validation of both the hydraulic and the numerical models has been made using prototype data obtained during an annual functional test of the bottom outlet. Measurements of sediment concentration were conducted at three downstream positions in the Aare River during the 2010 functional test as given in Table 1 (cf. also Figure 1).

At all sections, turbidity measurements with scattered light photometer and receptor as well as sediment load measurements using Imhoff cone were made. Turbidity measurements at section 1 were performed with a probe recording not only turbidity but also the dissolved oxygen content (O_2) of the river flow. The turbidity sensors used are based on the backscattering method, operating with infrared light. Data was recorded at intervals of less than 1 minute. Since there is no universal relationship between turbidity (here NTU) and suspended sediment concentration (SSC) (Truhlar 1976), a gauging process is necessary. To correlate the turbidity measurements to the sediment load, water samples have been taken at intervals of about 2–5 minutes. Sediment load was to settle in the Imhoff cone, the declared settling time was 30 minutes.

The 2010 annual inspection of the Räterichsboden reservoir bottom outlet was conducted on 14 September 2010, starting at 09:00. The bottom outlet consists of a sluice gate with the main dimensions opening height $h = 1.3$ m and opening width $b = 1.0$ m. On the day of the functional test, the reservoir level was at 1760.49 m a. s. l., which equals to a pressure of 81.86 mWC above the bottom outlet invert. To allow for a better inspection, gate opening occurred stepwise until an opening of about 61% was reached (0.8 m), corresponding to a theoretical outflow of about 24.6 m^3/s. After about 25 minutes, the gate was closed again.

3 RESULTS AND DISCUSSION

3.1 *Hydraulic model (VAW) vs. numerical simulation (LCH)*

All tests conducted in the hydraulic model study were also re-studied with the numerical model. Additionally the water level and the opening speed of the gate were also varied during the numerical model runs. Figure 6 shows two relatively identical test results of suspended sediment concentrations for fine sand sediment with rapid opening of the gate (VAW-LCH 1) and a prototype gate opening speed of about 0.25 m/min (VAW-LCH 2), respectively. The agreement of the peaks in terms of absolute value and timing is good. However, the decrease in concentration after the peak is different for lower water levels and slow gate opening (VAW-LCH 2). In contrast, at high water levels (VAW-LCH 1), the overall distribution curve agrees well except for the descending part with $t > 4$ min. e.g., after only 10 min (prototype value) the concentration reaches about 10 g/l in the hydraulic model, whereas the numerically simulated concentration value remains higher than 50 g/l.

So far, the comparison between hydraulic and numerical model results has generally shown good agreement. The outcome of some tests is therefore to some extent disturbing. While the result from the numerical simulation shows the expected behaviour, the concentration curve of the hydraulic model seems to be misleadingly delayed. Possible explanations are gallery

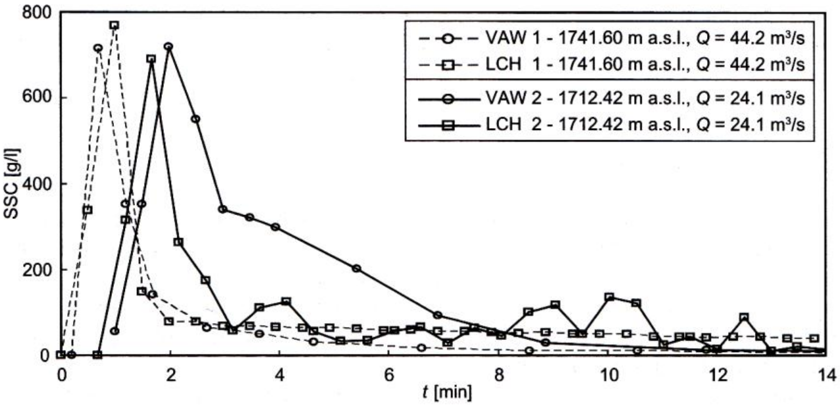

Figure 6. Suspended sediment concentration (SSC) over time t for fine sand at high water level with rapid gate opening (VAW-LCH 1) and low level with prototype gate opening (VAW-LCH 2).

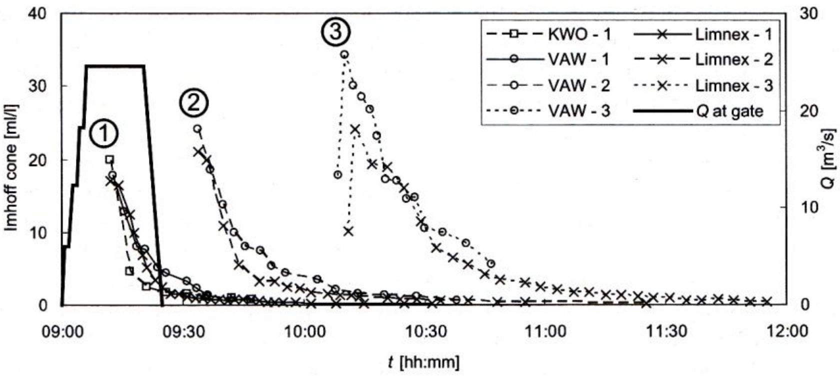

Figure 7. Comparison of sediment load determined by Imhoff cone in-situ measurements on 14 September 2010. The theoretical discharge Q due to gate opening value is shown. Sections according to Table 1.

clogging, model scale effects, especially for low water levels as well as the initial boundary condition (compactness) of the sediment deposits that possibly mobilized only after a certain time. The shapes of both curves and removed volumes correspond well, however.

3.2 *In-situ measurements on 14 September 2010*

The sampling during the annual functional test of the bottom outlet was done at three locations (see Table 1 and Figure 1). Figure 7 shows the results of the in-situ measurements downstream of the Räterichsboden reservoir. The results of KWO and Limnex refer to Imhoff cone measurements and are expressed by a volume concentration [ml/l]. Results of VAW measurements were determined as a mass concentration [g/l] from water samples. The conversion from a mass concentration [g/l] into a volume concentration [ml/l] has been done with a bulk density of approximately 2000 kg/m³ (Limnex 2010). The discharge was theoretically determined as a function of the gate position. The curves at the respective positions agree quite well. The peak concentration values follow the same trend for all measuring sections. It is noticeable that the peak concentration increases with distance from the bottom outlet; this is mainly attributed to a remobilization of bed material.

Whereas the temporal distribution of the sediment concentration is similar between model and prototype, the absolute values differ by an order of magnitude when comparing Figures 6 and 7. The reason for this is supposed to be mainly due to (i) model and scale effects, because the relevant sediment grain size distributions vary considerably between model and prototype, and (ii) to the different positioning of the measurement sections, i.e. immediately downstream versus 800 m and more from the bottom outlet.

4 SUMMARY AND CONCLUSIONS

To achieve a better estimation of the removed materials by pressure flushing from the Räterichsboden bottom outlet, a physical model was built at VAW. The physical model tests were simulated numerically with FLOW-3D at LCH. On-site measurements of flow turbidity downstream of Räterichsboden reservoir were recorded during the September 2010 flushing event and the suspended sediment concentration values compared to the results obtained both in the physical and numerical model.

Two major bottom outlet operation scenarios were defined: instantaneous and gradual slow gate opening. The physical model tests were performed with several types of sedimentary material such as quartz sand with various grains sizes and plastic granular material. The main tests were all conducted with fine sand. Numerical simulations using Flow-3D were run having the same initial and boundary conditions as the physical model. The simulated concentration curves match well with the physical model results. Some major differences can be observed with gradual opening and low water level, these are most likely due to potential scale effects or non homogeneous initial sediment deposits in the physical model. One has to bear in mind, however, that modeling two-phase water-sediment mixtures is always complex and source of uncertainties, both physically and numerically.

The on-site measurements confirmed the general shape of the suspended sediment release from the bottom outlet as obtained from the VAW and LCH tests, but with much lower concentration values than expected. As the first measurement section is already located some 800 m downstream, the short initial peak concentration value is possibly pronouncedly flattened and spread. The sampling method induces some lowering over time and space as well. Nevertheless, taking into account these uncertainties, the results of the monitored flushing event are in similitude with those of the physical and numerical models. These model tools can therefore be used to predict and estimate the flushed sediment from the reservoir.

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