SUCCESSFUL SEDIMENT FLUSHING CONDITIONS IN ALPINE RESERVOIRS

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SUMMARY

Sediment flushing is one of the most commonly used practices to control reservoir sedimentation. A wide range of knowledge is needed to manage successfully this kind of operation. Experience from on site observations, 3D-numerical and physical modeling are presented. The reservoir created by the Luzzone dam, built between 1958 and 1963 and heightened in 1998 to 225 m height in the Southern part of Switzerland served as test reservoir.

The construction of a large dam significantly modifies the flow regime of natural streams inside and downstream of the artificial lake. Considering the high sediment concentration during flood events, the entering flow shows a greater density than the ambient fluid. Suspended load can therefore be entrained along the reservoir bottom all the way down to the dam in the form of turbidity currents. These strong currents can erode and transport considerable sediment volumes within the reservoir itself. They can cover the bottom outlet, affect the operation of the power intake and reduce the storage capacity of the reservoir. Releasing water through low level outlets at this particular moment allows not only flushing its entry from sediment deposits, but also the evacuation of parts of the incoming suspended load.

Low level or bottom outlet operations can only take place successfully when the alluvial deposits, covering the entry of the outlet over considerable depth, can be eroded by opening the gates. Studies have been undertaken to determine the geotechnical properties of the accumulated sediments. In order to gather the maximum information over the whole extent of deposits in the reservoir, the following operations have been performed: deep core drilling over 30 m depth, surface dredging and gravity cores sampling performed from the water surface, and manual sampling by divers at the alluvial surface close to the dam. The encountered silt, settled under water and never dried out, shows a typical loose matrix with practically no signs of compaction. Their degree of saturation is 97% with a water content of 54% in volume. They can easily put into motion by even slow currents and offer only weak cohesion under compression load. Nevertheless they can develop strong cohesion under decompression load. This occurs typically when a cone with slopes as steep as 60° forms in the deposits during flushing around the bottom outlet entrance. Therefore geotechnical properties of the alluvial deposits have to be seriously studied before any flushing operation.

Measures are proposed in order to allow the partial transit of sediments through the lake during floods and to evacuate them directly downstream of the dam. In view of environmental impact, this operation has to take place when the discharges in the upstream and downstream reaches are high enough. The inflow is needed to initiate turbidity currents, while the downstream flow is needed to dilute the sediment concentration and prevent clogging of spawning grounds. The bottom outlet participates partially in the sediment evacuation at the moment of the major sediment inflow during floods. If the reservoir is full by that time, spillway operation can be reduced and clear water will remain in the reservoir. Another advantage of this procedure would be the reduced impact on wildlife and vegetation in the downstream river by combining the flushing operation with the natural flood event. To improve sediment transport capacity in the downstream reach, additional clear water can eventually be added directly downstream of the dam, either by separate water intakes or in the case of the Luzzone dam by an intermediate outlet.

INTRODUCTION

All lakes created on natural rivers are subjected to reservoir sedimentation. On the one hand the retention of important volumes of water and sediments during floods contributes to flood protection of the population and the land downstream of the dam; on the other hand, the accumulation of sediments in the reservoir can affect intake and outlet devices and reduce the storage capacity.

Sediment flushing is one of the most commonly used practices to control reservoir sedimentation. A wide range of knowledge is needed to manage successfully this kind of operation. The flushing procedure, even if carefully planned and prepared, can cause ecological damage downstream due to the high concentration of sediments during flushing and to later deposition in the waterway.

In order to gain further knowledge on the main parameters influencing flushing, transport in the reservoir itself and the characteristics of the alluvial deposits, investigations have been undertaken on a multi pillar approach, including field investigations, laboratory test and numerical simulation.

TURBIDITY CURRENTS

Field investigations

Test reservoir

In order to clarify the flow mechanism of river-induced turbidity currents in an artificial lake, field observations were carried out in the Alpine reservoir of Luzzone in Southern Switzerland and its main inflow river (Sinniger et al. 1994, De Cesare et al. 1998). A tributary area of 36.5 km^2 drains directly to the reservoir, while the total tributary area is approximately 100 km^2. The initial geometry of the reservoir in the deeper part is characterized by a V-shaped valley that has accumulated sediments for more than 30 years. The mean bottom width is now around 50 m. A trapezoidal section approximately characterizes the reservoir geometry with side slopes between 1:1 and 1:2. The bottom shape is nearly symmetrical in the reach near the dam. The average longitudinal slope along the reservoir bottom is about 4 %. The annual mean sediment inflow is approximately 38x10^3 m^3 (based on measured deposit volume).

Measurements at the main inflow river

The National Hydrological and Geological Survey (SHGN), in close partnership with the Blenio Hydropower Company (OFIBLE) and the Laboratory of Hydraulic Constructions (LCH), placed a fully equipped measuring station on the inflow river about 500 m upstream of the lake. The following measurements were made during two summer periods in 1995 and 1996:

- Discharge Q [m^3/s]
- Temperature T [°C]
- Photo-optical turbidity measurements [NTU]
- Automatic suspended sediment sampling during floods C_s [g/l] beyond a certain water level, for calibration of the optical sensor

During the two years of on site investigations in 1995 and 1996, no significant floods were observed. It was possible, however, to show the relationship between precipitation, water and sediment flow and turbidity current in the reservoir even for minor events. The inflow measurements showed large variations in water discharge, sediment concentration and water temperature (Figure 1).

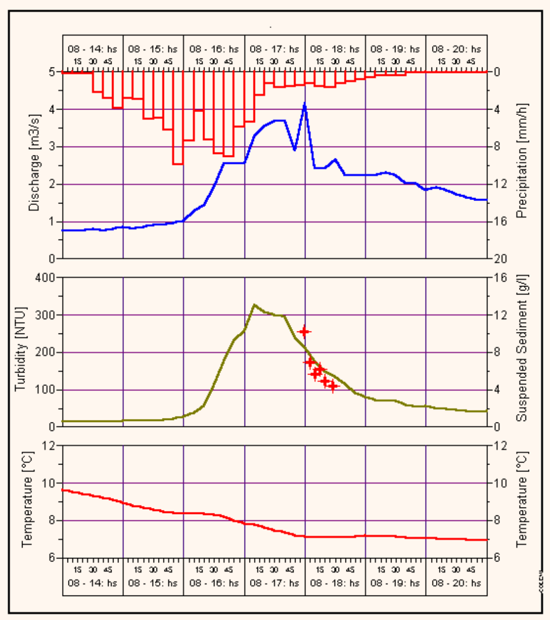


Figure 1. Measured precipitation, discharge, temperature, optical turbidity and suspended sediment samples for a typical small flood

Turbidity current monitoring at the bottom of the lake

As part of the overall study of sedimentation, continuous monitoring of the occurrence and flow behavior of turbidity currents in an artificial lake was carried out using an underwater current meter network. The system was able to detect and track density underflows. It consisted of six current meters located at the bottom of the lake at three stations A and B, 150 m and 800 m upstream of the dam and C at the confluence of the three major tributaries (Figure 2).

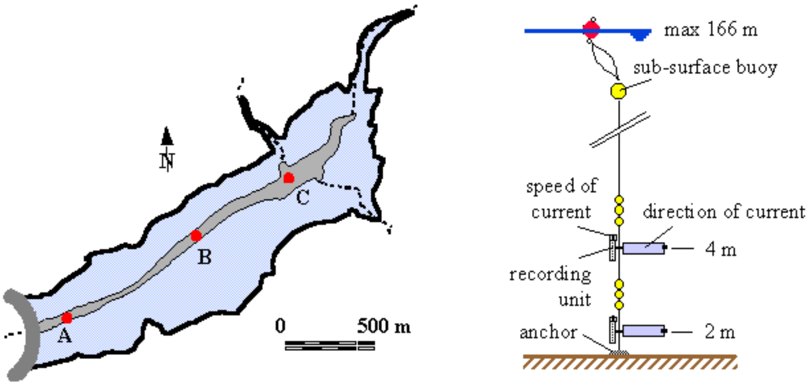


Figure 2. Location and vertical disposition of current meters of the underwater measuring network consisting of 3 stations A, B and C with 2 levels at each station

Two instruments were stacked vertically at each station, 2 and 4 meters above the bottom (Figure 2). Each of the verticals were anchored on the lake floor and kept tight with a sub-surface buoy, connected to a surface buoy for easy recollection. The recorded information was stored on data loggers inside waterproof casings on each individual instrument.

The current meters surveyed the following parameters at a rate of one record every thirty minutes:

- Mean average flow velocity during the 30 minutes interval, precision of 1.0 cm/s
- Instant direction of the flow associated to the magnetic north, precision of 5°
- Instant water temperature, precision of 0.1°C
- Water pressure, precision of 1 m

The current meters located at station C showed the most sensitive reaction on inflow variations. The instrument at 2 m from the bed recorded more than 700 occurrences during the five-month monitoring period from May to September 1995. The instrument at 4 m from the bed recorded five times less occurrences, showing that most of the occurrences at station C were low dimension bottom currents with heights of less than 4 meters.

Figure 3 represents the statistically analyzed directions of flow at station C, 4 meters above the bottom as a function of the mean velocity. The main flow direction indicates that the currents originate predominantly from the northeast tributary. No flow came from the south catchment area. The highest recorded velocity 2 m above the bed was 80 cm/s and 82% of all records were lower than 20 cm/s. The maximum velocity 4 m above bed level was 55 cm/s.

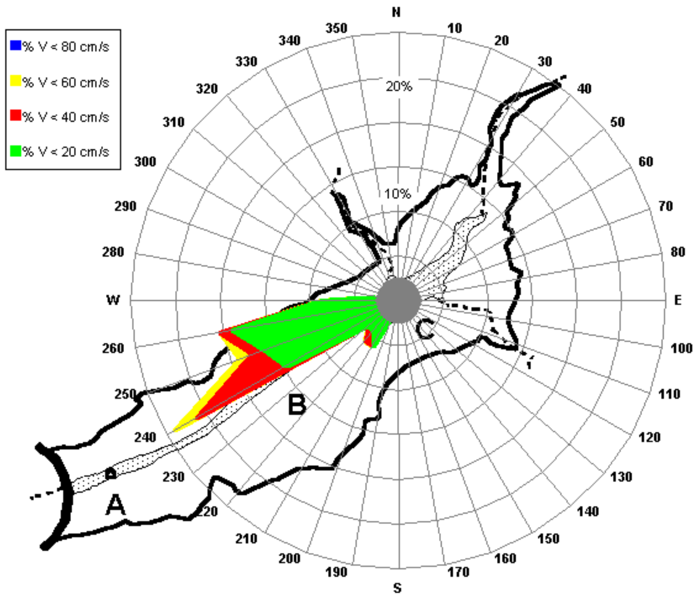


Figure 3. Observed directions at the bottom of the reservoir at station C, 4 m above ground, classified by current velocity. The flow is well oriented along the longitudinal axis of the lake

The directions at station B in the middle of the reservoir are fairly well aligned with the axis of the lake. The maximum velocity 2 m above bed level was still 73 cm/s. Only very few occurrences of flow were recorded at station A. They could just once be related to observed currents at the stations B and C both located upstream.

The only event where a current traveled through the whole lake of around 2.5 km length lasted seven hours in total. Its activity came to a rather abrupt end at each station and can be associated to a surge type event. Unfortunately, the upstream gauging station was not yet fully functional by that time, in early spring 1995, and no inflow measurements are available for the event. Similar observations were made during a storm in 1992, when an earlier measuring campaign in the same reservoir took place (Sinniger et al. 1994). The measurements indicate that density underflow activities are common close to the inflow rivers, whereas, further down in the reservoir, only few currents could be observed.

Numerical simulation

Turbidity current computations are complex by the unsteady nature of the flow. Variations in inflow and water levels in addition to continuous deposition or entrainment of sediment and entrainment of clear water cause changes in the density within the current. Reservoir topography is also non-uniform in the longitudinal direction, and will also gradually change over time as a result of sediment accumulation.

A numerical two-phase flow model has been developed and applied to simulate the river-induced turbidity currents in real reservoir geometry. The numerical model used is based on the general Navier-Stokes solver code CFX from Computational Fluid Dynamics Services (CFX-4.2 1997). It has been validated with laboratory experiments and compared with in-situ measurements of turbidity currents in a reservoir, collected during two summers (De Cesare 1998).

Suspension is directly treated in the CFX code through its homogeneous two-phase flow advection-diffusion model with a continuous Eulerian description. Separate mass balances for each phase are solved, but a common momentum balance for the mixture takes into account the changing mixture density due to the different volume fractions. The following assumptions apply:

- Mass and momentum transfers from one phase to the other are negligible
- The process is isothermal
- Phases are mixed on length scales larger than the molecular length scales and smaller than the numerical grid
- Water is defined as a continuous phase occupying connected regions of space
- Sediment particles are defined as a solid disperse phase distributed uniformly in a control volume
- Velocity differences between particles and fluid are negligible; hence one single flow field is calculated

User defined sediment deposition and erosion modules were added to take into account sedimentation and the interaction between the turbidity current and the reservoir bed material. The sediment exchange at the bottom of the reservoir can be described by a flux between the bed and the current, separated into a sediment entrainment and a sediment deposition term evaluated at a reference height slightly above the real bed level (Parker et al. 1986). Suspended sediment is constantly falling out of the current at a rate given by the sediment fall velocity and the mean volumetric concentration of suspended particles near the bed. The motion of the turbidity current exerts a stress on the bed and is capable of entraining sediments from the bed into suspension.

When a turbidity current reaches a barrier such as a dam, the forward velocity is converted back into potential energy as the current rises up against the face of the dam, and subsequently falls back down, initiating the formation of a muddy layer. The top surface of this highly sediment charged layer will extend along a nearly horizontal profile upstream from the dam. The volume of the muddy layer will increase and the interface will rise, as long as turbid inflow exceeds losses by the upward seepage of clear water from within the muddy layer due to sedimentation and compaction of solids.

For the inflow boundary condition a generic Maxwell distribution is used for both discharge and concentration evolution in time. The reservoir bottom interactions, which lead to sediment transport within the reservoir were analyzed with erosion-deposition maps as presented in Figure 4. All the turbidity current simulations showed that the erosion takes place in the upper steeper part of the reservoir, whereas the fine sediments deposit in the vicinity of the dam.

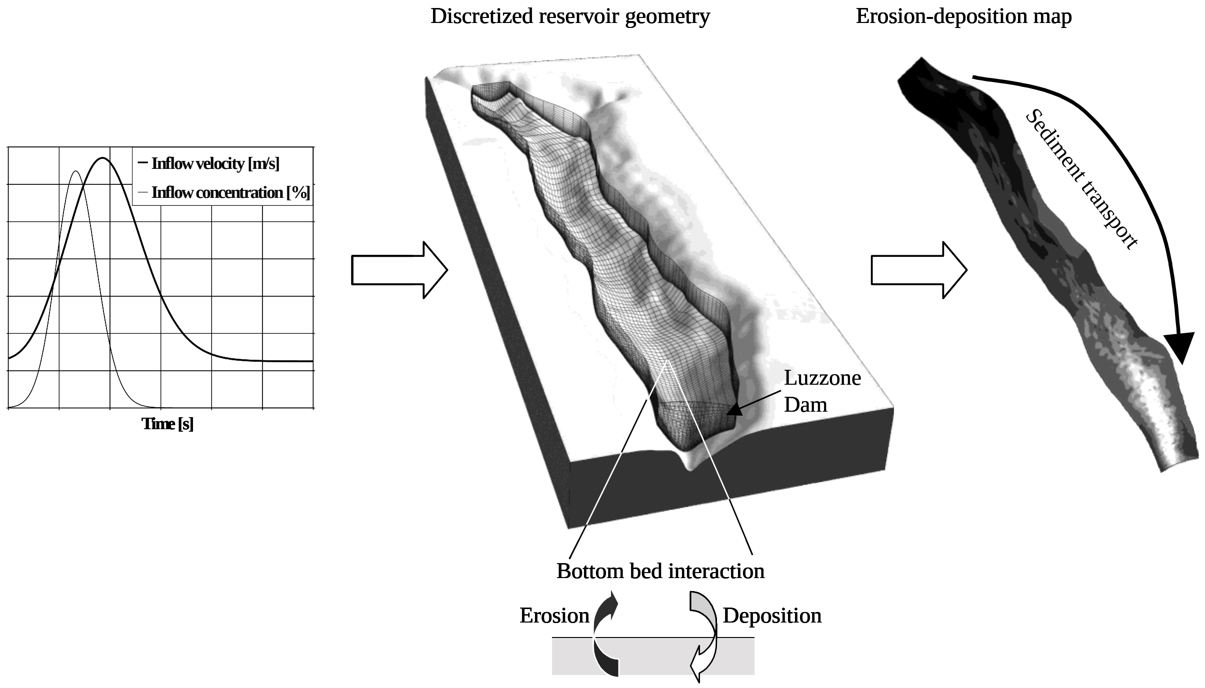


Figure 4. Scheme of numerical model with inflow conditions, discretized reservoir topography, bottom user interfaces and erosion-deposition map

To gain further knowledge on the importance of the different parameters introduced in the numerical model several computations have been performed by varying inflow, Q, concentration of suspended sediments, C_0, and a characteristic particle grain size diameter, d_{50} (Oehy et al. 2000). The influence of inflow and concentration on the flow behavior and the sediment transport in the turbidity current has been studied by means of four different inflow rates, which correspond to flood events with a recurrence interval of 1000, 100, 10 and 1 year, respectively, Q_{1000}, Q_{100}, Q_{10}, and Q_1. The 100, and 10 year floods have been calculated with an inflow concentration of both 2 and $5\%_{\text{vol.}}$.

The parameter study revealed that flow behavior and sediment transport within the reservoir are similar and quite independent of inflow conditions once a turbidity current is formed. In other words, the plunging phenomenon is the key hydraulic event, which makes turbidity current "release". The plunging is influenced by a large number of parameters, which are difficult to measure. Such parameters include concentration distribution, turbulence or thermal effects, slope, and geometry, which can be variable in time as a result of water level variations. It is worth noting that a minimum flood event is necessary to bring high sediment flow into the reservoir, and that, enough fine sediments have to be available on the bottom of the reservoir to feed the flowing turbidity current. Further, the results revealed that for mean particle diameters of 0.1 mm the turbidity current dies out and does not reach the dam. The transported sediment volumes within the lake can reach 30 times the inflow sediment volume. Mean velocities of up to 1.0 m/s are able to erode particles deposited during previous events.

Validation with experiments

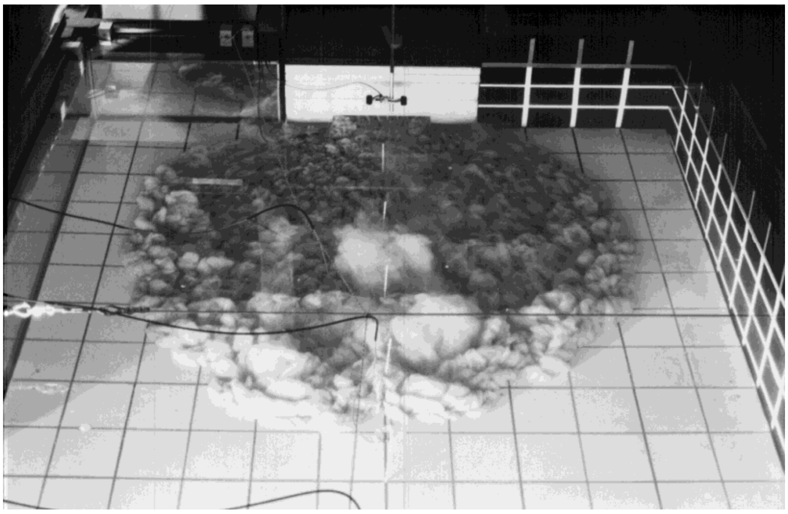
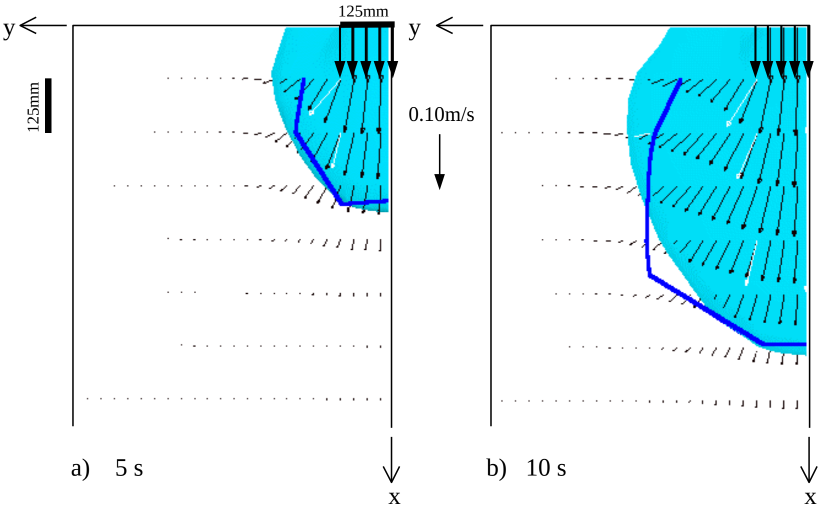


Figure 5. View of the expanding turbidity current in the experimental flume 25 s after opening of the gate, the current spreads out almost radial, 125mm x 125mm grid on PVC bottom

Physical modeling of turbidity currents was undertaken in an 8.4 m long, 1.5 m wide and 0.65 m deep flume (Beyer Portner et al. 1998, De Cesare et al. 1999a and b). Fine homogenous clay with a density of $\rho_s = 2{,}740$ kg m^{-3} and a mean particle diameter of $d_{50} = 0.02$ mm was used as suspended matter. The inflow current thickness is 0.05 m over a width of 0.25 m, centered in the flume. The bottom slope could be adjusted between 0 and 6 %, for the presented experiment, the slope was fixed at 1 %. The release velocity was 0.10 m/s with a constant concentration of 10 g/l. The measurements allowed the monitoring of a spreading turbidity current and its uniform flow over the total width of the flume (Figure 5).



a) 5 s

b) 10 s

Figure 6. Computed 2D flow field (black arrows) and model interface (gray surface); Measured velocity vectors (white arrows) and experimental interface (solid black line) of the spreading turbidity current a) 5 and b) 10 seconds after the opening of the gate

The turbidity currents in the laboratory were monitored by ultrasound probes functioning with the Doppler Method (Met-Flow 1996, Takeda 1995), thus giving a complete velocity profile in two directions, along the axes and laterally, at very short time intervals. Figure 6 shows the velocity distribution in the turbidity current expansion. The calculated and measured values are plotted on the same graph, in which numerical modeling results are presented by a surface of equal concentration located along the maximum concentration gradient. This gray surface fits well to the position of the interface between the turbidity current and the surrounding water, shown as a solid lack line. The computed velocity vectors are given on a fine plane grid situated 12 mm above the bottom at the same level as the Doppler transducers.

Figure 6 also shows the measured limits of the advancing current as a continuous bold line. The sharp kink in the line in Figure 4b is due to the sweeping process during data acquisition, which was performed from the axes x and y towards the exterior angle over a time span of about 1.5 seconds. The velocity distribution inside the expanding flow is very well predicted by the numerical modeling. The velocity vectors in the measured flow field confirm the direction and the magnitude of the computed velocity vectors.

CHARACTERISTICS OF ALLUVIAL DEPOSITS

Sediment sampling

Studies have been undertaken to determine the geotechnical properties of the accumulated sediments. In order to gather the maximum information over the whole extent of deposits in the reservoir, the following operations have been performed (Sinniger et al. 1999 and 2000):

1. Deep core drilling over 30 m depth (see Figure 7); the lengths of the 3 extracted cores were 21.4 m, 6.0 m and 5.6 m, they were sealed under water and transported plugged to the laboratory for analysis.
2. Surface dredging using a shovel dredger at 13 different locations along the talweg to gather an overview of the deposits, considered as fully disturbed.
3. Gravity cores sampling of 63 mm diameter, deep penetration was very hard to obtain, only two samples could be taken successfully, their lengths were 0.38 m and 0.13 m.
4. Manual sampling by divers at the alluvial surface close to the dam, this operation has been performed during manual sediment sluicing procedure to clear the water intake, considered as fully disturbed.

Operations 1 to 3 were performed by ship or pontoon from the water surface.

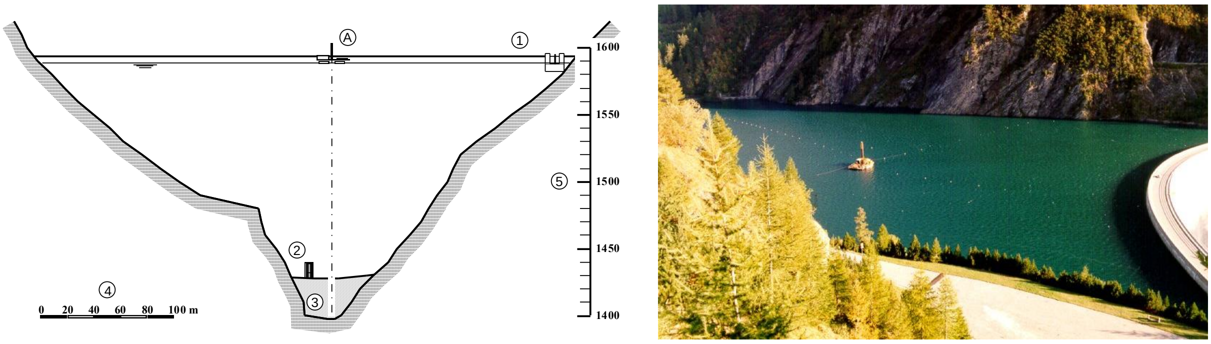


Figure 7. Schematic view and photograph of the sediment sampling from the lake surface by core drilling at position A close to the dam, ① spillway, ② water intake, ③ alluvial deposits, ④ horizontal axis in m, ⑤ vertical axis in m a.s.l.

Characteristics of the deposits

The encountered silt, settled under water and never dried out, shows a typical loose matrix with practically no signs of compaction. The grain-size distributions are given in Figure 8. The soil can be classified as silts with low plasticity limit (ML according to USCS).

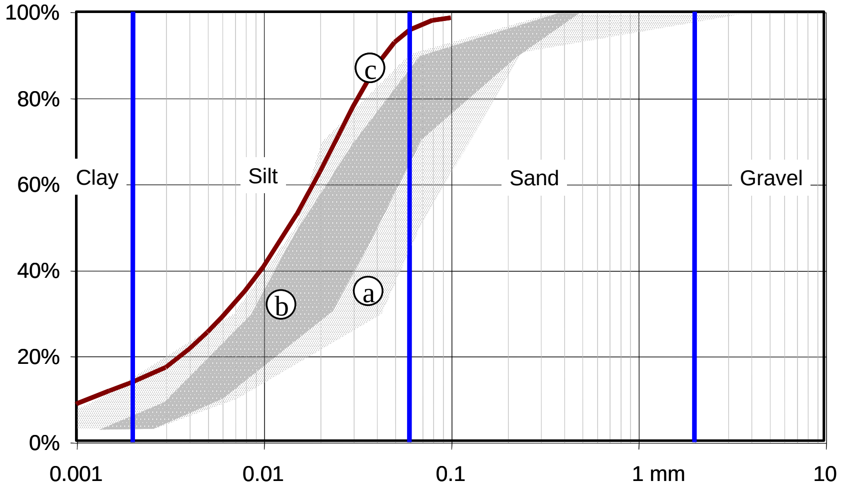


Figure 8. Grain-size distributions of the alluvial deposits from: a) deep core drilling 0-20 m depth, b) surface dredging along the talweg and c) manual sampling at the water intake

No significant stratification could be observed in the deposits, only slight differences in color due to organic matter contents could be observed. The samples from core drilling, sealed under water and therefore considered being undisturbed, were analyzed for material properties. The obtained characteristics are summarized in Table 1.

The undisturbed samples were 97% saturated with water, and the pores presented 61% of the total volume, therefore more than 50% of the deposits is still water. The sediments also showed very high plasticity and liquidity limits and; hence they could easily be put into motion and flushed away by only minor disturbances, such as turbidity currents.

Table 1. Characteristics of the alluvial deposits

Characteristics		**Sign**	**Value**	**Units**
Atterberg (consistancy) limits:	**liquidity:**	wL	37.1 ± 2.9	[%]
	plasticity:	wP	27.5 ± 2.0	[%]
Water contents:		w	53.6 ± 2.1	[%]
Apparent volumetric density (humid):		γ	16.8 ± 0.5	[kN/m^3]
Apparent volumetric density (dry):		γ_d	11.0 ± 0.5	[kN/m^3]
Volumetric density of grains:		γ_s	27.8 ± 0.5	[kN/m^3]

Triaxial shearing tests (low consolidated, saturated, undrained) were performed with probes taken between 0 and 20 m sediment depth. The behavior of the deposits under compression and decompression was analyzed.

Compression occurs naturally by charging the deposits with newly accumulated sediments, decompression or distressing occurs by removing matter laterally as it happens when part of the deposits slides away, typically when a cone is formed in the sediments during flushing or by trench cutting. The measured values are summarized in Table 2.

Table 2. Material properties of the alluvial deposits

Material properties	Sign	Compression	Decompression	Units
Friction angle:	φ'	32	32	[°]
Cohesion	c'	11	55	[kN/m^2]

The deposits don’t show intense resistance to compression, while they develop great cohesion under decompression, because negative pore pressure develops. Therefore, much higher apparent slopes than given by the pure friction angle can be observed in the deposits, see also Figure 9. The measured slopes attained almost 60°, while the angle of repose of the deposits is 32°.

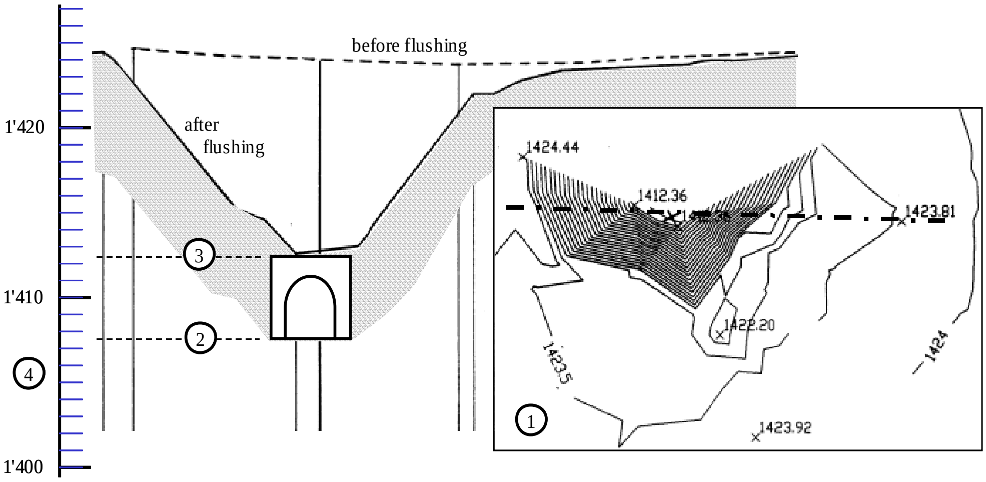


Figure 9. 18 m deep cone above the entrance of the bottom outlet, liberated after each flushing ① plane view of the cone, ② lower level of the outlet entry, ③ upper level of the outlet entry, ④ vertical axis in m a.s.l.

In conclusion one can state that even under more than 20 m sediment depth the deposits do not consolidate significantly and they remain very porous with more than half of their content being water. This is valid as long as they remain completely under water. Drying during the emptying of the reservoir or consolidation due to insufficient sealing of bottom outlet gates (high pressure gradient) can provide the sediment with very high compactness; their hydraulic removal will almost become impossible. Expensive mechanic equipment must be considered for elimination. On the contrary, fresh sediment, deposited close to the bottom outlet, can easily be removed by the induced flow during flushing and the safe operation of this vital component of the dam can be granted.

FLUSHING OPERATIONS

Requirements

Summarizing the previous chapters, one can state that the following ideal requirements should be satisfied in order to properly operate flushings in a deep reservoir with short-term floods:

- Temporarily high inflow discharge and concentration to initiate turbidity current
- Turbidity current as sediment and fresh water (high oxygen level) carrying medium inside the reservoir
- Alluvial deposits that have never dried and hence can be easily put into motion
- Low level outlet with sufficient discharge capacity for sediment laden water release
- Intermediate level outlet for clear water release for diluting during de-plugging of the bottom outlet

The subsequent conditions should be added:

- Hydrologic favorable situations (not during dry season)
- Downstream river reach with sufficient discharge capacity and enough natural discharge from its direct tributary for dilution of suspended sediment and for putting bed load into motion over a longer time than the flushing operation (minimal water supply in the downstream reach)
- Environmentally favorable situations (fishing, recreation)
- Legal allowance to operate the bottom outlet during favorable hydrologic conditions with respect to given concentration, duration and other restrictions
- Downstream (and upstream) measurement stations allowing the on-line monitoring of the operational efficiency operations

Lowering of the reservoir water level is generally not required and the maximum of clear water should be kept in the reservoir for future energy production and downstream flood protection.

Operation procedure

Very high concentrations normally occur only during the initial freeing of the bottom outlet entrance. This peak lasts as long as material can be flushed from the opening. Observed concentration is directly related to the discharge and can be controlled to a certain degree. A minimum discharge is required, higher discharge normally leads to higher sediment concentration, determined by experience (Boillat et al. 1994, Hug et al. 2000). Flushing operations according to the following rules revealed efficient removal of sediments for all the encountered situations.

- Flushing operation must be conducted before the sediments reach a critical depth or before they may dry and consolidate
- Flushing should initiate with the minimum required discharge
- The downstream sediment concentration and dissolved oxygen content should be monitored all along the operation
- Initial high sediment concentration can be diluted adding clear water
- A progressive increase in the flushing flows allows to damp the initial peak

Executing this operation in concomitance with natural floods upstream and downstream is favorable in every point of view. The needed water from inside the reservoir is "fresh" as being transported to the bottom by turbidity currents. It has a naturally high content of dissolved oxygen and its release will allow flushing some additional sediments coming from the upstream part of the reservoir or directly from the watershed. As the sediments are already diluted in the reservoir by the turbidity current, the released sediment concentration are generally lower than during natural floods without the presence of a dam (monitored using an upstream measurement station).

The eroded volume of the sediments can be defined by comparison of the local geometry of the deposits, before and after the flushing operations. This volume appears to be directly related to the flushing discharge.

Adding clear water either from an intermediate controlled outlet or from other sources can securely dilute the overall released water. Other sources are water intakes in nearby valleys or powerhouse release. The main goal is to reproduce conditions as natural as possible (discharge, concentration and dissolved oxygen), particularly in comparison with natural flood events.

The problem of bed load cannot be solved by the above stated method, but normally a new equilibrium will be obtained downstream (as observed during industrial gravel removal in rivers, which reduces significantly the availability of bed load). Possible artificial adding of bed load directly in the downstream reach during flushing may be considered, the material coming either from the delta in the reservoir, from dumps during construction (these should not be deposited in the reservoir but downstream of the dam) or other sources.

CONCLUSIONS

In order to optimize flushing procedures of artificial reservoirs created by dams, sediment transport processes and characteristics of the deposits were studied. To prevent damages to the ecosystem downstream of the reservoir, particular attention was paid on the sediment flushing process.

Turbidity current flow in a laboratory flume as well as field measurements during two summer seasons at the Luzzone reservoir in the Swiss Alps were used to validate a 3D numerical model. User-defined erosion and deposition modules that take into account the interaction between the current and the existing sediment deposits were used to simulate the balance between sediment deposition and erosion in the model.

The results of the computer modeling and field observations showed that turbidity currents caused by a large flood could entrain a substantial amount of bed sediment and transport this sediment within the current to a zone of deposition near the dam.

The numerical model can be used as a strategic evaluation tool for reservoir management. In the future the model will be applied to analyze various technical solutions to prevent sedimentation in the most vulnerable parts of the reservoir, the bottom outlet and the water intake. Based on this simulation, the optimal timing of the bottom outlet operation can also be determined to pass a more or less important part of the fine sediment yield beyond the dam during floods.

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