SEDIMENT MANAGEMENT EXAMPLES IN SWISS ALPINE RESERVOIRS

Jean-Louis BOILLAT, Jérôme DUBOIS, Giovanni DE CESARE, Eric BOLLAERT
Laboratory of Hydraulic Constructions, Swiss Federal Institute of Technology Lausanne, Switzerland

SUMMARY

Management of sediment deposits in Alpine reservoirs cannot be apprehended according to a classical approach in a generalized manner. Every situation has to be analyzed separately and the solutions designed properly. The presented examples illustrate well the diversity of encountered situations and the adopted methods to solve the sedimentation problems.

The **Gebidem** dam is situated in the watershed of the Massa River, with a surface of around 200 km^2, of which 65% are covered by glacier. The Massa River can be characterized by a glacial hydrologic regime marked by important discharges during the summer period. The Gebidem reservoir intercepts annually around 400 to 600'000 m^3 of solid material. These sediments, comprised mainly by sand and gravel, are being brought into the reservoir during the summer. Their evacuation is obtained by an annual flushing operated at complete drawdown after a rapid emptying of the basin. The accumulated material can though be removed from the reservoir within 3 to 4 days, in which the flushing flume has the tendency to fill up with sediments and to overflow laterally. Physical model tests carried out in 1994 in the Laboratory of Hydraulic Constructions of the EPFL have concluded with the recommendation to introduce an additional dilution discharge at the entrance of the flume in order to reduce the sediment concentration.

Commissioned in 1958 and heightened in 1991 by 13.5 m to a maximum height of 250.5 m, **Mauvoisin** is the second highest arch dam in the world. Due to the actual sediment level, the risk exists, at low reservoir levels, that water with high sediment concentration enters through the intake into the pressure tunnel and therefore damages the turbines at the hydroelectric power plant. In order to prevent these problems, and to ensure the safe operation in the next fifty years, it was decided to study the construction of a new water intake equipped with a flushing gallery, as well as a new bottom outlet, located above the existing ones. Proposed solutions were investigated by model tests to check their behavior and define the operating rules. The efficiency of the flushing process and the potential risk of damages to the fishes and the flora in the Drance River downstream of the dam have been examined in relation with the sediment concentration of the flushed discharge.

The lake of **Rossinière** was created in 1972 by the construction of a dam for the supply of the Montbovon power plant. This reservoir is actually characterized by preoccupying sedimentation problems. The dead volume is nearly full and sediment deposits are clearly visible in the upstream part of the lake. In order to re-establish the hydraulic and ecological functions, a set of complementary solutions have been imagined in order to generate a long term solution. Considering hydraulic, economical and environmental aspects, the final proposition consists of three interventions: a) creation of a sediment dumping volume in the lake, by means of extraction of ancient bed material; b) realization of an artificial settling reservoir by means of the construction of a mobile dam in the gorges, upstream of Rossinière; e) modification of the outlet operation processes of the surface and bottom gates of the Rossinière spillway in order to provide the transit of turbidity currents during floods.

INTRODUCTION

Management of sediment deposits in Alpine reservoirs cannot be apprehended according to a classical approach in a generalized manner. Although legal bases exist in Switzerland, the application of the main concepts and the respect of the related constraints are generally assigned to the cantonal authority. In this context, each case has to be analyzed individually when considering safety, environmental and economical criteria. Every situation has to be studied separately and the solutions designed properly.

Three examples are presented here to illustrate the diversity of encountered situations and the adopted methods to solve the sedimentation problems. The Gebidem and Mauvoisin reservoirs are located in the Alps, the one of Rossinière in the prealpine region (Figure 1).

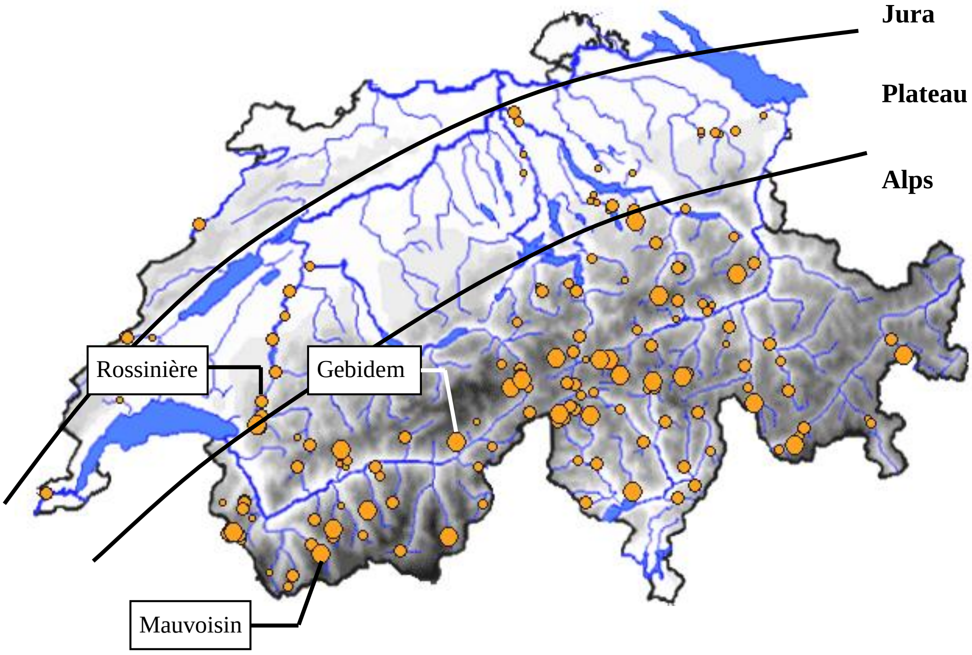


Figure 1: Location of Swiss dams (○)

THE GEBIDEM ANNUAL FLUSHING OPERATION

Framework

The Gebidem dam is situated in the watershed of the Massa River in Canto Wallis. With a surface of around 200 km^2, the catchment area is are covered by glacier for 65%. The Gebidem reservoir intercepts annually around 400 to 600'000 m^3 of solid material. These sediments, constituted almost exclusively of sand and gravel, are brought during the summer and their evacuation is obtained by annual flushing operated at complete drawdown after a rapid emptying of the basin (figure 2). The accumulated material can though be removed from the reservoir over 3 to 4 days. Between the reservoir and the river Rhone, the flushed sediments pass the narrow canyon of the Massa river and then through the 700 meter-long flushing channel (Figure 3 above). The actual retirement of the Aletsch Glacier leads to a progressive increase of the volume of sediments flushed annually. Consequently, a trend for silting in the channel was observed during the last decade.

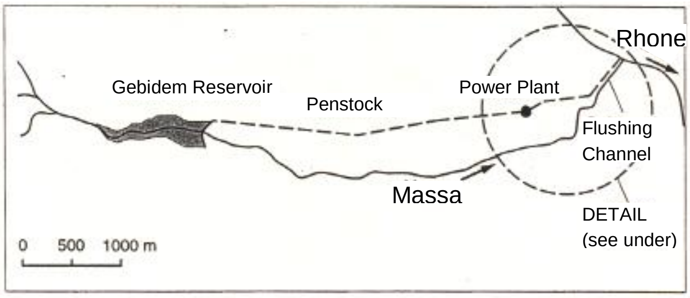
During emptying and clearing operations of the reservoirs, the company in charge with the exploitation has the responsibility to pay attention, as far as possible, not to damage fauna and flora of the downstream river. According to the cantonal guidelines, a maximum sediment concentration of 10 ml/l has to be respected. When applying this rule, 40 mio. m^3 water wuold be necessary to evacuate 400'000 m^3 of sediments. This water volume represents 10-16 % of the annual contribution. The actual flushing operations at Gebidem present sediment concentrations 4 to 6 time higher than the required value. Such a condition is admitted in this particular case, because the rocky canyon and the concrete channel downstream of the dam don't possess any particular natural life.

In order to improve knowledge on input and output of sediments in the channel of Gebidem, physical and numerical modeling were performed in 1994 in the Laboratory of Hydraulic Constructions of the Swiss Federal Institute of Technology (Boillat et al. 1996).

Figure 2: Flushing operation at Gebidem
left) Downstream part of the bottom outlet; right) Natural transport process in the reservoir

Physical Modelling

The physical model, at the scale of 1:15 reproduces part of the Massa gorge and the first section of the flushing channel over a distance of about 200 m (Figure 3 under). The tests undertaken can be classified in two categories, depending whether they concern the sedimentation stage or the erosion stage in the channel.



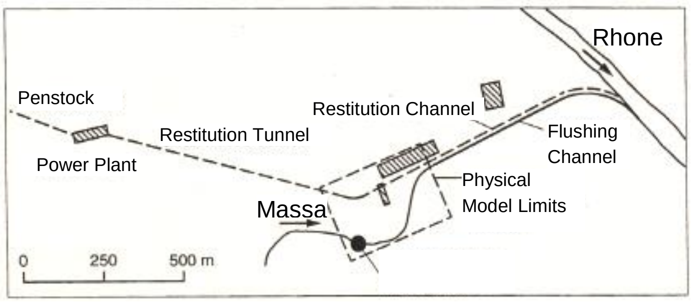


Figure 3: The hydroelectric scheme of Gebidem.
Upper figure) Situation. Lower figure) Downstream part with the limits reproduced on the physical model

Sedimentation Tests

The sedimentation tests formed the central part of the study. They brought into light the mechanisms of the alluvial deposits in the flushing channel of the Massa River and allowed to appreciate the performances of various alternatives of the channel design.

The tests, undertaken at constant discharge, show that to a given concentration corresponds an equilibrium slope, almost identical for all variants tested. In fact, in the particular flushing channel configuration of the Massa river, two equilibrium slopes develop: the first one at the first curve (the width ranging between 7 and 10m) and the second one in the remainder of the channel (the width being constant B = 10m). Figure 4, which presents both these equilibrium slopes measured for various tests, illustrates well this relationship slope–concentration and the absence of influence of layout alternatives. This observation has led to pursue the study on the erosion mechanisms, which influence the concentration in the flushing channel of the Massa River.

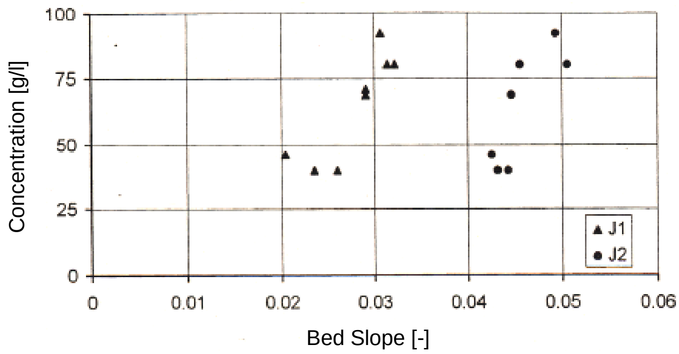


Figure 4: Relation between sediment concentration and equilibrium slope
J2: slope in the first curve; J1 slope in the downstream part of the channel

Erosion Tests

The objectives of the erosion tests were to describe qualitatively and quantitatively the sediment entrainment mechanism during flushing in the Gebidem reservoir. The flushing channel model of the Massa River was used to simulate what happens during flushing. These tests do not have the ambition of determining precisely the evolution of the solid discharge during the operation, but they allow comparing the concentration values for various flushing rates. The Massa River channel model was filled up uniformly with 20cm of sand over its whole length. Various water discharges were introduced upstream with no new sediment supply. With the help of an Imhof cone, the concentration was measured downstream from the model at regular time intervals (Figure 5).

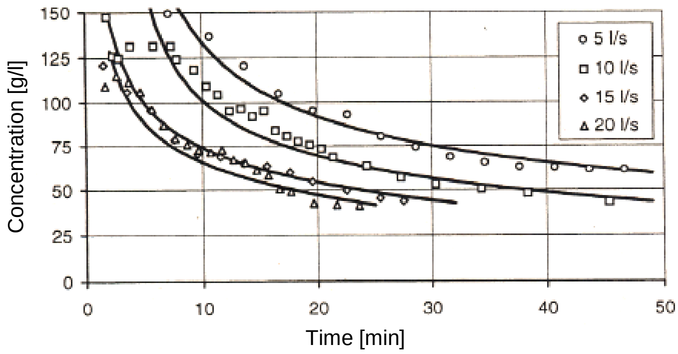


Figure 5: Time evolution of the sediment concentration at the model outlet

These results raise the following remarks:

- the concentration decreases more rapidly for large discharges rather than for small ones;
- the concentration evolution according to time is roughly the same for all discharges. It seems that there is a physical limit to the rate of decrease of the concentration, which is independent of the discharge.

It is useful to point out that at a given time, the volume of sediments which has transited as well as the longitudinal profile of the channel are not similar for the various discharges. This observation allows to explain to a great extent the difference of concentration between the tests at a given time. This last remark motivates the representation of Figure 6 which establishes the link between the concentration and the volume of transiting sediments, this for the five discharges studied.

In this manner, the difference between the curves is less distinctly marked than on Figure 5. This allows to say that for the same volume of sediments transported, therefore approximately for the same longitudinal profile of deposits, corresponds an identical concentration, whatever the discharge rate.

The notion "A sediment concentration leads to a bottom slope" could be observed, not only during the sedimentation tests, but also during erosion tests.

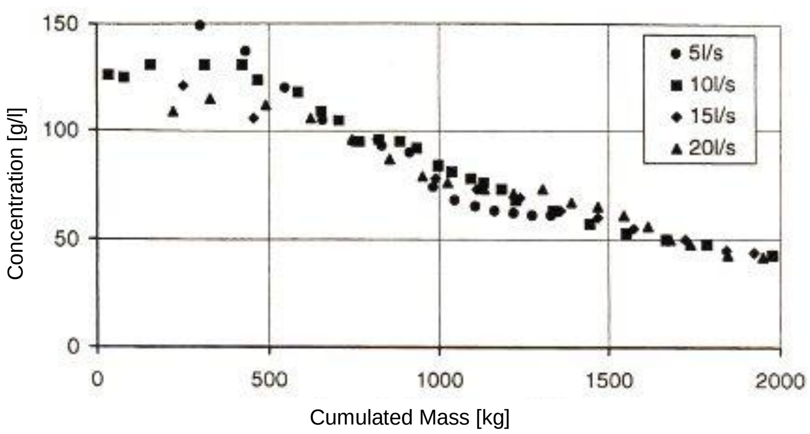


Figure 6: Evolution of the sediment concentration at the model outlet in function of the transported volume

<u>Numerical Modelling</u>

In order to evaluate the influence of the flushing discharge on the sediment transport from the reservoir down to the Rhone River, a non-steady numerical model has been applied. The main obtained results can be summarized as follows:

- the narrow canyon of the Massa River causes an important reduction of the sediment discharge issued from the bottom outlet;
- the maximal depth of sediments in the flushing channel is independent of the flushing discharge, it is all the more quickly attained as the discharge is important;
- the contribution of additional clear water at the entrance of the flushing channel will allow to reduce the maximal depth of the sediments.

The last effect is presented in Figure 7 under a non-dimensional form, where h^*_{20} is the maximal depth of sediments attained in the channel with a water discharge of 20 m^3/s and t^*_{20} the required time to reach it.

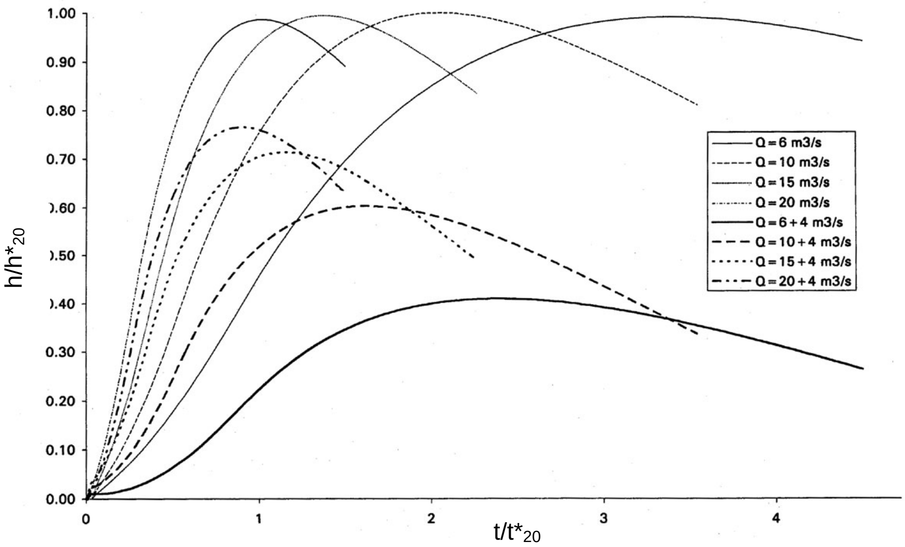


Figure 7: Non-dimensional time evolution of the sediment depth h in the flushing channel with and without an additional clear water discharge of 4 m^3/s

These studies concluded with the recommendation to introduce an additional dilution discharge at the entrance of the flume in order to reduce the sediment concentration (axis notation, cf. text).

THE NEW WATER INTAKE OF MAUVOISIN

Context

The Mauvoisin dam is located in the Val de Bagnes in region Valais in the Swiss Alps. Commissioned in 1958 and heightened in 1991 by 13.5 m to a maximum height of 250.5 m, Mauvoisin is the second highest arch dam in the world. The total maximum power production of the scheme is 550 MW, with a lake volume of 204 mio. m^3. During the 40 years of operation, the total amount of sediments accumulated in the basin is about 10 million m^3.

In 1985 the lake was emptied for the first time. Observation of sediment deposition around the intake structure resulted in raising the minimum water level during power generation from 1800 to 1810 m a.s.l. In 1995, the reservoir level was lowered to 1803 m a.s.l. It was noted that significant amounts of sediment enter the intake when the lake stage drops below 1810 m a.s.l. (Schleiss et al. 1996). The level of the deposits has now reached the water intake and bottom outlet openings. Under these conditions, there is a risk that, at low reservoir levels, water with high sediment concentration enters the intake to the penstock and subsequently damages the turbines at the hydroelectric power plant.

In order to prevent these problems, and to ensure safe operation during the next fifty years, it was decided to study the construction of a new water intake equipped with a flushing gallery, and a new bottom outlet, located above the existing ones. The new water intake and bottom outlet are clearly not designed to solve the sedimentation problem itself. The goal is to maintain an operational scheme by avoiding high sediment concentrations through the turbines. As the sediment level in the lake will nevertheless continue to rise, it is planed to build a second, and later a third, extension of the intake structure above the previous ones, when the alluviums reach the critical level (Figure. 8 left). The successive elements are connected through openings built in the top of the intake. The temporary metal sheets, which cover the opening, will be removed during the heightening operation.

The proposed solutions, designed by EWE-NOK Consulting Engineers Ltd., were investigated by model tests to check their behavior and define the operating rules. Only the new water intake project is presented hereunder, for which the design discharge of 34.5 m^3 /s is going to be divided through two openings with a surface area of 25 m^2 each, oriented 60° from each other (Figure 8 right). This design increases the inflow area at the intake yielding to a mean flow velocity of 0.7 m/s at the entrance section.

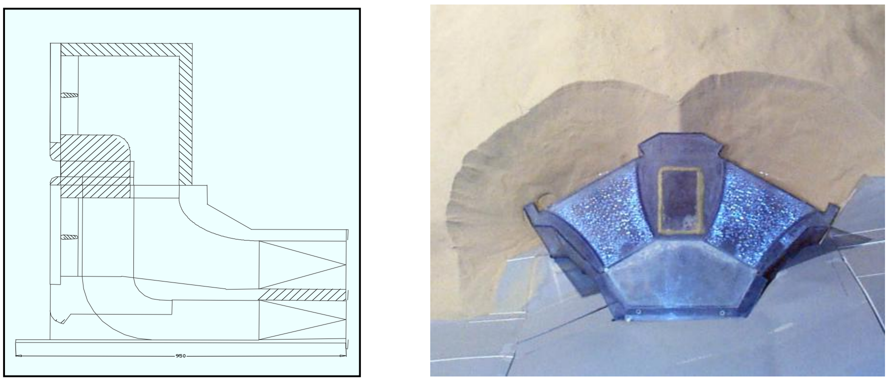


Figure 8: The new water intake of Mauvoisin.
left: Vertical section with the first extension; right: Top View of the model

Flushing Tests

The model tests for the new water intake were conducted in the Laboratory of Hydraulic Constructions of the Swiss Federal Institute of Technology in Lausanne (Hug et al. 2000) with three main objectives: First, was to optimize the new structures for approaching flow conditions and vortex formation. Second, was to evaluate the sustainability of the concept of further heightening of the structure. The third objective was to investigate the flushing behavior and to define operation rules. The last point will be discussed here.

Flushing operations were conducted with sediments at the sill of the water intake, for discharges of 5, 10 and 20 m3/s through the outlet. Flushing operations revealed efficient removal of sediments for all the tested situations. The eroded bed form looks like part of a cone whose vertical axis is centered on the outlet (Figure 10) and whose slope is equal to the angle of repose of the material (Boillat and Delley 1992, Sinniger et al. 1999 and 2000). The eroded volume of the sediments could 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 (Figure 9).

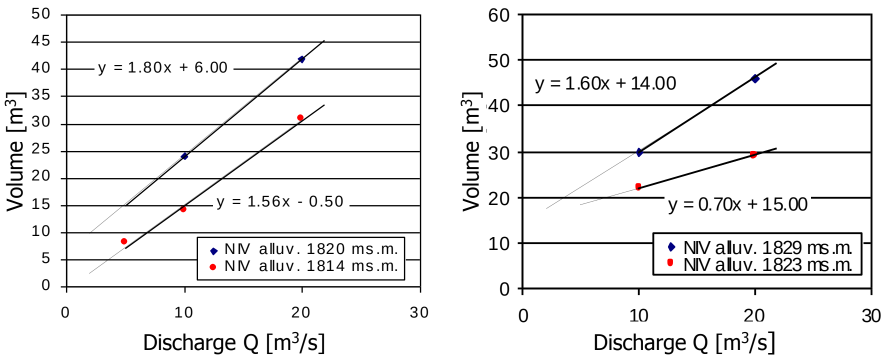


Figure 9: Relation between flushing discharge and volume of eroded sediments

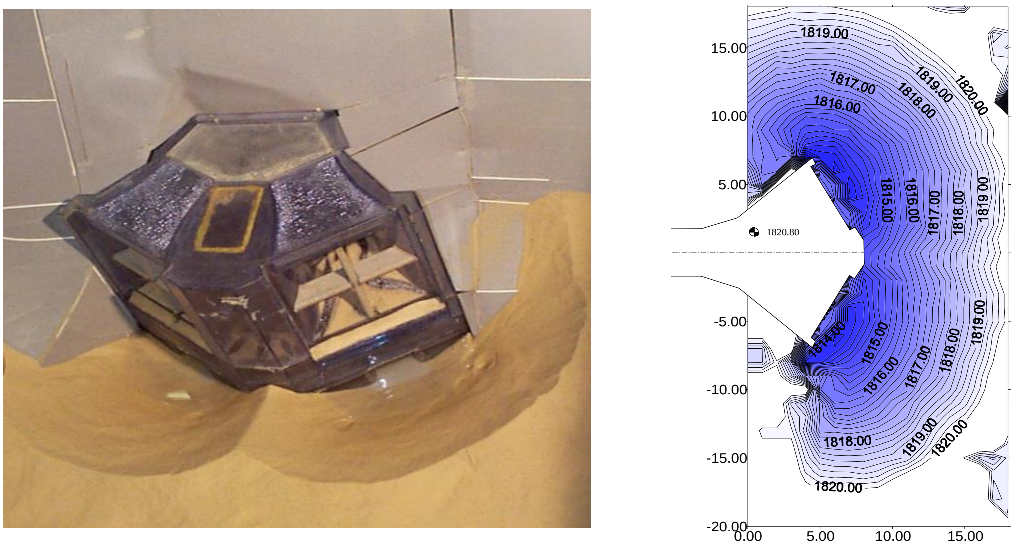


Figure 10: Erosion cone in front of the intake with an initial sediment level at 1820 m a.s.l.

The maximum sediment concentration value appears at the beginning of the flushing operation. The equilibrium state of the cone is reached after approximately 30 minutes on prototype. After that time, the sediment concentration is approximately zero (Figure 11).

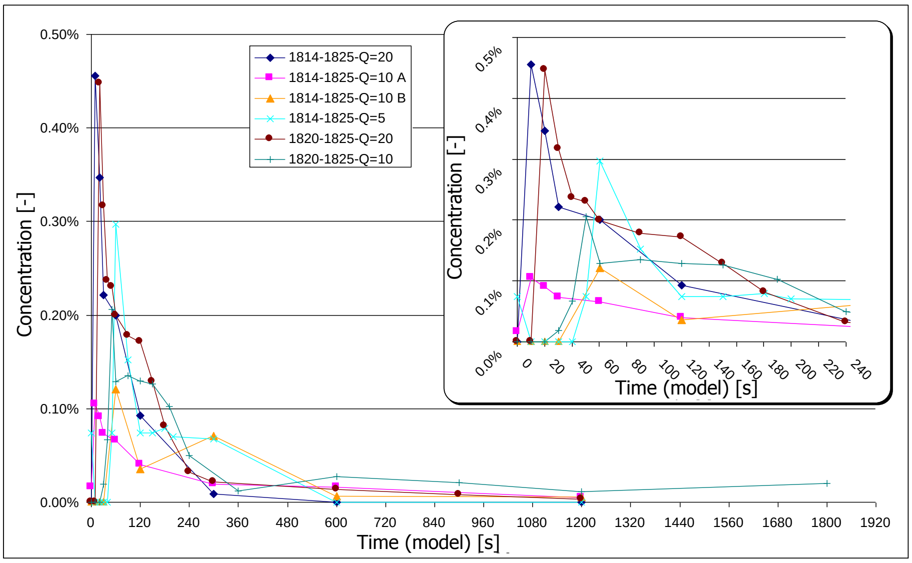


Figure 11: Evolution of the sediment concentration during 6 flushing tests

Flushing Procedure

Submitted to model tests, the sustainability concept based on further heightening of the structure was validated. To prevent damages to the ecosystem downstream of the reservoir, particular attention was paid on the sediment flushing process. The relationship between the flushing discharge and the volume of eroded sediments was established as well as the time evolution of the sediment concentration.

It is well known that high sediment concentrations during flushing operations may adversely impact downstream ecosystem. It can be noted here that the outflowing sediment concentrations should be monitored. A progressive increase in the flushing flows is thus expected to reduce the peak sediment concentration, and is recommended to mitigate any problem from high sediment concentrations.

Based on these results, a flushing procedure was defined, which accommodates the needs of flushing and limits the peak sediment concentrations.

A NEW CONCEPT FOR THE LAKE OF ROSSINIERE

Preamble

The lake of Rossinière was created in 1972 by the construction of a dam for the supply of the Montbovon power plant and has a volume of 2.9 millions m^3. The mean annual sediment transport was estimated at 10'000 m^3 of bed load and several 10'000 m^3 of suspended material. The engineers predicted a mean annual settling volume in the lake of 20'000 m^3, representing about 1.5 % of the total dead volume of 1.2 millions m^3. Flushing operations in order to evacuate settled sediments were planned every other year. These operations should normally be performed at free water surface conditions. The two realized flushing operations, the first one in 1975 and the other one in 1977, caused major problems particularly in relation with fish survival. Later on, bathymetric measurements indicated a settling rate nearly twice the predicted amount. For this reason, it was decided in 1994 to analyze the sediment transport processes up-stream of the lake in order to find a long-term solution to the problem. Presently, the dead volume of the lake is nearly full and, in the upstream part and along the edges, deposits are clearly visible (Figure 12).

Figure 12: Upstream view of the lake of Rossinière

Exploitation statistics of gravel quarries on the river upstream allowed an estimation of the mean annual bed load. The evaluation of sediments transported by suspension was carried out by bathymetric measurements in the lake. Turbidity data at the intake of the Montbovon power plant procure the volume of particles annually transiting the power plant. These investigations reveal that nearly 90 % of the sediment transport takes place by suspension ($d < 0.062$ mm). The grain size distribution shows that only fine-grained particles are depositing. The coarse material is principally captured at the “Chaudanne” site, 2 km upstream of the lake of Rossinière. The search for possible interventions considers hydraulic, economical and environmental aspects in order to generate a long-term solution. The final proposal consists of three complementary parts (Figure 13):

Sediment Dumping Volume In The Lake Of Rossinière

This intervention consists of the creation of a sediment dumping volume by excavation inside the lake of Rossinière. At this place, several boring investigations revealed the existence of a significant deposit of alluvial material, built up before the construction of the Rossinière dam and actually covered by a 3 to 6 m thick clay and silt layer, built up since 1972. This alluvial material, which reaches a thickness of almost 50 m, could be commercially exploited. This led to suggest the creation of an internal volume by excavation, allowing an appropriate storage of the commercially non-interesting fine-grained sediments situated above it. In function of bathymetric data and appropriate extraction techniques, an exploitation of 455'000 m^3 of alluvial material will enable the storage of 295'000 m^3 of fine sediment in the dead volume of the lake.

The execution will take about 4 years and will require temporary deposition zones on the right bank of the lake. Along the left bank, rehabilitation by sediment removal will be executed in order to restore the alluvial shore and access for fishers. The dredging includes the creation of a bottom channel in order to facilitate the transfer of turbidity currents during floods. Execution time depends on upstream interventions. This rehabilitation is characterized by economical advantages. Furthermore, no waste material disposal is required. However, this only solves the problem on a short-term. It becomes evident that a concept for the long term needs upstream interventions in order to stop the inflow of clay and silt particles.

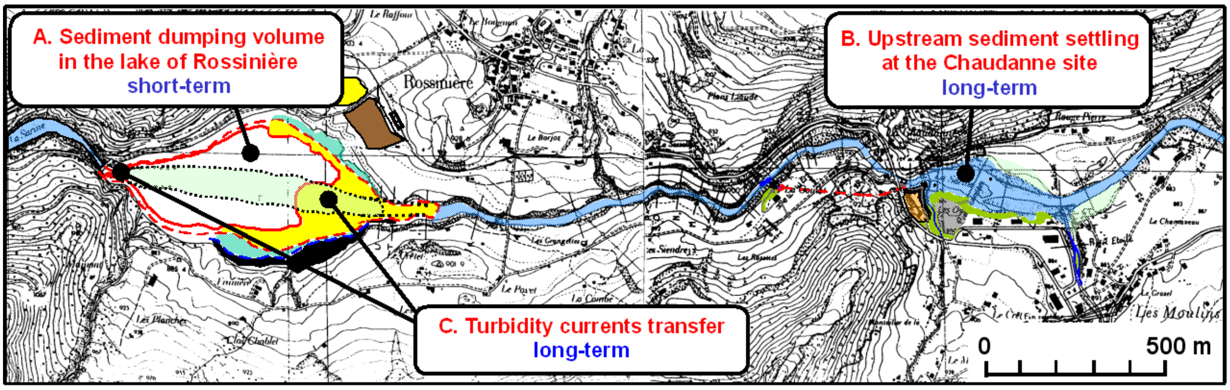


Figure 13: Three complementary parts of the finally proposed solution

Artificial Settling Reservoir At The Chaudanne Site

The second proposed intervention is located at the "Chaudanne" site, and aims the settling of fine-grained particles (clay, silt) actually transiting and depositing in the lake of Rossinière. This site already presents deposit characteristics due to the natural formation of a lake during floods. In order to increase the settling efficiency, the creation of an artificial sediment trap has been considered by construction of a gated dam in narrow gorges. This will produce a slowing-down of flow velocity and increase sedimentation. With a mean annual discharge of 13 m^3/s and a 1000-year peak value of 540 m^3/s, the dam structure has to be equipped with a large surface gate and two bottom radial gates, allowing the transit of high discharges without upstream submersion damage.

The construction of the gated dam needs a temporary diversion of the river. As a result of the particular dimensions of the gorges zone (max. height of 30 m, local width reaching 2.5 m), the excavation of a diversion tunnel in the rocks is necessary. Once the construction of the dam is finished, this tunnel offers the opportunity to direct water to a 5.2 MW small hydroelectric power plant. The downstream exit of the tunnel was chosen 400m downstream of the gorges, by considering the head difference, the influence of the lake of Rossinière on the backwater curve of the river and the presence of a good quality rock zone along the left bank. The mean annual energy production will be 13 GWh, generating a partial economical compensation to the project financing. Furthermore, the existence of the dam will significantly increase the flood safety in the upstream zone.

Transit Of Turbidity Currents During Floods

The third complementary measure is to increase the efficiency of the global concept. It consists in a modification of the bottom outlet operating procedure of the Rossinière dam on the one hand, and the application of a turbidity current transfer methodology on the other hand. At appropriate times, flushing of the sediment cone deposited near the bottom gates of the Rossinière dam will be done. The combined release of high sediment-laden bottom water and clean overflow allows controlling the downstream sediment concentration, in respect to environmental constraints. This operation could be done several times a year, during smaller floods. Furthermore excavation works on the whole length of the lake of Rossinière will create a bottom channel.

During floods, when the artificial basin at the Chaudanne site is loosing a part of his settling efficiency, the transiting sediment-laden flow enters the lake of Rossinière as turbidity current. This sediment-water mix will plunge due to gravity forces and thus follow the bottom channel in the lake to finally reach the Rossinière dam where it can be evacuated in a controlled manner.

Final Comments

The first proposal allows only a short-term rehabilitation of the lake of Rossinière, while the other two are part of a concept designed for a long-term solution. The complementary contribution of these three interventions would be able to reduce by 75–85 % the future sedimentation of the lake of Rossinière. During the different project stages, two problems have been investigated in detail:

- The settling efficiency of the artificial created reservoir, calculated by 2D finite-element modeling (Figure 14). This simulation was useful for design of interventions leading to maximization of the settling efficiency and to the project's environmental impact and its compensation measures.
- The numeric modeling of compensating submersion zones allowed performing a relationship between physical parameters (flow depth & velocity vectors), submersion frequency and future vegetation in order to evaluate the dynamic character of these zones

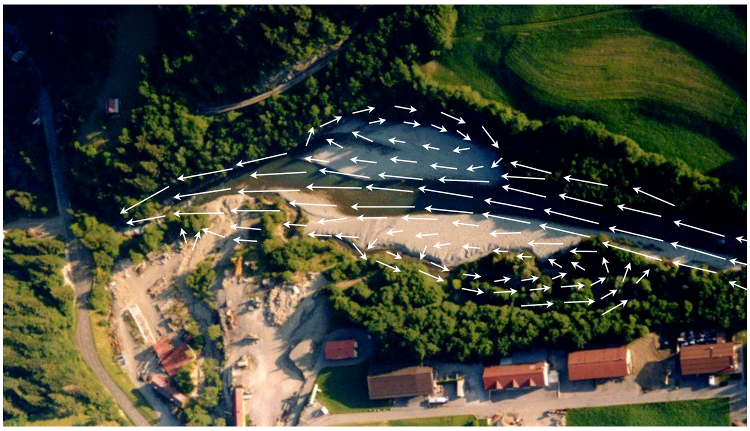


Figure 14: 2D simulated velocity field at the Chaudanne site (235 m^3/s)

Actually, a multidisciplinary workgroup has been constituted in order to evaluate and to improve the concept in order to find an overall agreement in respect to environmental, economical and technical constraints. Sustainable development is engaged.

CONCLUSIONS

The accumulation of sediments in artificial reservoirs is a real problem which was seldom seriouly considered during the conception and realization stages of the swiss dams. This lack has presently to be filled, having recourse to sustainable concepts.

For which concerns reservoirs sediments management, the three examples presented here above put in evidence the necessity to consider each case separately. The solutions are thus to be adapted to the local conditions, taking into account all the environmental, technical and economical parameters.

In the case of the Gebidem reservoir, adding clear water during flushing will not only reduce the sedimentation in the flushing channel but also dilute the sediment concentration at the outlet in the Rhone River. At the Mauvoisin reservoir, the owner solves temporarily the sedimentation problem with new bottom outlet and water intake structures, which are foreseen to be stepwise heightened. Regarding the lake of Rossinière, the solution consists in a general concept taking into account upstream sediment retention, dredging of the reservoir and operation rules favoring sediment transit during floods.

REFERENCES

Boillat, J.-L., Delley, P. (1992). "Transformation de la prise d'eau de Malvaglia; Etude sur modèle et réalisation", Wasser, Energie, Luft – Eau, énergie, air, 84. Jahrgang, Heft 7/8, Baden, Schweiz, pp. 145-160.

Boillat, J.-L., Dubois, J. Lazaro, P. (1996). "Eintrag und Austrag von Feststoffen im Spülkanal von Gebidem. Modellversuche und numerische Simulation", Verlandung von Stauseen und Stau-haltungen, Sedimentprobleme in Leitungen und Kanälen, 28./29. März 1996, ETH Zürich, Mitteilung Nr. 142,.der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), pp. 151-170.

Bollaert, E. and Boillat, J.-L. (1999). "Evaluation de la biodynamique d'une zone alluviale par simulation hydrodynamique", Génie biologique, Bulletin N°4, Zurich, Switzerland, pp. 20-25.

Hug Ch., Boillat J.-L., Lier P. (2000). "Hydraulic model tests for the new water intake of the Mauvoisin hydroelectric Scheme (Switzerland)", Proceedings of HYDRO 2000 - “Making Hydro more Competitive”, Session III: Sediment Management, 2-4 October 2000, Berne/Switzerland, pp. 161-170.

Schleiss A., Feuz B., Ämmer M, Zünd B. (1996): "Verlandungsprobleme im Stausee Mauvoisin. Ausmass, Auswirkungen und mögliche Massnahmen. Internationales Symposium", Verlandung von Stauseen und Stau-haltungen, Sedimentprobleme in Leitungen und Kanälen, 28./29. März 1996, ETH Zürich, Mitteilung Nr. 142,.der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), pp. 37-58.

Sinniger R. O., De Cesare G., Boillat J.-L. (1999). "Propriétés des alluvions récentes dans les retenues alpines", Wasser, Energie, Luft - Eau, Energie, Air // Jahrgang 89, Heft 9/10-1999, pp. 255-258.

Sinniger R. O., De Cesare G., Boillat J.-L. (2000). "Eigenschaften junger Sedimente in Speicherseen", Wasser, Energie, Luft - Eau, Energie, Air // Jahrgang 92, Heft 1/2-2000, pp. 9-12.