STATE OF THE ART OF SEDIMENT MANAGEMENT IN SWITZERLAND

Jean-Louis BOILLAT[1], Henri POUGATSCH[2]
[1]Laboratory of Hydraulic Constructions, Swiss Federal Institute of Technology Lausanne, Switzerland
[2]Federal Office for Water and Geology, Bienne, Switzerland

SUMMARY

The construction of a dam significantly modifies the flow conditions of natural streams inside and downstream of an artificial lake. One of the major consequences of this change is the progressive reduction of the hydraulic capacity in the alluvial beds, which have the tendency to congest. With the aim of keeping the evacuation potential of the natural hydraulic network for spillway operations during floods, the watercourses need to be maintained either by dredging or by regular flushing.

The surface erosion in the catchment area leads to reservoir sedimentation that cannot be tolerated without restrictions, because it will affect the safety of the dam and cause damage to the hydraulic structures, in particular to the turbines. In addition, the accumulation of alluvial deposits induces an unrelenting reduction of the storage capacity. In consequence the accumulated material has to be evacuated regularly. All classical methods such as flushing, dry or humid excavation, pumping, etc. can be applied to this effect.

These operations have to be carried out taking into account eventual consequences on the security of human life, possession, and on the natural environment. The accompanying measures need to attain the objective of reproducing conditions as natural as possible, particularly in comparison with flood events.

The legal bases and the resulting constraints are reviewed. Their application by the Cantonal Authorities is discussed in a general way.

INTRODUCTION

Most Swiss dams were built thirty to seventy years ago. Their dead storage, designed to accumulate the sediment yield, is in some cases completely filled. This leads to some problem concerning the exploitation or even affect the safe operation of the bottom outlet devices. A particular attention has to be paid to the reservoir sedimentation, because sixty percent of the Swiss electrical production is issued from hydro schemes.

If one classifies Switzerland's dams according to purpose, it will be seen that, among the 182 dams placed under the supervision of the Confederation (Figure.1), 172 are used for electricity production, mainly by storage power plants (Biederman 1985). Therefore, the water load usually follows a seasonal cycle, with filling in the summer and emptying in the winter. The highest water levels are reached in autumn or early winter, the lowest in April or May.

The retention of important volumes of water and sediment during floods contributes to the protection of the population and the land downstream of the dams. But the accumulation of sediments in the reservoir can affect parts of the construction or significantly reduce the capacity of water storage. One method for evacuating sediments from a reservoir is to flush them by opening the bottom outlet. This proceeding, even if neatly planned and prepared, can cause ecological damage to the downstream waterway. Alternative solutions have thus to be found in order to assure, on one side the safety and operational functioning of the dams, and on the other side an environmentally sustainable development.

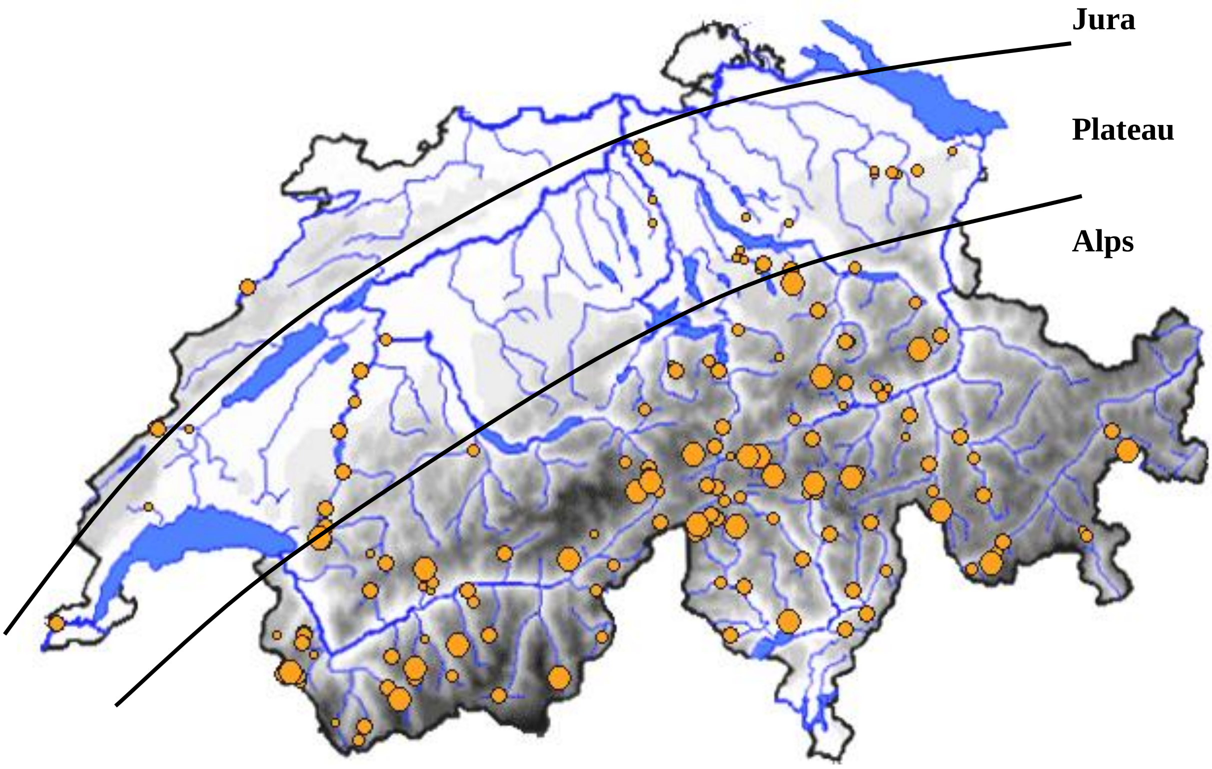

Figure 1: Location of Swiss dams (○)

LEGAL BASIS AND OPERATIONAL RULES

The Safety Concept

In Switzerland, the safety of dams is governed by the Federal Law regarding Supervision of Hydraulic Structures. It establishes on the one hand the Supervision of the Confederation (Art. 1), and on the other hand determines the aims and, therefore the duties of this supervision (Art. 3bis, par. 1) as follows:
"The Federal Council (Highest Executive Authority) will ensure that the necessary steps will be taken with existing and future storage installations to avoid, as far as possible, dangers and damage resulting from the existence of the installation, from insufficient maintenance or from the effects of war."

In an extraordinary event, that is, if the dam is found to exhibit an abnormal behavior or, if a new hazard emerges, the management of the installations must take the appropriate steps promptly; if necessary, the reservoir has to be drawn down and, in any case, the Supervising Authority has to be informed as soon as possible.

In order to be able to satisfy this requirement, the Federal Ordinance regarding the Safety of Storage Works impose that the reservoirs must be equipped with a bottom outlet of sufficient capacity (Art.4). The sluice gate has different complementary functions. First, it will be used to control the first filling operation of the reservoir. It will then be needed for preventive and emergency emptying. It must also be able to maintain the reservoir empty, when needed. It can also have to contribute to floods evacuation. Finally it will constitute the sluicing and flushing device for the sediments evacuation.

In a general way, the safety of dams is best provided when due consideration is given to the following tenets: Structural Safety, Monitoring, and Emergency Concept (Pougatsch et al. 1998), (Figure 2)

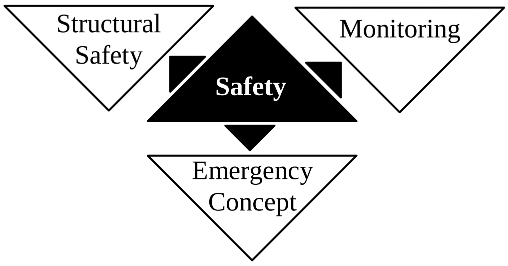

Figure 2: The Swiss safety concept

First of all, dams have to be correctly designed for all loading and operating conditions. However, a risk cannot be totally eliminated; it is therefore necessary to perform dedicated checks in order to detect at an early stage any kind of danger (e.g. a damage, a structural deficiency, a threat to safety). At least, the emergency concept will make it possible to manage any situation of danger. The water alarm system is part of the appropriate emergency preparations.

The Flushing Operation Rules

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. Such operations can only be carried out with the authorization of the Canton which statutes on the operation moment and modalities. Before delivering the flushing permission, the Authority will ensure itself that the sediments cannot be evacuated by an other mean, respectful of the environment and financially supportable. In the case of sluicing or flushing, in order to maintain the impact to biology as low as possible, the Authority will define in particular:

- the moment of flushing and the operating rules;
- the maximal concentration of the matter in suspension to be respected during the operation;
- if it will be necessary to rinse out the waterway in order to wash the fine material deposits.

All these conditions are mentioned in the Federal law regarding water protection (Art. 40) and in the related Ordinance (Art. 42).

The Federal law regarding Fishery is also to be respected for all what concerns technical interventions on rivers. The responsibility is once again attributed to the Canton.

The conditions put by the canton can differ from case to case, but they are generally related to following items:

- the safety of the dam is concerned;
- alternative technical, ecological and economical tolerable solutions will have the priority;
- sluicing and flushing operations must be conducted with the aim of limiting the interference on the river downstream; the season, the fauna and flora development cycles as well as the natural flow conditions have to be considered;
- Measurements of sediment concentration and oxygen content have to be done during the operation and documented.

EROSION AND SEDIMENT TRANSPORT PROCESSES

With the perspective to find the optimal way to manage the sediment flux through a scheme, it seems important to have an overview on the erosion and sediment transport processes. In a general way, sediment production, transport and silting can be summarized by the diagram presented on Figure 3. Surface erosion occurs in the watershed and the sediment particles are transported by the natural water network down to the reservoir where they will settle down, unless a protection mean divert them to the downstream reach of the river.

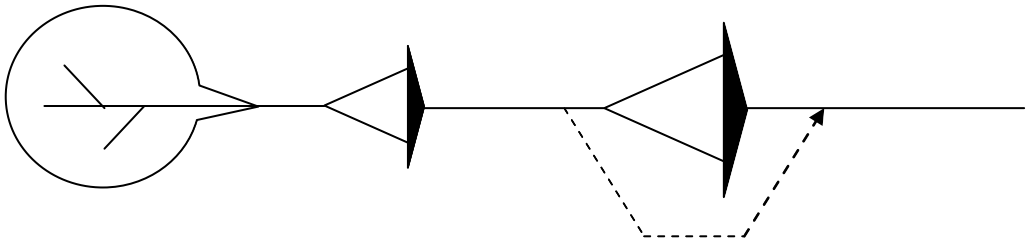

Figure 3: Erosion and sediment transport process diagram

Erosion On Watersheds

There are not many accurate data on the rates of reservoir sedimentation, but it is commonly accepted that about 1-2% of the worldwide reservoirs capacity is lost annually (Jacobsen 1999). Analysis of data from 14 reservoirs in Switzerland showed that this percentage is only about 0.2% in Alpine reservoirs (Oehy et al. 2000). The lower filling rates are results of geologic characteristics of these basins at high altitude.

Surface erosion is generally produced by wind or rain. The last is the main cause in alpine watersheds, where this complex process is influenced by many factors. The most important of them concern the erosivity of rainfall and the erodibility of the soil. Erosivity of rainfall is related to the intensity and the total amount of precipitation. The erodibility of a soil is influenced by its physical properties, like grain size distribution and organic matter content, and by the nature and density of cover as vegetation or large blocks of rock. Besides these main parameters, slope steepness is particularly important as it influences the transport capacity of run-off. This determines which quantity of the detached soil is to be transported down slope. In alpine regions the temperature must also be taken into account as frost contributes to rock degradation and a decreasing glacier may deliver large areas of very erosive soil, the moraines.

Based on collected data in 19 alpine watersheds, a statistical analysis was made (Beyer-Portner 1998) in order to establish a relation between the annual soil loss and several erosion parameters. Different combinations were tested when considering the physical reliability of the examined relations. From the remaining regressions, the one with the highest correlation coefficient is given by equation 1:

(1) $$V_A = 556.05 \cdot 10^{-9} \cdot H_{Summer}^{0.607} \cdot SE^{0.091} \cdot SV^{6.042} \cdot \Delta L_G^{0.154} - 267$$

where,

V_A [m^3 km^{-2} an^{-1}] : annual sediment yield per unit area

H_{Summer} [mm] : amount of rainfall during the Summer (June to September)

SE [%] : part of the watershed covered by soil of high erodibility

SV [%] : part of the catchment area without vegetal cover

ΔL_G [%] : annual variation of the glaciers' length in relation to their total length

The correlation of Equation 1 is equal to 0.75. Figure 5 shows that this model describes soil loss of Alpine watersheds with satisfying accuracy. For the cases with little erosion volumes, as Ferden, Les Toules, Rossinière and Solis, the soil loss is nevertheless largely over estimated.

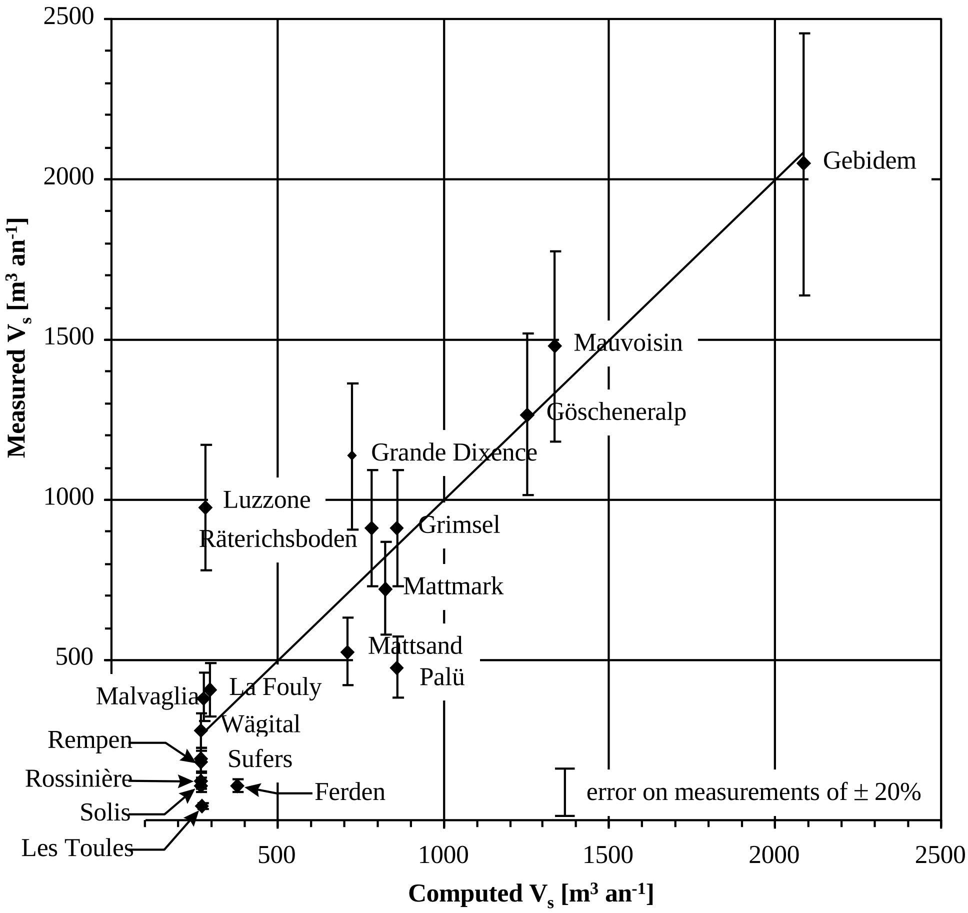

Figure 5: Comparison between measured and computed soil loss for 19 Alpine watersheds

Reservoir Sedimentation

Reservoir sedimentation results from sediment transport in the tributaries. Coarse material is transported on the river beds and feed the delta which forms at the entry in the lake. Fine material moves in suspension and increases the flow density. During floods, the sediment suspended concentration in the inflowing rivers is generally high enough to cause the flow to plunge in the reservoir as a so called density or turbidity current (De Cesare 1998) and (De Cesare and Schleiss 1999). This current follows the Talweg towards the deepest area, generally near the dam, where the sediments settle down (Figure 6).

In the Alpine reservoirs, the most important silted volume is generally due to turbidity currents and constituted of fine particles in the granulometric fraction of silts (Sinniger et al. 1999 and 2000). The poor vegetation in high altitude explains the low clay fraction and the non cohesive character of the deposited sediments. In some cases, the decreasing of glaciers tends to progressively increase the contribution in coarse sediments.

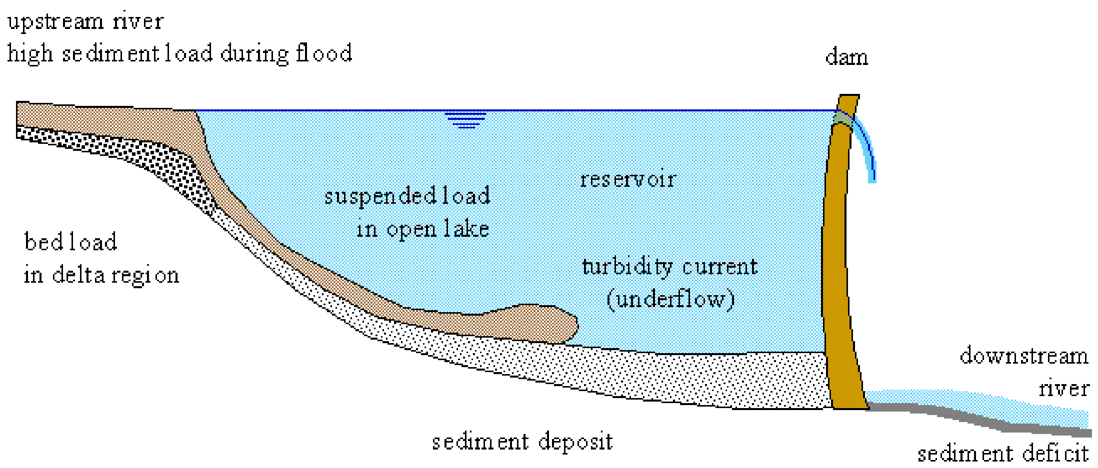

Figure 6: Schematic drawing of sediment transport in the upstream and downstream reaches, and by turbidity currents inside an artificial reservoir (De Cesare et al. 1998)

Downstream Effects

The presence of a reservoir on a waterway may cause a deficit in the sediment flux downstream. This effect can lead to a degradation of the river, generally due to erosion. Simultaneously, negative effects can be observed on the aquatic fauna and flora. These environmental considerations have to be taken into account when defining the minimal water supply in the downstream reach and further when operating sluicing or flushing of sediments.

Furthermore, it could be observed in several cases that the normal discharge reduction due to the reservoir incites the riverside residents and the nature itself to reduce the free section of the downstream reach. This will be the origin of damage due to floods, when the spillway is functioning.

CONSEQUENCES OF RESERVOIR SEDIMENTATION

Reduction Of The Live Storage

The interception in reservoirs of the bed load and of the most part of suspended load lead to the reduction of the live storage capacity. This will have a negative effect not only from an economical point of view, by raison of a reduction in the energy production, but also when considering the flood protection, due to the loss of the flood attenuation capacity.

Silting up of intake

The increase of the sediment level due to the silting up of the reservoir will progressively attain the sill of the water intake headwork. The entrainment of sediments through the penstock down to the turbines will provide important abrasion. This will necessitate high costly upgrading works and production interruption. If no measure will be taken in order to avoid the sedimentation increase, the choking of the intake is to be feared.

Choking Of Bottom Outlet

As mentioned above, the bottom outlet is the most important safety device of the reservoir. Its choking, resulting from sedimentation, can simply not be tolerated. Such cases have already occurred in the past as for example at the Rempen dam in Canton Schwytz. In this specific case, the bottom outlet was closed by sediments, due to lack of regular sluicing operations. A comparable situation occurred at the Luzzone dam in Canton Tessin but, in that case, the sediment plug formed behind the sluice gate blowed up from itself, after repeated opening operations.

REMEDIES INVENTORY

Upstream Interventions

Watershed Erosion Prevention

A major cause of increase in reservoir sedimentation is related to the destruction of the vegetal cover on the watershed. This can have its origin in human activities like ski practice or in natural events like wind storm causing deforestation. This erosion leads to increasing soil instability and runoff. The sedimentation problems encountered in reservoirs can thus be damped by reforestation and vegetation seeding during spring.

An other important source of sediments supply is related to landslides. Such instabilities can be controlled by different ways including anchoring systems, soil drainage and stepped fittings of steep slopes.

Upstream Interception

If the reservoir is supplied by water diverted from neighboring catchments, careful attention will be needed to exclude the sediment content from the intake. This will involve settling of coarse grain sizes in the impoundment caused by a diversion dam or weir and subsequent flushing through sluices, and by providing settling basins to remove the fine particles, for return to the parent river. Such an example is presented in figure 7.

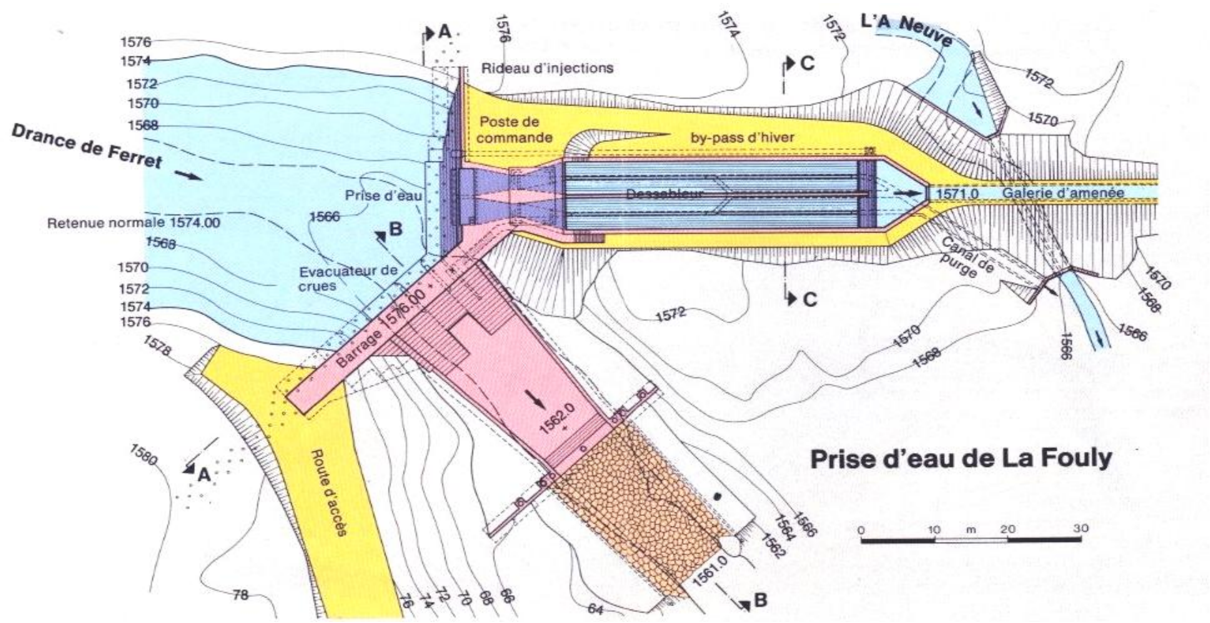

Figure 7: Plan overview of the water intake of La Fouly, part of the hydroelectric scheme of Emosson

Bypass During Floods

An efficient solution to protect reservoirs against sedimentation is to build a bypass gallery in order to divert the bed load during floods. The aim is to drive the coarse material, during floods only, with a minimum of water content. In normal flow conditions, the gallery will be closed in order to catch all the water in the reservoir. The effect of the bypass gallery will be to reduce significantly the delta formation in the upper part of the reservoir.

In Switzerland, 5 reservoirs are equipped with a bypass gallery. It concerns little detention volumes of rather daily or weekly compensation basins, between 200'000 and 4 millions m^3. All are realized on rivers with relatively steep slopes, their main characteristics are summarized in Table 1 (Vischer 1997).

For the design of the gallery, particular attention must be focused on the sediment transport capacity, which has to be higher than the initial share, to the resistance of the floor against abrasion and to the outlet position, over the downstream river bed in order to avoid the obstruction by sediment deposits. The opportunity to take into account the discharge capacity of the gallery for flood evacuation is also interesting.

Table 1: Main characteristics of the five Swiss sediment bypass galleries (Vischer 1997)

Reservoir name (River)	Commissioning Year (Scheme)	Total length [m] (acceleration reach [m])	Slope of the flat reach [%] (Max. slope [%])	Cross section surface [m²] (Form)	Capacity [m³/s] (Regime)	Natural catchment area [km²]
Pfaffensprung (Reuss)	1992 (Amsteg)	282 (25)	3 (35)	21 (horseshoe)	220 (Free surface)	390
Egschi (Rabiusa)	1949 (Rabiusa Realta)	360 (20)	2.6 (21)	6.2 (circular)	~ 50 (free surface) 70 (pressurized)	108
Runcahez (Somvixer Rhein)	1962 (Vorderrhein)	572 (85)	1.4 (25)	15.2 (arched)	110 (free surface) 190 (pressurized)	50
Palagnedra (Melezza)	1978 (Maggia)	1760 (50)	2 (30)	30.2 (circular)	220 (free surface) 250 (pressurized)	140
Rempen (Wägitaler Aa)	1986 (Wägital)	450 (22)	4 (25)	9.2 (horseshoe)	80 (free surface) 100 (pressurized)	25

Reservoir sedimentation management

Sluicing And Flushing

The construction of low level bottom outlet can also be valuable for flushing sediments provided that the intake does not become blocked up (Boillat and De Cesare 1994). An important difference has to be made between sluicing, meaning the outflowing with totally or partially filled reservoirs, and flushing, when considering the sediment evacuation at free surface flow.

Sluicing has to be considered as a control and safety operation intended to insure the gate operation. In such a case, the eroded bed formed in the reservoir looks like a part of a cone, whose vertical axis is centered on the outlet (Boillat and Delley 1992). High sediment concentration in the outflow can be reduced when progressively increasing the sluicing discharge (Hug et al. 2000).

Flushing is a generally complex operation for which optimal conditions are required, in particular concerning:

- the natural flow conditions in the downstream river,
- the sediment transport capacity all along the downstream tributary,
- the seasonal life cycle conditions of the fauna in the downstream river,
- the bio-chemical properties of the sediments.

Based on the analysis of the situation, the best procedure has to be established, including real time control measurements, with the possibility of modifying the forecasted instructions and even of interrupting the flushing operation if the nature is threatened.

Dry Excavation And Dredging

When the required conditions are not fulfilled for the flushing to be allowed, the removal of the sediments can be achieved mechanically with the assistance of bulldozers (Figure 8) or dredgers. The excavated material will then be transported and, as far as possible, recycled. In most cases, places have to be found for the storage of the sediments. Exceptionally, it could be authorized to divert the sediments to the natural stream, under the condition that no damage be caused to the environment or when sediments are needed for a particular purpose. This can be the case with gravel for fish spawning.

Figure 8: Dry excavation of the fine sediments (silts) in the compensation basin of Les Esserts, part of the hydroelectric scheme of Emosson

Sucking

An other method for the evacuation of sediment consists in sucking a liquid/solid mixture from the bottom of the reservoir (Figure 9). The pumping device is equipped with a boring head in order to facilitate the disintegration of the deposits. The volume of the pumped mixture and its concentration are automatically measured in order to define the removed sediment volume. The sediment/water mixture will normally be conducted in decantation basins. It can also be diverted into the downstream river, with a controlled discharge.

For example, sucking operations were performed in the Luzzone Reservoir in order to clear the water intake opening (Figure 9 left). The extraction of 17'000 m^3 of sediments in 1983 and 25'000 m^3 in 1984 were thus achieved.

Downstream Prevention and Control

In order to maintain the required discharge capacity in the downstream river, artificial floods can regularly be induced through the bottom outlet opening. As it has been mentioned before, such operations have to be realized in wet periods.
Concerning the sediment deficit, the river profile has to be controlled in order to mitigate the erosion process in the natural bed. This can be done by the construction of sills or weirs across the water course.

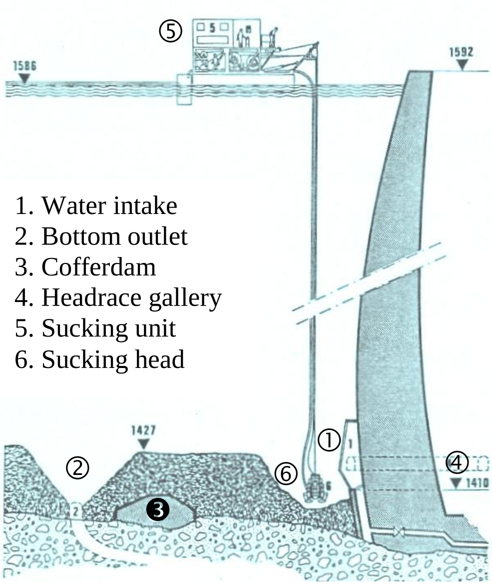

Figure 9: Left: schematic drawing of sediment sucking in the Luzzone Reservoir (1983-1994)
Right: floating sucking unit at the water surface

CONCLUSIONS

After the filling of the dead storage volume, reservoir sedimentation will affect the dam's safety when choking up the bottom outlet opening. Furthermore, it will cause damage to the hydraulic structures, in particular to the turbines, due to sediment carriage.

In addition, the accumulation of alluvial deposits induces an unrelenting reduction of the live storage capacity, meaning negative effects on the water supply or energy production, and also on the flood protection. Therefore, more and more attention has to be paid to sediment management in the reservoirs in order to maintain them safe and operational.

Legal bases exist in Switzerland for the sediment management in rivers influenced by the presence of reservoirs. The application of the main concepts and the respect of the related constraints are generally assigned to the cantonal authority. However, no precise rule exist which have to be systematically applied. Each case has to be analyzed individually when considering safety, environmental and economical criteria. A particular attention has to be paid to the environmental impacts induced by the removal of sediments. In this frame, fish protection holds an important place.

For these reasons, all possible interventions for erosion mitigation on the catchment area, bed load diversion from the tributaries, sluicing or flushing of reservoir sediments, dry or humid excavation of the deposits, pumping, etc. have to be considered in order to remedy the reservoir sedimentation process.

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