Swiss examples of the impacts of dams on natural environments and management strategies for sediment control

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1. Dams in Switzerland

Switzerland, and particularly its alpine region, is rich in streams and rivers. This water resource is intensively used in all watersheds, mainly for electric power generation. Moreover, most rivers have been “partly corrected” to protect adjacent land and property against floods. Therefore, about 24 per cent of the Swiss river courses have been modified, and this proportion reaches 40 per cent in the Plateau (low lying) region. A total of 160 large dams, with a wall higher than 15 m, exist in Switzerland, with a total storage capacity of about 4 km^3 (Figure 1, www.swissdam.ch). This volume corresponds to 2 per cent of the total water stored in natural lakes (mainly Lake Geneva, Lake Constance and Lake Maggiore) and 10 per cent of the total volume of water leaving Switzerland annually.

It is considered that the full potential for hydroelectricity generation in Switzerland has almost been reached. Hydropower represents about 60 per cent of Switzerland's electricity requirements. The range of dam impacts on natural environments depends on the type of water exploitation: water storage or run-of-river dams. Large dams in Switzerland are of the first type, essentially accumulating water during summer and producing electricity in winter. Therefore the major impacts on the natural environment include a drastic reduction in water discharge downstream of the dams, a reduction in sediment and nutrient loadings, a shift in the discharge frequency distribution during the year, a reduction in number and amplitude of floods, and rapid changes in water level (hydropeaking). Some of these impacts also occur with run-of-river dams.

2. Three case studies of sediment impact and control management

A major issue in reservoir management is sediment control. In most alpine reservoirs, this issue is not taken seriously and the water storage capacity slowly reduces with sediment accumulation. In these cases, some sediment flushing is performed for security purpose (mainly to maintain an access to the emergency drain). In other reservoirs, periodic flushing of sediments is

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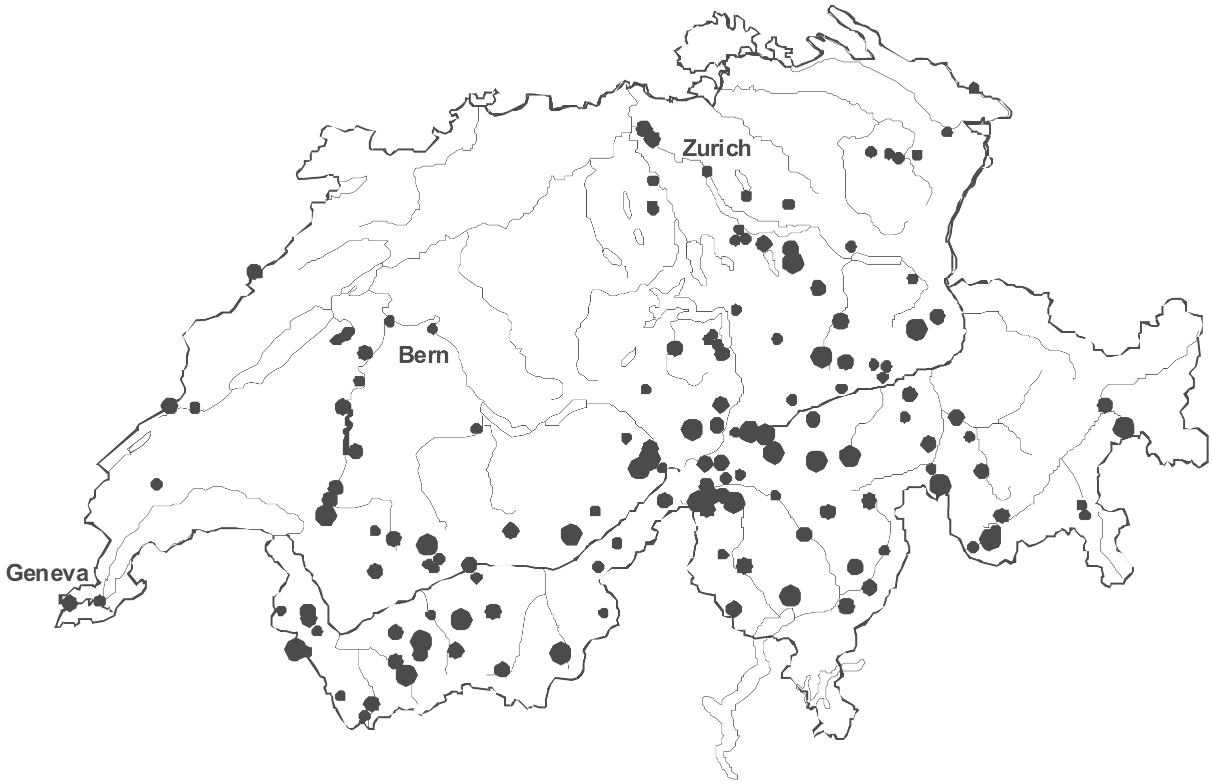

Figure 1 Location of the major dams and reservoirs in Switzerland. Circle size gives a relative indication of reservoir volume (Data source: www.swissdam.ch)

carried out, causing downstream impacts on river biota. Three case studies are briefly discussed here: the modified flow regime of the upper Rhone River (major tributary of Lake Geneva), sediment management of the Verbois reservoir on the Rhone River, downstream of Geneva, and the Wettingen reservoir on the Limmat River, downstream of Zurich.

2.1 Storage dams: sediment storage and partial flushing

Upstream of Lake Geneva, the Rhone River watershed comprises nine major storage hydropower dams built on tributaries, including the Grande Dixence (reservoir of 400×10^6 m^3) and the Mauvoisin dams (203×10^6 m^3). The present cumulated storage capacity of these major dams is $1{,}220 \times 10^6$ m^3, which represents 20 per cent of the mean Rhone River runoff to Lake Geneva. Electricity is mainly produced in the winter by releasing water stored during the summer. A major concern about the sustainability of these sources of energy is the loss of storage volume due to the accumulation of coarse and fine sediments. For example, the Mauvoisin dam was commissioned in 1956 and about 300,000 m^3 of sediment accumulates in the reservoir each year. In 30 years up to 10×10^6 m^3 of sediments have settled in the lake, which represents a sedimentation rate of approximately 60 cm a^{-1}. Close to the dam wall, and also close to the water intake and bottom outlet, the sediment accumulation rate ranges from 20 to 40 cm a^{-1} (Durand, 2001). Similar values are also observed in the Grande Dixence reservoir. These sediments render the exploitation of the dam hazardous and safety measures have to be taken. A project to flush sediment in the Mauvoisin reservoir has been abandoned, not because of the numerous impacts on the river downstream, but for security reasons. The current solution is to raise the water intake and the bottom outlet, probably twice within the next 50 years (Durand, 2001). At the Grande Dixence dam, a new type of floating water intake has even been invented to avoid the sediment accumulation issue.

The examples above show that dams and reservoirs form very efficient traps for sediments. Moreover, the exploitation of the dams has considerably modified the hydrological regime of the Rhone River, with an increase in discharge in winter and a reduction in summer. Loizeau and Dominik (2000) have shown that between 1915 and 1949, discharges larger than 400 $m^3 s^{-1}$ occurred on average 55 days each summer, whereas this has been reduced three-fold since 1965 to 15 days each summer. In addition, larger floods (> 600 $m^3 s^{-1}$) have disappeared almost totally since the 1960s. As the river capacity to transport particles is directly related to the discharge (Gregory and Walling, 1973), the reduction in major floods in the summer has induced a reduction in the particle capacity transport of the river. This process, in addition to the particle retention by the dam, has led to an overall reduction in sediment loads to Lake Geneva by a factor of two. Loizeau *et al*. (1997) have documented such a decrease by emphasizing the decrease in the sediment accumulation rate in the Rhone delta area in Lake Geneva. The impact of such a decrease on the lake functioning has not been elucidated. In particular, the role of the undercurrents, formed by the intrusion of the sediment-laden water of the Rhone River, in the oxygen supply of the deep water of the lake is still unknown. The decline in the number and amplitude of floods, due to the shift in the hydrological regime, has probably reduced the magnitude of these undercurrents and their oxygen supply (Loizeau and Dominik, 2000).

This type of dam is not sustainable for the production of electricity in the long term. Siltation in reservoirs is a process that reduces the productive volume and, up to now, it is too expensive to restore the initial available storage volumes.

2.2 Run-of-the-river dams with sediment flushing: the Verbois dam

The Verbois dam was built in 1942 across the Rhone River, downstream of Geneva for electricity production. The reservoir formed behind the dam is 11.4 km long with a surface area of 1.32 km^2, and an initial volume of 13.6×10^6 m^3. The Rhone River, at this location, comprises waters from the Lake Geneva outlet (mean annual discharge 252 $m^3 s^{-1}$) and waters of the Arve River (mean annual discharge 80 $m^3 s^{-1}$). Despite its much lower water contribution, the Arve River is the main sediment supplier to the dam, because of the strong erosion occurring in its alpine watershed that includes the Aiguilles Rouges and Mont Blanc mountains. The average annual sediment load is about 1×10^6 t, of which 50 per cent settles in the reservoir. Since 1945, 20 flushing events have been carried out to evacuate the accumulated sediments: every two years between 1945 and 1951, then with four- or five-year intervals until 1969, and finally every three years to 2003. These flushing events were fairly efficient because they removed, on average, 91 per cent of the deposited sediments (Figure 2, data from Sidler *et al*., 2006). About 17 per cent of the initial volume is currently filled with sediments (2.5×10^6 m^3). Numerous environmental

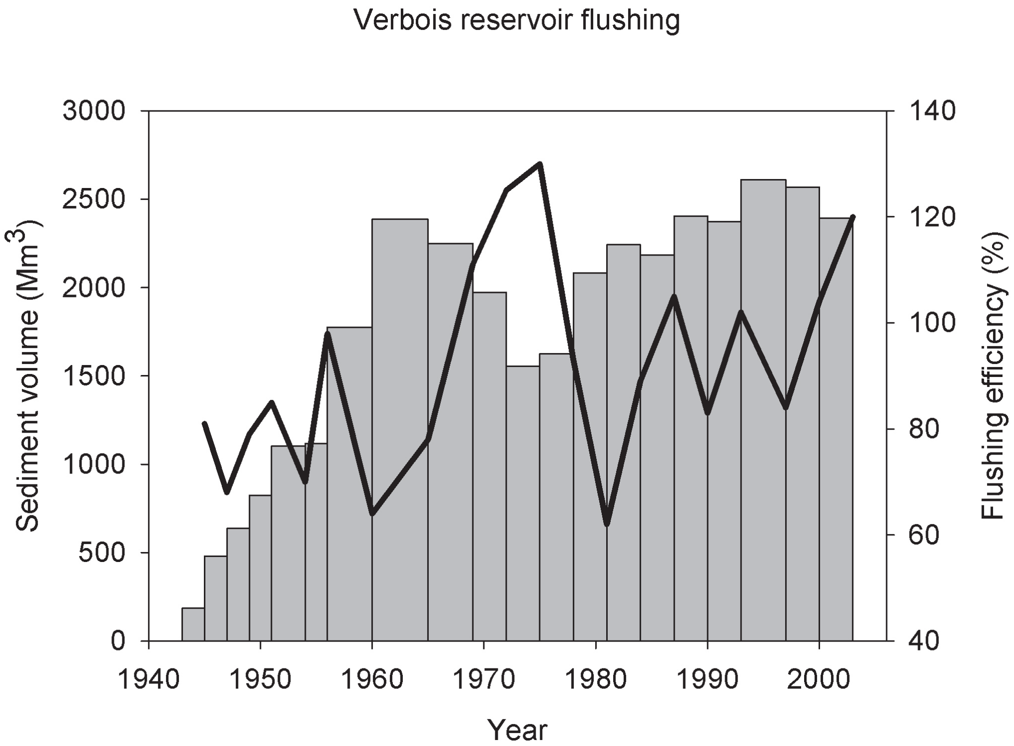

Figure 2 Change in sediment volume in the Verbois reservoir (bars) and the efficiency of flushing events (line) (Data source: Sidler *et al*., 2006)

downstream impacts of the sediment flushing have been identified: dramatic turbidity increase, with suspended matter concentration rising to 17 g l^{-1}; reed bed destruction; fish downward translocation; and juvenile fish mortality due to water quality alteration (Hofmann *et al*., 2001). Under pressure from anglers' societies, new reservoir management plans are being evaluated by the dam owner in collaboration with the Geneva state offices. Scenarios under study include a continuation of the flushing every three or six years, a partial lowering of the lake level during periods of flooding and sediment dredging.

Simulations for a 50-year period indicate that, for all scenarios, filling of the reservoir will take place, with a final sediment volume varying between 3 and 6×10^6 m^3, which corresponds to one-fifth to one-half of the initial volume, respectively (Bollaert *et al*., 2006). Sedimentation will reach a steady state after 10 to 20 years, depending on the scenario. Therefore, the dam should be exploitable forever. However, the issue of the fate of the reservoir and its large volume of sediments, which are also contaminated by heavy metals and persistent organic pollutants (Wildi *et al*., 2006), remains open until the dam is decommissioned.

2.3 Run-of-river dams without sediment flushing: the Wettingen dam

The Wettingen reservoir is a run-of-river dam on the Limmat River, 20 km downstream of the city of Zürich. It is an 18 m high dam that forms a 7 km long reservoir. The hydrological situation of the dam is somewhat comparable to the Verbois dam, because the main contribution to the discharge is the Limmat River, flowing out from Lake Zurich, with a mean annual discharge of

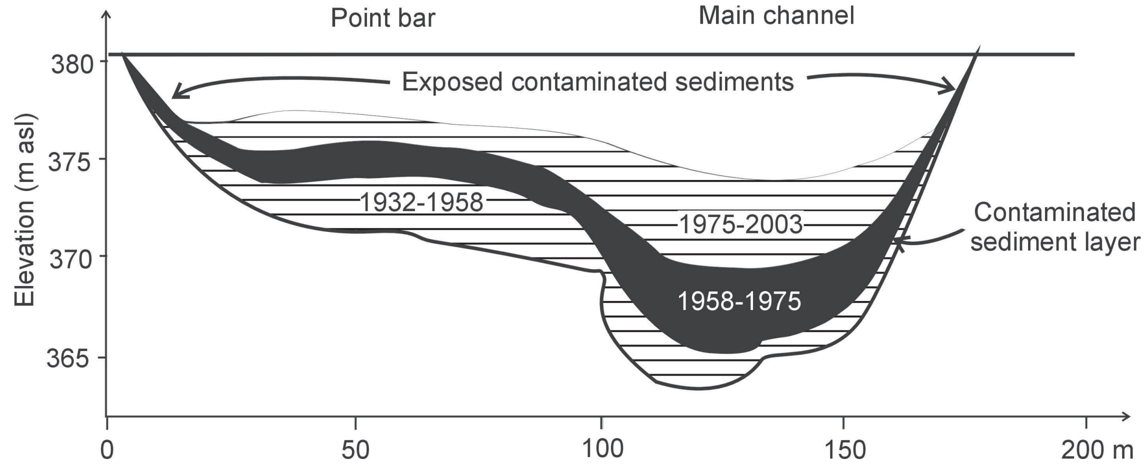

Figure 3 Transverse profile of the accumulated sediment in the Wettingen reservoir, 1,300 m upstream of the dam (Data source: Jüstrich *et al.*, 2006).

96 m^3 s^{-1}. The main tributary of the Limmat River is the Sihl River, with a mean annual discharge of 7.3 m^3 s^{-1}. This river drains an alpine region and provides most of the particulate matter to the reservoir. No sediment flushing has been carried out since the dam construction in 1930–1933. Based on a series of bathymetric surveys, Jüstrich *et al.* (2006) have calculated that the sediment volume stored in the reservoir varies between 18,000 to 50,000 m^3 a^{-1}. In 2003, it is estimated that a total of 2.4×10^6 m^3 of sediment have been stored in the reservoir. This volume represents 45 per cent of the initial storage volume. Discrete sampling of the suspended matter upstream and downstream of the reservoir was carried out in 2005, during both normal and flood conditions (Jüstrich *et al.,* 2006). Results show that about 50 per cent of the sediment load is stored in the reservoir during normal flow, whereas this proportion rises to 90 per cent during flood conditions. In addition, the sediment load during flood conditions was 4,000 times higher than during normal flow. This enormous difference emphasized the importance of rare events in the sediment dynamics of a reservoir. This reservoir suffers also from past contamination of the sediments (Figure 3). Wildi *et al*. (2003) have shown that sediments deposited between the 1960s and the early 1970s are loaded with contaminants (heavy metals and organic micropollutants). According to Swiss legislation on contaminated sites, the pollutant concentrations in the sediments exceed the "limit of investigation" and the reservoir should therefore be considered as a contaminated site

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