# RESERVOIR SEDIMENTATION AND SUSTAINABLE DEVELOPMENT

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## 1. Introduction

The today's world wide yearly loss of storage capacity due to sedimentation is already higher than the increase of capacity by the construction of new reservoirs for irrigation, drinking water and hydropower. Thus the sustainable use of the reservoirs is not guaranteed in long term. In the case of deep and long reservoirs the sedimentation rate is much below the world mean value. Nevertheless the sedimentation threatens also these reservoirs, since turbidity currents are sporadically transporting large volumes of sediments down to the dam. There the concentrated deposits are hindering the safe operation of the outlet structures as intakes and bottom outlets.

After only 30 to 40 years of operation, sedimentation has become a serious problem in many reservoirs located even in catchment areas with moderate surface erosion as in the Alps. The mentioned turbidity currents are often the determining process for the transport and deposition of the sediments in such reservoirs. These underwater avalanches with a high suspended-sediment concentration follow the thalweg of the lake to the deepest area near the dam, where the sediments can affect the operation of the bottom outlet and the power intake. To control the sedimentation within the reservoir, the effects of obstacles, screens, water jets and bubble curtains on the turbidity current were investigated with physical experiments and numerical simulations. The investigations showed that turbidity currents can be influenced effectively by properly designed constructive measures.

After the discussion of reasons and problems of reservoir sedimentation, possible measures against sedimentation are presented. Then some examples of application of mitigation measures against turbidity currents are given together with design recommendations.

## 2. The problem of reservoir sedimentation

Reservoir sedimentation is a problem that will keep those responsible for water resources management occupied more than usual during the decades to come. All sorts of impounding structures are concerned: large dams, in the form of fill or concrete dams, as well as river barrages comprising weirs, power plants, locks, impounding dams and dykes (Figure 1). Impounding facilities are always costly, but this is justified by their various potential uses.

Although the aim behind the efforts to create reservoirs is storing water, other substances are carried along by the water and are usually deposited there. This is a result of dam construction, dramatically altering the flow behaviour and leading to transformations in the fluvial process with deposition of solid particles transported by the flow (Chella et al. 2003). Each reservoir created on natural rivers, independent of its use (water supply, irrigation, energy or flood control), can have its capacity decreased due to deposition over the years. In an extreme case, this may result in the reservoir becoming filled up with sediments, and the river flows over land again.

A reservoir, like a natural lake, silts up more or less rapidly. In actual fact, reservoirs may completely fill with sediments even within just a few years, whereas natural lakes e.g. in Alpine foreland, may remain as stable features of the landscape for as much as 10'000 or 20'000 years after they were formed during the last Ice Age.

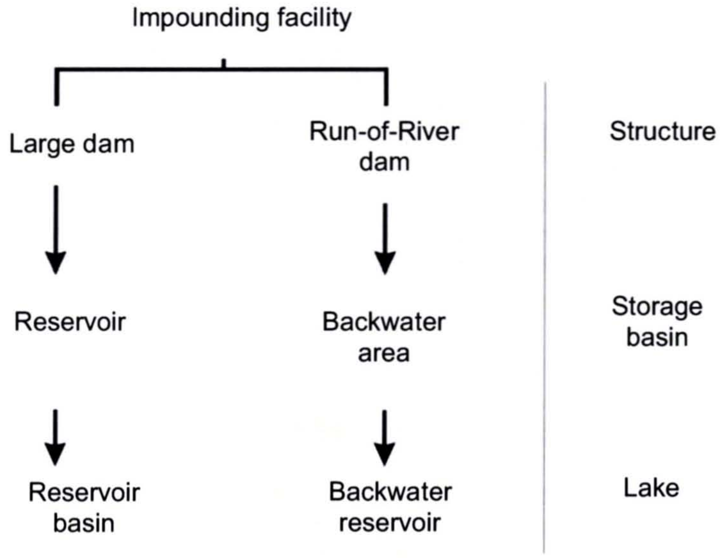

Figure 1: Classification of impounding facilities

Reservoir sedimentation reduces the value of or even nullifies the dam construction investment. The use for which a reservoir was built can be sustainable or represent a renewable source of energy only where sedimentation is controlled by adequate management, for which suitable measures should be devised. Lasting use of reservoirs in terms of water resources management involves the need for de-sedimentation.

The planning and design of a reservoir require the accurate prediction of erosion, sediment transport and deposition in the reservoir. For existing reservoirs, more and wider knowledge is still needed to better understand and solve the sedimentation problem, and hence improve reservoir operation.

## 3. Consequences of reservoir sedimentation

The accumulating sediments successively reduce the water storage capacity (Fan and Morris 1992). Consequently, at long-term the reservoir operates only at reduced functional efficiency. Declining storage volume reduces and eventually eliminates the capacity for flow regulation and with it all water supply, energy and flood control benefits (Graf 1984, International Committee on Large Dams (ICOLD) 1989). Reservoir sedimentation can even lead to a perturbation of the operating intake and to sediment entrainment in waterway systems and hydropower schemes (Boillat et al. 1994, Schleiss et al. 1996, De Cesare 1998). Depending on the degree of sediment accumulation, the outlet works may be clogged by the sediments. Blockage of intake and bottom outlet structures or damage to gates that are not designed for sediment passage is also a severe security problem (Boillat and Delley 1992, Schleiss et al. 1996). Other consequences are sediments reaching intakes and greatly accelerating abrasion of hydraulic machinery, decreasing their efficiency and increasing maintenance costs (Boillat and Delley 1992).

## 4. Sedimentation rate

There are no accurate data on the rates of reservoir sedimentation worldwide, but it is commonly accepted that about 1 – 2 % of the worldwide storage capacity is lost annually (Jacobsen, 1999). A detailed collection of sedimentation rates in regions all over the world can be found in Batuca and Jordaan (2000). The evolution over the last century and the predicted future development of the volumes of water-storage capacity lost due to reservoir sedimentation and the volumes of installed water-storage capacity in the world are presented in Figure 2 (Oehy 2003). Bearing in mind that the annual increase of storage volume due to the construction of new reservoirs is close to 1 %, the problem of sustainability becomes apparent (Oehy et al. 2000). If there are no effective measures undertaken, until the end of the 21st century, the major part of the worldwide useful volume will be lost.

The sedimentation rate of each particular reservoir is very variable. It depends more particularly on the climatic situation, the geomorphology and the conception of the reservoir including its outlet works. Based on an analysis of data of 14 reservoirs, Beyer Portner (1998) showed that on average in Switzerland only about 0.2 % of the storage capacity is lost annually due to sedimentation (Figure 3). The lower sedimentation rate in the Alps is due to the geologic characteristics, mainly rocky mountains, of the catchment areas at high altitudes (Oehy 2003).

Beyer Portner and Schleiss (2000) described the annual erosion volume per surface by an empirical equation, which is based on the analysis of sedimentation data of 19 Swiss reservoirs located in the Alps.

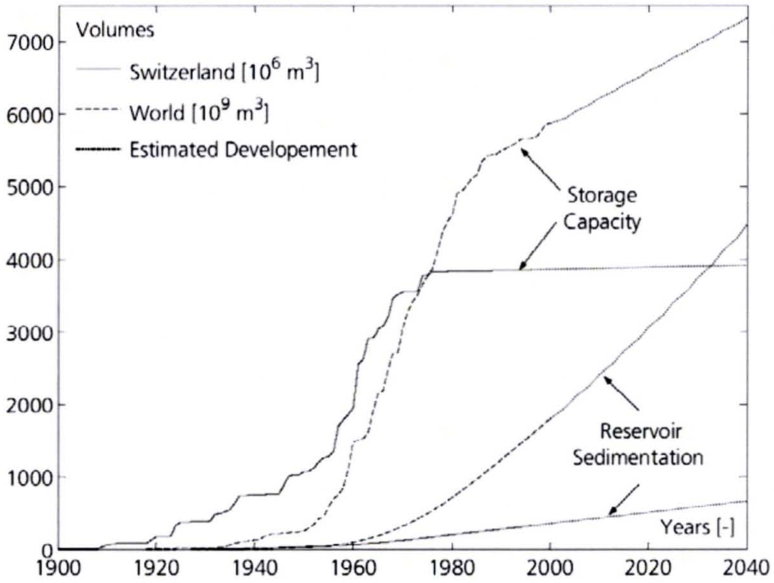

Figure 2: Increase of the reservoir capacity by the construction of new dams and storage volume loss by sedimentation worldwide and in Switzerland, after Oehy (2003)

## 5. Reservoir sedimentation by turbidity currents

In big Alpine reservoirs, turbidity currents are often the governing process in reservoir sedimentation by transporting fine materials in high concentrations. The erosion of the soil within a catchment area is at the origin of the material transported by a river. The erosion process starts in the high mountainous regions, and continues in the highlands and plains and ends in the lakes or in the sea respectively where it comes - due to the decreasing flow velocity - to sedimentation. Depending upon the sediment supply from the watershed and flow intensity in terms of velocity and turbulence, rivers usually carry sediment particles within a wide range of sizes. During flood events the fraction of sediments smaller than sand reaches 80 to 90 % of the total sediment carried by the river (Alam 1999, Sinniger et al. 1999), and the total sediment discharge is usually significant. If the sediment concentration is high enough it may come to turbidity current.

The turbidity currents belong to the family of sediment gravity currents. These are flows of water laden with sediment that move downslope in otherwise still waters like oceans, lakes and reservoirs. Their driving force is gained from the suspended matter (fine solid material), which renders the flowing turbid water heavier than the clear water above. When a sediment laden river flows into a big reservoir, the coarser particles deposit gradually and form a delta in the headwater area of the reservoir that extends further into the reservoir as deposition continues (Figure 3). Finer particles, being suspended, flow through the delta stream and pass the lip point of the delta. If after the lip point of the delta, the difference in density between the lake water and inflowing water is high enough, it may cause the flow to plunge and turbidity current can be induced. During the passage of the reservoir, the turbidity current may unload or even resuspend granular material. Subsequently the sediments are deposited along the path due to a decrease in flow velocity caused by the increased cross-sectional area. Fine sediments (clay and silt sizes) are usually the only sediments that remain in suspension long enough following over long distances the reservoir bottom along the thalweg through the impoundment down to the deepest point in the lake normally near the dam to reach the outlets. At the dam the sediments settle down.

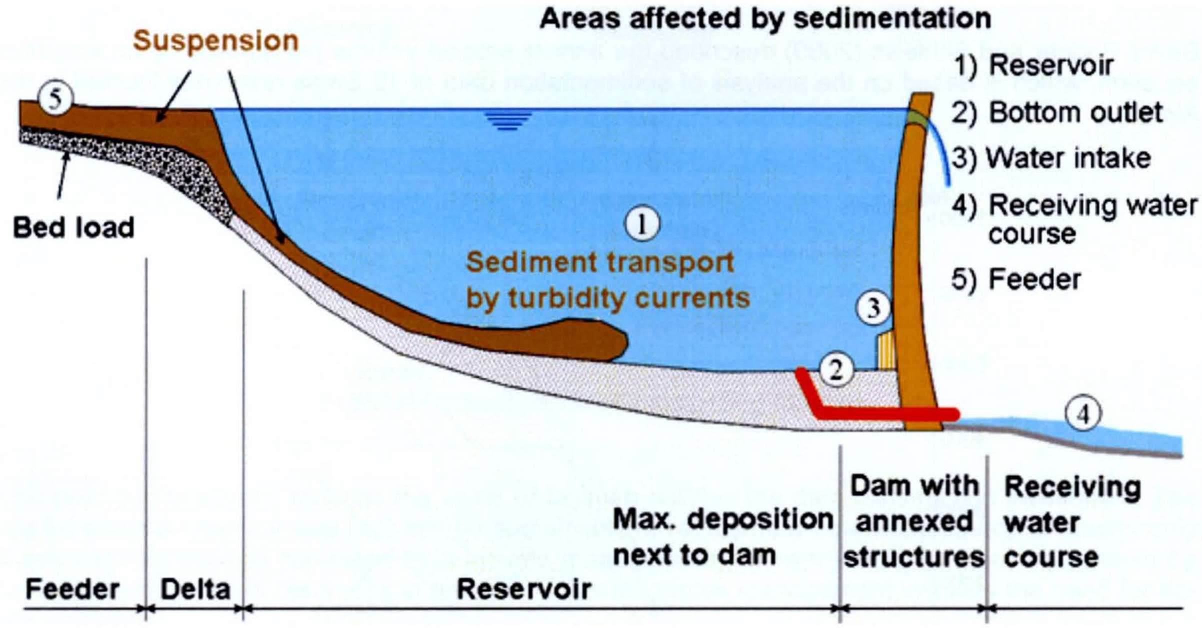

Figure 3: Areas affected by sedimentation in the surroundings of a reservoir (De Cesare 1998)

## 6. Measures against reservoir sedimentation

Over the years several measures against reservoir sedimentation have been proposed (Schleiss and Oehy 2002). But not all of them are sustainable, efficient and affordable. For example the raise of dams and outlet works doesn't provide a long-term solution (Boillat, J.-L. and Delley, P. 1992).

There is a strong need to limit sediment accumulation in reservoirs in order to ensure their sustainable use. Management of sedimentation in Alpine reservoirs cannot be apprehended by a standard generalized rule or procedure. Furthermore, sediment management is not limited to the reservoir itself, it begins in the catchment areas and extends to the downstream river. Every situation has to be analysed for itself in order to determine the best combination of solutions to be applied. The possible measures are summarized in Figure 4 and grouped according to the areas where they can be applied.

An integrated approach to sediment management that includes all feasible strategies is required to balance the sediment budget across reservoirs (Morris 1995). Integrated sediment management includes analysis of the complete sediment problem and application of the range of sediment strategies as appropriate to the site. It implies that the dam and the impoundment are operated in a manner consistent with the preservation of sustainable long-term benefits, rather than the present strategy of developing and operating a reservoir as a non-sustainable source of water supply (Morris 1996). A sustainable sediment strategy should also include the downstream reaches; therefore monitoring data should also include downstream impacts as well as sedimentation processes in the reservoir (Morris and Fan 1997).

The actually known measures can be subdivided in measures taken in the catchment area, in the reservoir or at the dam itself as shown in Figure 4. Oehy (2003) and Oehy & Schleiss (2007) proposed and studied several technical measures against turbidity currents.

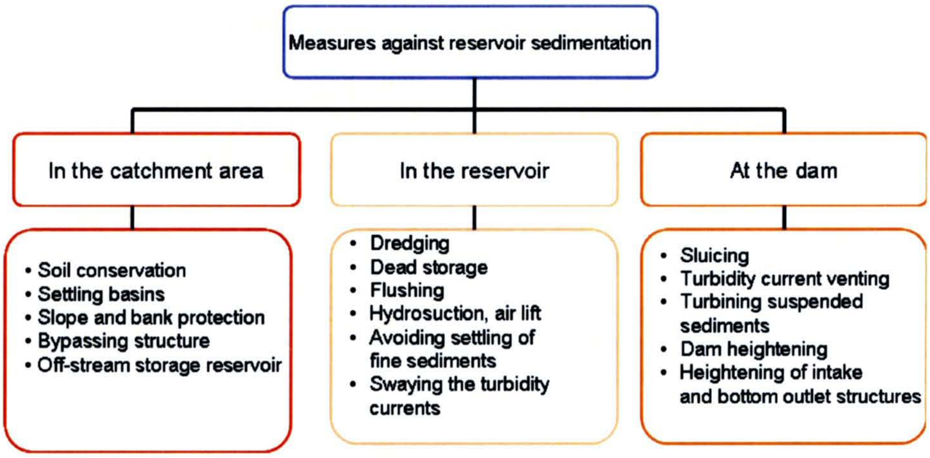

Figure 4: Inventory of possible measures for sediment management (Schleiss and Oehy, 2002)

## 7. Summary

The today's world wide yearly mean loss of storage capacity due to sedimentation is already higher than the increase of capacity by the construction of new reservoirs for irrigation, drinking water and hydropower. Thus the sustainable use of the reservoirs is not guaranteed in long term. In the case of alpine reservoirs the sedimentation rate is much below the world mean value. Nevertheless, sedimentation threatens also these reservoirs, since turbidity currents are sporadically transporting large volumes of sediments like an underwater avalanche down to the dam. There the concentrated deposits are hindering the safe operation of the outlet structures as intakes and bottom outlets. Many possible measures against sedimentation are known from practice, but they are strongly depending on the local conditions. For alpine reservoirs technical measures, which can govern turbidity currents are of special interest. The problematic of sedimentation and sediment management should be considered in the early stage of the design of the reservoir in order to obtain sustainable solutions. Although methods for erosion volume estimation and empirical relationships for trap efficiency estimation are available, unfortunately this is still not the case for many reservoirs built recently all over the world.

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