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SEDIMENT MANAGEMENT OF ALPINE RESERVOIRS CONSIDERING ECOLOGICAL AND ECONOMICAL ASPECTS

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Abstract: Alpine Regions are regarded as a valuable source of clean drinking water and of great importance for hydro power use. Management of water as an extremely valuable resource is guaranteed by numerous reservoirs enabling a third essential task: flood protection. Sediments are transported in rivers originated from natural geomorphological processes in alpine regions accumulating material in reservoirs. Thus storage capacity is reduced interfering with the needs of water supply, flood protection and hydro power. However, the lack of transported material in downstream sections heavily affects ecological variety, river bed stability and groundwater. A wise management of sediments on basis of experiences gained on national level is needed to establish trans-national actions to preserve existing reservoirs and to avoid uncontrolled exploitation by constructing new storage capacity.

Keywords: Sediment management, Alpine region, sustainability, Ecological aspects, Economic impacts, European Water Framework Directive, Impact analysis

1 INTRODUCTION

Alpine water reservoirs are major vital components of water supply, renewable electric energy generation, recreation but mainly flood protection for alpine regions as well as large downstream areas. Sustainability of these reservoirs is severely threatened by sedimentation resulting from natural geomorphologic processes. The loss of reservoir capacity must be faced either by building new ones in the fragile alpine environment or by enhancing dams and dikes along rivers and cities occupying valuable land. To maintain storage volume measures to reduce sedimentation should be initiated. If sedimentation has already occured or may not be prevented methods of excavation must be taken into consideration such as flushing or mechanical removal. These are very expensive tasks and may affect sensitive alpine environment seriously. However, failing to do so results in the loss of storage capacity and consequentially the loss of flood protection abilities, water supply reliability and hydro power generation potential.

As flood protection is a major task and of high public interest trans-national strategies are needed to implement a sustainable management aiming on a dynamic balance to avoid reservoir sedimentation as well as degradation processes of rivers in the peri-alpine belt to reduce the risk of floods and to avoid severe damages to infrastructure and private property. Accumulation in reservoirs reduces valuable morphological processes of rivers downstream affecting biologic diversity and ecologic dynamics.

2 ALPINE ENVIRONMENT

Alpine regions can be characterized by high energy potential and characteristic landform elements (Hewitt, 1972), high elevations, steep slopes, rocks, and availability of snow and ice (Barsch and Caine, 1984). As this kind of characterization is based on a certain subjectivity it is impossible to propose a commonly acceptable boundary definition for the alpine sediment system. Beside diagnostic attributes spatial and temporal variability has to be taken into account, too.

In respect of sediment transport processes the specific hydrologic, geomorphologic, and climatic conditions of alpine regions are regarded as the major driving forces. The interaction of these different phenomena results in the highest sediment transport rates. Areas with the highest erosion rates are nearly identical with the major alpine areas worldwide: the Himalaya in the Asian region, the Andes in Southern America, the Pacific Coast of Northern America, and the Alps in Europe. Erosion rates of more than 1.000 $t \cdot km^{-2}$ per year can be observed on a global basis (Fig. 1).

Fig. 1 Global Patterns of Sediment Yield (Walling and Webb, 1983)

Looking on world´s drainage basins shows rates of sediment yield varying from 4 to 2.581 $t \cdot km^{-2} \cdot yr^{-1}$ excluding basins with an area less than 10.000 km^2 (Mahmood, 1987). However, these rivers do not produce the world´s highest sediment yields as do smaller rivers and tributaries. The Pacific Asiatic-Australian sector demonstrates the most intensive rates of erosion. Figures in the range of 10.000 to 50.000 $t \cdot km^{-2} \cdot yr^{-1}$ have been reported at stations from basins with drainage areas of only some several hundred km^2 in China, Taiwan, Philippines, Indonesia, New Guinea and New Zealand (Walling, 1994) due to active tectonics and volcanism, steep slopes, dissected mountain relief composed mainly of sedimentary rocks, high precipitation amounts and intensities, high and irregular run-off and human influence.

High rates of erosion mainly occur in regions where there is high intensity of rainfall. The water balance of Alpine regions is affected by specific *hydrological* conditions which itself are a consequence of the relief, shape and formations of the mountains. Increased precipitation, decreased evaporation, temporarily storage of water as snow and ice, and an efficient run-off system typically results in a high availability of water also for the surrounding peri-belt region. For the European Alps the annual precipitation can reach values of more than 3.000 mm in high ranges while transpiration may drop to 100 mm over snow-covered areas. Significantly higher values for precipitation of 6.000 mm per year or even more are reported from gauging stations from other parts of the world. Average values of 1.481 mm for precipitation, 513 mm for transpiration, and 961 mm for discharge are given by Schaedler and Bigler (1992) for Switzerland. However, significant variations of precipitation are typical for mountainous areas (Fig. 2). While the intensity of rain-/ snowfall together with the presence and condition of snowfields mainly affects the short-term run-off, seasonal changes of storage or release of water from snowfields/ glaciers affects the annual discharge.

Additionally present research work on climate changes addresses to long-term effects on alpine hydrology. Extreme hydrologic situations, mainly on short-term basis, can result in natural disasters in the alpine environment as well as major flooding events in the downstream sections of the rivers.

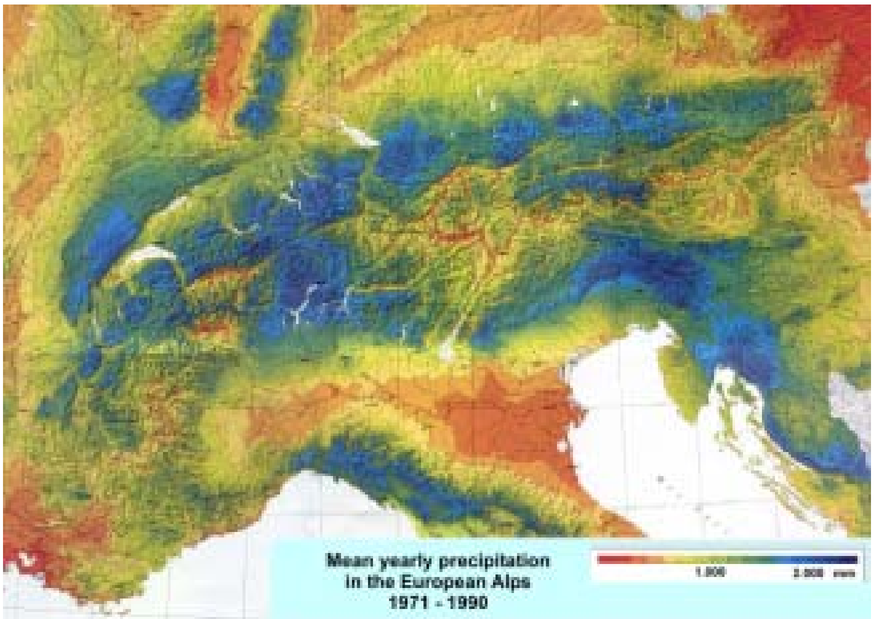

Fig. 2 Mean Annual Precipitation in the European Alps (Schwarb *et al.*, 2001)

Beside precipitation *geomorphologic* processes are essential for the sediment transfer system of alpine basins. In essence, sediments may be derived from wheathering processes and from glacial and fluvial erosion processes from different sources and may be routed by glacial, fluvial and mass movement. The dominant characteristic of materials in alpine areas is that they are not usually supply-limited. A further feature is that there is normally a great range of sediment sizes which are not systematically sorted and which are stochastically supplied to the fluvial system. In addition to the sediment which is derived from glacier sources, there are additional sources of sediment derived from storage between the slopes and the stream channel, whilst avalanches, rock slides and debris falls further supplement the sources. In torrential drainage basins it has been shown that there is a range of sediment sources including landslides, gulley erosion and more general soil erosion. Occasionally, where deposits are stored in alpine valleys, such deposits may fail and temporarily give very high values of sediment yield.

Furthermore volcanic and tectonic activity as well as soil conditions affect erosion processes strongly additionally influenced by vegetation, land use and human impacts.

3 SEDIMENT MANAGEMENT OF ALPINE RESERVOIRS

Induced by the availability of sediments and transported by an efficient fluvial system in alpine environments material accumulates in natural depressions and lakes as well as man-made reservoirs. While temporary storage of sediments in natural basins is often welcomed the accumulation in reservoirs reduces its ability to deliver the benefits for which it was built, e.g. flood protection, water storage for irrigation and drinking water supply, hydro power generation, dotation of navigable rivers during low flow conditions, groundwater recharge, stabilization of river bed, touristic purposes.

In general the lowest elevation of a reservoir can be located near the barrier which offers opportunities, together with the ability to reduce the water level by technical means, to manage the sedimentation process in a certain way. However, sorting processes of the material can often be observed with coarse material settling at the upstream section of the reservoir and fine sediments traveling across the water body as suspended load.

Options to manage sedimentation can divided in three common ways (White, 2001):

- Minimizing sediment loads entering reservoirs,
- Minimizing deposition of sediments in reservoirs,
- Removing accumulated sediments from reservoirs.

As the characteristic and operation of dams differs from that of run-off reservoirs management strategies have to be adapted to the specific type of installation.

3.1 Reduction of Sediment Input

There are three common ways of achieving this objective (White, 2001):

- Catchment conservation programmes and engineering measures to control erosion,
- Upstream trapping of sediments,
- Bypassing of high sediment loads.

For alpine ranges these methods are limited. Conservation programmes by cultivating vegetation can only be applied in lower elevation areas with moderate temperatures while in upper parts changes of the slopes by forming terraces may reduce soil erosion. Upstream trapping faces the problem that the sediment supply from the mountain slopes is not limited and fills such constructions in the tributaries shortly. As a consequence they have to be managed, too, to preserve storage volume for high flow situations with the risk of sudden sediment peaks. The third category of measures focuses on high flow situations with high sediment content and their bypassing around the reservoir using channels or tunnels.

The first two options disturb the natural sediment transfer system if they are not just counterbalancing human impacts. The possible lack of sediments in the downstream sections of the river basin may cause erosion problems. Bypassing is limited to short term events and simulates natural conditions in the downstream reach avoiding severe disturbances of the ecosystem.

3.2 Dam Induced Reservoirs

Sedimentation rates of alpine reservoirs in average are smaller than those of lowland facilities. Nevertheless the loss of storage capacity may have dramatic consequences as singular events in the alpine environment may carry extreme amounts of sediments in a very short time. Solids transported into storage basins are mainly suspended particles (80% - 90% for smaller reservoirs, up to nearly 100% for bigger ones) while bed load is of less importance. Large amounts of suspended material is carried by the fluvial system during flood events often resulting in a turbidity current while entering the reservoir. Depending on the bottom slope it may have a significant velocity which may result in the remobilization of recently deposited material, the increase of the density of the current and additional acceleration. This mechanism is one of the major driving forces for sediment movement in alpine lakes as most conditions for turbidity currents are fulfilled (Oehy *et al.*, 2000):

- High concentration of suspended material entering the reservoir,
- Significant water depth at the inlet of the lake,
- Marginal flow velocities in the water body,
- Steep bottom slope of the reservoir,
- Narrow geometry of the lake.

Turbidity currents may transport significant amounts of sediments close to the dam resulting in depositions which can block technical installations and interfere with operation and safety issues. In some cases it is possible to use the phenomenon of turbidity currents or concentration of sediment laden flood waters to sluice fine sediments through the reservoir and discharge them to the downstream section thus avoiding sedimentation.

Methods to remobilize already deposited material can be divided into operational options and technical measures. *Operational measures* focus on the relocation of the sediments from the reservoir into the downstream reach as suspended load. The easiest way, from a technical point of view, seems to be flushing operation of the reservoir by opening the gates at high water level. To be able to erode depositions, especially if consolidated, more time and water is needed compared to sluicing operation. The economic disadvantages through the loss of water for e.g. hydro power use (peak-demand power plants in high elevation locations) may exceed the costs of alternatives significantly. Additionally long lasting flushing operations with high sediment concentrations affect the ecosystem downstream (see chapter 4). A more moderate method to transfer deposited sediments downstream uses artificial remobilization and discharge of the sediment laden flow through the turbines of the power plant. The concentration of the sediments in the downstream section can be limited by the intensity of remobilization to meet ecologic requirements and interests of stake-holders. However, some modifications at the turbine runners and sealings are necessary to avoid damages caused by abrasion.

Technical measures are mostly using different dredging techniques (Fig. 3) to either relocate the material into the downstream section or deposit it outside of the water body.

All options, especially technical measures, encounter additional problems in the alpine environment compared to lowland applications. The specific conditions described in Chapter 2 affect time, duration and costs of sediment removal. Reservoirs at high elevations are often situated in remote areas with limited access making it difficult or even impossible to transport large equipment.

Fig. 3 Water Injection Dredger at Lake Margaritze (Austria)

For example, Lake Margaritze, a small artificial reservoir in the Austrian Grossglockner region at an altitude of 2.000 m (6.560 ft), is accessible by a paved road. It needs more than 15 truck loads to carry a small water injection dredger, disassembled in parts, to the site. 6 - 8 weeks are necessary to assemble the equipment at the lake before it is operationable. Due to climatic conditions transportation to the lake is limited to spring time, while disassembling and transport downhill has to be finished before the freezing period. Thus operation is limited to the summer months. Beside logistic difficulties (preparation, operation, supply) and resulting costs administrative issues have to be taken into consideration, too. As alpine regions are sensitive environments high elevated areas are often protected as National Parks resulting in restrictions to minimize the impacts of technical measures like noise, exhaust, possible contamination, etc.

3.3 Run-Off Reservoirs

In general run-off reservoirs are backed-up rivers with a certain flow velocity depending on discharge and geometry. In narrow reservoirs flow velocities may reach similar values during flood events compared to the original situation of the natural river. Run-off reservoirs are often part of chains of such installations along the river affecting sediment transport, deposition as well as evacuation measures. Sediment management strategies have to take into account differences resulting from this interlinked operation.

Reservoirs in lower alpine regions commonly do have a wider cross-section than in upper parts. Sedimentation may result in silting up the banks and near-bank areas which, if consolidated and vegetated, reduce flow capacity during flood events. To be able to keep most of the sediments in suspension and sluice them through the reservoir the flow should be concentrated along the original river bed to ensure sufficient water depths and flow velocities. To achieve such a guidance of the flow it can be necessary to build submerged dikes or similar constructional elements.

As sediment composition in alpine regions often is characterized by a great variety of size classes ranging from very coarse material down to very fine particles a significant sorting process takes place along the reservoir. While fine sediments may pass through the water body as suspended load and be discharged downstream rock and gravel material settles at the inlet and can not be remobilized by e.g. flushing operation. Therefore different management strategies must be applied to reduce sedimentation or to evacuate run-off reservoirs.

Technical measures are mostly based on dredging operations. Depending on operational issues, hydrological conditions and infrastructure two major strategies can be applied:

- Dredging on dry bed using conventional wheel- or chain-driven machinery,
- Dredging of submerged material using barges with different equipment.

The first possibility is often much more economic and commonly used to dredge coarse material at the inlet of the reservoir. To be able to work on dry bed the water level is lowered accordingly. As a consequence the head of the reservoir is reduced affecting power generation and financial issues. Additionally a concept is essential of how to use the excavated material. Depending on the size classes, the composition, distances for transportation, availability of disposal sites and amount of dredged material different options have to be examined like usage for construction purposes or disposal. From the point of sustainable river morphology the coarse material should be reused as bed load material for the downstream section if a natural reach follows the reservoir. Sophisticated planning is necessary to avoid negative consequences of redeposited material in the river downstream (transport capacity, reduction of flood protection, uncontrolled mass movement of bed load material, etc.).

Operational measures are mainly focused on flushing operations. It can be distinguished between flushing without lowering water level resp. head and flushing with lowering water level. In most cases the necessary critical shear stress to remobilize the deposited sediments can only be achieved by lowering the gates and supported by higher discharge during small flood events. Numerous aspects have to be taken into account to ensure effectiveness and safety issues. For alpine regions major uncertainties are meteorological and hydrological conditions. Flushing operations must be applied for a certain time duration to be effective, however, forecast of precipitation is often poor in mountainous regions. On the other hand sudden hydrological events, also on small-scale and in downstream sections of the drainage basin, may dramatically affect run-off conditions by adding flood waters to higher discharge during flushing operations.

4 ECOLOGICAL ASPECTS

The described methods to evacuate sediments from reservoirs affect the ecosystem in different ways. Generally all organisms are struck but consequences are different for each of the categories. While fishes have a certain ability to escape, smaller organisms at the surface of the sediments/ river bottom and within the interstitial (upper part of the sediments) are nearly unable to move. However, as the alpine environment is characterized by extreme changes between low flow and high flow situations organisms are mostly adapted to flood events and hide within coarse bed material.

Dredging operations result in a disturbance of the organisms through mechanical destruction of their living environment and/ or displacement. If the water level is lowered to excavate on dry bed additional parts of the environment are affected by falling dry for much longer periods of time. While the effects are more local most of the organisms are lost and recolonization is dependent on organisms drifting downstream from upper sections of the river. In alpine environments ecosystems can change rapidly along rivers as changes in altitude significantly affect living conditions. As a consequence natural recolonization cannot always be assured.

Flushing operations are affecting a much wider area than dredging as huge amounts of sediments are remobilized and discharged downstream. Ecological consequences are significantly dependent on the size classes of the sediments. Fine sediments will settle in downstream sections and may cover coarse bed material which is an important living space for small organisms. To avoid or minimize negative impacts flushing operations should take place more often with smaller amounts of remobilized sediments rather than a single event with massive sediment discharge from the reservoir. In addition post-flushing operation can significantly reduce impacts on the downstream section if additional water is released after the evacuation process to distribute fine sediments on a bigger area. In alpine areas flushing operations may be valuable from an ecological point of view if coarse material can be drifted downstream.

Disturbances through evacuation measures are complex and cannot be traced and judged by single parameters or indicators. In fact disturbances are ecologically relevant only if changes of the structure of the biocoenosis can be observed. Therefore examinations have to cover:

- Kind and intensity of changes of the biocoenosis,
- Time period until original state is reestablished.

Analysis has to cover hydrology, hydraulic conditions, morphology, floodplains and meadows, chemistry, organisms, structure of habitats, etc. and needs time-consuming data collection (Fig. 4). To be able to estimate the intensity of disturbances the data-collection has to be performed prior to the foreseen measures as well as following the evacuation action.

Fig. 4 Data-collection to Describe Ecologic Conditions Prior and Past Evacuation Measures: Sampling of Fish and Small Organisms (left) Freeze Core to Gain Grain Size Distribution of River Bottom (right)

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