Albayrak, Ismail; Felix, David; Schmocker, Lukas; Boes, Robert M.

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Hydrolink

RESEARCH PROJECTS ON RESERVOIR SEDIMENTATION AND SEDIMENT ROUTING AT VAW, ETH ZURICH, SWITZERLAND

BY ISMAIL ALBAYRAK, DAVID FELIX, LUKAS SCHMOCKER AND ROBERT M. BOES

Reservoir sedimentation is a global concern and is expected to aggravate in the near future due to climate change and the linked increase in sediment availability below retreating glaciers. There is an increasing need for efficient sediment management to maintain the active storage volumes in reservoirs and to improve the continuity of sediment transport along rivers from upstream to downstream of dams. The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich, Switzerland, has conducted several basic and applied research projects on reservoir sedimentation and possible countermeasures (*e.g.* sediment bypass tunnels and increased fine sediment transport through power waterways).

Figure 1. Griessee Reservoir with retreating glacier in the background, leading to higher sediment yield. (Photograph: D. Ehrbar, VAW, ETH Zurich)

Introduction

Hydropower is the most important source of renewable energy in Switzerland and constitutes the backbone of the Swiss electricity generation portfolio. Many reservoirs are located in the periglacial environment, *i.e.* in catchment areas of which at least 30 % is glacierized[1]. Climate change and the envisaged transition to a more sustainable energy supply system according to the 'Swiss Energy Strategy 2050' will challenge the existing infrastructure. The retreat of many glaciers in Switzerland may have significant impacts on water resources, but it may also provide opportunities such as new sites for hydropower reservoirs. New natural proglacial lakes have recently started to form at the termini of a number of retreating glaciers in the Swiss Alps. These reservoirs partly form naturally at rock rims after glacier retreat, yet some need a man-made dam to ensure their long-term stability.

However, the sediment yield and discharge downstream of retreating glaciers tend to increase, resulting in higher reservoir sedimentation. For sustainable reservoir operations, it is imperative to consider reservoir sedimentation and to plan and implement effective countermeasures. A number of field, laboratory as well as numerical research projects at VAW of ETH Zurich deal with reservoir sedimentation and associated countermeasures. They are briefly described hereafter.

Hydropower Potential and Reservoir Sedimentation in the Periglacial Environment Under Climate Change

The goal of this project was to better understand the effects of climate change on reservoir sedimentation and hydropower development in the Swiss periglacial environment. The study was divided into three parts, namely a systematic investigation of the hydropower potential in Swiss periglacial catchments, a field investigation of sediment fluxes into and inside periglacial reservoirs, and the numerical investigation of long-term sedimentation processes and patterns in such reservoirs.

In the first part, a framework based on an evaluation matrix with 16 economical, environ-

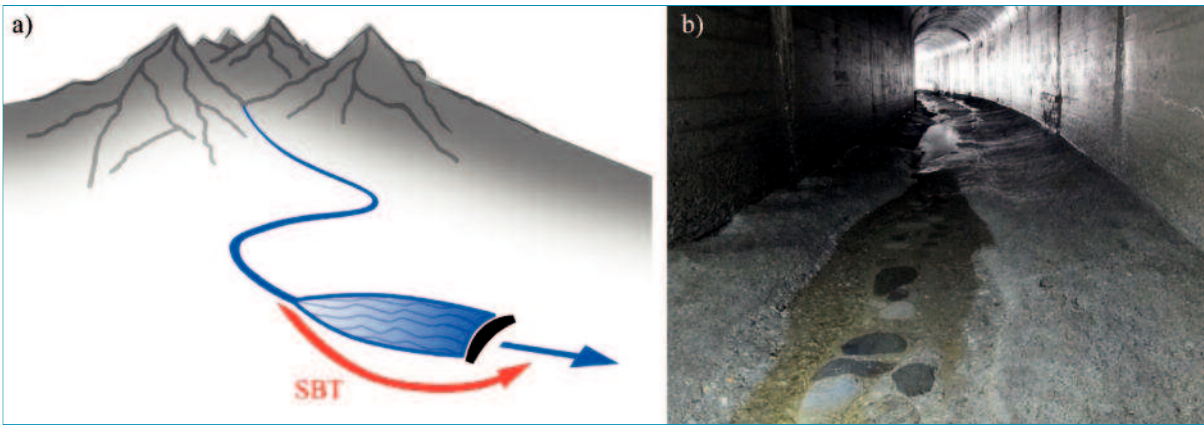

Figure 2. (a) Schematic view of an in-stream reservoir with sediment bypassing[7] and (b) abraded concrete invert of the Runcahez SBT, Switzerland (Photograph: M. Müller-Hagmann, VAW, ETH Zurich)

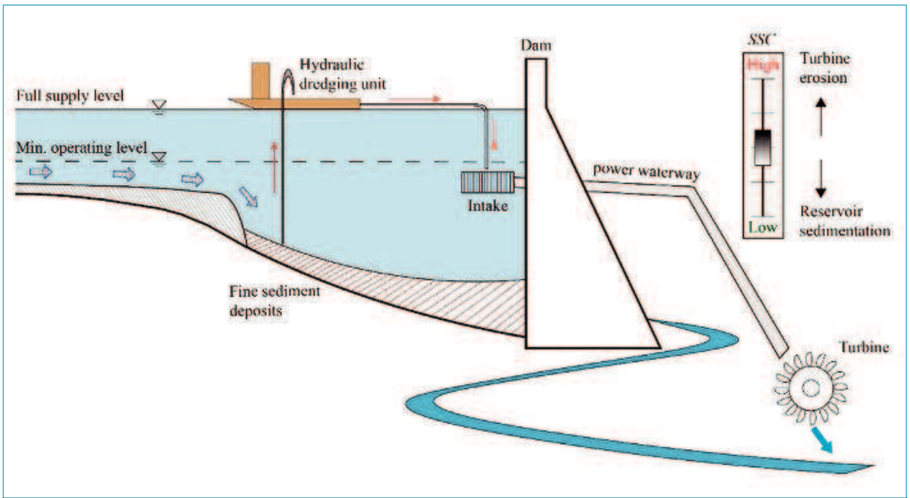

Figure 3. Increasing suspended sediment concentration (SSC) in turbine water as a countermeasure to reservoir sedimentation

mental and social criteria for consistent rating of all potential Swiss sites was developed and applied[2,3]. These criteria include the long-term run-off evolution, natural hazards, sediment continuity, protected areas, the visibility of new dams from populated places and effects on tourism. Seven suitable reservoir sites for new potential hydropower plants (HPPs) were retained, which are estimated to add 1.1 TWh of electricity per year[3]. With these new reservoirs, the intermediate goal of the Swiss Energy Strategy for hydro-electricity in 2035, *i.e.* 37.4 TWh/a, can be met. The infill time of all seven reservoir is 500 years or more, although it highly depends on the future retreat of glaciers. In the second part of the project, suspended sediment concentration (SSC), particle size distribution, bathymetry and flow velocity were investigated in the three Swiss periglacial reservoirs Griessee (Fig. 1), Gebidem and Lac de Mauvoisin with infill times between roughly 30 and 1000 years, to better understand sedimentation processes and delta formation[3]. All three reservoirs suffers from sedimentation problem and countermeasures are needed for their sustainable operation. A combination of water sample analysis, laser *in-situ* scattering and transmissometry (LISST) and Acoustic Doppler Current Profiler (ADCP) was applied in the field measurements. In the last part, a 1-D numerical model was implemented using the software BASEMENT[4] to simulate both the delta formation of coarse sediments and the lake-wide sedimentation from non-stratified (homopycnal) flows. The model was validated with data from the Gebidem Reservoir and then applied to a potential future periglacial reservoir[2,3]. Based on the project findings, implications on future reservoir operations, considering climate change, were discussed[2,3].

Hydroabrasion in high speed flow at sediment bypass tunnels

Sediment bypass tunnels (SBTs) are an effective routing technique to reduce reservoir sedimentation, diverting sediment-laden flow around the dam, thus allowing the re-establishment of the natural sediment continuity along the river (Figure 2a). Moreover, SBTs enhance the operating safety of dams by increasing the outflow capacity, which is not sufficient anymore at many schemes[5,6,7]. Despite these advantages, no guideline for the design and operation of SBTs is available and many SBTs face severe invert abrasion due to high-speed sediment-laden flows, putting SBT operation at risk and causing high maintenance costs (Figure 2b). To address these problems, four research projects have been conducted at VAW. The first project focused on flow characteristics, particle motion, particle and invert material properties, which are governing parameters of hydro-abrasion[6,8,9,10]. The study was conducted in a Froude-scaled laboratory flume modeling the physical processes present in a straight section of SBTs. The findings contributed to a better understanding of the physical processes underpinning hydro-abrasion of SBTs, and led to the modification of an abrasion prediction model[10]. A second and complementary *in-situ* investigation was conducted at three Swiss SBTs[7]. Various invert materials were tested and the obtained data were used to calibrate the above-mentioned abrasion model. Furthermore, the field data contributed to improve and optimize the bypass design and reservoir operations for better bypass efficiency [7]. The findings of both studies led to initiate the third and on-going research project entitled “Hydro-abrasion at hydraulic structures and steep bedrock rivers”[11]. The focus of this project is to investigate the effects of low aspect ratios of channel width to water depth and of sediment hardness and shape on sediment transport and hydro-abrasion in a laboratory flume, mimicking SBTs and high-gradient mountain streams. The fourth project dealt with the morphological effects of SBT operation on downstream river reaches by means of a field study at the Solis SBT in the Canton of Grisons, Switzerland, and by systematic numerical modelling of the SBT sediment pulses and their downstream effects in terms of both bed slope development and bed material composition[12]. The outputs of these projects contribute to establish a general guideline for sustainable and efficient design and operation of SBTs and other hydraulic/civil structures exposed to hydro-abrasion[5,13].

Reduction of reservoir sedimentation by increasing fine sediment transport through turbines

Sediment flushing through dam bottom outlets with water level drawdown is a technique to manage sedimentation problems in small reservoirs. However, this is rarely feasible for large reservoirs due to important water losses. In addition, environmental regulations may limit the admissible suspended sediment concentration (SSC) downstream of dams, or request that sediment transport is not hindered significantly by dams. An option to reduce sedimentation in HPP reservoirs in compliance with such environmental requirements is to increase the transport of fine sediments through power waterways – and hence the turbines – to the downstream river reach[14] (Figure 3). This has the advantages that (i) the SSC downstream of dams and powerhouses is low compared to those during occasional reservoir flushing operations, and (ii) no flushing water is lost for electricity generation. The disadvantage of this option is that turbines are exposed to higher sediment loads which may intensify hydro-abrasive wear. Turbine wear can be mitigated by appropriate turbine design and coatings as well as by limiting the SSC and particle sizes in the turbine water.

The topic of turbine erosion and its negative effects (*e.g*. reduced turbine efficiency, production losses, increased maintenance costs) have been investigated since 2012 in the scope of an interdisciplinary research project at the high-head HPP Fieschertal in the Swiss periglacial environment. Various techniques for monitoring of suspended sediment load, turbine erosion and efficiency changes were tested and further developed [15,16]. Based on the acquired data, an analytical erosion model[17] was adapted and calibrated for coated Pelton buckets[15]. This model can be used to estimate acceptable SSCs and particle sizes for the option of increasing the fine sediment transport through power waterways and turbines. By this way, the negative effects of reservoir sedimentation and turbine erosion can be balanced in order to maximize the profitability and maintain the operational flexibility of storage hydropower schemes.

Dr. Ismail Albayrak is a research scientist and lecturer at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich since 2011. He received his MSc. in hydraulic engineering from Istanbul Technical University in 2003 and his PhD in the field of environmental hydraulics at the Federal Institute of Technology in Lausanne (EPFL) in 2008.

Dr. David Felix joined the VAW of ETH Zurich as a teaching assistant and scientific collaborator in 2010. From 2012 to 2017 he focused on the PhD-project on turbine erosion described in the present article. He continues working on suspended sediment and turbine erosion as a postdoctoral researcher.

Dr. Lukas Schmocker joined the hydropower team of the Swiss Competence Centre of Energy Research – Supply of Electricity (SCCER-SoE) in 2014 with a research focus on hydropower production and infrastructure adaption. In parallel, he is working as a project manager in flood management at the consulting company Basler & Hofmann.

Dr. Robert M. Boes is Professor of hydraulic structures and Director of the VAW at ETH Zurich. His research works focus on sustainable hydropower, reservoir sedimentation and flood propagation, among others. He was formally the head of the Dam Construction Group at TIWAG-Tiroler Wasserkraft AG, an Austrian utility.

The sediment load in the power waterway may be increased by hydraulic dredging (pumping) of previously settled fine sediment in the vicinity of the turbine water intakes (Figure 3). The flow rate in the dredging pipe is regulated in such a way that the SSC in the turbine water is acceptably low. The particle size may be limited by the suitable selection of dredging area (sufficiently distant from the reservoir inflow), as well as by screens or settling tanks on the dredging boat.

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