HOW RESERVOIRS PRESERVE THEIR POTENTIAL

Little strokes fell big oaks – and this also applies to the Alps: Due to weather-related erosion, stones, gravel, sand, and silt enter the reservoirs and reduce the storage volume. A research team from the Swiss Federal Institute of Technology in Zurich has now proven that sediment bypass tunnels can significantly mitigate the sedimentation problem.

Klaus Jorde is head of the research program on hydropower at the Swiss Federal Office of Energy and has extensive experience as a consultant on hydropower projects worldwide. One problem he encounters repeatedly is the increasing sedimentation of reservoirs: «The influx of stones, gravel, and fine sediments reduces the storage volume of reservoirs over the years, thus diminishing the potential for energy storage. Worldwide, more storage volume is lost due to sedimentation than gained through the construction of new reservoirs,» says Jorde. The extent to which a reservoir is affected by sedimentation depends on numerous factors such as geology and erosion in the catchment area, transport capacity of the inflow, size of the reservoir, and average residence time of the water in the reservoir. Certain reservoirs face significant sedimentation issues after just a few years, while others still have no problem even after 100 years.

Silting of reservoirs is also a pressing issue in Switzerland. According to a recent study by the United Nations University in

The Solis reservoir in the canton of Grisons was built between 1982 and 1986 at a cost of 25 million Swiss francs (CHF) at the time and lost half of its storage volume in the following 30 years, even though gravel was regularly dredged at the inlet of the reservoir. To remedy the situation, a 37 million CHF sediment bypass tunnel was put into operation in 2012, which diverts stones, gravel, sand and fine sediment around the dam to counteract sedimentation. The inlet of the tunnel can be seen in the photo below, left. View against the direction of flow of the Albula River. Photo: Ismail Albayrak

A technical report about the results of a research project in the field of hydropower, which is financially supported by the Swiss Federal Office of Energy. The report has been published on ee-news.ch (October 2023).

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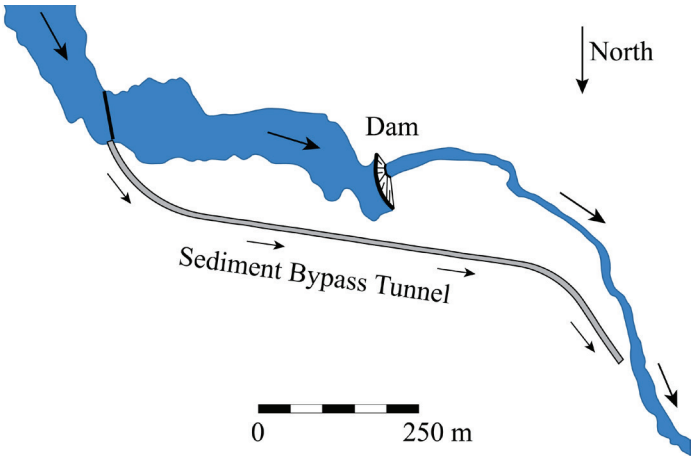


The bypass tunnel begins in the reservoir. Other bypass tunnels take in sediment-laden water already at the inlet of the reservoir, which is very effective, but results in higher construction costs because the tunnel must be longer. Illustration: RESEMO final report

Stones, gravel, sand and fine sediments are returned to the Albula via the sediment bypass tunnel without being deposited in the Solis reservoir. View against the direction of flow of the Albula River. Photo: VAW

Canada, Swiss reservoirs will lose 33% of their storage volume to sedimentation by the year 2050. However, Prof. Robert Boes, director of the Laboratory of Hydraulics, Hydrology, and Glaciology (VAW) at the Swiss Federal Institute of Technology (ETH) Zurich, assesses the situation differently: «Based on our estimation, the average sedimentation will not be as high. However, we do see some reservoirs that already have problems with significant sediment deposits and that require urgent solutions.» Sedimentation not only reduces the storage volume but can also become a safety issue if the deposits reach the dam and block the inlets or outlets through which water is extracted or discharged from the reservoirs, especially during critical situations.

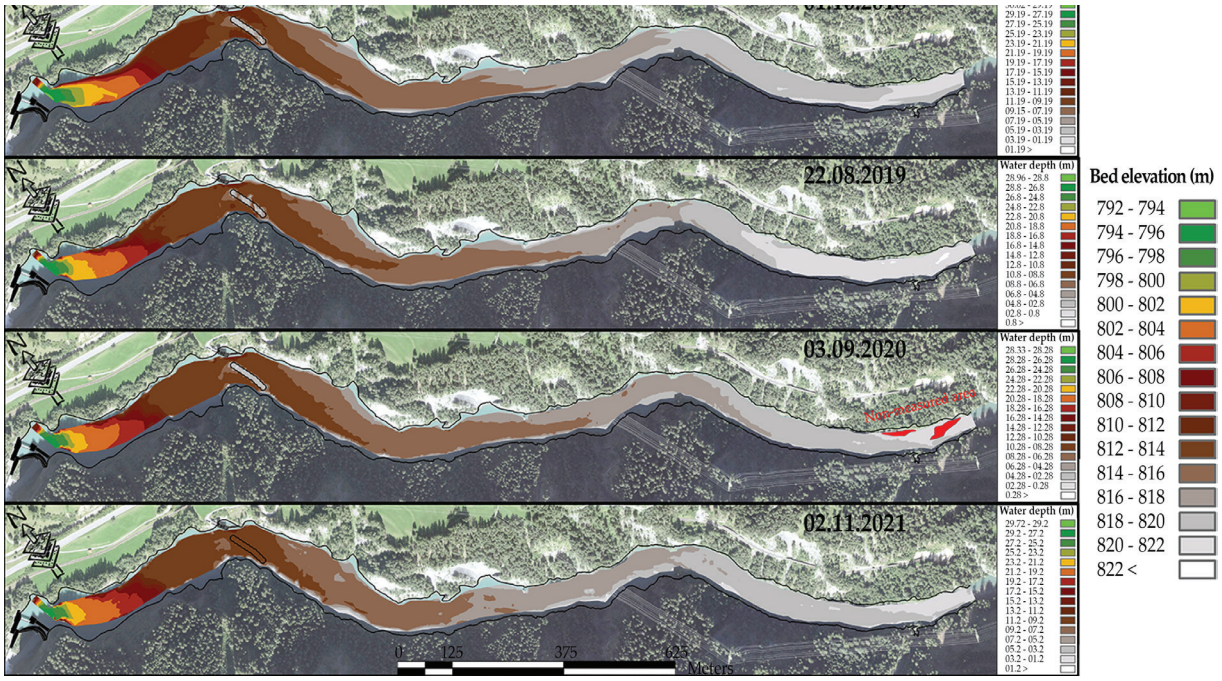
The ETH researchers carried out a two-day measurement campaign on the Solis reservoir in October 2018, August 2019, September 2020 and November 2021, respectively. Among other things, the height of the reservoir bed, i.e. the bathymetry, and the water flow velocities in the reservoir were determined and samples containing suspended matter and sediment deposits were taken and analyzed. The corresponding measuring instruments were mostly placed on a remote-controlled boat. Photo: Final report RESEMO

Keeping sediment away from reservoirs

The Solis reservoir below Tiefencastel in the canton of Graubünden was long-known for its sedimentation problem. Calculations had shown that the Albula River carries so much sediment into the reservoir so that it could no longer be used after 20 years. For this reason, the Zurich Municipal Electric Utility (ewz), which operates the reservoir through the Mittelbünden power plants, constructed a so-called sediment bypass tunnel. It was put into operation in 2012. The 968-meter-long tunnel diverts sediment-laden inflow (see textbox below) around the reservoir. As a result, the amount of stones, gravel, sand and silt that would normally accumulate in the reservoir basin has been drastically reduced. Instead, it is naturally flushed downstream by the Albula River through the bypass tunnel. The bypass tunnel is only in operation during flood discharges when large amounts of water

SEDIMENT

The term ‹sediment› includes mineral particles of all sizes: the large ones (stones, gravel, coarse sand) are transported as bedload on the river bed. Finer sediment (finer sand, silt, clay) remains mostly suspended in the water column. Sediments and floating materials (mainly wood) are included in the term ‹solids›.



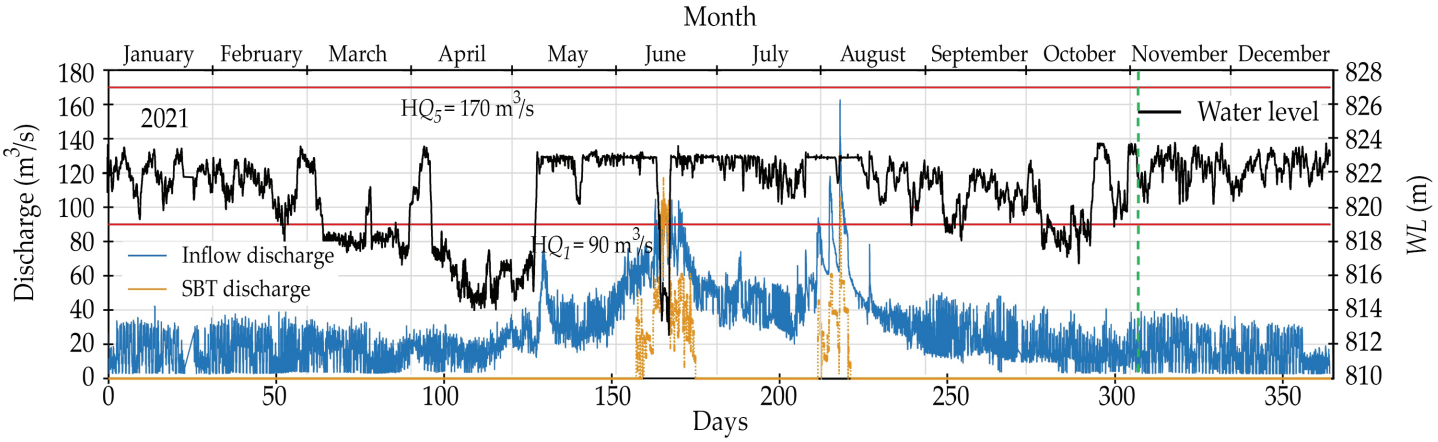
The color scale illustrates the elevation of the Solis reservoir bed during the study period from 2018 to 2021. Flow direction of the Albula River is from right to left. Illustration: RESEMO final report

and sediment are transported from upstream mountainous areas to the reservoir.

For the past ten years, a research team from VAW has been investigating the efficiency of the Solis sediment bypass tunnel and whether there are any optimization possibilities to be considered when constructing new bypass tunnels. The researchers have employed sophisticated methods to reliably determine the amount of sediment in a mountain stream and the sediment inflow into the reservoir. The project received financial support from the SFOE.

Sedimentation massively reduced

The multi-year measurements show that from October 2018 to November 2021, nearly 50,000 cubic meters of sediment were deposited in the reservoir. In the same period, approximately 200,000 cubic meters of sediment were diverted around the reservoir through the sediment bypass tunnel. Without the tunnel, the reservoir bed would have risen by an average of about 1 meter during that time. In other words, thanks to the bypass tunnel, only 12% of the sediment contained in the inflow settled in the reservoir, compared to 83% without the tunnel (the remaining 17% would have been



Solis reservoir in the operating year 2021: The graph shows the discharge of the Albula River at the mouth into the reservoir (blue) as well as the discharge through the bypass tunnel (orange). The graph shows that the bypass tunnel was in operation during two rainy periods in June and early August with discharges up to 162 m³/s. In mid-June, the operator temporarily lowered the reservoir water level significantly (black line), which caused the bypass tunnel to discharge significantly more sediment. Graphic: RESEMO final report

MEASURES TO REDUCE RESERVOIR SEDIMENTATION

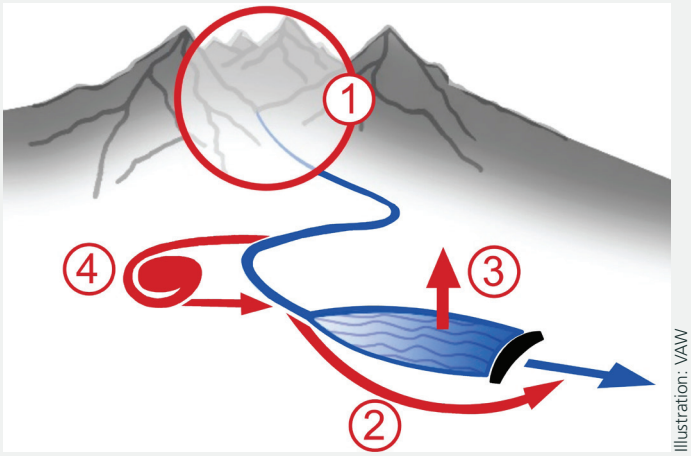


Illustration: VAW

The construction of bypass tunnels is a way to mitigate reservoir sedimentation. There are other methods against sedimentation that are currently being tested or are already in use:

1. Measures upstream of the reservoir can help reduce the influx of sediments into the reservoir. For example, erosion in the catchment area can be reduced through reforestation. Stones, gravel, and sand can also be intercepted with sediment retention barriers, i.e. check-dams (which need to be regularly emptied). Another option could be the creation of an additional ‹desanding lake› downstream of glaciers, where sediments naturally settle before reaching downstream reservoirs.

2. Sediment bypass tunnels convey the sediments around the reservoir to the downstream river reach. In Switzerland, twelve bypass tunnels are in operation at small and medium-sized reservoirs.

3. Sediments can be dredged, pumped out, or flushed out from the reservoir. For example, the small Gibidum reservoir in the canton of Valais is emptied every one to two years, and the sediments are thereby flushed out. The possibility of turbining water containing fine sediments (as in Bolgenach/Vorarlberg) is currently not widely used but could be an option in the future if the corresponding research projects are successful.

4. Structural modifications are also possible, such as heightening a dam to increase the storage volume and compensate for the water volume lost due to sediments. This was done, for example, in 1989/91 at Lac de Mauvoisin in Valais. For new facilities, it might be advantageous to build them in neighboring valleys and to capture the water of the main waterway and only restitute it after desilting. In this way, sediments can be efficiently kept away from the reservoir.

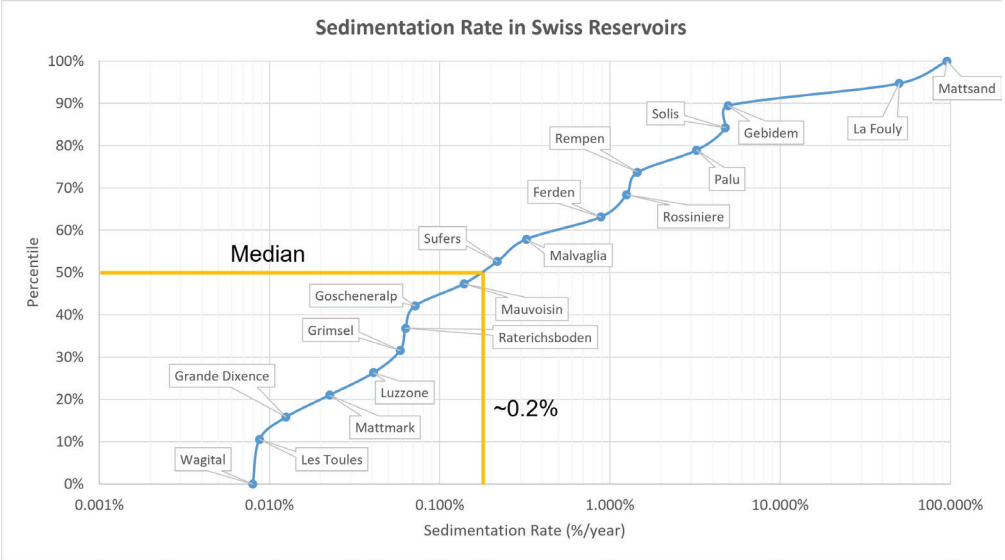
conveyed via turbine water or dam outlets). As a result of this measure, the annual sedimentation has been reduced from 81,000 m^3 to 17,000 m^3.

The effectiveness of sediment bypass tunnels has been already known for some time. However, the new findings are particularly interesting because the Solis bypass tunnel receives the sediment-laden water not at the inlet of the reservoir but in the middle of the reservoir (and from there diverts it around the dam). «We have demonstrated that this type of sediment bypass tunnel also has an efficiency comparable to other bypass tunnels in Switzerland or, for example, in Japan,» says project leader and VAW researcher Ismail Albayrak.

Recommendations for operators

The Albula River is impounded shortly after Tiefencastel by the Solis dam. The distance between the mouth of the reservoir and the inlet of the sediment bypass tunnel is over two kilometers. When the mountain river carries sediments into the reservoir, the sediment-laden flow is slowed down by the reservoir water. The higher the water level, the slower the sediment transport. This means that reservoir operator can accelerate the sediment transport from the backwater area to the inlet of the bypass tunnel by lowering the water level. Furthermore, if the water level is sufficiently lowered, the incoming Albula River can even erode sediments that were previously deposited in the reservoir, transporting them to the bypass tunnel. Consequently, more sediment can be diverted through the tunnel than the Albula River transports into the reservoir during the same period.

In mathematical terms, this means that the bypass tunnel now operates with an efficiency of over 100%. The ETH researchers have shown that under favorable operating conditions (low reservoir water level), the efficiency can reach up to 250%. The bypass tunnel now functions as a system that «sucks out» sediments from the reservoir, thereby incre-



The graph shows the sedimentation rate (sediment deposited per year compared to the reservoir volume) for selected Swiss reservoirs by taking into the account possible sediment management measures. The logarithmic x-axis shows that the sedimentation rate of the large Grande Dixence reservoir in Valais, for example, is only about 0.02 %, while it is about 5 % per year for the Solis reservoir. The blue curve illustrates the frequency distribution (y-axis): For half of the reservoirs considered, the sedimentation rate is above 0.2 %, for the other half it is below (orange mark). It should be noted that the sedimentation rate alone is only one of several indicators of how quickly (further) measures need to be taken against sedimentation. Graphic: Dahal (2022)/VAW with data from Beyer Portner and Schleiss (1998).

asing its storage volume. Based on these observations, the scientists can provide precise guidelines to the operator of the Solis reservoir: «For high efficiencies between 70 % and 250%, the minimum water level should be 813 meters above sea level,» states the project›s final report.

New research approaches are needed

Sediment bypass tunnels can effectively mitigate reservoir sedimentation, as demonstrated by the Solis example. However, the technical solution also has its disadvantages: Due to significant costs, bypass tunnels are only feasible for smaller reservoirs. Moreover, it is economically unfavorable that water diverted through the tunnels cannot be used for power generation.

Therefore, additional approaches are needed to counteract reservoir sedimentation. One such approach is being investigated by ETH researchers at the Bolgenach reservoir in Vorarlberg: Fine sediments deposited in the reservoir are pumped up from the reservoir bed and added to the water used for electricity production in small doses. The researchers aim at determining the maximum permissible sediment concentration and particle sizes so that both turbine erosion and reservoir sedimentation can be reduced, allowing for efficient and sustainable power plant operation.

- The **final report** of the project ‹Reservoir sedimentation, management and operation at the case study reservoir Solis› (in short: RESEMO, in German: ‹Stauraumverlandung, -management und -betrieb am Fallbeispiel Stausee Solis›) is available at: https://www.aramis.admin.ch/Texte/?ProjectID=41723
- For **information** on the project, please contact Klaus Jorde (klaus.jorde@kjconsult.net), external head of the SFOE Hydropower Research Program.
- Further **technical papers** on research, pilot, demonstration and flagship projects in the field of hydropower can be found at www.bfe.admin.ch/ec-wasser.

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