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NAWARE – Sustainable storage hydropower for a resilient future energy system

NAWARE – Nachhaltige Speicherwasserkraft für ein resilientes Energiesystem der Zukunft

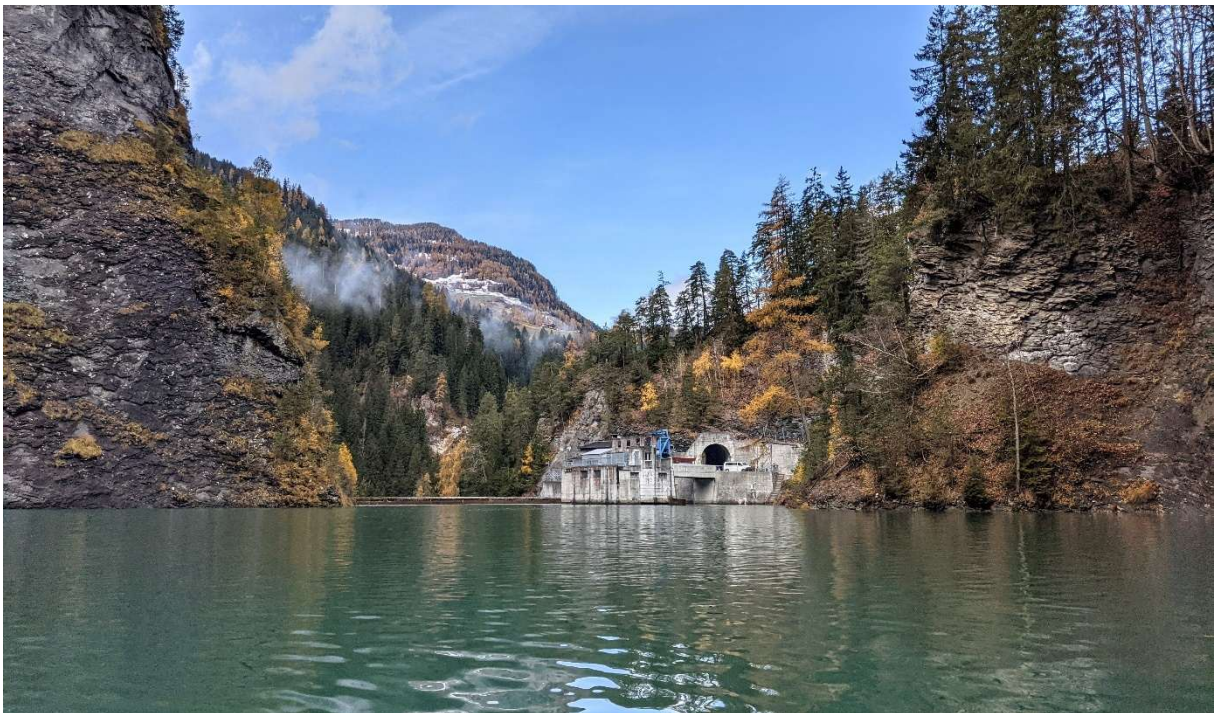


Photo: Solis reservoir (VAW 2021)



ETH zürich



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ETH Zürich
Laboratory of Hydraulics, Hydrology and Glaciology (VAW)
Hönggerberggring 26
CH-8093 Zürich
vaw.ethz.ch

Authors:

Dr. Sudesh Dahal, VAW, dahal@vaw.baug.ethz.ch
Dr. Frederic Evers, VAW, evers@vaw.baug.ethz.ch
Prof. Dr. Robert Boes, boes@vaw.baug.ethz.ch

SFOE project coordinators:

Dr. Michael Moser, michael.moser@bfe.admin.ch
Dr. Klaus Jorde, klaus.jorde@kjconsult.net

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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.



Summary

For decades, hydropower has been an important pillar of the Swiss electric power system, flexibly providing both generation of electric energy and its storage. Simultaneously to the deployment of new renewables including solar and wind in line with the Swiss Energy Strategy 2050, considerable efforts are necessary to maintain hydropower's role as the backbone of an increasingly volatile electric power system. Among other factors, reservoir sedimentation has a negative impact on hydropower storage capacities. Using a sedimentation rate of 0.2% p.a. derived by previous studies, the Swiss Federal Office of Energy (SFOE) forecasted a loss in hydropower energy storage capacity of about 7% (~620 GWh) from 2019 to 2050. This project aims at reducing the uncertainties related to the assessment of reservoir sedimentation with long-term numerical simulations including the effects of climate change and different sediment management strategies.

An enhanced 1D numerical model is used to investigate dynamic processes of reservoir sedimentation and to evaluate the effectiveness of different sediment management strategies. The bypassing efficiency of a type-B Sediment Bypass Tunnel (SBT) is found to be sensitive to reservoir operation, and can be optimized based on the timing of opening of the SBT inlet relative to a flood wave. For non-glaciated Swiss catchments, the average sediment yield computed solely as a function of river discharge is estimated to decline slightly for increasing climate change severity. However, severe climate scenarios include the risk of extreme flood events, thus posing a wide range of uncertainty. A properly planned sediment management strategy (e.g., bypassing, sediment relocation within the reservoir, excavation, adaptive operation) can be effective in mitigating further impacts of sedimentation, and a methodology is demonstrated to quantify the sediment management effectiveness that can support optimization process.

Based on observed data from Swiss reservoir and enhanced by numerical simulations, an advanced methodology is proposed to conduct regional estimates of reservoir sedimentation rates and hydropower storage capacities, which includes a new multi-parameter equation for sediment trapping efficiency. For the largest 35 Swiss reservoirs accounting for 95% of hydropower storage capacity, the weighted average sedimentation rate is estimated as 0.059% p.a. and the hydropower storage potential as of 2025 is computed as 8000 GWh considering the loss of active storage due to sedimentation. The hydropower storage loss rate, distinguished from the gross sedimentation rate, is estimated as 0.053% p.a., forecasting a loss of 1.59% or 127 GWh in the next 30 years.

Zusammenfassung

Seit Jahrzehnten ist die Wasserkraft ein wichtiger Pfeiler des Schweizer Stromsystems, da sie sowohl die Erzeugung als auch die Speicherung von elektrischer Energie flexibel ermöglicht. Parallel zum Ausbau neuer erneuerbarer Energien wie Solar- und Windenergie im Einklang mit der Schweizer Energiestrategie 2050 sind erhebliche Anstrengungen erforderlich, um die Rolle der Wasserkraft als Rückgrat eines zunehmend volatilen Stromsystems aufrechtzuerhalten. Unter anderem wirkt sich die Verlandung von Stauseen infolge Feststoffeintrags negativ auf die Speicherkapazitäten der Wasserkraft aus. Unter Verwendung einer aus früheren Studien abgeleiteten Verlandungsrate von 0.2% p.a. prognostizierte das Bundesamt für Energie (BFE) einen Verlust der Speicherkapazität der Wasserkraft von etwa 7% (~620 GWh) zwischen 2019 und 2050. Dieses Projekt zielt darauf ab, die Unsicherheiten bei der Bewertung der Verlandung von Stauseen durch langfristige numerische Simulationen zu verringern, wobei die Auswirkungen des Klimawandels sowie verschiedener Strategien der Feststoffbewirtschaftung berücksichtigt werden.

Ein verbessertes 1D-Numerikmodell wird verwendet, um dynamische Prozesse der Verlandung in Stauseen zu untersuchen und die Wirksamkeit verschiedener Feststoffbewirtschaftungsstrategien zu bewerten. Die Effizienz eines Sedimentumleitstollens (engl. *Sediment Bypass Tunnel*, kurz: SBT) vom Typ B ist empfindlich gegenüber dem Stauseebetrieb und kann auf der Grundlage des Zeitpunkts der



Öffnung des SBT-Einlasses im Verhältnis zu einer Hochwasserwelle optimiert werden. Für nicht vergletscherte Schweizer Einzugsgebiete wird geschätzt, dass der durchschnittliche Sedimenteintrag, der ausschließlich als Funktion des Zuflusses berechnet wird, mit zunehmendem Fortschritt des Klimawandels leicht zurückgehen wird. Allerdings bergen extreme Klimaszenarien das Risiko extremer Hochwasserereignisse und sind daher mit einer großen Unsicherheit behaftet. Eine gut geplante Feststoffbewirtschaftung (z. B. Umleitung, Sedimentverlagerung im Stausee, Aushub, adaptiver Betrieb) kann weitere Auswirkungen der Verlandung wirksam mindern, und es wird eine Methodik zur Quantifizierung der Wirksamkeit der Feststoffbewirtschaftung vorgestellt, die den Optimierungsprozess unterstützen kann.

Auf der Grundlage von Messwerten an Schweizer Stauseen und unterstützt durch numerische Simulationen wird eine erweiterte Methodik zur regionalen Schätzung der Verlandungsraten in Stauseen und der Speicherkapazitäten für Wasserkraft vorgeschlagen, die eine neue, mehrere Parameter berücksichtigende Gleichung für das Sedimentrückhaltevermögen umfasst. Für die 35 größten Schweizer Stauseen, die 95% der Wasserkraftspeicherkapazität ausmachen, wird die gewichtete durchschnittliche Verlandungsrate auf 0.059% p.a. geschätzt und das Wasserkraftspeicherpotenzial für 2025 unter Berücksichtigung des Verlusts an aktiver Speicherkapazität aufgrund Feststoffeintrags auf 8000 GWh berechnet. Die Speicherkapazitätsverlustrate der Wasserkraft, die sich von der Bruttoverlandungsrate unterscheidet, wird auf 0.053% p.a. geschätzt, was einem Verlust von 1.59% bzw. 127 GWh in den nächsten 30 Jahren entspricht.

Résumé

Depuis des décennies, l'énergie hydraulique est un pilier important du système électrique suisse, assurant à la fois la production et le stockage d'énergie électrique de manière flexible. Parallèlement au déploiement de nouvelles énergies renouvelables, notamment solaire et éolienne, conformément à la stratégie énergétique suisse 2050, des efforts considérables sont nécessaires pour maintenir le rôle de l'énergie hydraulique en tant que pilier d'un système électrique de plus en plus volatile. Entre autres facteurs, la sédimentation des réservoirs a un impact négatif sur les capacités de stockage de l'énergie hydraulique. Sur la base d'un taux de sédimentation de 0.2 % par an, calculé à partir d'études antérieures, l'Office fédéral de l'énergie (OFEN) a prévu une perte de capacité de stockage d'énergie hydroélectrique d'environ 7% (~620 GWh) entre 2019 et 2050. Ce projet vise à réduire les incertitudes liées à l'évaluation de la sédimentation des réservoirs grâce à des simulations numériques à long terme incluant les effets de changement climatique et de différentes stratégies de gestion des sédiments.

Un modèle numérique 1D amélioré est utilisé pour étudier les processus dynamiques de sédimentation dans les lacs de retenue et évaluer l'efficacité de différentes stratégies de gestion des sédiments. L'efficacité de dérivation d'une galerie de dérivation des sédiments (en anglais *Sediment Bypass Tunnel*, SBT) de type B est sensible à l'exploitation du réservoir et peut être optimisée en fonction du moment d'ouverture de vanne à l'entrée du SBT par rapport à une onde de crue. Pour les bassins versants suisses non glaciaires, on estime que le rendement sédimentaire moyen, calculé uniquement en fonction du débit fluvial, diminuera légèrement à mesure que le changement climatique s'aggraverait. Cependant, les scénarios climatiques extrêmes comportent un risque d'inondations extrêmes et sont donc associés à une grande incertitude. Une stratégie de gestion des sédiments bien planifiée (par exemple, dérivation, déplacement des sédiments dans le réservoir, dragage, exploitation adaptative) peut atténuer efficacement les effets supplémentaires de la sédimentation, et une méthodologie permettant de quantifier l'efficacité de la gestion des sédiments est présentée, qui peut soutenir le processus d'optimisation.

Sur la base des mesures effectuées dans les lacs de retenue suisses et à l'aide de simulations numériques, une méthodologie avancée est proposée pour réaliser une estimation régionale des taux de sédimentation des réservoirs et des capacités de stockage hydroélectrique, qui comprend une nouvelle équation multiparamétrique pour l'efficacité de rétention des sédiments. Pour les 35 plus grands réservoirs suisses, qui représentent 95 % de la capacité de stockage hydroélectrique, le taux de



sédimentation moyen pondéré est estimé à 0.059 % par an et le potentiel de stockage hydroélectrique à l'horizon 2025 est calculé à 8000 GWh, en tenant compte de la perte de stockage actif due à la sédimentation. Le taux de perte de stockage hydroélectrique, qui se distingue du taux de sédimentation brut, est estimé à 0.053 % par an, ce qui laisse prévoir une perte de 1.59 % ou 127 GWh au cours des 30 prochaines années.



Main findings («Take-Home Messages»)

The main findings of this study are briefly outlined below:

- Numerical modelling allows for an efficient investigation of reservoir sedimentation dynamics and evaluation of the effectiveness of different sediment management strategies. The main challenges in 1D modelling are related to geometry updating under high magnitude of bed level changes associated with simultaneous bedload and suspended load processes. The most important parameters are the sediment inflow equations, sediment grain size distribution, and approach for sediment exchange between bed and suspension.
- The bypassing efficiency of a type-B Sediment Bypass Tunnel (SBT) is governed by the reservoir water level and the timing of opening of the SBT inlet relative to a flood wave. A marginal cost-benefit analysis can be done to optimise the SBT operation mode considering the costs of no energy generation during SBT operation and the benefits of additional peak energy generation potential with enhanced active storage.
- For the case of non-glaciated catchments in Switzerland, if sediment yield is solely estimated as a function of river discharge, then the degree of sedimentation slightly reduces with increasing severity of climate change scenario, i.e., the RCP8.5 climate scenario leads to slightly less sedimentation than the RCP4.5 and RCP2.6 scenarios. However, the range of uncertainty within each RCP scenario widens with the climate scenario severity.
- A novel equation for the sediment trapping efficiency is developed based on multiple parameters related to catchment and reservoir characteristics. Then, an improved methodology is showcased to conduct regional estimations of sedimentation rates and hydropower storage capacities by segregating the sediment deposition in active and inactive zones. The application to the Swiss fleet of reservoirs yields a weighted average sedimentation rate of 0.059% p.a. and a hydropower energy storage capacity of 8000 GWh as of 2025. The loss in hydropower storage capacity is estimated as 0.053% p.a., forecasting a loss of about 1.6% or almost 130 TWh in the next 30 years.



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List of abbreviations

BTR	Bedload to Total-load Ratio
CIR	Capacity Inflow Ratio
RDR	Reservoir Drawdown Ratio
TE	Trapping Efficiency
SFOE	Swiss Federal Office of Energy
SBT	Sediment Bypass Tunnel
SME	Sediment Management Effectiveness
SSP	Shared Socioeconomic Pathways
VAW	Laboratory of Hydraulics, Hydrology and Glaciology



1 Introduction

1.1 Overview of this report

This report is prepared as an executive summary of the doctoral thesis titled “Sedimentation management in Alpine reservoirs for sustainable hydropower under climate change” written by Dr. Sudesh Dahal at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich. The thesis report is attached as an Appendix of this report. A brief summary of the main findings of the thesis is provided hereafter.

1.2 Background and motivation

Reservoirs are vital hydraulic infrastructure worldwide for water storage that can be used for multiple purposes such as energy generation, water supply, irrigation, flood control, and other purposes. However, their sustainable operation is increasingly challenged by sedimentation, which leads to a reduction in water storage capacity alongside dam safety issues associated with rise in sediment levels up to the dam outlets (Morris and Fan 1998). The global rate of storage loss due to sedimentation is estimated to be in the range of 0.5 to 1% per year (Basson 2009).

Switzerland is home to more than 200 large reservoirs, supplying roughly 56% of annual hydropower generation and providing seasonal storage to regulate winter energy demand. The sedimentation rate in Swiss reservoirs is estimated as 0.2% of storage capacity lost per year (Schleiss et al. 2016). Although this rate does not seem alarming, it is important to consider sedimentation issues as Switzerland’s electricity is heavily reliant on hydropower, mostly supplied by storage reservoirs (Boes et al. 2021). Moreover, the sediment yields of Alpine watersheds are expected to intensify due to the combined effects of climate change and human activities (Syvitski 2003; Guillén-Ludeña et al. 2018).

Despite remarkable advancements, several gaps remain in the current state-of-the-art concerning the investigation of reservoir sedimentation and its countermeasures for sustainable reservoir operation. The commonly cited Swiss sedimentation rate of 0.2% per year is based on a median value of largely varying reservoirs, and may yield unreliable estimates of the total energy storage capacity in Switzerland. Numerical investigation of sedimentation management in mountain terrain poses several challenges related to hydraulic flow transitions, geometry updating, and integration of fluxes associated with sediment management. Existing practices of estimating sediment trapping efficiency are primarily governed by a single parameter, which may not adequately represent the sedimentation dynamics inside a reservoir.

A comprehensive understanding of reservoir sedimentation processes is therefore essential to assess long-term storage availability and to investigate sustainable sediment management strategies, i.e., the measures to manage sediment (e.g., by removal, routing, etc.) to extend the service life of a reservoir. Numerical models offer a feasible and practical tool for such studies. They can be applied to test different scenarios of sediment management, and the results can be further analysed for economic optimisation. Moreover, future long-term simulations under climate change scenarios can be conducted to estimate the temporal evolution of reservoir storage capacities.

The motivation behind this study, including the knowledge gaps, is explained in detail in Chapter 1 of the Appendix.



1.3 Objectives

The main objective of this study is to advance the knowledge of reservoir sedimentation and sediment management strategies under climate change scenarios through the application of numerical modelling based on high-quality field data, with a particular focus on Swiss case studies. The findings are ultimately used to develop a methodology to derive generalized estimates of reservoir sedimentation and hydropower storage in a region, with an application to Switzerland. The specific objectives of this study are outlined in Chapter 1 of the Appendix.

2 Methodology

Two Swiss case study sites are selected for detailed investigations in this study: Solis and Gigerwald reservoirs. Solis is a daily to weekly compensation reservoir constructed in 1986 with 4.1 Mm³ initial gross storage, that has been equipped with a type-B Sediment Bypass Tunnel (SBT) since 2012. Gigerwald is a seasonal storage reservoir constructed in 1978 with an initial gross storage of 35 Mm³. The data required for numerical modelling were mostly obtained from the respective dam operators, and partly by conducting field measurements.

Solis reservoir has been impacted by a large amount of sedimentation since its construction. The available bathymetry datasets of 1998 and 2001 are referred for the calibration of a 1D numerical model to represent the governing sedimentation processes. Then, an SBT operation event during a 5-year flood in June 2018 is referred for the investigation of fluxes associated with SBT operation and validation of the 1D numerical model for representing the sediment bypassing processes. A novel equation is derived for the estimation of bedload bypassed through the SBT, which facilitates the integration of SBT operation processes into the 1D numerical model. For the Gigerwald reservoir, sedimentation from 2005 to 2008 is adopted for model calibration, and a period of 2018 to 2019 is selected for model validation.

Different scenarios of SBT operation are formulated for the Solis reservoir based on varying timings and durations relative to a flood wave. These scenarios are numerically simulated using the validated 1D model to quantify the SBT efficiency and change in active storage. The results are eventually used to conduct a marginal cost-benefit analysis to identify the optimum scenario of SBT operation corresponding to a set of base energy and peak energy prices.

Climate change scenarios for the Solis and Gigerwald reservoirs are referred from the Hydro-CH-2018-Runoff ensemble (Muelchi et al. 2021). Three different scenarios based on the degree of greenhouse gas emissions are investigated: RCP2.6, RCP4.5, and RCP8.5. Each scenario includes a wide range of climate models that are analysed to derive three different representative models for each scenario: R-mean, R-max, and R-min, representing the mean, maximum, and minimum sediment yield computed based on transport capacity. Then, numerical simulations of sedimentation are conducted until the end of this century (2100) for both reservoirs by using the boundary conditions of water and sediment inflows corresponding to each climate scenario. Furthermore, different scenarios of sediment management (SBT operation, excavation, sediment relocation, etc.) are simulated and the results are analysed to evaluate the sediment management effectiveness (SME) computed as the percentage reduction of an impact relative to the impact without sediment management.

Finally, a methodology is showcased for conducting estimations of reservoir sedimentation and its impacts on hydropower storage in a regional fleet of reservoirs. Three parameters are found to be correlated with the sediment Trapping Efficiency (TE) of a reservoir: i) Capacity Inflow Ratio (CIR), computed as a ratio of gross water storage capacity to annual water inflow volume, ii) Bedload to Total Load Ratio (BTR), expressed as a fraction of bedload sediment in the total



sediment inflow, and iii) Reservoir Drawdown Ratio (RDR), representing the degree of reservoir water level fluctuations. Based on these parameters, a novel equation is derived for TE estimates, that allows the estimation of the sedimentation rate for a given sediment input from the respective catchment. The estimation of hydropower storage capacity requires the segregation of the active storage from the gross storage, which is done using equations based on a single variable RDR, derived using the validated numerical model. The overall methodology is applied for the Swiss fleet of reservoirs to quantify the representative sedimentation rate and future total hydropower storage capacity in Switzerland.

The detailed methodology of this study is provided in Chapter 3 of the Appendix.

3 Numerical model enhancement, calibration, and validation

The numerical simulations in this study are conducted using the BASEMENT software that allows simulation of highly unsteady flows with distinct sediment transport modes in arbitrary geometry under varying boundary conditions (Vetsch et al. 2024). Challenges in the existing 1D modelling approach are investigated and addressed by implementing new features in the modelling code. The geometry updating methodology is revised by implementing dynamic ranges for distributing bedload and suspended load across cross-section nodes, which prevents unrealistic geometry after large magnitude of sediment deposition or erosion. The hydraulic stability at river–reservoir transitions is enhanced by damping convective acceleration for Froude numbers close to one. The SBT is represented as an external sink at the cross-section near the tunnel inlet, that bypasses water and sediment based on specified boundary conditions.

The 1D model calibration is successful in both the reservoirs (Solis and Gigerwald) for qualitatively reproducing the longitudinal bed profile evolution and quantitatively matching the sediment volumes. Using another dataset, the calibrated models are also validated to sufficiently reproduce the sedimentation processes. The fluxes associated with SBT operation are well-represented by the external sink in the numerical model. The most sensitive parameters for modelling are identified to be the sediment grain size distribution, the estimation of sediment inflows for both bedload and suspended load, and the approach for sediment exchange between the bed and suspension.

The details of model enhancement, setup, calibration, and validation can be found in Chapters 4 and 5 of the Appendix.

4 Simulation and optimisation of SBT operation scenarios

The validated numerical model of the Solis reservoir is used to simulate different scenarios of SBT operation during the flood wave of June 2019. First category includes a scenario without SBT operation with the aim of quantifying the potential impacts mitigated by the SBT operation. The second category includes three different scenarios with different reservoir water levels during the SBT operation. In the third category, the SBT operation scenarios are formulated with different starting and ending points relative to the flood wave, thus representing different



durations of sediment bypassing. The results of variable durations are also used for a marginal cost-benefit analysis with the view of obtaining the optimum SBT operation scenario considering both technical and economic aspects.

Simulation results indicate that the SBT operation in June 2019 was effective to bypass approximately 89% of the potential sediment volume that would have been otherwise deposited in the reservoir. Scenarios with varying reservoir water levels reveal the dynamic distribution of sediment deposition along the reservoir. Lowering the reservoir water level during type-B SBT operation facilitates the transport of coarser particles and can even mobilize previously deposited sediments toward the SBT inlet. Thus, SBT operation at lower reservoir water level of 813 masl has a higher bypassing efficiency of 73% compared to only 31% and 22% at water levels of 816 and 819 masl, respectively. However, a potential drawback of the higher SBT efficiency is the release of higher sediment concentrations in the downstream reach which might be harmful for aquatic ecosystems.

SBT operation of longer duration leads to higher bypassing efficiency and greater active storage volumes. However, the downside of SBT operation is the reduction in energy generation as the powerplants need to be shut down during that period. Thus, a cost-benefit assessment is important to analyse the trade-off between recovery of active storage capacity and reduction in energy generation. For the Solis SBT, during the 2019 June flood, the optimal SBT operation duration is found to be 178 hours, based on a base energy price of 60 €/MWh and two values of peak energy prices of 300 and 450 €/MWh, respectively. However, the approach to compute the net benefit is highly sensitive to the difference in unit energy prices of base and peak load. For instance, in the price range of 60 and 150 €/MWh, no clear optimum exists in the mentioned price range, as the net-benefit may continuously decline without any inflection point.

The results of all these scenarios and analyses are detailed in Chapter 6 of the Appendix.

5 Future simulation of sedimentation and sediment management under climate change scenarios

Future discharge inflow under climate scenarios for both Solis and Gigerwald reservoirs are computed based on the runoff data from Hydro-CH2018 (Muelchi et al. 2021). Then, the sediment input into the reservoir is computed using the calibrated sediment inflow equations for both bedload and suspended load. For Gigerwald, the dam and reservoir configurations are modified to represent the new outlet structures constructed in 2025, i.e. a bottom outlet at elevation 1254.8 masl and a minimum reservoir operation level at 1280 masl. For both reservoirs, the initial condition is set at 2021 based on the most recent geometry data, then the simulations are targeted to run until 2100.

Results of the Gigerwald reservoir simulations for R-mean models indicate that the average annual deposition rates are 0.077 Mm³/yr for RCP2.6, 0.068 Mm³/yr for RCP4.5, and 0.065 Mm³/yr for RCP8.5. The active storage capacity declines from 28.9 Mm³ in 2021 to 23.5 Mm³ (-18.7%) under RCP2.6, 23.8 Mm³ (-17.7%) under RCP4.5, and 24.1 Mm³ (-16.6%) under RCP8.5 in 2100. This means that the degree of sedimentation is projected to reduce slightly with increasing severity of the climate scenario. Within each RCP, uncertainty ranges represented by the R-min and R-max models are simulated to quantify the impact on sedimentation. The uncertainty in sediment deposition tends to widen with the climate scenario



severity because single floods can dominate cumulative deposition. For example, the R-max model of RCP8.5 features a 623 m³/s flood peak event in 2087 that supplies a substantial amount of sediment dominating the impact of all other smaller floods between 2021 and 2100.

Scenarios of additional sediment management in the Gigerwald reservoir are simulated for the R-mean model of the RCP4.5 scenario to quantify the sediment management effectiveness (SME) and to identify the associated costs. Reducing the threshold sediment concentration (SSC) for shutting down the inflow from the neighbouring Weisstannen valley helps to mitigate the sediment aggradation near the dam at the cost of reduced water supply into the reservoir. For instance, lowering the SSC threshold from 4 g/l to 3 g/l increases the SME from 29% to 38%, associated with a water volume loss of 23% as compared to 17%. Sediment relocation by periodic extra lowering of the reservoir water level is useful to reduce the loss in active storage capacity. For instance, the active storage can be recovered by 14% at the cost of 7.5% less hydropower generation due to relocation operation. Excavation of already deposited sediment seems to be the most favourable option in terms of active storage recovery. A high SME of 69% can be achieved by excavating 30,000 m³/year of sediment from the reservoir during low submergence. However, the practical application of such scenarios could be largely limited by the cost of excavation equipment, accessibility inside the reservoir, and disposal of excavated sediment.

For the Solis reservoir, the inflowing annual sediment volumes under R-mean models are 0.106 Mm³/yr for RCP2.6, 0.081 Mm³/yr for RCP4.5 and 0.096 Mm³/yr for RCP8.5. Simulation results under all RCP scenarios indicate that the delta foreset will advance close to the dam in the near future, i.e. the upcoming decade. This is mainly caused by the settling of suspended sediment particles. In addition, substantial discharges are released through outlets downstream of the SBT inlet during high floods exceeding the SBT discharge capacity (133 m³/s under low water level). These high inflows at low reservoir levels can supply a large amount of sediment towards the delta. The projected years when the toe of the delta foreset reaches the dam are 2031, 2034, and 2035 for the R-mean models of RCP2.6, RCP4.5, and RCP8.5, respectively.

The projected sediment supply into the Solis reservoir under RCP4.5 has a wide uncertainty range represented by its R-min and R-max climate models (-62% to +148% around the R-mean model). The range is widest for RCP8.5, followed by RCP4.5, and then RCP2.6. The uncertainty range for RCP2.6 is -52% to +80% around the R-mean model.

The results of all the climate scenario simulations are explained in detail with illustrations in Chapter 7 of the Appendix.

6 Reservoir sedimentation and hydropower storage in Switzerland

A new methodology is demonstrated to estimate the reservoir sedimentation rate and hydropower storage capacity in a regional fleet of reservoirs. The methodology is based on different reservoirs of Switzerland, with an aim to derive a Swiss-wide overview. In absence of sufficient field data, additional data are generated by numerical modelling of multiple synthetic reservoirs based on the validated numerical model of the Gigerwald reservoir. Using those data, a new equation for sediment trapping efficiency (TE) is derived as a function of three different parameters: CIR, BTR, and RDR.

Thirty-five reservoirs of Switzerland are found to contribute about 95% of the national hydropower energy storage capacity, and are thus selected for further analysis. The new TE



equation is applied to those 35 reservoirs based on the known values of CIR, BTR, and RDR. In absence of reliable sediment yield data, the approach of Schröder and Theune (1984) is applied to derive a range of sediment yields for each reservoir. The sedimentation rates in the 35 reservoirs are computed using the estimated sediment yield and the newly computed TE. Based on weighting by gross water storage capacities, the weighted average sedimentation rate of those 35 reservoirs is found to be 0.059% p.a., within an uncertainty range of 0.018 to 0.1% p.a.

The estimation of hydropower storage capacities is done by using distribution factors for active zone storage and deposition based on RDR. This is applied to all the 35 reservoirs, and the weighted average rate of loss in hydropower storage capacity is computed to be 0.053% p.a., within the range of 0.016 to 0.09% p.a.

As of 2025, the estimated hydropower storage capacity for the 35 Swiss reservoirs is approximately 7600 GWh (range of 7408 to 7792 GWh), computed based on their active storage volumes. Considering the 95% representation by the 35 reservoirs, the hydropower storage capacity in the overall context of Switzerland is estimated as 8000 ± 202 GWh. Assuming no additional change apart from loss due to sedimentation, the national hydropower storage capacity (100%) is projected to be approximately 7668 ± 427 GWh at the end of this century (2100), i.e. on average 332 GWh lower than today.

The details of all these estimations are provided in Chapter 8 of the Appendix.

7 Conclusions

This study presents enhanced methodologies to conduct detailed investigations of reservoir sedimentation and sediment management using a 1D numerical modelling approach. To achieve a more realistic cross-section geometry after large amounts of sediment deposition/erosion, a new methodology is developed that dynamically identifies the distinct ranges for bedload and suspended load distribution within a section, based on threshold parameters related to water depth at each node. The model is successful to represent sediment dynamics in different scales of reservoirs, as seen in the calibration and validation results of the Solis and Gigerwald reservoirs.

A 1D numerical model can incorporate the processes associated with SBT operation by simulating the SBT as a sink of water and sediment at the location of its inlet. Synchronously lowering the reservoir water level during SBT operation leads to higher bypass efficiencies. However, a greater SBT bypassing efficiency is associated with the release of higher sediment concentrations into the downstream river reach. Thus, it is essential to examine environmental constraints while aiming at maximised sediment management. Optimisation of SBT operation during a flood event can be done based on threshold inflow discharges to determine the start and end of operation. A marginal cost-benefit analysis based on unit base and peak energy prices is useful to identify the most economically favourable SBT operation scenario.

An analysis of climate scenario data is presented to estimate sediment inflows into a reservoir, that is essential for long-term simulations of future sedimentation and sediment management, e.g. until the end of this century. Applied to the cases of the Gigerwald and Solis reservoirs, the model results offer valuable insights into the effects of climate change on sediment yield and deposition patterns. In case of non-glaciated catchment, if the sediment yield is estimated solely as a function of river discharge, then the average sediment inflow slightly reduces with an increasing severity of climate change. This is related to the reduction in water yield, particularly during summer months, leading to lower sediment transport capacities. The



uncertainty range within each scenario tends to widen with the severity of the climate scenario. As demonstrated by modelling results, sedimentation in the Gigerwald reservoir can be further mitigated by implementing one or more of the following strategies: (i) reducing the sediment concentration threshold for shutting down the inflow from the neighbouring Weisstannental, (ii) sediment relocation by periodic extra lowering of reservoir level, and (iii) mechanical excavation of deposited sediment. In the case of the Solis reservoir, the propagation of the delta foreset towards the dam appears inevitable in the near future. Therefore, a thorough investigation and application of supplementary sediment management measures (such as dredging or mechanical excavation) is crucial for the sustainable operation of the Solis reservoir.

An improved methodology is showcased to compute representative values of reservoir sedimentation rate and hydropower energy storage capacity in a regional fleet of reservoirs. A novel equation for the sediment trapping efficiency is formulated based on multiple parameters related to catchment and reservoir characteristics. The application to Switzerland leads to an improved understanding of reservoir sedimentation and seasonal hydropower storage across the Swiss fleet of reservoirs. Based on weighting by the gross water storage capacities of 35 reservoirs, the weighted-average sedimentation rate in Switzerland is computed to be 0.059% p.a. The estimated hydropower storage in the top 35 Swiss reservoirs is 7600 ±192 GWh in 2025. This value is extrapolated to 8000 ± 202 GWh for the overall reservoirs in Switzerland.

A more detailed conclusive remarks of this study are provided in Chapter 9 of the Appendix.

8 Recommendations

8.1 Recommendations for further research

Building on the findings of this study, some limitations and gaps in the current knowledge are also identified. These are listed below:

- Incorporating and evaluating the relevance of turbidity current processes could yield more practical results in future numerical modelling approaches.
- Future studies should also aim to quantify possible variations in the catchment sediment yield resulting from changes in precipitation patterns, land cover, and other climate-related factors.
- More recent climate change scenarios should be adopted, e.g., combined RCPs and Shared Socioeconomic Pathways (SSPs) based on IPCC (2023).
- It is recommended to refer the Swiss hydrological scenarios of CH2025 in further research. CH2025 will build upon the foundations of CH2018, incorporating updated scientific insights and delivering extended climate and hydrological products.
- The term “Sediment Management Effectiveness (SME)”, introduced in this study, may alone not fully represent the overall feasibility of a strategy, as it does not account for the costs associated with sediment management activities. Therefore, an integrated metric that incorporates both technical performance and economic feasibility would be more relevant and valuable for informed decision-making.
- In this study, the generalisation of sedimentation across the Swiss reservoir fleet is based on limited field data, with sediment yield representing the greatest source of



uncertainty. This analysis can be revisited and refined as more field data become available, enabling more precise and reliable estimates.

8.2 Recommendations to practitioners

Based on the findings of this study, the following recommendations are made for practitioners to enable them to analyse and deal with the problem of reservoir sedimentation:

- For reservoirs equipped with type-B Sediment Bypass Tunnel (SBT), the operators should synchronise the lowering of reservoir water level and the opening of the SBT inlet to ensure a high bypassing efficiency. The timing of SBT operation relative to a flood wave can also be economically optimised as demonstrated by this study for the case of the Solis reservoir.
- If a reservoir inflow consists of diverted water from adjacent catchments, then those indirect inflows can be regulated during the period of high sediment concentrations to mitigate the supply of sediment into the reservoir. This is demonstrated for the case of the Gigerwald reservoir in this study with the analysis of the Weisstannental sub-catchment intakes.
- For reservoirs having adequate inactive storage, a potential sediment management strategy is to relocate the deposited sediment from the active storage to the inactive storage, thus recovering a part of the useful active storage. However, this is just a short-term solution as it only prolongs the impact of sediment into the future without any removal of sediment from the system. This example is demonstrated in this study for the case of Gigerwald reservoir.
- For any sediment management strategy implemented into a reservoir, it is essential to quantify the effectiveness of that strategy in mitigating the targeted impacts. The new metric “Sediment Management Effectiveness (SME)” formulated in this study can be utilized for the quantification of impact mitigation.
- A novel equation for trapping efficiency estimates is derived in this study, which incorporates multiple parameters related to catchment and reservoir operation. For further planning and study, it is advised to implement this equation as it tends to incorporate the dynamic sedimentation processes occurring inside a reservoir.
- Continuous monitoring of inflows from the catchment (water and sediment) and reservoir operation is highly recommended as it provides essential information for further planning of sediment management strategies.

9 National and international cooperation

This project involves collaborations with the following partners (in alphabetical order):

Axpo Power AG

Axpo Power AG is the owner and operator of the Gigerwald reservoir and supported the field-work campaign by providing a survey boat and facilitating access to the reservoir. In addition, Axpo has provided valuable data related to reservoir bathymetry, inflow discharge, and sediment concentrations.



Energy Science Center (ESC) at ETH Zurich

The doctoral student of this project was enrolled in the RESPONSE Doctoral Program which has a collaboration with the Energy Science Center of ETH Zurich. ESC is involved in the organization of some workshops and conferences related to the field of energy.

European Union

This project was co-funded by the European Union Horizon 2020 program within the Marie Skłodowska-Curie Actions project 'RESPONSE - to society and policy needs through plant, food and energy sciences' (ID: 847585).

ewz

The case study reservoir Solis is owned and operated by ewz. VAW has collaborated with ewz to conduct the field measurements at Solis as well as to acquire data related to reservoir operation.

Swiss Committee on Dams (STK)

There were contacts to the STK working group on sediment flushing and reservoir emptying. The project received financial support for the field measurements from the STK's research fund.

Swiss Federal Office of Energy (SFOE)

The SFOE is a project partner, which supported the following activities:

- conducting annual review meetings to discuss the results and plan further tasks;
- hosting the doctoral student of this project during the secondment period;
- assisting in the preparation of a comprehensive overview of hydropower storage in Switzerland.

A workshop to exchange knowledge and experiences took place on November 17, 2023 at VAW, ETH Zurich, with participants from various operators, engineering consultants, federal offices, and research organisations.

10 Publications and other communications

10.1 Conference papers

Dahal, S.; Evers, F.M.; Boes, R.M.; Vetsch, D.F. (2022). 1D numerical modelling of sedimentation propagation in a narrow reservoir. Extended abstract, In 7th IAHR Europe Congress: Innovative Water Management in a Changing Climate. Abstract Book (pp. 20-21).

Dahal, S.; Maddahi, M.; Albayrak, I.; Evers, F.M.; Vetsch, D.F.; Stern, L.; Boes, R.M. (2023a). Efficiency evaluation and simulation of Sediment Bypass Tunnel Operation: Case study Solis Reservoir. Proc. 12th ICOLD European Club Symposium "Role of dams and reservoirs in a successful



energy transition" (Boes, R.M., Droz, P. & Leroy, R., eds.), Taylor & Francis, London: 469-478, <https://doi.org/10.1201/9781003440420-52>.

Dahal, S.; Evers, F.M.; Boes, R.M.; Vetsch, D.F. (2024a). Sedimentation in a narrow reservoir under climate change and sediment bypass tunnel operation scenarios. In Proceedings of the 10th IAHR International Symposium on Hydraulic Structures, Zurich, Switzerland. <https://doi.org/10.3929/ethz-b-000676029>.

10.2 Journal papers

Dahal, S.; Evers, F.M.; Boes, R.M.; Vetsch, D.F. (2023b). 1D numerical modelling of Sediment-Bypass-Tunnel operation in a narrow reservoir. In *Proceedings of the 40th IAHR World Congress 2023*, Vienna, Austria. https://doi.org/10.3850/978-90-833476-1-5_iahr40wc-p0190-cd.

Dahal, S.; Boes, R.M.; Evers, F.M.; Albayrak, I.; Vetsch, D.F. (2025). Bypassing efficiency evaluation and optimization of sediment bypass tunnel operation in a narrow reservoir using 1D numerical modelling. *Journal of Hydro-environment Research*. <https://doi.org/10.1016/j.jher.2025.100668>.

10.3 Dissertation

Dahal, S. (2025). Sedimentation management in Alpine reservoirs for sustainable hydropower under climate change. Doctoral Thesis No. 31235 and VAW-Mitteilung 282 (Boes, R.M., ed.), Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zürich. <https://doi.org/10.3929/ethz-c-000784021>
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