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Sedimentation in a narrow reservoir under climate change and sediment bypass tunnel operation scenarios

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Abstract: *Reservoir sedimentation is one of the main issues interfering with the sustainable operation of many hydropower reservoirs as it causes a reduction of storage capacity and may also affect dam safety. The rate of sedimentation is anticipated to change due to changes in flow following climate change. Although quantifying the variation of sedimentation is subject to high uncertainty, sediment yield is mainly expected to increase for Alpine catchments due to retreating glaciers and thawing permafrost. Sediment Bypass Tunnels (SBTs) are hydraulic structures to counteract sedimentation problems as they allow for bypassing incoming sediment (bedload and parts of the suspended load) around the dam into the tailwater reach. This study deals with the SBT in Solis reservoir (Switzerland) where an SBT has been operating for more than a decade to counteract sedimentation. The aim is to evaluate the performance of the Solis SBT under climate scenarios by conducting 1D numerical simulations. The Hydro-CH2018-Runoff ensemble is referred for the future projection of river inflows into the Solis reservoir. In absence of quantified impact on the sediment input, it is computed from calibrated sediment transport equations based on monitored data. The model is found useful to simulate future sedimentation and to compare scenarios of SBT operation during flood events. Considering the impact of SBT operation on energy generation due to water losses, SBT operation during two different floods is more effective than its operation in a single flood for a given total duration of operation.*

Keywords: *Reservoir Sedimentation, Sediment Bypass Tunnel, Climate Scenarios, Numerical Modelling*

1. Introduction

Sedimentation has a negative impact on the sustainable operation of reservoirs by causing a loss of storage capacity as well as dam safety issues due to impaired functionality of outlet structures (Kondolf et al. 2014, Schleiss et al. 2016). This impact intensifies with rising water demand and climate-related pressures, especially as existing feasible locations for reservoir construction are already extensively utilized (Annandale et al. 2016).

Switzerland also faces a challenge with reservoir sedimentation, given its reliance on hydropower storage for electrical energy in the critical winter period (Boes et al. 2021). Therefore, investigating sedimentation processes and developing effective sediment management strategies should have high priority. However, the absence of well-monitored sediment yield and sedimentation rates on a national level poses a major constraint, hindering optimal management and the ability to conduct more in-depth investigations.

Climate change is expected to have a substantial impact on mountain streams, mainly causing modifications in flow regimes (Muelchi et al. 2021). There are three different climate scenarios for Switzerland based on the degree of greenhouse gas emissions: RCP2.6 (low emission), RCP4.5 (medium emission), and RCP8.5 (high emission). The future prediction of discharge in major rivers of Switzerland are available from the Hydro-CH2018-Runoff ensemble (Muelchi et al. 2021). Generally, river runoff is anticipated to increase during the winter months and decrease during the summer months. The interconnected relationship between catchment and river flow also causes alterations in sediment transport, affecting both supply and transport capacity. However, it is highly uncertain and challenging to quantify the magnitude of impact on a specific catchment's sediment yield (Guillén-Ludeña et al. 2018). In general, the sediment yield is expected to increase because of glacial retreat exposing formerly accumulated sediment (Lane et al. 2017, Delaney and Adhikari 2020). Contrastingly, the sediment transport capacity of rivers is anticipated to decrease because of lower discharge during summer months which can cause reduction in sediment input with increasing severity of climate change (Pralong et al. 2015). Nevertheless, in view of these uncertainties sediment management infrastructures need to be designed to cope with an aggravation of sedimentation in the upcoming decades due to climate change.

Sediment routing helps in partially restoring the natural continuity of river sediment (Morris 2020). This process involves either diverting sediment through Sediment Bypass Tunnels (SBTs) or sluicing it through dam outlets. SBTs are hydraulic structures constructed in a reservoir to divert the sediment-laden flow (both bedload and suspended load) around the dam through a tunnel releasing the flow in the downstream river reach. For instance, Switzerland and Japan have successfully implemented SBTs to address the sedimentation issue at a number of dams (Auel and Boes 2011, Kondolf et al. 2014).

The efficiency of an SBT is evaluated as the ratio of bypassed volume of sediment through the SBT to the incoming sediment volume. It depends primarily on the inflowing sediment transport rate and operating conditions of the reservoir and SBT (Albayrak et al. 2019). Studying the operation of existing SBTs advances the understanding of the governing hydraulic and morphologic processes and provides a basis for enhancing the bypassing efficiency. However, the investigation of different operation strategies solely through field measurements to assess the parameters influencing SBT efficiency is costly. Therefore, numerical simulations can be an efficient way to support such studies, provided sufficient data are available for model setup and calibration. Furthermore, numerical models have the capability to represent multiple sediment fractions and different transport modes that are essential to replicate the sediment sorting processes along the reservoir (Ehrbar et al. 2018, Dahal et al. 2021).

This study presents the case of the Solis reservoir in Switzerland and introduces an approach for conducting long-term simulations of reservoir sedimentation management through SBT under climate change scenarios. The operation of the SBT in the Solis reservoir is well-monitored (Albayrak et al. 2023) offering valuable data essential for model validation. The calibration of numerical modelling of monitored SBT operation events in the Solis reservoir during the 2019 flood is given in Dahal et al. (2023a, 2023b). The BASEMENT software (Vetsch et al. 2023) is used for 1D numerical modelling. The validated model enables the simulation of additional scenarios related to future climate change. Currently, this study involves future projections until the year 2028, and the same concept can be applied to conduct more simulations for the more distant future.

2. Study Area

The Solis reservoir is situated on the Albula River in the Canton of Grisons, Switzerland. A 61 m high arch dam was constructed in 1986 which created a reservoir with an initial total volume of 4 Mm^3. The layout map in Figure 1 shows a narrow fjord-like reservoir that extends about 3 km upstream from the dam. The Albula river is the inflow source which drains about 900 km^2 of watershed area including the Julia river tributary. In response to sedimentation problems leading to a storage loss of roughly 50% until 2009 (Auel and Boes 2011), an SBT was commissioned in 2012 to mitigate further sediment aggradations.

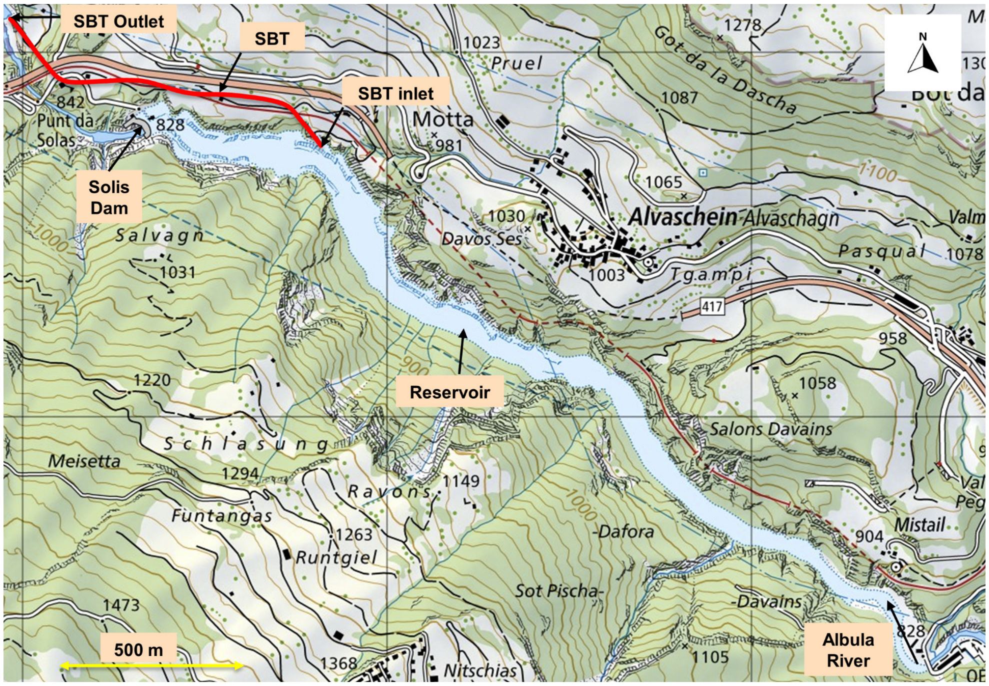

Figure 1. Layout map of Solis reservoir (background map source: Swiss Federal Office of Topography).

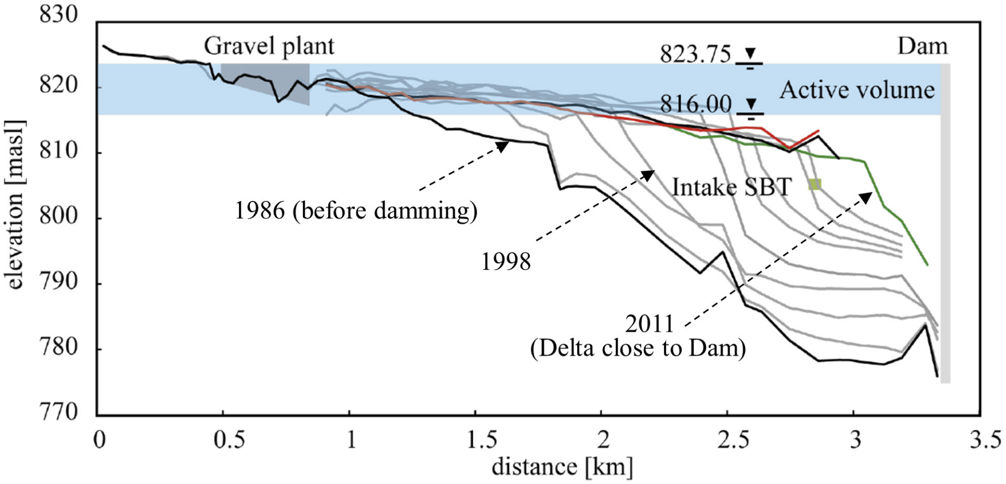

Figure 2. Temporal and spatial evolution of Solis reservoir bed profile from 1986 to 2011, and location of the SBT intake structure; flow from left to right (modified from Müller-Hagmann 2017).

The temporal and spatial progression of the sedimentation delta is illustrated in Figure 2. By 2011, the delta had advanced close to the dam along with the rising of bed level at that location, posing a threat to the safe operation of the dam outlets. The primary source of sediment inflow into the reservoir is the Albula river, as the sediment from the Julia river tributary is effectively retained by two reservoirs within that sub-catchment. A gravel plant is located at the upstream end that extracts a part of the inflowing coarse sediment.

An SBT was commissioned in 2012 with the aim of minimizing further sedimentation (Oertli and Auel 2015). As typical for "type-B" SBTs (Boes et al. 2019, Hager et al. 2020), the Solis SBT has its inlet at the middle reach of the reservoir. Due to the submerged nature of the inlet during regular reservoir operation, it is necessary to lower the reservoir level prior to and during the SBT operation to ensure efficient bypassing of sediment-laden inflows (Albayrak et al. 2023). The theoretical discharge capacity of the Solis SBT is 170 m^3/s at full supply level which corresponds to a 5-year flood peak.

3. Methods

This study involves the prediction of future scenarios of sedimentation and SBT operation in the Solis reservoir by conducting 1D numerical simulations. The BASEMENT software is applied for modelling which includes the processes of unsteady flow and multiple grain sediment transport in both modes of bedload and suspended load (Vetsch et al. 2023). The model calibration for the Solis reservoir case is given in Dahal et al. (2023a, 2023b). The model setup corresponds to the date of latest available bathymetry data from November 2021. The simulations are run until 1st October 2028 for different scenarios using climate projections RCP4.5 and RCP8.5.

The future predictions of the Albula river discharge are referred from the Hydro-CH2018-Runoff ensemble (Muelchi et al. 2021). Each emission scenario has multiple climate models: 12 models for RCP2.6, 25 models for RCP4.5, and 30 models for RCP8.5. All these models give a future estimate of river flows until the end of this century (2100). RCP2.6 is not adopted for this study considering it as an unlikely scenario. A preliminary assessment is done to identify the average climate models for both RCP4.5 and RCP8.5 scenarios. The averaging of the hydrographs from multiple climate models causes flattening of the flood peaks which is not appropriate for sediment projections. Thus, the average climate model is identified based on the average of sediment projections given by all hydrographs. The different climate models of RCP4.5 and RCP8.5 are preliminarily assessed by computing future projection of sediment volumes until 2050 using calibrated sediment transport equations (Dahal et al. 2023b). The climate model yielding similar sediment volume as the average projected sediment volume is adopted as the average model representing the respective climate scenario. The average climate models of emission scenario RCP4.5 and RCP8.5 are used in this study to compare the future evolution of reservoir sedimentation. Then the average model of RCP4.5 is referred for comparison of sediment management scenarios using the SBT.

The overall sediment transport into and through the reservoir is classified into Bedload (BL) and Suspended Load (SL). The locations of sediment inflow sources and outflow sinks are shown in Figure 3.

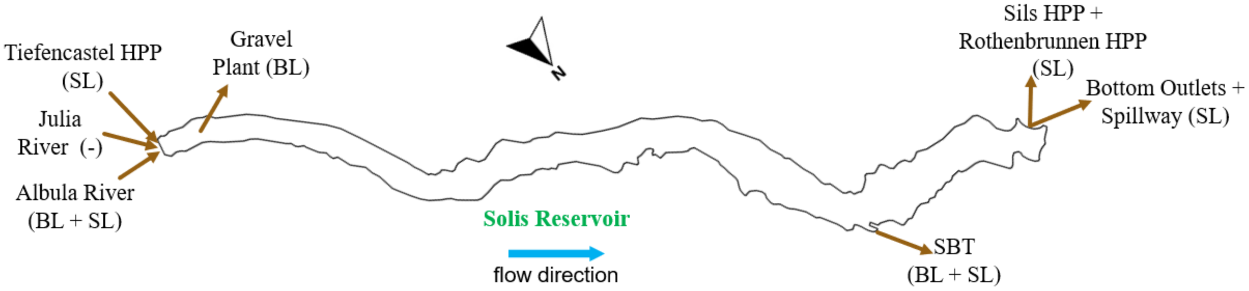

Figure 3. Locations of sediment inflow and outflow at the Solis reservoir.

The numerical model is initialized with the geometry derived from the bathymetry of November 2021. The model domain is discretized into 89 cross-sections at an average 25 m spacing. The upstream boundary conditions are defined by the input time series values of water, BL, and SL. The downstream boundary is located at the dam and defined as reservoir water level time series. In addition, a sink is imposed at the location of the SBT inlet that extracts water, BL, and SL during the SBT operation.

The inflow discharge hydrograph at an hourly resolution is generated from the average model of the corresponding climate scenario. The climate model has a daily resolution hydrograph which is analyzed to include hourly fluctuations based on hourly monitored data in the past (1987-2014). The inflow hydrographs for the average models of RCP4.5 and RCP8.5 are given in Figure 4. The reservoir operation is derived as a relation with inflow discharge based on previously monitored operation, which is imposed as the downstream boundary condition in the model.

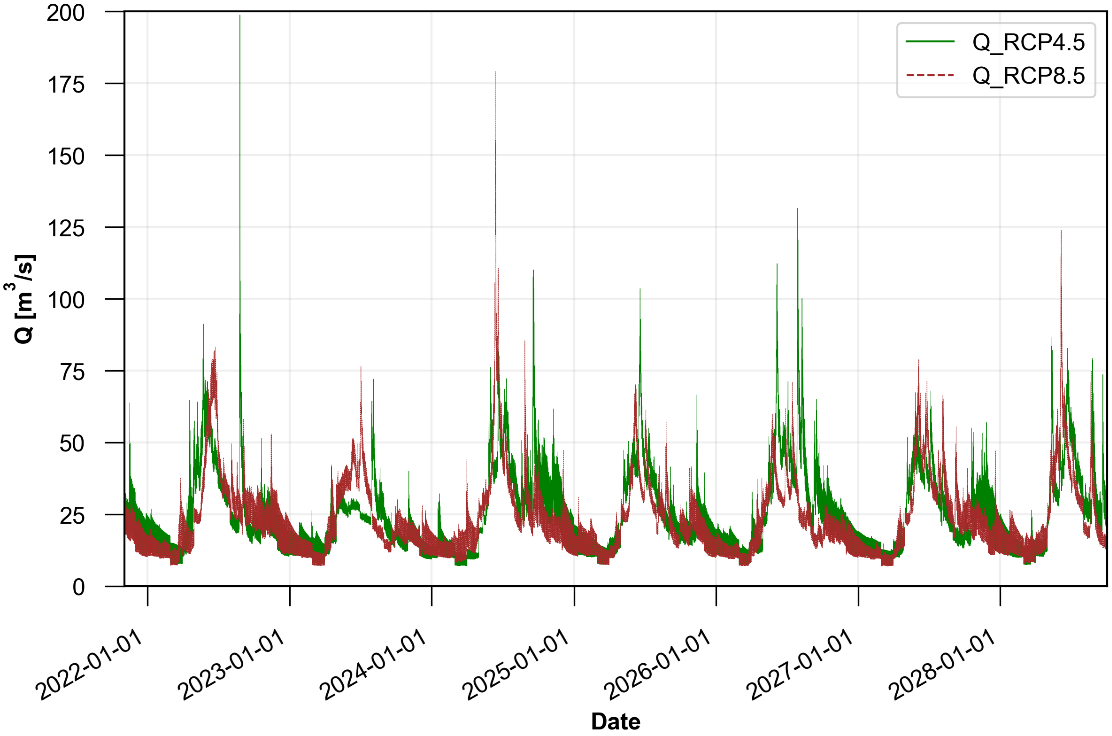

Figure 4. Inflow hydrographs for average models of RCP4.5 and RCP8.5.

The prediction of sediment inflow is highly uncertain as it may be governed by multiple parameters related to catchment erosion, human interventions, and transport capacity. For this study, the future projection of sediment inputs associated with climate change is derived from the transport capacity relations that are calibrated for monitored sedimentation for both bedload and suspended load (Dahal et al. 2023b). The inflow SL is computed from a rating equation derived for the Suspended Sediment Concentration (SSC) in the Albula river (Albayrak et al. 2023). SL released through the Tiefencastel HPP is referred from the monitored data of another similar powerplant (Sils HPP) in the same region (Albayrak et al. 2023). The net BL inflow (considering gravel extraction) is computed using the empirical sediment transport equation by Wong and Parker (2006) with modified coefficients for multi-grain sediment to derive similar average values as recommended by previous studies (Müller-Hagmann 2017, Albayrak et al. 2023).

Table 1 shows the scenarios formulated for numerical simulation. Scenario-I includes two climate scenarios to compare the effects on sedimentation without sediment management. The SBT operation scenarios are generated on the basis of timing of flood peaks within a year. Two scenarios are formulated with different timings of SBT operation (Scenario-II in Table 1). Both scenarios have a total SBT operation duration per year of 4 days. Scenario S2-1 incorporates continuous operation of SBT for 4 days during the annual peak flood event, while scenario S2-2 involves two SBT operation events for 2 days each during two flood events: annual maximum flood, and another smaller flood. As the reservoir operation has a strong influence on SBT efficiency (Dahal et al. 2023a), the reservoir water level is gradually lowered to 813.5 masl during the SBT operation. The discharge through the SBT is derived from a relation between inflowing discharge and reservoir water level. Figure 5 shows a plot of the hydraulic boundary conditions during the SBT operation for the annual flood peak of 2026. Similar hydraulic boundary conditions are generated for all other years.

Table 1. Scenarios for numerical simulation.

Scenario Category	Simulation ID	Climate Scenario	SBT operation duration per year (hours)	SBT operation events per year
Scenario-I	S1-1	RCP4.5	0	0
	S1-2	RCP8.5	0	0
Scenario-II	S2-1	RCP4.5	96	1
	S2-2	RCP4.5	96	2

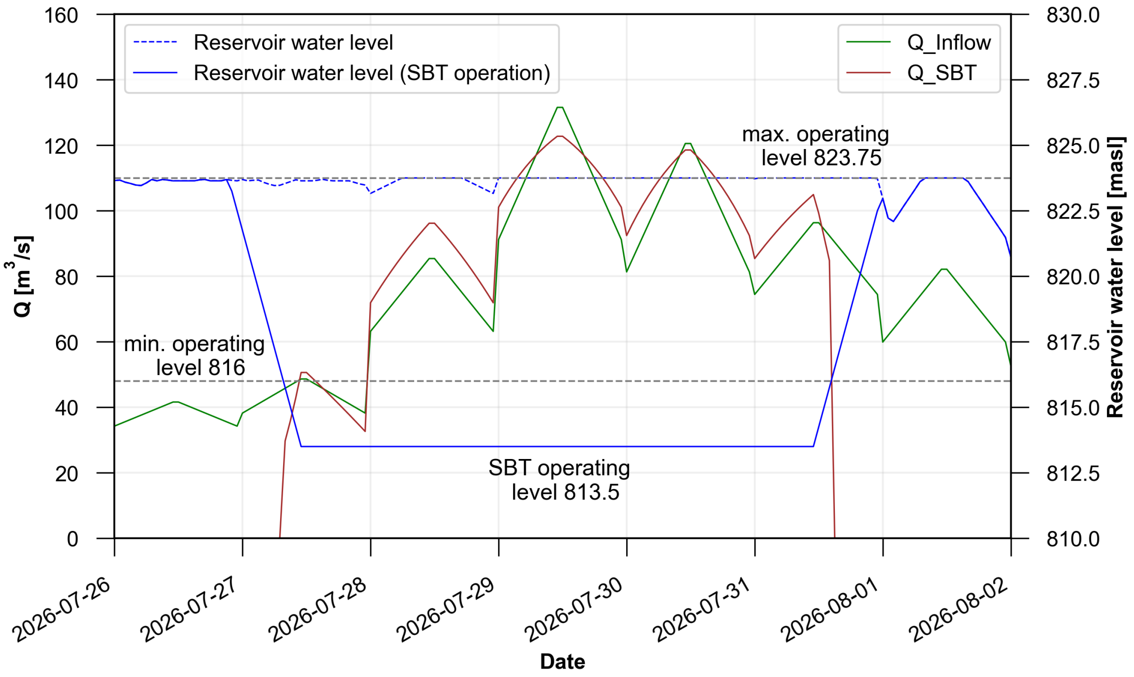

Figure 5. Hydraulic boundary conditions during an SBT operation event (scenario S2-1).

The BL bypassed through the SBT is computed as a function of discharge through the SBT and reservoir water level derived from the monitored data using a Swiss Plate Geophone System (SPGS) between 2019 and 2021 (Albayrak et al. 2022). SL outflow through the SBT is automatically implemented in the model due to extraction of water containing suspended particles of a given concentration computed by the model at that location.

The model incorporates four distinct sediment fractions to effectively capture the sediment sorting process. Through the analysis of measured particle size distributions, fractions of 6.4 mm and 39.4 mm are designated as coarse materials, while fractions of 0.022 mm and 0.045 mm are chosen to represent suspended particles. The selection of these sediment fractions is based on trial simulations aimed at attaining the closest match with monitored sedimentation.

Finally, the model simulations are performed for the period from 3rd November 2021 to 1st October 2028. The results are then analyzed to compute the SBT efficiencies and the evolution of active storage volume.

4. Results

The results of future sedimentation simulations for climate scenarios RCP4.5 and RCP8.5 are shown in Figure 6 as longitudinal bed profile evolution. A summary of sediment volumes is given in Table 2. Both scenarios have high sediment deposition throughout the reservoir because of no sediment management activity, so that the reservoir acts as a strong sediment trap. Comparatively, the scenario RCP8.5 causes less sedimentation throughout the reservoir. This is mainly attributed to a lower amount of sediment inflowing from the Albula river (Table 2). The resulting active storage are 0.892 $\mathrm{Mm^3}$ and 0.950 $\mathrm{Mm^3}$, respectively, for RCP4.5 and RCP8.5.

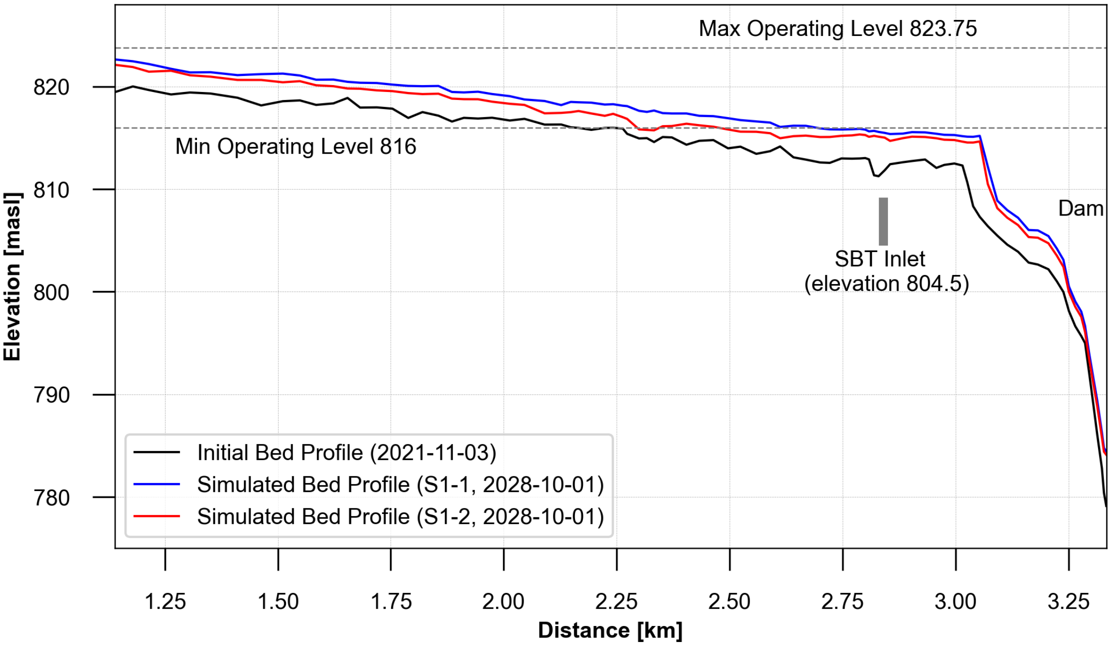

Figure 6. Longitudinal bed profile evolution for climate scenarios RCP4.5 and RCP8.5 without SBT operation.

Table 2. Result of numerical simulation of different climate scenarios (without SBT operation).

Simulation ID	Sediment Volumes ($\mathrm{m^3}$)				Active Storage ($\mathrm{Mm^3}$)
	BL inflow	SL inflow	Total inflow	Net deposition	
S1-1	63,747	423,766	487,513	324,879	0.892
S1-2	38,945	332,690	371,635	238,243	0.950

Figure 7 shows a plot of future simulations of different SBT operation scenarios for the RCP4.5 climate scenario. Compared with the scenario without sediment management, the SBT operation helps to reduce the depositions throughout the reservoir. Even though the deposition in the reservoir upstream of the SBT inlet is significantly reduced, the deposition downstream of the SBT inlet is still considerable. This is caused by the lowering of the reservoir level during high floods exceeding the capacity of the SBT, when suspended sediments are partly conveyed towards the dam where they settle to a large part. Furthermore, the scenario of SBT operation in two different flood events causes slightly less sedimentation than a single yearly SBT operation with the same total duration. The SBT efficiency increases from 59.8% to 66.3% by just adapting the timing of SBT operation without changing the total duration. Table 3 gives a summary of sediment volumes, water used for SBT operation, and resulting active storage.

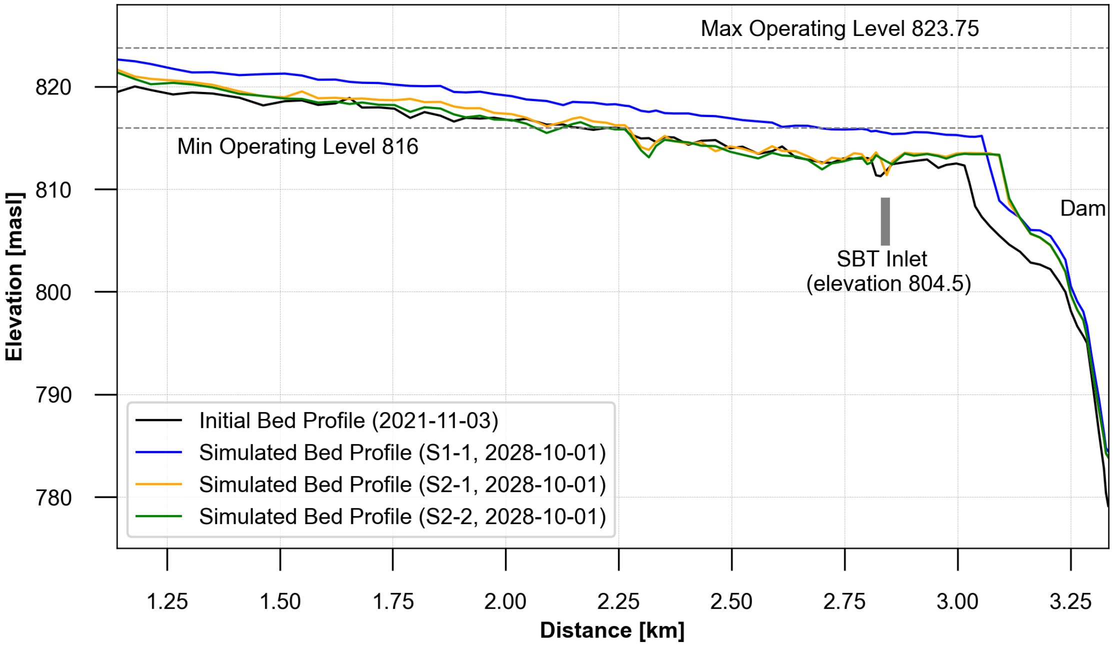

Figure 7. Longitudinal bed profile evolution for scenarios of SBT operation with climate scenario RCP4.5.

Table 3. Result of numerical simulation of different SBT operation scenarios with climate scenario RCP4.5.

Simulation ID	Sediment Volumes (m^3)							SBT efficiency (%)	Water volume through SBT (Mm^3)	Active Storage (Mm^3)
	BL inflow	SL inflow	Total inflow	BL outflow (SBT)	SL outflow (SBT)	Total outflow (SBT)	Net deposition			
S2-1	63,747	423,766	487,513	57,372	234,208	291,580	142,633	59.8	174.3	1.009
S2-2	63,747	423,766	487,513	67,838	255,156	322,994	110,223	66.3	211.7	1.033

5. Discussion and Conclusion

Future estimates of sedimentation and sediment management have been conducted for the case of the Solis reservoir under different scenarios related to climate change and SBT operation mode. If the sediment inflow is only governed by the sediment transport capacity, then it seems that the amount of sedimentation reduces with increasing severity of climate impacts: RCP8.5 causes less sedimentation than RCP4.5. This is mainly attributed to the decrease in river flows during the summer months, which has been experienced in previous studies as well (Pralong et al. 2015). However, the sediment transport relation itself may change because of changing catchment characteristics leading, e.g., to changing particle size distributions, which is not considered in this study.

If there is no sediment management, then the reservoir is subject to sedimentation throughout its entire length causing a considerable reduction in active storage. In addition, the advancing delta near the dam may impair the functioning of dam outlets. This emphasizes the importance of having a sediment management infrastructure such as a Sediment Bypass Tunnel (SBT). A properly planned SBT operation can help to convey a large amount of incoming sediments to the tailwater reach. The results of SBT operation scenarios indicate that the bypassing efficiency will increase if the SBT is operated at two different flood events rather than a single flood event for the same duration. This depends on the duration and magnitude of a flood wave. In the climate scenario RCP4.5 with SBT operation divided into two different flood hydrographs, more sediment can be bypassed than for the scenario with SBT operation during a single flood wave for a given duration of 96 hours.

However, if the incoming flood has a larger magnitude than the hydraulic capacity of the SBT, then the lowering of the reservoir level can cause some sediment propagation past the SBT inlet towards the dam. SBT operation in floods exceeding the SBT capacity will release a part of the flow and incoming sediment (mainly suspended particles) downstream to form a deltaic deposit (Figure 7). An approach to minimize deposition downstream of the SBT inlet could be to reduce the duration of SBT operation (and reservoir lowering) during large floods to allow a part of incoming sediment to be deposited in the upstream reach. Later this deposit can be remobilized with a moderate flood and can be bypassed through the SBT. Such scenario can be tested using the same 1D model. An alternative would be to operate the dam bottom outlet once the discharge capacity of the SBT is exceeded to create another sink for suspended sediments and vent them through the dam.

SBTs are hydraulic structures that effectively minimize the amount of sedimentation depending on the proper planning of their operation during flood events. A 1D numerical model represents a tool for projecting future reservoir sedimentation for different sediment management techniques, that is essential for proper planning of reservoir operation. The efficient operation of SBT aided by a planning tool such as a numerical model is favorable to ensure a more sustainable use of reservoirs.

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