Aggradation and Widening in a Dam-Regulated Alpine River

Aggradation et élargissement dans une rivière alpine régulée par un barrage

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RÉSUMÉ

Il est bien documenté que les barrages perturbent le transport naturel des sédiments en aval dans les rivières, ce qui entraîne souvent des impacts négatifs sur les écosystèmes en aval. Le blindage du lit, le rétrécissement et l'incision sont fréquemment observés en aval des barrages. Dans cette étude, nous examinons les dynamiques morphologiques multidéca-dales opposées observées dans la rivière Spöl en Suisse, qui est impoundée depuis les années 1960. Au cours de la dernière décennie, un tronçon de 2,6 km en aval de la confluence avec la rivière Cluozza non régulée a connu une importante aggradation, un élargissement, un affinement des sédiments et une augmentation des dynamiques morphologiques, attirant l'attention des autorités locales et de la communauté scientifique. Depuis 2000, le tronçon étudié est soumis à un programme de crues écologiques, qui libère des crues annuelles du barrage en amont, avec des débits imitant les crues saisonnières d'avant la mise en place du barrage. À l'aide d'images aériennes haute résolution, de modèles de terrain numériques et de séries chronologiques hydrologiques, nous reconstruisons la trajectoire morphologique de ce tronçon depuis la construction du barrage et évaluons les facteurs qui sous-tendent ces changements. Tant les événements hydrologiques artificiels que naturels contribuent à un équilibre modifié entre l'apport sédimentaire en amont et la capacité de transport, façonnant des dynamiques transitoires dans la morphologie et la composition des sédiments de la rivière. Par exemple, l'événement de vidange du réservoir de 2009 a fortement modifié les formes de lit et la composition des sédiments, tandis que les grandes crues naturelles de la Cluozza ont entraîné des changements significatifs, notamment l'aggradation, l'avulsion et l'élargissement. Les crues expérimentales ont été concomitantes avec des changements morphologiques intensifiés. Cette étude met en évidence le rôle crucial des affluents non régulés et leur rôle modifié dans l'équilibre entre l'apport en sédiments et les régimes de débit modifiés dans les rivières alpines régulées.

ABSTRACT

It is well-documented that dams disrupt natural downstream sediment transport in rivers, often leading to negative impacts on downstream ecosystems. Channel armoring, narrowing, and incision are frequently observed downstream of dams. Here, we investigate the opposite multidecadal morphological dynamics observed in the Spöl River in Switzerland, which has been impounded since the 1960s. Over the past decade, a 2.6 km stretch downstream of its confluence with the unregulated Cluozza River has experienced significant aggradation, widening, sediment fining, and increased morphological dynamics, drawing attention from local authorities and the research community. Since 2000, the study reach has been subject to an ecological flood program, which releases annual floods from the upstream dam, with discharges that mimic pre-impoundment seasonal high flows. Using high-resolution aerial imagery, digital terrain models, and hydrological time series, we reconstruct the morphological trajectory of this reach since dam construction and assess the factors driving these changes. Both artificial and natural hydrological events contribute to an altered equilibrium between upstream sediment supply and transport capacity, shaping transient dynamics in the river's morphology and sediment composition. For example, the 2009 reservoir flushing event heavily modified bedforms and sediment composition, while major natural floods from the Cluozza have been followed by significant changes, including aggradation, avulsion, and widening. Experimental floods have been concomitant with intensified morphological changes. This study highlights the crucial role of unregulated tributaries and their altered role in the balance between sediment supply and modified flow regimes in regulated alpine rivers.

KEYWORDS

Alpine rivers (Rivières alpines), Unregulated tributaries (Affluents non régulés), Sediment supply (Approvisionnement en sédiments), Morphological evolution (Évolution morphologique).

1 INTRODUCTION

Alpine river systems often experience significant changes in sediment transport and morphology due to the presence of dams. While dams disrupt the natural downstream sediment flux and alter the flow regime, unregulated downstream tributaries can partially restore sediment supply, potentially counteracting the effects caused by sediment deficits and influencing downstream river dynamics under the dam-modified flow regime.

This study aims to explore the multidecadal morphological evolution of an impounded Alpine river, the Spöl River in Switzerland, focusing on the interactions between dam regulation, including an experimental flood program, and the sediment supplied by an unregulated tributary. By analyzing high-resolution spatial and temporal data, including hydrological time series, remotely sensed imagery, and sediment size assessments, we seek to reconstruct the morphological evolution of the system and identify the key driving factors.

2 STUDY SITE

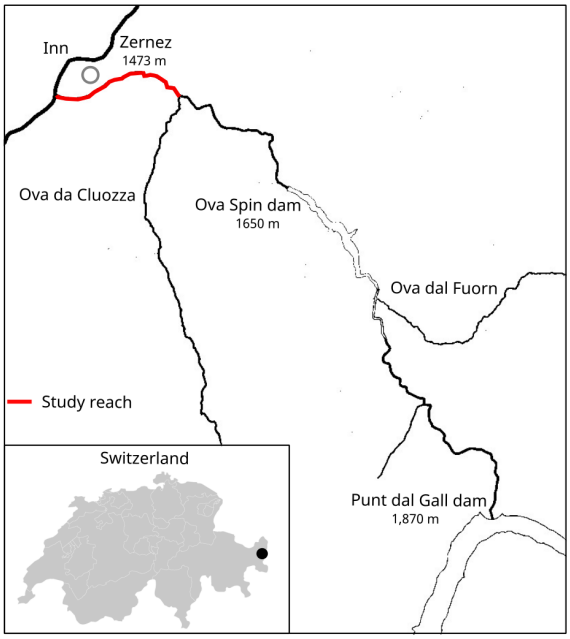

Fig. 1: Map of the region and location of the study site.

The Spöl River is located in the central Alps, on the border between Switzerland and Italy, with a catchment area of 286 km². It merges with the River Inn near Zernez, Switzerland. Since the 1960s, the river has been impounded by two dams, Punt dal Gall and Ova Spin, which strongly regulate its flow and sediment regimes. The study site is a 2.6 km reach located downstream of the Ova Spin dam, extending from the unregulated Cluozza tributary to the Inn River (Fig. 1). This reach is partially confined by bank protection structures and passes through the village of Zernez, with reducing slopes and a large floodplain. The Cluozza River, characterized by a snowmelt-driven flow regime, contributes substantial amounts of coarse sediment, particularly during seasonal flood events, which influence the downstream reach of the Spöl River. The Spöl River has been subject to an ecological flood program from the Ova Spin dam, aimed at restoring the river's ecological functions.

3 METHODS

This study is divided into two main components: (1) **analysis of historical imagery and digital terrain models**, and (2) **hydrological analysis**. The dataset consists of 15 historical orthophotos (SwissTopo) in black-and-white or RGB format, with resolutions ranging from 1 m (1956) to 0.1 m (2022). In addition, three digital terrain models (DTMs) were obtained from SwissTopo (SwissAlti3D), with resolutions ranging from 2 m to 0.5 m. The analysis includes image segmentation to extract the wet channel and sediment bars, followed by the calculation of reach-averaged and 50-m sub-reach averaged morphological parameters, including active width, sinuosity, bar area, slope, bed elevation, in-channel vegetation area, and estimates of grain size.

For the hydrological analysis, we used a 10-minute averaged discharge time series from the Cluozza River (freely available upon request from the FOEN site), spanning from 1973 onwards. Additionally, rainfall data from nearby meteorological stations were used as a proxy for flood events, given the lack of gauges downstream of the Ova Spin dam. The Ova Spin dam releases a seasonal ecological flow into the Spöl River, with discharges of 0.3 m³/s (October-April) and 0.9 m³/s (June-September). A peak-over-threshold approach was applied to the Cluozza River discharge data to identify significant flood events with a probability of occurrence lower than 0.5% (greater than 4.63 m³/s). We attempted to link the magnitude of flood events to the morphological changes occurring in the Spöl.

4 RESULTS

Fig. 2 illustrates an example of the temporal variation in channel morphology under the dam-regulated flow

regime, including ecological floods. Before the construction of the dam, the orthophotos from 1959 and 1961 reveal that the river exhibited a well-sorted sediment composition, with coarser fractions, such as boulders, present along the entire reach, typical of alpine rivers. Following the dam's completion in 1968, reduced discharges and continuous sediment inputs from the Cluozza River led to the formation of bars of finer gravel by 1978. This morphological change was accompanied by a shift in sediment composition, with an increased presence of gravel and finer materials, as well as signs of aggradation driven by the combined effects of Cluozza sediment inputs and the highly regulated discharge from the Ova Spin Dam. Despite numerous flood events in the Cluozza, the stream power of the Spöl appeared insufficient to mobilize the accumulated sediments by 2003, as evidenced by the large gravel bars distributed along the entire reach. However, in 2009, a major reservoir flushing event from Ova Spin, with a peak discharge of 85 m^3/s (65 times the mean annual flow in the Spöl), remobilized much of the aggraded sediment, exposing the coarser fractions again and nearly causing the disappearance of the gravel bars. The initiation of the Ecological Floods program in 2000, which aimed to release floods with a return period of one year based on pre-dam hydrology (Qmax ≈ 25 m^3/s), has been followed by aggradation even after the major 2009 flushing. In subsequent years (2015, 2019, 2022), river bars reappeared along the entire reach. In particular, near Zernez, aggradation and channel widening were observed.

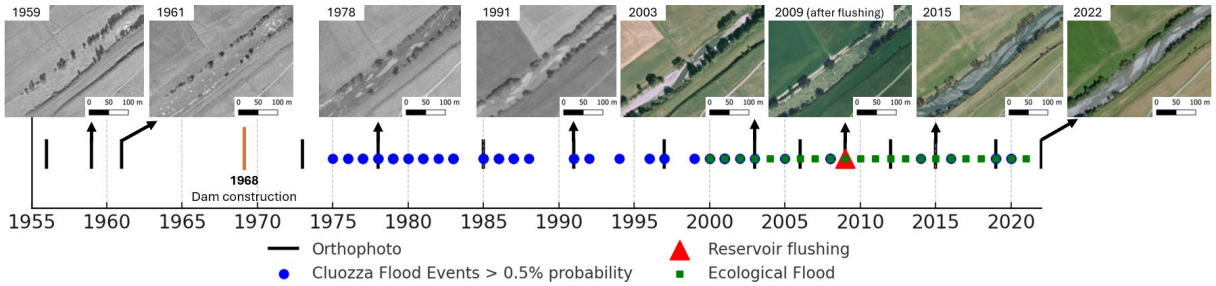

Fig. 2: Timeline showing changes in Morphology and timing of major flood events

Following the construction of the dams in 1968, the mean channel width (Fig. 3a) decreased gradually by 17%, from nearly 24 m to 20 m by 1991. After the initiation of ecological floods in 2000, there was a slight increase in width until 2009, when the flushing event occurred, causing the wet channel width to decrease to its minimum before rapidly increasing thereafter. Total bar area (Fig. 3b) showed a gradual increase until 2009, when most of the bars were washed away during the flushing event. After 2009, the bar area experienced a stepwise increase, possibly due to more frequent and larger sediment-supplying flood events from the Cluozza River, which the ecological floods could not match. Notably, in 2019, two ecological floods were released consecutively, with peak discharges of Qmax=25 m^3/s and Qmax=40 m^3/s. The latter likely triggered significant aggradation and widening near the village of Zernez. Here, the riverbed aggraded to levels higher than the top of the previous bank protection structures, burying them and depositing large amounts of gravel onto the floodplain, thus initiating a major localized widening process. A DEM of differences (DoD) analysis between the 2023 and 2019 DTMs revealed up to 2 meters of aggradation in the widening zone near the village of Zernez. Finally, low-flow channel sinuosity remained relatively stable throughout the period, fluctuating between 1.036 and 1.056, with no signs of avulsion processes.

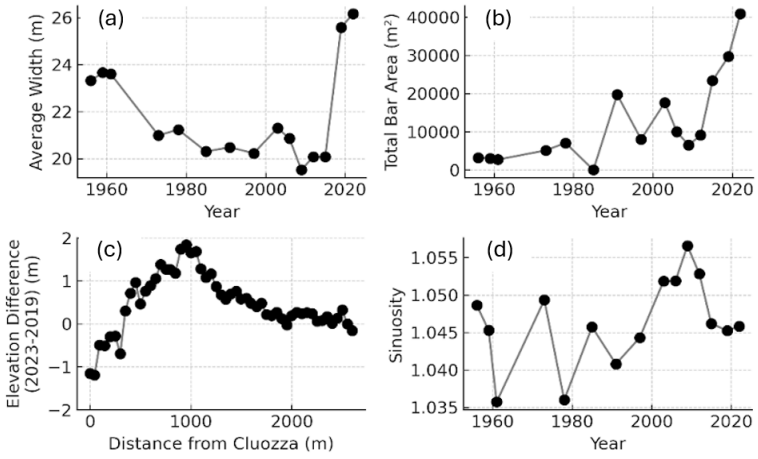

Fig. 3. (a) Time series of average active channel width; (b) Time series of total bar area; (c) 50 m-averaged elevation difference (DEM of Differences) between 2023 and 2019 along the study reach; (d) Time series of sinuosity.

5 CONCLUSIONS

The results of this study emphasize the significant role of unregulated tributaries in determining the balance between sediment supply and sediment transport capacity in dam-regulated Alpine rivers. The observed gradual processes of aggradation and river widening downstream of the Ova Spin Dam in the Spöl River highlight the importance of accounting for natural sediment supply and the impacts of ecological flood programs in river management. Observation and analysis of river morphological trajectories are critical for managing the often-unexpected channel responses of aggradation and widening, which create challenges for local communities and stakeholders. Morphological and sediment monitoring should be included in planning and assessing the river's response to ecological flood programs.

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