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Integrating flow-, sediment- and instream wood-regimes during *e-flows* in the Spöl River (Swiss Alps)

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Abstract

Integrating flow-sediment and wood regimes in the design of *e-flows* (i.e., environmental or experimental flows, floods, or releases) is of great importance, particularly in forested rivers with unregulated tributaries and /or active hillslopes affected by mass movements processes. In such cases, large quantities of sediment and wood can be supplied to the main regulated channel. This is the case of the Spöl River in the Swiss Alps. The Spöl river is regulated by two dams but undergoes a restoration program based on the release of annual experimental floods since the year 2000. Despite these *e-flows*, the river is facing significant aggradation and other associated processes, such as bank erosion, channel widening, or vegetation dieback. Instream wood is supplied to the river from the forested slopes affected by snow avalanches, landslides, debris flows and windstorms, eroded riverbanks, and vegetated islands. In 2018, we enhanced the existing monitoring framework to include observations of sediment and instream wood transport. Before and after flows, sediment was tagged, the grain size was measured at different locations, and wood stored within the river was tagged, measured, and georeferenced. We surveyed topographical cross-sections and performed aerial surveillance with a drone. Moreover, during the *e-flows*, a video camera was installed at a bridge to film the events. This contribution summarizes preliminary results from these surveys. Results will be key for the design of future river restoration in the Spöl, but also for the management of regulated mountain rivers in general.

Keywords: Please list a maximum of 5 keywords

1. INTRODUCTION

Dam construction significantly alters the water-sediment-wood regimes (Poff et al., 1997; Wohl et al., 2015; and 2019). Dams change flow conditions, reduce sediment transport capacity (Schmutz and Moog, 2018), impact riparian vegetation, and instream wood dynamics. Such changes significantly influence river habitat, which in turn impacts the river ecosystem. To mitigate such alteration of rivers, *e-flows* (i.e., environmental, experimental flows, floods, or releases) have been implemented, usually solely based on analysis of hydrology and ecological variables (Olden et al., 2014; Williams et al., 2019). Recently, existing methods and legislation just started to consider sediment and morphodynamics (Meitzen et al., 2013; Acreman, 2016; De Jalón et al., 2017; Hayes et al., 2018). But much less is known about how to consider the feedback with the riparian vegetation (e.g., Džubáková et al., 2015), and the role of instream wood is completely overlooked. Alpine forested rivers do not only convey water and sediment, but they also transport and store varying quantities of instream wood (i.e., downed trees, trunks, branches, and root wads laying on the river). An extensive literature has shown the beneficial effects of wood on the geomorphology and ecology of rivers (Swanson et al., 2020). Instream wood helps maintain active geomorphological processes and enhances complex landforms that keep a rich and diverse community of organisms. By interacting with the flow and sediments, deposited instream large wood sustains the good status of the river (Ruiz-Villanueva et al., 2016a; Wohl et al., 2019). On the other hand, large quantities of sediment and wood transported during floods, including *e-flows*, can pose a danger to infrastructures such as bridges (De Cicco et al., 2018). Thus, assessing the size, quantity, and transport of both sediment and instream wood is very important to diagnose river status and evaluate the potential success of any restoration measure. However, unlike for flow, for which time-series are usually available to characterize the flow regime (in terms of magnitude, frequency, duration, timing, and rate), analogous data is much more limited for sediment and very few exist for wood (Wohl et al., 2019). Therefore, it is essential to monitor instream wood transport in rivers. Like sediment, the transport of instream wood depends on the magnitude and duration of the flow (Ruiz-Villanueva et al., 2016b), but little is known about the effects of *e-flows* on the dynamics of wood. Are the e-flows mobilizing instream wood? If so, how much wood is mobilized and when? Which sizes are being entrained and transported? And for how long? Does the *e-flow* succeed in maintaining sufficient recruitment, storage, and transport of wood that produces the desirable river morphological and ecological characteristics? This contribution presents a pilot study of *e-flows* in the Spöl River in the Swiss Alps, which includes the monitoring of instream wood and aims to answer these questions.

2. STUDY SITE

The Spöl River is the largest river in the Swiss National Park (SNP), on the Italian-Swiss border. It flows from Punt dal Gall dam at the Livigno reservoir through a 6 km long confined valley within the SNP before entering a second reservoir, the Ova Spin. Three kilometers downstream this reservoir, the lower Spöl meets its major tributary, the Ova da Cluozza stream (drainage area 27 km^2), and then flows into the Inn River at Zernez 5.5 km downstream.

Before the dams construction and flow regulation in 1970, natural floods were seasonal and frequent in the Spöl: a snow-melt flow regime produced high flows in spring-summer and low flows in winter, and intense precipitation triggered frequent floods in summer and early autumn. Following the construction of the dam, between 1970 and 2000, the river flow was homogenized throughout the year and reduced up to less than 1 m^3/s in winter. This almost constant and low flow resulted in a lack of coarse sediment transport and the accumulation of very fine material, algae, and moss. The homogenization also meant a reduction of habitats and a drop in biodiversity. However, unlike other dammed rivers, where sediment supply is completely interrupted by the dam, the Spöl River continued to receive sediments and wood from unregulated tributaries. In the upper Spöl, small streams and torrents deliver sediment, and in the lower reach, the Ova da Cluozza stream is the most important supplier (Figure 1).

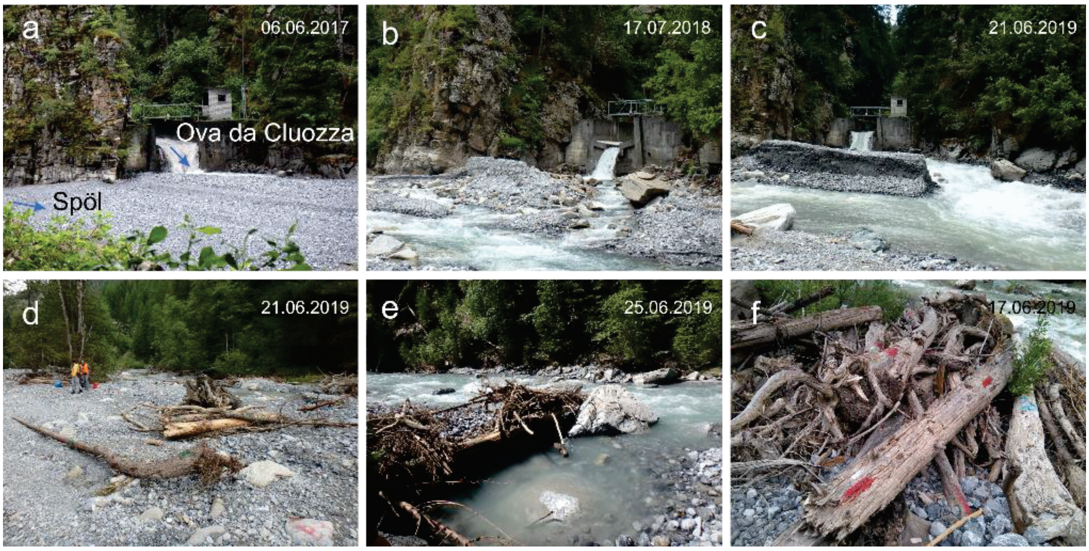

Figure 1. Pictures showing the Spöl and Ova da Cluozza junction (3 km downstream from Ova Spin reservoir) in 2017 (a), 2018 (b), and 2019 (c). A gauge station operated by the Federal Office for the Environment (ID 2319) measures Ova da Cluozza water depth and discharge continuously. Examples of how instream wood influences the Spöl River processes and forms, boosting sediment deposition upstream and pool formation (d-f). Pictures: Virginia Ruiz-Villanueva.

To improve the ecological conditions in the river, the Spöl undergoes a restoration program based on the release of experimental floods from the two reservoirs. Thirty-four experimental floods have been released once or twice a year between 2000 and 2021 and their effects have been monitored regularly (e.g., Robinson and Uehlinger, 2003; Mürle, and Ortlepp, 2005; Mannes, et al., 2008; Robinson et al., 2011; Consoli et al., 2021; Mathers et al., 2021). Results showed that the river recovered part of its mountain character, and the *e-flows* mitigated some of the negative effects of the river regulation. However, the monitoring has been mostly focused on biological and ecological features, and much less has been done to understand the biomorphological changes, including changes in vegetation and wood regime. How the experimental floods affect sediment transport is still not fully understood, and very little is known about the transport of instream wood during the released floods.

Given the inflow of sediment from tributaries and the lack of natural flows, the river is facing a significant accumulation of sediments. In the lower Spöl, the experimental floods and the natural floods in Ova da Cluozza (of much lower magnitude) remobilize only part of the stored sediment (Figure 1). Following the sediment aggradation, we observed other associated processes, such as bank erosion, channel widening, or vegetation dieback. One important concern is the bed elevation under bridges crossing the river, for example, a wooden bridge located near Zernez, as the riverbed aggrades. The reduction of the bridge capacity to convey water may result in the bridge blockage by sediment and wood and flooding in the nearby areas.

The main sources of instream wood to the river are the forested slopes affected by snow avalanches, landslides, debris flows and windstorms, and the riverbanks and vegetated islands. Instream wood supply is relatively low in the Spöl, but it may rise abruptly, as happened after snow avalanches in 2018 in the lower reach. Sediment aggradation-associated processes such as those mentioned above may also increase the supply of instream wood in the future.

3. MATERIAL AND METHODS

Extensive field surveys were carried out before and after the *e-flows* on a 1,5km reach in the lower Spöl (from the confluence with Ova da Cluozza to the wooden bridge near Zernez) between 2018 and 2021 (partially interrupted in 2020 due to the pandemic).

During these surveys, in-channel sediment grain size was measured. The Wolman pebble count method was applied to several sampling locations, measuring more than 100 pebbles at each site. In addition, ground-based vertical photographs were acquired to complement the grain size measurements with photogranulometry estimates. During the surveys in 2018 and 2019 painted plots were also used to monitor sediment transport (Mao et al., 2016).

Topographical cross-sections were acquired with a dGPS at different locations along the studied reach. The SNP flew a drone (Wingtra One drone and an AscTec Falcon 8 depending on the survey, both equipped with a high-resolution RGB camera), under base-flow conditions before and after the flows. Between 10 and 50 ground control points were deployed along the reach, measured with a dGPS, and used for the rectification of the acquired images. The post-process of the imagery was done with the Software Pix4D.

Most wood stored within the river was measured, tagged (with metal and plastic numbered tags), and georeferenced with the dGPS. The main characteristics were also recorded: length, diameter, decay stage class, geomorphic position, and anchorage. During the flood, transported floating wood was also counted and visually classified in three size categories, small (length < 1m, diameter < 0.1 m), medium, and large wood (length >3m, diameter >0.3 m approx.). The video and visual count are used to estimate the wood flux (number of wood pieces/time) and compared with the flow hydrograph. Moreover, the digital data is used to train and test a machine learning algorithm that is being developed to automatically identify and track wood in video images (Aarnink et al., 2021).

4. PRELIMINARY RESULTS

Preliminary results showed that the flows easily remobilized and even completely removed fine material (Figure 2), like fine gravel, sand, and silt, but coarser material (i.e., coarse gravel and cobbles) only traveled short distances of up to a few hundred meters when mobilized. From 13 painted plots in 2019, 92% of the painted pebbles were transported, from which 305 pebbles were recovered after the first e-flow (sizes ranging between 15 and 50 mm), up to 450 m downstream from their initial location.

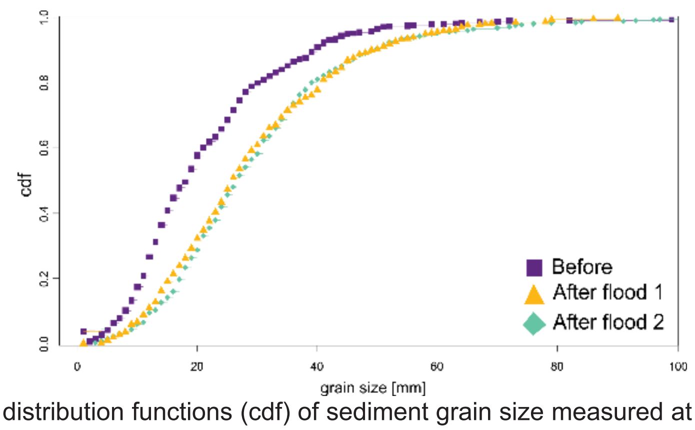

Figure 2. Cumulative distribution functions (cdf) of sediment grain size measured at 4 locations before and after the first and second *e-flows* in 2019.

In 2019 two e-flows were released in a short period of a few days, and as shown in Figure 2, the first flood mobilized and significantly changed the river granulometry, while the second one was less effective in mobilizing sediment, although it had a higher discharge.

Regarding the instream wood, only a small fraction of the available wood was mobilized by the *e-flows*, but part of it traveled relatively long distances reaching the wooden bridge and the confluence with the Inn River. The instream wood mainly traveled during the beginning and the peak of the *e-flows*, with very much less transport afterward (Figure 3).

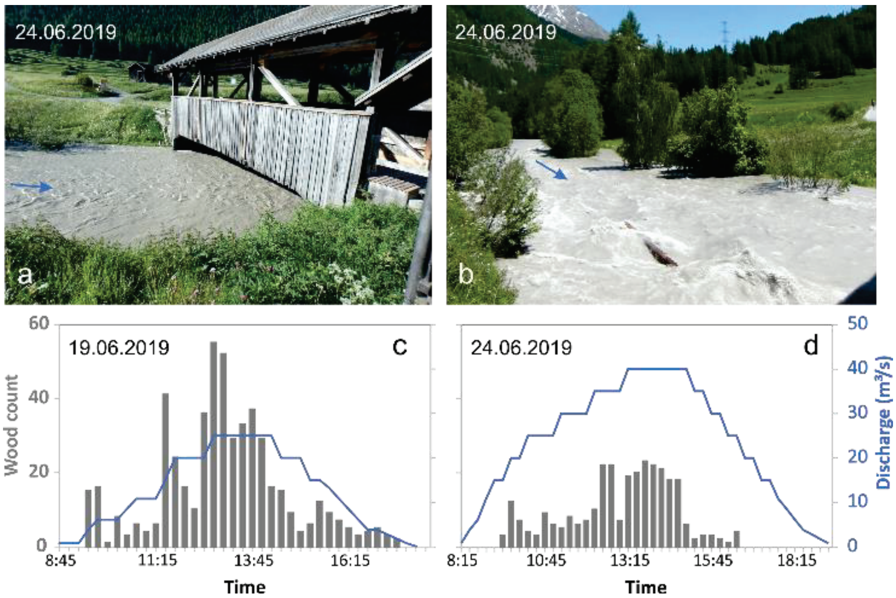

Figure 3. (a) The wooden bridge during the peak flow of the second flood in 2019; (b) and a view from the bridge towards upstream showing a large piece of wood piece approaching. Blue arrows show the flow direction; (c) hydrographs of two *e-flows* released in 2019 (blue) and the number of instream wood pieces transported (grey). Picture: Virginia Ruiz-Villanueva.

As shown in Figure 3, in 2019, when two sequencing *e-flows* were released, most of the wood was effectively entrained and transported during the first flow, even if the second *e-flow* had a higher discharge.

5. CONCLUSIONS

E-flows have become an increasingly common practice in dammed rivers aiming to reduce ecological impacts. Knowing the current sediment and instream wood transport will be essential to understanding the effectiveness of the flood operations. This study is thus key for the design of future river restoration in the Spöl, but also for the management of regulated mountain rivers in general.

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