May 9-12
Kyoto-Japan
2017

2nd International Workshop on
Sediment Bypass Tunnels

Ecological effects of SBT operations on a residual river: Solis SBT case-study

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Abstract

Sediment trapping and decreased flow variability are two major alterations caused by dams, generating downstream ecological consequences as well as reservoir problems, such as reduced storage capacity. Sediment Bypass Tunnel (SBT) operation is one technique towards re-establishing sediment connectivity and enhancing flow variability in downstream rivers. In this study, we evaluated the ecological effects of a new SBT in an alpine stream (Albula) in Switzerland over 2 years, including 5 major SBT operations. Hyporheic organic matter processing (sediment respiration), primary production and macroinvertebrate assemblages were analysed along a 4-km stretch of the residual river to better understand the ecological impact among different ecosystem properties. Results showed a clear reduction in organic matter processing, primary production and macroinvertebrate density and richness in response to SBT operations. The main factors dictating the impact of SBT operations were the maximum discharge and cumulative volume of sediment released from the SBT. We found temporal and spatial shifts in macroinvertebrate community composition with tributaries playing a positive role in ecosystem recovery following an SBT operation. Based on these results, SBT operations apparently act as short-term (pulse) disturbances to receiving waters, enhancing sediment connectivity and flow variability. Importantly, however, thresholds on the magnitude and frequency of operations should be considered to prevent catastrophic disturbances detrimental to riverine ecosystems downstream.

Keywords: sediment replenishment, flow variability, environmental impact, sediment respiration, macroinvertebrates.

1 Introduction

Dams are one of the greatest man-made modifications of natural flow regimes in rivers (Nilsson *et al.* 2005). Over 50,000 large dams (>15 meters in height) are documented in the world and more than 3,700 are planned for the near future (Nilsson *et al.* 2005, Zarfl *et al.* 2014). They retain about the 99% of upstream sediment delivery in reservoirs (Williams and Wolman 1984), causing not only morphological and ecological effects on downstream waters (Poff and Ward 1989), but major technical problems in reservoirs (Brandt 2000, Gregory 2006).

To mitigate ecological and technical problems caused by sediment regime changes from dam operations, different techniques are used to reduce sediment accumulation in reservoirs and to re-establish sediment regimes below dams. However, most of these techniques, such as sluicing or flushing, also can harm various ecological properties of river ecosystems. (Brandt 2000) showed how sediment additions by flushing can affect river geomorphology and (Rabení *et al.* 2005) and (Crosa *et al.* 2010) documented how sediment deposition can affect riverine fish and invertebrates. An alternative technology, in hydrologically and topographically suitable systems, are Sediment Bypass Tunnels (SBTs), which connect reservoirs with the stream below the dam. SBTs are operated during flood events, when water and suspended sediment from upstream enter the reservoir. In countries such as Switzerland and Japan, SBTs are increasingly used despite the lack of knowledge on the ecological consequences to river and floodplain ecosystems below such structures.

The primary goal of this study was to investigate the ecological effects of SBT events in a Swiss river during the first years of operation in order to gain a better understanding of SBT use in flow/sediment regime management. We hypothesized a reduction in ecosystem properties such as organic matter processing, primary production by periphyton and macroinvertebrate community composition, mainly due to the high scouring power of SBT events. We tested our hypothesis by sampling along a longitudinal gradient below the SBT outlet. More specifically, hyporheic sediment respiration was used as an indicator of organic matter processing (Doering *et al.* 2011), periphyton biomass as an indicator of primary production, and macroinvertebrate assemblages as an indicator of biodiversity response to SBT events.

2 Study site and sampling

The study was conducted on the Albula River (SE Switzerland). The Albula is 40-km long and drains a 950 km^2 catchment. Average discharge is ca. 35 m^3/s with natural peaks in summer due to snowmelt and precipitation events resulting in discharges >130 m^3/s (HQ100). The Albula is regulated at the Solis reservoir, located just downstream of Tiefencastel. Downstream of the dam, the river flows through a narrow canyon for about 7 km until the town of Sils. A Sediment Bypass Tunnel was built in 2012 about 500 m upriver of the dam to reduce sediment accumulation in the reservoir. The tunnel is 973-m long, 4.5 x 4.7-m in size, has a 1.9% slope and flow capacity of 170 m^3/s (Auel and Boes 2010).

The 4-km long study section was located between the dam and Sils. Three small tributaries enter the study section: Rain Digl Lai, Grossbach and Prodavosbach located at 350, 1500 and 5000 m downstream of the SBT outlet, respectively. Six sampling sites were established along the study section. Site 1 was located 50 m upstream of the SBT outlet and used as a control site unaffected by SBT events. The other sampling sites were located downstream of the SBT outlet (100, 400, 500, 4900 and 5000 m; and placed above and below potential sediment input sources such as tributaries) (Figure 1).

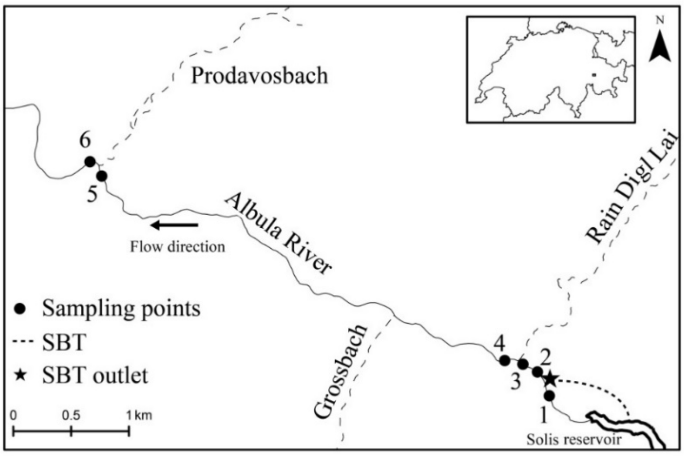

Figure 1: Map of the study stretch below Solis reservoir showing the study sites. SBT = sediment bypass tunnel (from Martin *et al.* 2017).

Sampling campaigns were conducted five times each year in late spring, summer and early autumn, when the possibility of having a high flow event was greatest (high flow events are weather related and thus unpredictable). Sampling dates were adjusted each year to account for sampling after a particular SBT event, although a known pre-event sampling was performed in May of each year. In 2014, three major SBT events occurred. Sampling was conducted just after flow returned to residual levels: After the first SBT event in late May and in August after June and July events. Two sampling campaigns were conducted in September and November 2014 to examine recovery following major SBT events. The first SBT event in 2015 also occurred in late May with a post event sample collected soon after. Another SBT event occurred in June 2015 followed by flushing releases over a number of days. Sampling campaigns took place once flows returned to residual levels in July, September and October 2015 (For more details, see Martín *et al.* 2017).

3 Methods

3.1 Sediment respiration, periphyton and macroinvertebrates

Hyporheic sediment respiration (SR, 3 samples per site and date) was measured at each site as the change in O_2 concentration over time using Plexiglas® tubes (5.2 cm diameter, 32 cm long) to incubate hyporheic sediments (after methods in Uehlinger *et al.* 2002). Hyporheic sediments were pre-sieved to 8 mm to exclude metabolically inactive large sediments: i.e. large stones (Doering *et al.* 2011). Tubes half-filled with sediments and half with water were sealed with rubber stoppers and buried into the sediment for 3 to 4 hours for incubation. Temperature and oxygen concentration were measured before and after incubation. Calculations of respiration were based on O_2 consumption in the tube water (r: g O_2 m^{-3} h^{-1}) and then recalculated as respiration per kg sediment (R: g O_2 kg^{-1} h^{-1}) as follows:

$$R = r\ Vw\ /\ Gw \qquad [1]$$

where Vw is water volume in the tube (m^3) and Gw is sediment dry weight (kg). Respiration rates were normalized by a reference temperature of 20°C to minimize seasonal variations due to temperature changes using the Arrhenius equation as described in Naegeli and Uehlinger (1997).

Five rocks were randomly collected from each site on each date. In the laboratory, periphyton was removed from the surface of stones using a metal brush and rinsed with deionized water. Subsamples of the suspension were filtered through Whatman GF/F filters. Filters were dried at 60°C for 24 h, weighed, combusted at 450°C for 4 h and reweighed. The rock surface area was calculated by wrapping rocks with aluminium foil and using a weight-to-area relationship. Periphyton biomass was expressed as g AFDM/m^2.

Three benthic samples were collected using a Hess sampler (250-um mesh, 0.04 m^2 area) from each site on each visit and preserved with 70% ethanol. Additionally, in 2015, samples from tributaries were collected as a reference for sites unaffected by dam or SBT releases. In the laboratory, macroinvertebrates were handpicked and identified to family level (Ephemeroptera, Plecoptera, Trichoptera, Diptera, Crustacea) or order level (Oligochaeta) and counted. Density and taxa richness were calculated for each sample.

3.2 Data analysis

A stepwise multiple regression on log(x+1) transformed data was used to determine what predictive factors (distance to tunnel outlet, Max SBT Q, Max tot Q, Cum. water volume, event duration and Cum. sediment volume) influenced measured ecosystem properties. Variables were excluded in a backward direction when the Akaike Information Criterion (AIC) values of the alternative models were lower and the variables involved were significant (based on Analisys of Variance, ANOVA). Relative variable importance was calculated according to the metric 'LMG' using the package 'relaimpo' in R (Grömping 2006).

Two Non-metric Multidimensional Scaling (NMDS) analyses based on Bray-Curtis distance and calculated on log(x+1) transformed densities were carried out, one by-site to examine longitudinal patterns, and one by-date to examine temporal patterns. Samples from sites non-affected by SBT events (Tributaries and Site 1) were excluded in the by-date analysis to avoid interference with the affected samples. To test for among-groups differences, an Analysis of similarity (ANOSIM) was conducted. All analyses were carried out using R software (R Development Core Team 2014).

4 Results

Stepwise regression showed that respiration was related to maximum SBT Q and sediment amount of each event ($R^2 = 0.22$), with both variables showing similar relative importance. Periphyton AFDM was related to distance to the tunnel (8% of importance), maximum discharge (47%) and sediment amount of each event (44%) ($R^2 = 0.43$), whereas variation of periphyton chl-a was best explained by maximum SBT discharge ($R^2 = 0.46$). Both macroinvertebrate density and richness were related to maximum SBT discharge as well to distance to the tunnel outlet, with distance being relatively less important than maximum discharge (90%) (density, $R^2 = 0.34$ and taxa richness, $R^2 = 0.25$, respectively) (Table 1).

Table 1: Stepwise multiple regression on ecosystem properties (response variable) against predictive physical variables. Significance level of single factors: *p <0.05, **p <0.01, ***p <0.001. (Modified from Martín *et al.* 2017).

Response variable	R^2	Predictive variables	Relative importance %	p-value
SR	0.22	Max SBT Q	56	*
		Cum. sediment vol.	44	***
Periphyton Biomass	0.43	Distance from SBT outlet	8	*
		Max SBT Q	47	***
		Cum. sediment vol.	44	**
Periphyton Chlorophyll a	0.46	Max SBT Q	100	***
Macroinvertebrate Density	0.34	Max SBT Q	100	***
Macroinvertebrate Richness	0.25	Distance from SBT outlet	10	*
		Max SBT Q	90	***

The effects of SBT events on macroinvertebrate assemblages differed between 2014 and 2015. Macroinvertebrate composition was similar among sites in 2014 (ANOSIM, R = 0.0, p = 0.70), whereas two distinct groups were evident in 2015 (ANOSIM, R = 0.5, p = 0.001). In 2015, Sites 1-3 were grouped together and Sites 4-6 were clustered with the two sampled tributary assemblages. Macroinvertebrate assemblages also changed over time, showing a significant temporal shift after SBT events with a recovery to previous assemblage compositions after the SBT events (Figure 2). For example, assemblages in 2014 shifted to a dominance of Oligochaeta and Chironomidae initially after the SBT events, followed by another shift to a more diverse assemblage as the system recovered (ANOSIM, R = 0.6, p = 0.001). In contrast, after the first SBT event 2015, assemblages also shifted but returned to pre-event assemblage composition within a month after the events (ANOSIM, R = 0.3, p = 0.001).

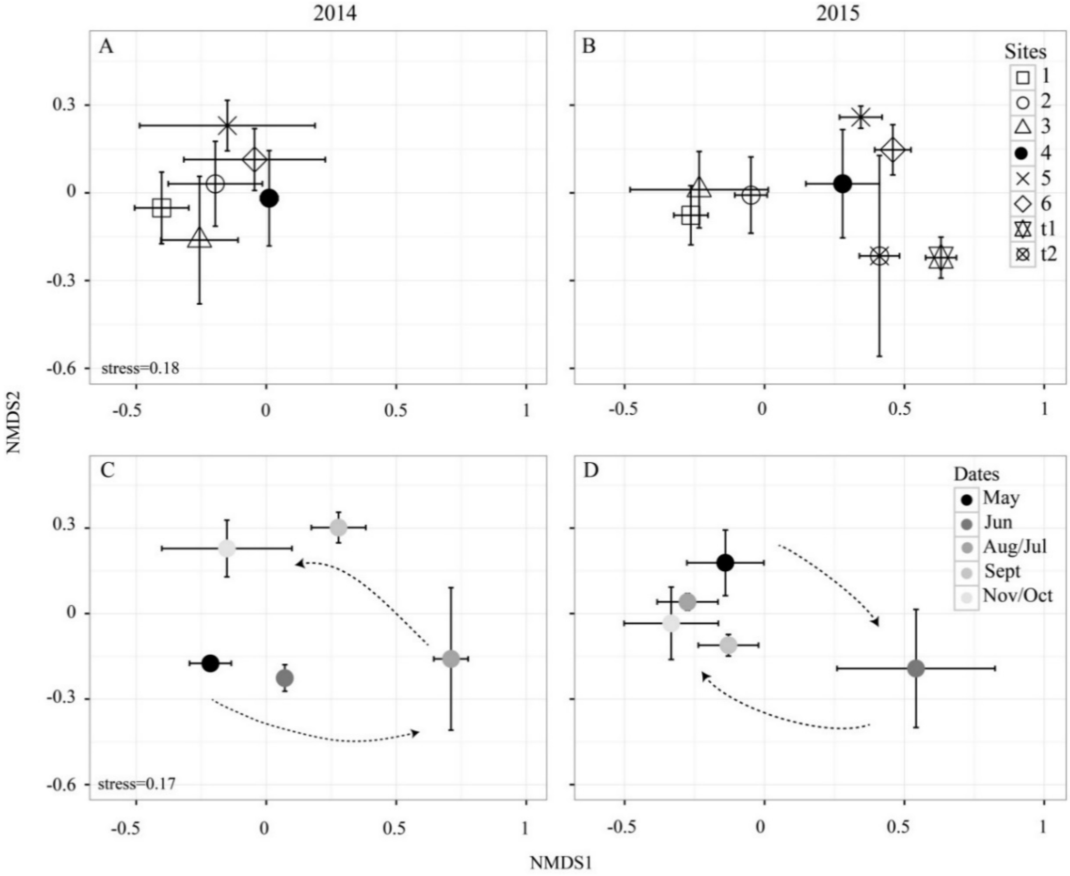

Figure 2: NMDS plots based on benthic macroinvertebrate densities. A and B plots show spatial variation among sites. C and D plots show temporal variation among dates. Legend in B applies for panel A, and legend in D applies for panel C. Dotted arrows in panel C and D illustrate temporal changes (Martín *et al.* 2017).

5 Discussion

The results suggest that Sediment Bypass Tunnel events affected the structure and function of the Albula River downstream of the dam. According to our results, mainly the large events had an effect on hyporheic respiration, suggesting small sediment-laden events did not mobilize deeper layers of the stream bed. Additionally, SBT alterations on hyporheic sediment respiration were not related to distance from the SBT outlet, showing all sites below the SBT had similar impacts.

Periphyton levels and macroinvertebrate densities in the top layer of the stream bed were reduced by SBT events, likely caused by the scouring effects of high flows. This result was expected, as similar reactions have been detected in other studies of flood (natural and e-flows) effects on rivers (Mcmullen and Lytle 2012, Espa *et al.* 2015, Robinson *et al.* 2004). Biotic response patterns were associated with SBT event magnitude, with larger events having greater impacts and recovery to pre-event communities being faster after smaller events (Robinson 2012). Tributaries in the section appeared to enhance the recovery of macroinvertebrate assemblages following SBT events, acting as a source of invertebrates (Robinson *et al.* 2003).

In summary, we found that SBTs events can be used as environmental flows to simulate more natural flow/sediment regimes of receiving waters, improving the longitudinal connectivity of sediments of rivers impounded by dams. Determination of SBT event thresholds for each system are recommended to reduce ecological risk from extreme magnitude events (Konrad *et al.* 2011, Olden *et al.* 2014). Further studies are needed to better understand mid and long-term ecological response patterns and promote the knowledge in the adaptive management of flow-regulated rivers.

Acknowledgement

Funding for the study was provided through the BAFU project „Wasserbau & Ökologie“. We thank the EWZ for providing discharge data. We thank C. Jolidon and S. Blaser for field and lab assistance.

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