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Ecological effects of sediment bypass tunnels

Eduardo J. Martín, Michael Doering, Christopher T. Robinson

Abstract

Different techniques, including Sediment Bypass Tunnels (SBTs), are used to re-establish sediment regimes downstream of dams. Our goal was to evaluate the ecological effects of a new SBT in an alpine stream in Switzerland. Sediment respiration (SR), fine particulate organic matter (FPOM), periphyton biomass and macroinvertebrate density and richness were analysed along a 5 km stretch of the river. Sampling was conducted upstream and downstream of sediment input sources, including the SBT and major tributaries, to determine the ecological impact of SBT high flow events. Our results showed that SR, periphyton biomass and macroinvertebrate density and richness decreased after SBT events due to water and sediment scouring/deposition. These results suggest SBT events act as short-term disturbances, but may potentially enhance sediment regimes downstream of dams in the long term.

1 Introduction

Sediment dynamics are an important feature of rivers and floodplains, maintaining habitat heterogeneity and turnover, and organic matter dynamics (Yarnell *et al*,. 2006). However, anthropogenic alterations have modified, and even eliminated, natural sediment regimes of rivers and floodplains, leading to ecosystem degradation via river-bed colmation, habitat loss and homogenization, and organic matter accumulation (Williams *et al.*, 1984; Brandt, 2000). One of the greatest man-made modifications of river ecosystems is through dams. Nilsson *et al.* (2005) documented that over 50,000 large dams (>15 meters in height) exist in the world, trapping up to 99% of upstream sediment delivery in reservoirs (Williams *et al.*, 1984). Besides the ecological effects, sediment accumulation in reservoirs can cause technical problems in reservoir operation. According to Sumi *et al.* (2004), worldwide reservoir storage capacity decreases around 570 km^3 annually. To overcome ecological and technical problems caused by sediment regime changes from dam operations, different techniques such as flushing or sluicing of reservoirs are used to reduce sediment accumulation in reservoirs and to re-establish sediment regimes below dams. However, these techniques 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 to sediment flushing by opening dams are Sediment Bypass Tunnels (SBTs) in hydrologically and topographically suitable systems. SBTs 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 combination with an earlier lowering of the water level in the reservoir, the high flow event mobilizes accumulated sediments and transports them through the SBT. 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. This study investigated the ecological effects of SBT events in a Swiss alpine river during one year. Sediment respiration, periphyton biomass and macroinvertebrates were used as ecological indicators to examine SBT events in the river since they respond rapidly to flow and sediment alterations and are used to evaluate and define the ecological conditions of stream ecosystems (Niemi *et al.*, 2004).

Sediment respiration is an ecosystem function property that refers to organic matter oxidation by microbial heterotrophs, e.g. bacteria, in the hyporheic zone of rivers, regulating carbon cycling and CO_2 fluxes into the atmosphere, among other ecosystem processes (Andrews *et al.*, 2001). It is mainly driven by temperature and organic matter content (Doering *et al.,* 2011). Periphyton includes bacteria, fungi and archaea that comprise biofilms covering streambed stones. Biofilms can influence nutrient uptake and the retention of suspended particles (Battin *et al.*, 2003). Macroinvertebrates are aquatic organisms such as insects that inhabit streambeds and provide resources for higher trophic levels in riverine/floodplain food webs. Periphyton and invertebrates in most alpine streams show peaks of growth in autumn, due to the lack of flow events, warm temperatures, light availability and constant discharge (Uehlinger *et al,*. 2010). The specific goals of the study were to:

- Identify and quantify the effects of SBT events to river floodplain structure and function using sediment respiration, periphyton biomass and macroinvertebrates as ecological indicators.
- Study temporal patterns in the ecology of the system following SBT events using the above ecological indicators.

2 Methods

2.1 Study Site and field sampling

The study was conducted on the Albula River, Canton Grisons (SE Switzerland) in the Rhein basin. The Albula is 40-km long and drains a 950 m^2 catchment with an average elevation of 2300 m a.s.l. 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, the river flows through a narrow canyon for about 7 km until the town of Sils. The canyon causes a heterogeneous stream morphology due to its curved longitudinal profile and the presence of large rocks and wood accumulations that generate riffles, runs, pools and backwaters. A Sediment Bypass Tunnel was built in 2012 about 500 m upriver of the dam to reduce sediment accumulation in the reservoir.

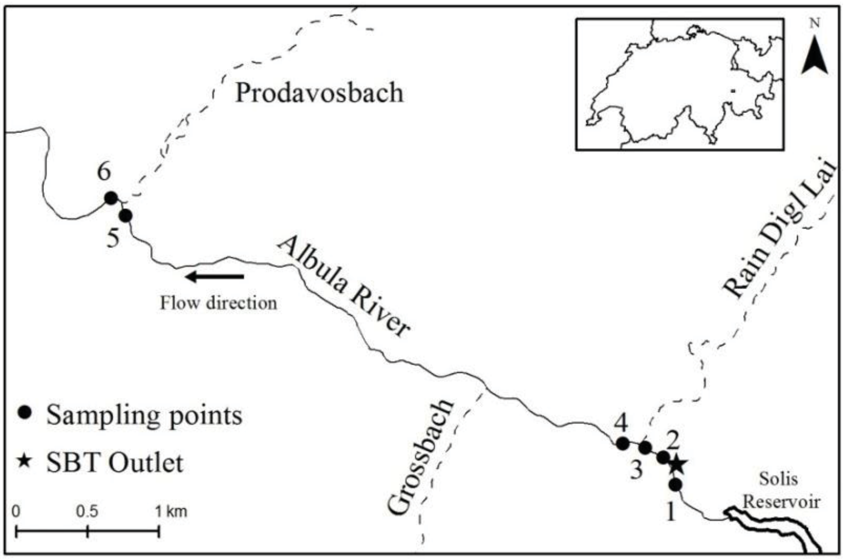

Figure 1: Map of the study stretch below Solis reservoir showing the study sites

The 5-km long study section is located between the dam and a downstream power plant at Sils (Figure 1). 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. The first site was located 50 m upstream of the SBT outlet, and the others 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). Three SBT events occurred in 2014 with discharges of 84 (May 23), 114 (June 29) and 160 m^3/s (August 13). Sampling campaigns took place before the first event (May 13), after the first event (June 5) and after the third event on August 28, September 22 and November 11. In between SBT events, spill water had a constant release except for a period in October (Figure 2).

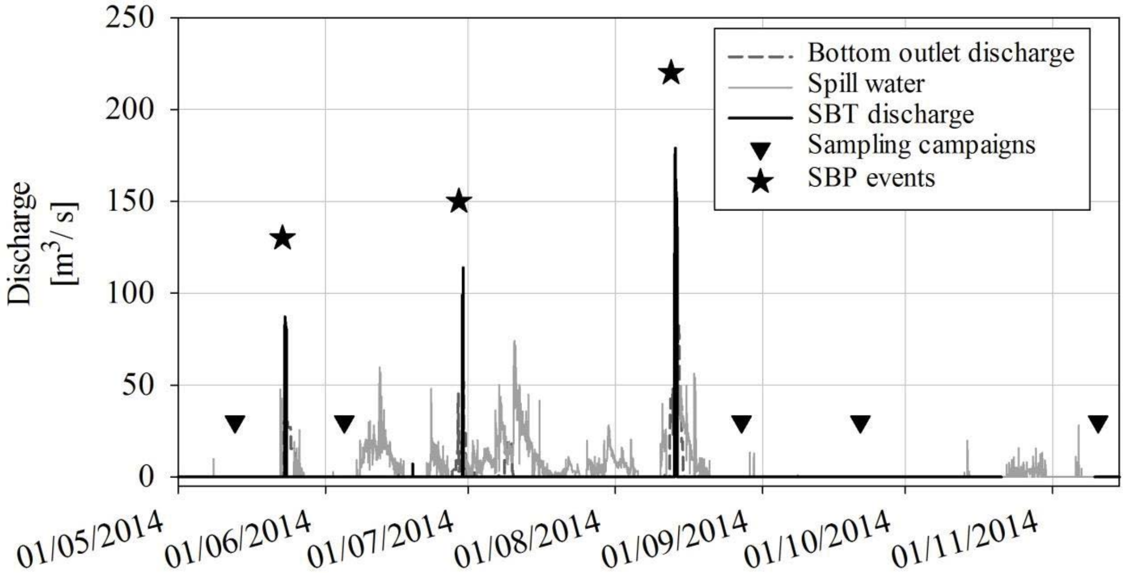

Figure 2: Discharge of the Albula River as bottom outlet flow, spill water flow and SBT flow. Triangles indicate sampling campaign dates and stars show SBT events

2.2 Sediment respiration

Hyporheic sediment respiration (SR, n = 3 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). To avoid the respiratory effect of epilithic algae, ~10 cm of the sediment surface layer was removed. 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 with a portable oxygen meter (Hach HQ40d connected to a LD0101 oxygen probe). After incubation, samples were stored at -20°C until analysed. 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:

$$R = r\, Vw / Gw \tag{1}$$

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:

$$R_{20°C} = R_T / 1.072^{\,T\text{-}T20°C} \tag{2}$$

where $R_{20°C}$ is respiration rate at 20°C and T is the water temperature in the tube at the end of the incubation as described in Naegeli *et al.* (1997). In the laboratory, coarse particulate organic matter (CPOM, > 2 mm) was separated from sediments. CPOM samples were dried at 60°C for 48 h, weighed, combusted at 450°C for 4 h and reweighed. Sediments and organic particles <2 mm were dried at 60°C for 48 h, combusted at 450°C for 4 h and reweighed to determine fine particulate organic matter (FPOM). CPOM and FPOM were expressed as g of ash-free dry mass (AFMD)/kg sediment. Only the FPOM data are presented in this paper.

2.3 Periphyton

Five rocks were randomly collected from each site on each date, stored in plastic bags, and kept frozen at -20°C until analysed. 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.

2.4 Macroinvertebrates

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. In the laboratory, macroinvertebrates from each sample 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.

2.5 Data analysis

The open-source program R 3.0.1 (R Development Core Team 2010) was used for all statistical analyses. All data were log(x+1) transformed to give a normal distribution (Sokal *et al*,. 1995). To evaluate temporal effects in the stretch, data were pooled by date. ANOVA was used to test for temporal differences between campaigns for each measured variable: SR, FPOM, periphyton, macroinvertebrate density and taxa richness. Tukey's HSD was used as a post-hoc test when differences were significant.

3 Results

3.1 Sediment respiration and FPOM

Sediment respiration differed between dates (ANOVA: $F_{(4,73)} = 5.08$, $p = 0.001$) (Figure 3). $R_{20°C}$ decreased from 1.7 to 1.2 mg O_2 (32% decrease) after SBT event 1 (June) and to 0.9 mg O_2 (47% decrease) after events 2 (July) and 3 (September) (Tukey's test, $p < 0.05$). About one month after event 3, $R_{20°C}$ increased to 1.4 mg O_2 (48% increase) and remained similar in November. Variability in respiration in this later period was higher compared to June (coefficients of variation (CVs) = 68% and 33%, respectively). FPOM did not differ among dates (ANOVA: $F_{(4,73)} = 2.03$, $p = 0.1$) and no correlation was found between FPOM and SR ($r^2 = 0.04$) (Figure 3).

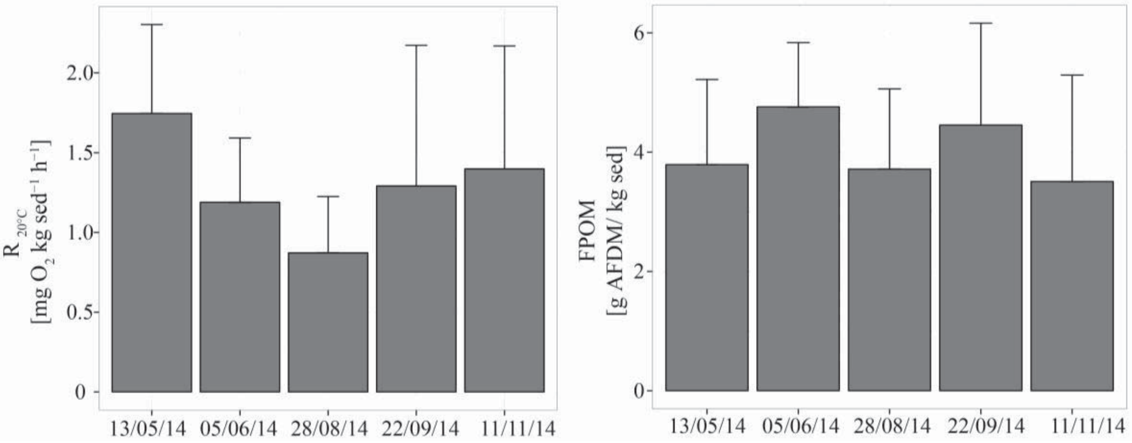

Figure 3: Mean sediment respiration at 20°C ($R_{20°C}$) and FPOM (mean ±1SD, n = 18 per date) using data from all sites per date

3.2 Periphyton

Periphyton showed a similar pattern as sediment respiration with biomass being different between dates (ANOVA: $F_{(4,125)} = 10.54$, $p < 0.0001$). After the first event, periphyton biomass decreased 47% compared to the first date and decreased 83% after SBT events 2 and 3 (Tukey's test, $p < 0.05$). One month after event 3, biomass significantly increased by 300% (Tukey's test, $p < 0.05$) with another increase of 84% after 2 months (Tukey's test, $p < 0.05$). Variation was substantially higher in November than in September (CVs = 230% and 64%, respectively) (Figure 4).

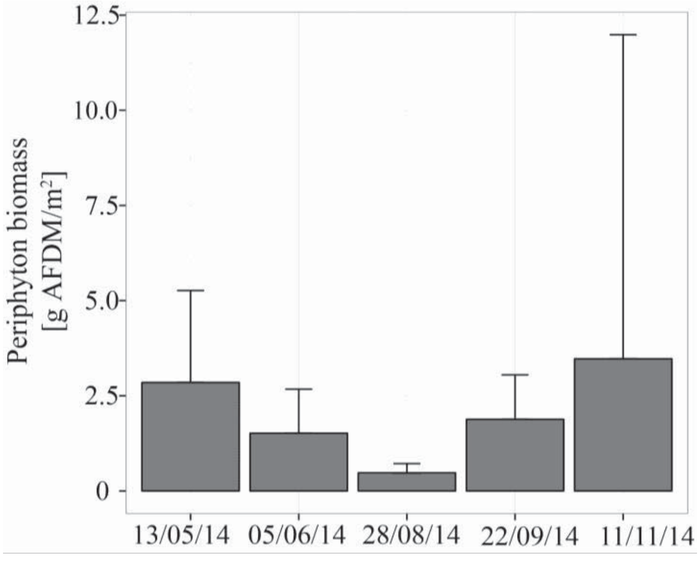

Figure 4: Mean periphyton biomass (mean ±1SD, n = 30 per date) using all sites combined for each date

3.3 Macroinvertebrates

There were significant flood effects on macroinvertebrate density (ANOVA: $F_{(4,73)} = 33.39$, $p < 0.0001$) and taxa richness (ANOVA: $F_{(4,73)} = 10.19$, $p < 0.0001$) (Figure 5).

Macroinvertebrate density decreased from 4618 ind/m^2 in the first campaign to 1287 ind/m^2 after event 1, and decreased to 90 ind/m^2 after events 2 and 3 (Tukey's test, $p < 0.05$). One month after event 3, density increased again to 1786 ind/m^2 (Tukey's test, $p < 0.05$) and remained relatively stable after that. Taxa richness had a similar trend as density, except for a significant increase in taxa richness two months (November) after the last event (Tukey's test, $p < 0.05$) (Figure 5).

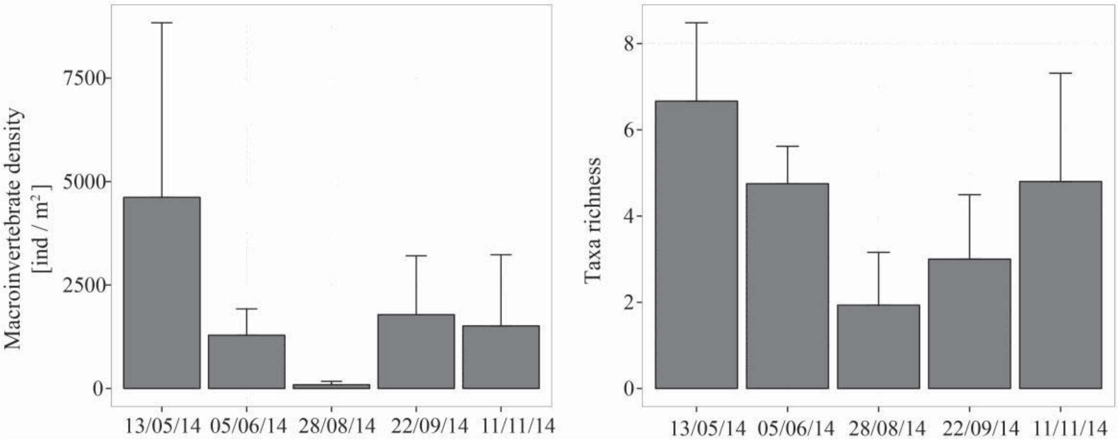

Figure 5: Macroinvertebrate density and taxa richness (mean ±1SD; n = 18) using data from all sites per date

4 Discussion

The results suggest that Sediment Bypass Tunnel events affected the structure and function of the Albula River downstream of the dam. Sediment respiration, as an indicator of ecosystem function, was reduced after each event. Further, the decrease in respiration appeared to be related to event intensity. Apparently, water and sediments delivered by the SBT had enough force to mobilize or scour the top 30 cm (at least) of the river bed where the sediment samples were collected. Heterotrophic microbes (e.g., bacteria) were likely disturbed or scoured from bed sediments, thereby decreasing respiration rates after events. In addition, suspended sediments from SBT events may have been deposited during each event, thus decreasing respiration rates due to their low metabolic activity. The reduction in ecosystem respiration is likely a combination of these two factors.

According to Wei *et al.* (2008) and Aristi *et al.* (2014), spill waters from dams can be sources of dissolved and suspended particulate organic matter, which may enhance the concentration of organic matter in streambeds and increase respiration processes after SBT events. The lack of a clear pattern following SBT events in organic matter could indicate patchiness in the scouring and accumulation of (scoured/deposited) sediments due to the morphological heterogeneity of the channel. High CV values found in the last campaigns (September and November) in sediment respiration and FPOM suggest high spatial heterogeneity in the study stretch in terms of the distribution and abundance of organic matter and in respect to erosion and deposition areas.

Periphyton biomass also was affected strongly by the SBT events, being reduced by 83% after the three SBT events. These results are similar to those found in previous studies by Uehlinger *et al.* (1998) and Robinson *et al.* (2004) in which periphyton was reduced following experimental floods. In this study, abrasion potential was likely high due to the high sediment load during an SBT event. Following SBT events, periphyton also showed rather quick recovery, although being quite variable due to site differences.

Macroinvertebrate density and taxa richness showed a clear reduction after the SBT events. Such a reduction in macroinvertebrate abundance to high flows has been shown in various systems (e.g., Lytle, 2000; Bruno *et al.*, 2009; Robinson *et al.*, 2012). Both medium and high SBT events decreased taxa richness and density due to the high discharge through the canyon (> 75 m^3 in all cases). Further, spill water releases from the dam at the beginning of November also appeared to decrease macroinvertebrate density, as November densities were lower than in October. Taxa richness, in contrast, showed a recovery in November with values close to pre-SBT event values. This recovery may indicate a rapid recolonization by individuals of different taxa that were not affected by a SBT event or by adult insect oviposition of eggs in the study section. The presence of tributaries in the study section can have a positive effect on macroinvertebrate recovery, as suggested by Robinson *et al.* (2003). Seasonality may also affect the recovery of macroinvertebrates and determine which organisms will recover more rapidly than others depending on when a SBT event happens.

In summary, high flows from SBT events seem to have enough power to modify habitat conditions along the study stretch, thereby affecting different key ecosystem variables such as sediment respiration, periphyton biomass and macroinvertebrate abundance and richness. Regardless of these short-term effects, the system seems to recover quite quickly, in a matter of weeks to months. SBT events could be used as experimental flows (Olden *et al.*, 2014), activating erosion and deposition processes that were lost due to regulatory actions of the dam. The potential high impact of SBT events, which are close to unusual high flow events (HQ100) and in frequency, likely have long-term implications on river ecosystems below SBTs. Further studies are needed to understand the long-term effects of SBT events on river/floodplain ecosystems.

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Authors

Eduardo J. Martín (corresponding Author)
EAWAG, Swiss Federal Institute of Aquatic Science and Technology
8600 Dübendorf, Switzerland.
Email: eduardo.martin@eawag.ch

Michael Doering
ZHAW, Zurich University of Applied Sciences
Grüental
8820 Wädenswil, Switzerland.

Christopher T. Robinson
EAWAG, Swiss Federal Institute of Aquatic Science and Technology
8600 Dübendorf, Switzerland