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Effects of sediment bypass tunnels on sediment grain size distribution and benthic habitats

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ABSTRACT: Four reservoirs in Japan and Switzerland with sediment bypass tunnels (SBT) as strategy against sedimentation were monitored to analyze their effects in terms of up- to downstream morphological and biotic changes. Sediment grain size distribution (GSD), local bed characteristics, microhabitat abundance and invertebrate richness were analyzed. It was found that GSD at reservoirs with newly established SBTs are fine in the up- and coarse in their downstream waterway due to lack of conveyed sediments in the past. Analysis of biotic data directly below the dams reveal that microhabitat richness is low and lentic species abundance is high compared to upstream, while these differences decrease further downstream. Microhabitat and invertebrate richness in the downstream adjust to the upstream values with increasing operation years clearly showing the positive effects of long-term SBT operation.

1 INTRODUCTION

Anthropogenic impacts have altered river systems worldwide with about 15% of the global annual river runoff stored in manmade reservoirs (Nilsson et al. 2005). A dam impounding a river interrupts the natural flow and hinders continuous sediment transport resulting in changes in downstream flow regime, bed morphology and ecosystem (Poff et al. 1997, Brandt 2000, Kondolf et al. 2014, Aristi et al. 2014). A reservoir traps the incoming sediments leading to sediment starving conditions and degradation downstream if no appropriate action is taken. Sedimentation management encompasses a large variety of strategies including flushing, sluicing and bypassing (Morris & Fan 1998, Kondolf et al. 2014). Sediment bypass tunnels (SBT) are one strategy routing sediment load around reservoirs thereby avoiding accumulation (Vischer et al. 1997, Sumi et al. 2004). The number of tunnels worldwide is still limited due to high construction and maintenance cost. Most tunnels are located at gravel bed rivers (GBR) in mountainous regions at small to medium-size reservoirs where a considerable amount of coarse material is entrained. A SBT is operated in supercritical free-surface flow conditions with flow velocities up to 15 m/s with tunnel lengths ranging from some hundred up to 4000 m (Auel & Boes 2011). The tunnel intake is located either at the reservoir head or inside the reservoir depending on the desired operational conditions. A SBT has the advantage that only newly entrained sediment from the upstream reach is diverted into the downstream thereby reestablishing the sediment connectivity. The sediment pulse is therefore of natural character as the pre-dam conditions are reestablished during floods. Already accumulated sediments in the reservoir are normally not mobilized. Auel et al. (2016) show for two Japanese SBT that they are an effective strategy to counteract sedimentation thereby considerably enlarging reservoir life. The downstream released sediments lead to morphological changes in the river bed with formerly degraded sections being filled (Fukuda et al. 2012, Facchini et al. 2015). Besides morphological changes, also the benthic habitat is largely affected by flushing or bypass operations (Robinson et al. 2003, 2004, Martin et al. 2015).

In this paper we analyze the downstream effects of SBT operation on bed morphology and benthic habitats exemplary for four different reservoirs in Switzerland and Japan, the two countries with highest number of SBT in operation and planning.

2 METHODS

Four reservoirs, where SBTs as a sedimentation strategy are applied, were monitored in 2014 to analyze the effects of tunnel operation and resulting sediment augmentation in the downstream. These were Pfaffensprung and Solis in Switzerland, and Asahi and Koshibu in Japan (Tab. 1). Sediment grain size distribution (GSD), local bed characteristics, microhabitat and invertebrate richness were analyzed up- and downstream of these reservoirs. The SBTs Asahi and Pfaffensprung are already operated for 17 and 93 years, respectively (termed *old* hereafter), whereas Koshibu and Solis are *new* with no and two years of operation, respectively.

The benthic biota can be mainly divided into lentic and lotic species corresponding to biota preferring still or flowing water, respectively. Whereas upstream of dams lotic species dominate, lentic ones are abundant downstream of dams where high discharge is scarce. We hypothesize that the longer the SBT is in operation, the lower the up- to downstream difference in GSD, microhabitat and invertebrate richness.

2.1 *Study area*

2.1.1 *Asahi reservoir*

The 86 m high Asahi dam is located in the Kii Peninsula, Nara Prefecture, Japan, and operated by Kansai Electric Power. The reservoir is part of the Okuyoshino pump storage hydropower scheme together with the upper Seto dam. Operation started in 1978 with an original reservoir volume of 15.5×10^6 m^3. The catchment area is 39.2 km^2 and mostly covered by forest with a maximum altitude of 1,800 m a.s.l. The upstream Asahi river reach is a GBR with steep slopes of 2% at the reservoir head up to about 4% further upstream. Due to large landslides in the catchment, reservoir sedimentation progressed by about 0.5% per year. Therefore, construction of a SBT was initiated and put into operation in 1998 (Nakajima et al. 2015). 77% of the incoming sediments were bypassed since then (Auel et al. 2016). The tunnel design discharge is $Q_d = 140$ m^3/s, the gate is opened at $Q > 5$ m^3/s, whereas smaller flows are directed into the reservoir through a weir opening. From March to September, the tunnel is opened about 12 h during daytime to enhance downstream ecological conditions. The mean annual inflow is low with $Q = 2.5$ m^3/s, floods occur in the rainy season from July to September partially until November with an annual mean of $Q = 299$ m^3/s.

2.1.2 *Koshibu reservoir*

The 105 m high Koshibu dam, constructed in 1969, is located in Nagano Prefecture, Japan, and operated by the Ministry of Land, Infrastructure, Transport and Tourism. The 58×10^6 m^3 large reservoir is used for power generation, flood control and irrigation (Kashiwai & Kimura 2015). The Koshibu River is located in an area of high erosional activity due to both heavy rainfall (1600-2000 mm/a) and large seismic activity. The catchment area is 288 km^2 with a maximum altitude of 3,120 m a.s.l. Sedimentation in 2012 reached 17×10^6 m^3 despite of frequent dredging operations (Kashiwai & Kimura 2015). Hence, 29% of the original reservoir volume was filled by then with a mean annual sedimentation rate of 0.68%. The construction of a SBT was initiated in 2009, is currently in its final stage and will presumably start regular operation in 2017. An upstream check dam will retain the coarsest sediment fractions to be used as construction material. The tunnel design discharge is $Q_d = 370$ m^3/s, while the gate is planned to be opened at $Q > 80$ m^3/s (Kashiwai & Kimura 2015). The mean annual inflow and flood discharge is $Q = 3.4$ m^3/s and $Q = 317$ m^3/s, respectively. As one reservoir purpose is flood control, the mean flood outflow is lower with $Q = 203$ m^3/s.

2.1.3 *Solis reservoir*

The 61 m high Solis dam, built in 1986, is located in the Swiss Alps, canton of Grisons. It is operated by the Electric Power Company of Zurich and used for hydropower generation. The dam retains the water from the Albula River, resulting in a 4.1×10^6 m^3 large reservoir of narrow shape. The mean annual inflow is 25 m^3/s, coming from the Albula and Julia Rivers with a total catchment area of 900 km^2 as well as upstream hydropower plants (Auel et al. 2011). The mean catchment elevation is 2150 m a.s.l. Both rivers are GBR with mean slopes of about 1.5% and 5% for the Albula and Julia, respectively. The HQ100 (flood event with 100 year return period) accounting for both rivers was reported with 280 m^3/s (Auel et al. 2010, 2011) based on data from 2003 by the Federal Office for the Environment (FOEN) but increased to 428 m^3/s in 2015 due to updated statistical data for the Julia River. The average annual sediment aggradation in the reservoir is 8.0×10^4 m^3 (Auel et al. 2010, 2011).

In 2012 about half of the reservoir was filled (Oertli & Auel 2015) corresponding to an annual sedimentation rate of 1.9%. In the same year, construction of a SBT was completed. Since then, the tunnel successfully operates and already diverted a major flood of 288 m^3/s on August, 13th 2014 (Oertli & Auel 2015). The tunnel design discharge is $Q_d = 170$ m^3/s corresponding to a five year flood event, the mean annual flood is $Q = 131$ m^3/s.

2.1.4 *Pfaffensprung reservoir*

The 32 m high Pfaffensprung dam is located in the Swiss Alps in the canton of Uri, commissioned in 1922 and operated by the Swiss Federal Railways. The 1.55×10^5 m^3 small reservoir has the function of a compensation basin as part of the Reuss River cascade hydropower schemes (Müller & Walker 2015). The SBT was constructed at the same time as the reservoir itself. The tunnel design discharge is $Q_d = 220$ m^3/s and the catchment is 390 km^2 with a mean elevation of 2300 m a.s.l. The Reuss upstream of Pfaffensprung is a GBR with a mean slope of 4%. The Pfaffensprung SBT is in operation for about 135 days per year during the high flow period from April to November (Müller & Walker 2015). The nearest gauging station Reuss-Andermatt operated by FOEN is located about 9 km upstream, while about 20 small tributaries drain into the Reuss in between Andermatt and the reservoir, which are not accounted for. The mean annual flood at that station is $Q = 101$ m^3/s, and the HQ100 = 251 m^3/s, while Müller & Walker (2015) report HQ100 = 460 m^3/s most likely taking the tributaries into account.

2.2 *Data collection*

Data was collected on May 13th and July 24–25th 2014 at Asahi and Koshibu, and on August 28th and 30th 2014 at Solis and Pfaffensprung reservoirs. Samples were taken at up to four different locations at each site (Fig. 1): Upstream of the reservoir (US), directly downstream of the dam (DS-D), downstream of the SBT outlet (DS-SBT), and downstream of the first tributary confluence (DS-TC).

At each location, the local bed slope S_b and river width B were measured at least three times using the

Table 1. Reservoir characteristics.

		Asahi	Koshibu	Solis	Pfaffensprung
Original volume	[10^6 m^3]	15.5	58	4.1	0.15
Dam completion		1979	1969	1986	1922
Catchment size	[km^2]	39	288	900	390
SBT completion		1998	2016	2012	1922
SBT length	[m]	2383	3982	968	282
SBT Q_d	[m^3/s]	140	370	170	220
Flood HQ100	[m^3/s]	1200	1300	280/428*	251*/460
Mean an. Flood HQ1	[m^3/s]	299	317/203**	131*	101*
Mean an. inflow	[m^3/s]	2.5	3.4	25	7.1*

Data taken from Auel & Boes (2011), Kashiwai & Kimura (2015), Müller & Walker (2015), Nakajima et al. (2015). * Data from FOEN ** Data from MLIT (inflow/outflow).

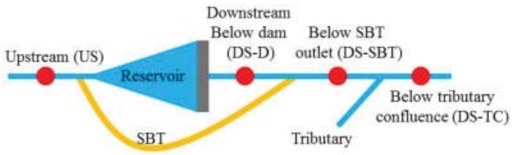

Figure 1. Sketch of sample locations.

Figure 2. Photographs of macro invertebrate samples: a) mayfly, b) stonefly, c) caddisfly (courtesy of S. Kobayashi).

distance laser Impulse 200 from Laser Technology Inc. B was measured from bank to bank, defined as the origin of major vegetation growth, e.g. shrubs or trees. The GSD was analyzed with minimum 10 photographs taken at each location using manual counting with a 25 node grid superimposed. Only grains below the nodes were accounted for, leading in total to 254 ± 66 stones at each location. Possible armoring layers were not removed prior to the photo shot.

We defined 18 types of microhabitats: A splash zone, B leaves pack, C bedrock, D tree root, E moss mat, F wood, G cobbles, H embedded cobbles, I gravel, J sand, K emerged plant, L submerged plant, M deposited leaves pack, N mud, O filamentous algae, P spring, Q seepage, R plant cover. The abundance of each microhabitat was recorded by four levels: 0-no, 1-minor, 2-frequent, 3-major. Benthic invertebrate samples were taken at riffle and pool sections to account for variation in microhabitat structure. Sample collection was done with a D-framed net (opening: $500 \times 500\,mm^2$, mesh size: 0.5 mm) for 10 to 20 minutes by two persons. Samples were separated for lotic (riffles and fast flows) and lentic species (pools and other slow flows). Invertebrates were preserved by Ethanol and taxa were identified in the laboratory using a microscope. We focused on macro invertebrates such as mayflies, stoneflies, caddisflies, and coleopterans, we did not analyze small invertebrates such as worms and midges (Fig. 2).

We separated the abundance of each taxon into 4 levels: 0-not present, 1-less than 9 individuals, 2-less than 99 individuals, 3-more than 100 individuals. Each taxon was classified by its life type and habitat specialty according to Merritt & Cummins (1996), Takemon (2005) and our data set. Life types are classified as swimmers, gliders, clingers, burrowers, net-spinners and case makers. Habitat specialties are riffle specialists with taxa being more in riffles than pools across all locations, pool specialists with taxa more in pools than riffles, and generalists with taxa other than the previous two conditions.

2.3 *Data analysis*

GSD were plotted at each location and diameters D_{16} to D_{99} where 16% to 99% of the particles pass the sieve, were analyzed. In Japan,D_{60} is widely used as a representative for a gravel bed (Yamamoto 2010), whereas the *effective* diameter D_m is used in Switzerland (Meyer-Peter & Müller 1948):

$$D_m = \sum d_{mi} \Delta p_i \tag{1}$$

where d_{mi} = mean D of fraction i and Δp_i = weight proportion. D_m does not equal D_{50}, the median diameter, but represents a mean value. Furthermore, the GSD pattern is described by the uniformity coefficient $\sigma_u = (D_{84}/D_{16})^{0.5}$.

The microhabitat richness σ_{mh} is defined as the number of bed types present at the site. The higher σ_{mh} the more diverse microhabitats are present in the river reach. The bed coarseness index σ_{bed} was estimated from the weighted average of the relative abundance of five bed material types as:

$$\sigma_{bed} = \frac{5C+4G+3H+2I+J}{C+G+H+I+J} \tag{2}$$

The relative abundance of organic versus inorganic habitats is defined as the sum of the relative abundance of organic over the total number of microhabitat types as:

$$\sigma_{org} = \frac{(B+D+E+F+K+L+M+N+O+R)}{\sum_{1}^{18} \text{all microhabitats}} \quad (3)$$

with 0 = fully inorganic covered bed to 1 = fully organic covered bed.

The invertebrate species richness σ_{inv} is defined as the number of taxon found at each location. The higher σ_{inv} the more diverse species are present. The relative abundance of net-spinners versus gliders follows as:

$$\sigma_{net} = \frac{\text{Netspinner}}{\text{Netspinner} + \text{Glider}} \quad (4)$$

The net spinner prefers stable beds for their living, whereas the glider prefers clean stones surfaces, which is typical of a frequently disturbed bed. Thus, a high index shows the preference of the community for bed stability. The relative abundance of pool versus riffle specialists is defined as:

$$\sigma_{po} = \frac{\text{Pool}}{\text{Pool} + \text{Riffle}} \quad (5)$$

The higher σ_{po} the higher the preference of the community for slow-flow conditions.

The similarity of the composition in microhabitats and invertebrate community between upstream and downstream locations (at DS-SBT) was analyzed using the Bray-Curtis similarity index (Bray & Curtis 1957):

$$I_{BC} = \sum_{i} \min\left(\frac{n_{i,UP}}{N_{UP}}, \frac{n_{i,DS-SBT}}{N_{DS-SBT}}\right) \quad (6)$$

where $n_i =$ abundance of each microhabitat type or invertebrate taxon, and $N_i =$ sum of the abundance of all microhabitat types or all invertebrate taxa. $I_{BC} = 0$ if no common type or taxon between the two sites was found, and $I_{BC} = 1$ if exactly the same composition between the two exists.

3 RESULTS AND DISCUSSION

3.1 *Grain size distribution*

Figures 3 and 4 show the GSD for the Japanese and Swiss sites at up – and downstream locations for both riffles and pools. Table 2 lists all D for each location. The pool GSD mostly follows the riffle ones, however some, as Solis US and Pfaffensprung DS-SBT, considerably differ. This is due to fines that tend to settle in pool areas.

The two *new* SBT Koshibu and Solis show similar behavior, with fine GSD in the up- and coarser ones in the downstream. GSD at Koshibu dam reveals a remarkably finer distribution upstream ($D_{60} = 57$ mm) compared to DS-SBT ($D_{60} = 100$ mm). This is to be

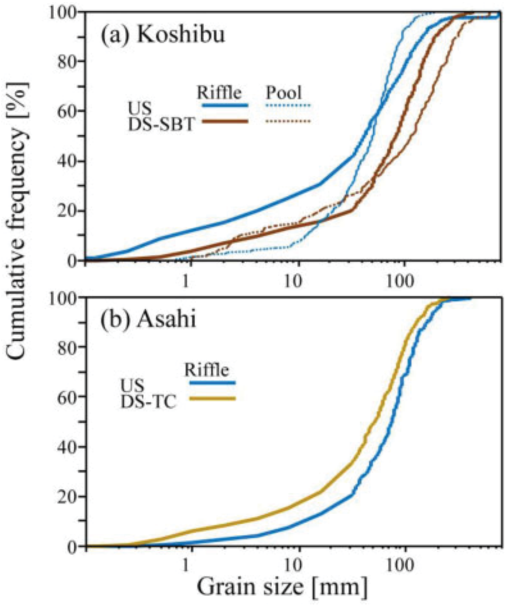

Figure 3. GSD at riffle and pool locations of a) Koshibu, and b) Asahi dams.

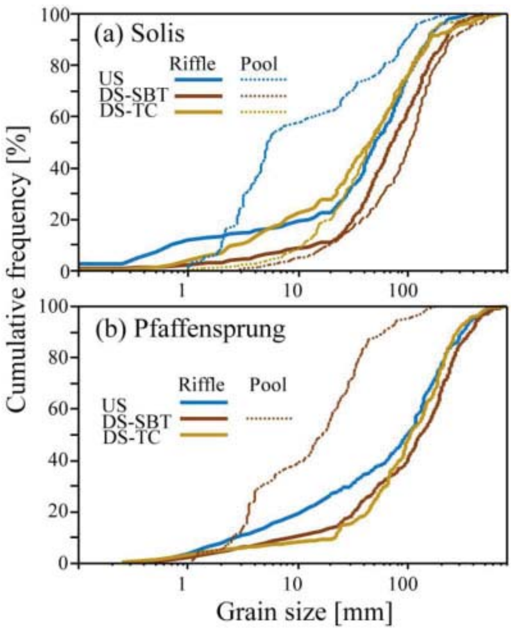

Figure 4. GSD at riffle and pool locations a) Solis, and b) Pfaffensprung dams.

expected as the SBT is still not operating, and sediments are entirely trapped in the reservoir or excavated. GSD at Solis is fine upstream ($D_{60} = 71$ mm), coarser below the SBT outlet ($D_{60} = 95$ mm), and again getting finer below the confluence ($D_{60} = 61$ mm). The tunnel was operated only three times before the sample date, and the SBT intake is not located at the reservoir

Table 2. Characteristic diameter for riffle locations.

	Asahi		Koshibu		Solis		Pfaffensprung			
	US	DS-TC	US	DS-SBT	US	DS-SBT	DS-TC	US	DS-SBT	DS-TC
D_{16} [mm]	21	12	2	17	8	27	6	7	26	33
D_{50} [mm]	75	51	42	84	50	71	45	98	130	104
D_{60} [mm]	86	63	57	100	71	95	61	132	177	146
D_{84} [mm]	130	105	119	168	126	173	132	238	289	230
D_{99} [mm]	280	218	759	365	300	402	571	564	643	513
D_m [mm]	81	60	72	97	68	98	76	130	163	138
σ_u	2.5	3.0	7.3	3.2	4.0	2.5	4.6	6.0	3.4	2.7

head but only 450 m upstream of the dam. Hence the upstream bed had to adjust to the bypass operation in the first events where almost no coarse sediment was bypassed (Hagmann et al. 2015). During the flood on August, 13th 2014, with a peak of $Q = 288\,m^3/s$, about 80,000 m^3 sediment were bypassed (Facchini et al. 2015). This event seems to have mobilized coarse material from the reservoir head consequently explaining the coarse GSD at US-SBT. However, the fine GSD at the confluence is not consistent as the sediment should be coarse either due to coarse sediments entrained after the bypass operation or to the lack of sediments from the past. A possible explanation is an open gravel pit in the sample location vicinity entraining most likely fines into the river. The study of Facchini et al. (2015) showed decreased bed elevation after the event of August, 13th in the upper section of the downstream reach indicating that sediment and water from the tunnel passed through and eroded the bed.

The two *old* SBT Asahi and Pfaffensprung show ambiguous behavior. It is expected that all coarse sediments are transported through the SBTs, hence the GSD should be of similar size up- and downstream. However, GSD at Asahi is coarse upstream ($D_{60} = 86$ mm) and finer at DS-TC ($D_{60} = 63$ mm), while at Pfaffensprung the GSD upstream and DS-TC are similar (US: $D_{60} = 132$ mm, DS-TC: $D_{60} = 146$ mm), but coarser directly below the SBT outlet (DS-SBT $D_{60} = 178$ mm). In case of Asahi, the tributary 1.2 km below the dam may provide finer material, in case of Pfaffensprung the coarse material may be due to the locally steep bed slope.

Comparison of data in Table 2 reveal that D_m lays in the range of D_{60} rather than D_{50} with a deviation of only 9±8% compared to 35±20% for the latter, supporting the idea that $D_{60} \approx D_m$ and that D_m is equally valid to represent a gravel bed GSD. Furthermore, it is found that D_{99} is very large being 428±315% higher than D_{60} and still 186±132% than D_{84} due to their wide distribution with $\sigma_u = 3.9 \pm 1.5$ typical for GBR.

Figure 5 shows D_{60} as a function of S_b for the four SBTs together with data from Japanese GBR (Mikuniya & Chibana 2011). In general, S_b decreases along a stream, and accordingly the material gets finer due to sorting and abrasion (e.g. Gomez et al. 2001), which is supported by our data and Mikuniya & Chibana (2011). However, as we analyzed only local values, some downstream S_b are steeper and/or coarser compared to its upstream (e.g. Solis at TC and Pfaffensprung) due the fact that fining and river bed flattening are large scale processes being relevant in the catchment scale.

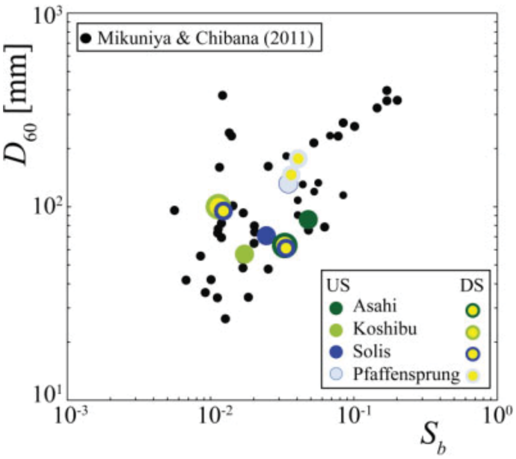

Figure 5. D_{60} as a function of S_b with data from both 43 Japanese GBR (Mikuniya & Chibana 2011) and the SBT river sections studied herein.

3.2 *Habitat features*

Figure 6 shows the three habitat parameters σ_{mh}, σ_{bed}, and σ_{org} as functions of the stream location. Figure 6a reveals that the microhabitat richness σ_{mh} drops for Asahi and Solis directly downstream of the dam likely due to the lack of discharge in the dam vicinity hindering morphological changes, but recovers further downstream. Sediment supply through the tunnel might have supported increasing richness downstream for these two dams.

Data of Koshibu reveals that σ_{mh} at DS-SBT is higher than at US, disclosing that it is not an adequate dam impact indicator in that case as the SBT is still not in operation. Furthermore, at Pfaffensprung, the richness at DS-SBT was slightly lower than upstream although the bypass is operated often (∼135 days/a) and for a long time (96 years). Therefore, the effect of

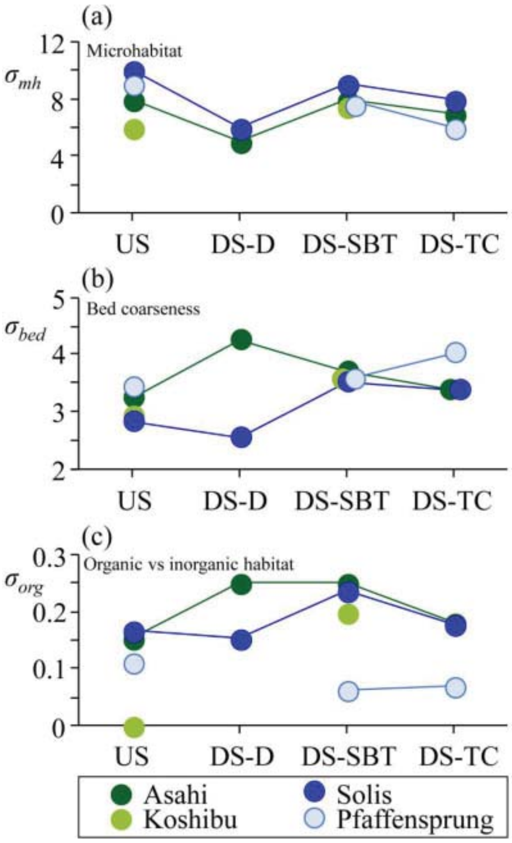

Figure 6. a) Microhabitat richness σ_{mh}, b) bed coarseness index σ_{bed} and c) relative abundance of organic versus inorganic habitats σ_{org} as functions of stream location.

bypass operation was apparent in some but not all of the four cases in terms of microhabitat richness.

Figure 6b shows that the bed coarseness index σ_{bed} is in general higher down- than upstream, with the exception of DS-D at Solis. Also at Koshibu, σ_{bed} was higher at DS-SBT than US, whereas it is almost similar between US and DS for Pfaffensprung. These results may be explained by the fining process after bypass operation. However, at Solis, σ_{bed} is low at DS-D presumably due to flushing of fine sediments from the reservoir trough the bottom outlets in 2007 and 2008.

Figure 6c shows that the organic index σ_{org} tends to be higher at DS than US except for Pfaffensprung and DS-D of Solis. At Koshibu, σ_{org} is substantially higher down- than upstream. This is likely related to an increased abundance of mud, moss, and filamentous algae at DS-SBT probably due to reduced flow velocity and increased bed material stability.

Figure 7 gives an overview of the taxonomic richness as a function of the stream location for riffles (a) and pools (b). Data reveal that invertebrate species richness, especially mayfly and caddisfly species, was generally lower in Swiss than in Japanese sites. However, our study was conducted in a period when the lowest richness out of five surveys in 2014 was

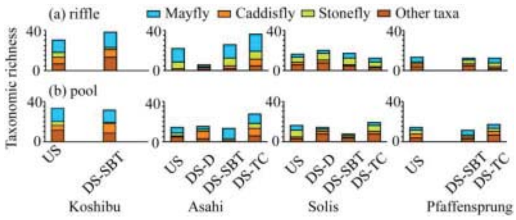

Figure 7. Taxonomic richness as function of stream location for a) riffles, and b) pools.

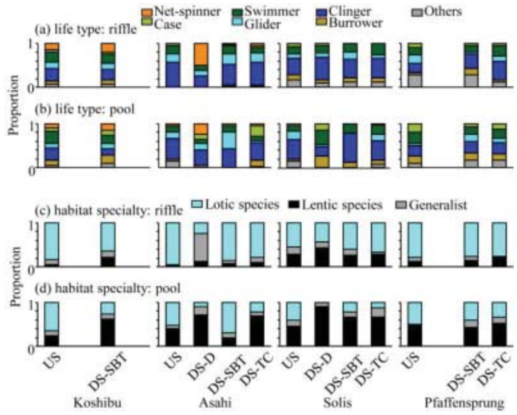

Figure 8. Life type proportion at a) riffle, and b) pool, and habitat specialty proportion at c) riffle, and d) pool as functions of stream location.

recorded (Martin et al. 2015). At Asahi, the richness of riffle communities was substantially low at DS-D but as high as upstream at DS-SBT. This indicates the positive effect of the SBT on species richness supporting results from Mitsuzumi et al. (2009) reporting increase of species richness since 1998. However, in general no clear difference between US and DS locations is observed. For example Koshibu dam does not reveal lower richness (but instead a slight increase) as one may expect as a consequence of permanent lack of sediments.

Figure 8 shows the invertebrate life type and habitat specialty as functions of the stream location. Figure 8a and b reveal that no net-spinners were found at the Swiss sites and clinger species are abundant throughout all locations. At Koshibu at DS-SBT, the proportion of net-spinners was high and the ones of gliders low, compared to its upstream location. At Asahi at DS-D, the proportion of net-spinners was higher compared to its up- as well as further downstream. Increase of net-spinners and decrease of gliders below dams without SBT have been revealed at several dams in Japan (Hatano et al. 2005).

Figure 8c and d reveal the evident finding that lotic species are abundant in riffle areas, whereas vice versa lentic ones are more present in pools. Data of Asahi and Solis reveal that in dam vicinity (DS-D) the abundance of lotic species is minimal regardless of specialty but

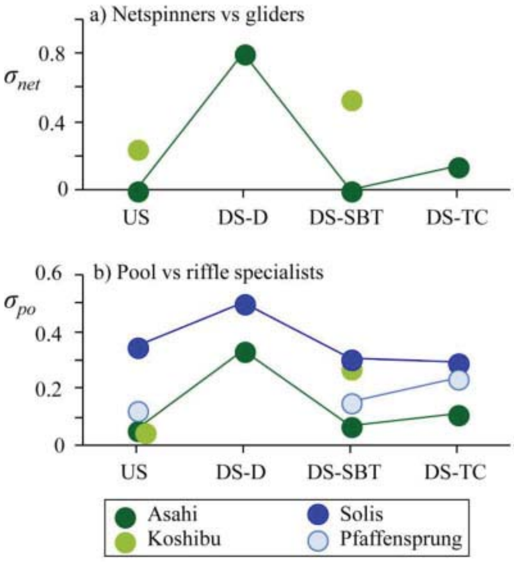

Figure 9. a) Relative abundance of net-spinners versus gliders, b) relative abundance of pool versus riffle specialists as functions of stream location.

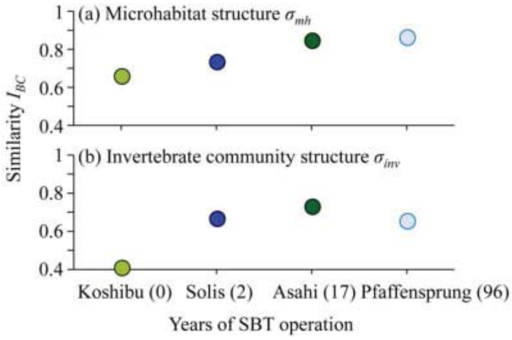

Figure 10. Bray-Curtis similarity index I_{BC} of a) microhabitat, and b) invertebrate community as functions of years of SBT operation.

increase again further downstream showing the positive effects of SBT operation. Data of Pfaffensprung and Solis reveal that up- and downstream proportions are similar, indicating the positive SBT operation effect. As the latter SBT only operated for two years, the effect seems to be immediate. Koshibu data reveal that lentic species are of higher proportion downstream compared to US in pools as well as riffles indicating lack of areas where lotic species may prosper. Increase of pool specialists and decrease of riffle specialists below dams without SBT have been shown for a large number of dams in Japan (Kobayashi et al. 2016) supporting the findings herein.

The difference in life type proportion (Figs.8a, b) is also reflected in the net spinner index σ_{net} (Fig. 9a, calculated only for riffle community). Net spinners prefer stable beds for constructing their nets while gliders prefer unstable stones. σ_{net} was higher for sites, which are considered to have coarse and stable bed materials, such as DS-D of Asahi and DS-SBT of Koshibu.

The difference in proportion of habitat specialty (Figs. 8c, d) is also reflected in the pool specialist index σ_{po} (Fig. 9b, calculated only for riffle community). σ_{po} was higher for sites, which are considered to have slow flow conditions due to a coarse bed creating patches of stagnant areas between the roughness elements, such as DS-D of Asahi and Solis, and DS-SBT of Koshibu.

The similarity index I_{BC} in microhabitat composition σ_{mh} (Fig. 10a) between up- and downstream (DS-SBT) shows a clear increasing trend with increasing bypass operation. This is partly due to similar GSD and less organic microhabitats in the downstream for dams with longer bypass operation. It appears that habitat composition recovers toward the upstream condition with increasing years of bypass operation. Also I_{BC} for the invertebrate composition σ_{inv} (Fig. 10b) between up and downstream (DS-SBT) increased for dams with longer bypass operation. This is partly related to the increase of gliders over net spinners for the Japanese sites and the increase of riffle over pool specialists for both Japanese and Swiss sites. A large difference in similarity between Koshibu and Solis and small one among Solis, Asahi, and Pfaffensprung may suggest that the recovery of invertebrate community towards the upstream condition may occur within a few years of bypass operation.

Both, microhabitat and invertebrate community structure tend to be similar between US and DS-SBT for dams with older SBTs. The environment has recovered substantially to a previous state for Asahi and Pfaffensprung and is apparently improving at Solis.

4 CONCLUSION

Four reservoirs in Japan and Switzerland with adjacent SBTs as a strategy against sedimentation are analyzed in terms of up- to downstream morphological and biotic changes due to tunnel operation. It was found that GSD at *new* SBTs (recently inaugurated) are fine in the up- and coarse in their downstream due to lack of conveyed sediments. However, the *old* ones do not reveal similar GSDs between up- to downstream locations, suggesting that GSD changes are effected by further parameters such as downstream tributaries, slope instabilities and dam operation. Analysis of biotic data reveal that directly below dams microhabitat richness is low and lentic species (e.g. net-spinning caddisfly) abundance is high, while these differences decrease further downstream, and riffle specialists dominate in case of *old* SBTs. It is shown that microhabitat and invertebrate richness downstream of reservoirs adjust to their upstream values with increasing SBT operation. This finding clearly reveals the positive ecological effects of SBT operation.

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