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SEDIMENT DERIVATION BY BYPASS TUNNEL RESTORES DOWNSTREAM ENVIRONMENT*

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SUMMARY

We reviewed studies of the effect of SBT on the downstream environment to clarify whether SBT has a positive effect on downstream, and to understand the key features of SBT that promote the environmental recovery of the degraded reaches. Major results of the studies are listed as follows.

1. Below-SBT site in the downstream of dam was more like upstream of dam than above-SBT site in the downstream of dam, in terms of bed grain size, microhabitat composition, and invertebrate community.

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* *La dérivation des sédiments par une galerie restaure les conditions environnementales dans les tronçons en aval*

2. Environmental recovery of downstream reaches, evaluated by upstream-downstream similarity in microhabitat composition and invertebrate community, corresponded with the years of SBT among the 4 dams.
3. Comparison of among-sites dissimilarity in invertebrate community among 3 types of rivers (non-dam, dam without SBT, dam with SBT) suggested a positive effect of SBT on habitat fragmentation.
4. Turbidity of downstream during and after floods and red tide occurrence in the reservoir decreased after the start of SBT.
5. Although bed level didn't increase constantly, grain size, pool-riffle structure, gravel-bar changed as expected within a several years after the start of SBT.
6. Invertebrate community of downstream became more like that of upstream of dam within 2–3 years after the SBT in terms of both taxon richness and taxonomic composition.
7. Sediment releases by SBT acted as natural pulse disturbances that lower invertebrates and ecosystem functions, followed by their rapid recovery.
8. Numerical and field studies showed that the downstream channel becomes steeper and the riverbed becomes unarmored conditions by SBT. Surface grain size distribution can change quickly even by one SBT release.
9. Turbidity decreased after the SBT operation. Algae, invertebrates, and fish decreased after each event but they recovered to a pre-event level soon.
10. Although test-run of SBT had been done for several years, there was no evidence of the recovery in the invertebrate community of downstream reaches towards an upstream state.

Downstream environment is expected to recover to a pre-dam state within a few to several years after the start of SBT if surface bed materials are reworked and exchanged. The downstream recovery by SBT that release mainly fine sediment will be examined by ongoing monitoring in multiple Japanese dams.

RÉSUMÉ

Le nombre d'études sur la dérivation de sédiments par les galeries et l'impact de ces opérations sur l'environnement en aval (par exemple, morphologie du lit, matériau du fond et invertébrés benthiques) a augmenté ces dernières années. Nous les avons examinées pour voir si le fonctionnement des galeries de dérivation des sédiments (GDS) a eu un effet positif sur l'environnement en aval, et pour comprendre les principales caractéristiques des opérations de dérivation favorisant l'amélioration écologique des tronçons dégradés. Les principaux résultats sont les suivants :

1. Le site après la GDS en aval du barrage était plus similaire au site en amont du barrage que le site avant la GSD en aval du barrage, en termes de taille de grain de lit, de composition de microhabitats et de communauté d'invertébrés.
2. La renaturalisation de cours d'eau aval, évaluée par la similarité amont-aval dans la composition des micro-habitats et la communauté des invertébrés, correspondait aux années de fonctionnement des galeries de dérivation de chaque barrage.

3. La comparaison de la dissimilarité dans la communauté des invertébrés parmi les rivières sans barrages, les barrages sans GDS et les barrages avec GSD suggèrent un effet positif des GDS sur la fragmentation de l’habitat.
4. La turbidité à l’aval pendant et après les inondations et l’apparition de la marée rouge dans le réservoir ont diminué après le début de fonctionnement de la GDS.
5. Bien que le niveau du lit n’ait pas augmenté après le début de fonctionnement de la GDS, la granulométrie du lit, la structure des bassins et les bancs de gravier ont évolué comme prévu dans les années après le début de la mise en service de la galerie.
6. La communauté des invertébrés de l’aval ressemble davantage à celle de l’amont du barrage dans les 2 à 3 années après de la mise en service en matière de richesse en taxons et de composition taxonomique.
7. La dérivation des sédiments par la galerie ont agi comme des pulsions perturbatrices naturelles entraînant une réduction des invertébrés et des fonctionnalités de l’écosystème, suivie d’une récupération rapide.
8. Les études numériques et de terrain ont montré que le canal en aval devenait plus raide et que le lit de la rivière tendait à être proche des conditions non traitées par la GDS. La distribution de la granulométrie de surface peut changer rapidement même suite à une seule opération de dérivation sédimentaire.
9. Le pic et la turbidité moyenne ont diminué après la dérivation des sédiments. Les algues, les invertébrés et les poissons ont diminué après la sortie des sédiments mais ils se sont rétablis rapidement.
10. Bien que le test de dérivation de sédiments ait été effectué pendant plusieurs années, il n’y avait aucune preuve de récupération dans la communauté des invertébrés en aval.

L’environnement en aval devrait revenir à l’état antérieur au barrage en quelques années, voire plusieurs années après la mise en service de la galerie de dérivation si les matériaux de surface sont retravaillés et échangés. La dérivation de l’écoulement et des sédiments peut être importante. La récupération de l’environnement en aval n’était pas évidente dans un barrage qui libère principalement des sédiments fins.

Keywords: Ecology Ecologie, Grain Size Distribution Granulometrie, Insect Insecte, Rehabilitation Rehabilitation, River Bed Degradation Erosion Du Lit De La Riviere, Sedimentation Alluvionnement, Asahi Dam, Koshibu Dam, Solis Dam, Pfaffensprung Dam, Miwa Dam, Koshibu Dam, Matsukawa Dam.

1. INTRODUCTION

Sediment and flow are essential elements of river ecosystem as they are the basis of aquatic habitats, sets of physical conditions required for the life of various organisms. Biodiversity and ecosystem integrity would be damaged by both excess and shortage of sediment in the channel. Channel degradation due to excavation works or upstream barriers (i.e., dams) is a major environmental issue in many Japanese rivers especially for downstream reaches and coastal areas [1]. Degraded channels are typically incised cross-sectionally, homogenized longitudinally, and dominated by coarse materials [2] [3]. Substantial loss of spatial heterogeneity in flow and bed materials exclude many aquatic species that require certain flow and bed conditions for their habitats. On the other hand, degradation often induces invasion and overgrowth of aquatic species adapted to the unfavorable conditions, which can finally lead to a development of aquatic community unfamiliar to natural rivers.

Sediment bypass tunnel (hereafter SBT) as a countermeasure of reservoir sedimentation [4] [5] is an effective way of supplying large amount of sediment to degraded channels in the downstream of dams. The construction of SBTs in the world is still limited, and most of them are located in Switzerland and Japan so far [5] [6]. Sediment flushing, slucing, and dam removal are other possible measures that supply large amount of sediment to the downstream [7]. Sediment supply by SBT has different consequences on the downstream as compared to the other measures. First, SBT transports sediment that are naturally delivered from upstream. The other measures mainly transports sediment that has been deposited in the reservoir for a long time and includes disproportionally more fine sediment that adversely affects aquatic habitats. Second, the other measures often generate extremely high concentrations of sediment in the water, which rarely occurs in natural floods and is often lethal especially for fish.

Although transport of natural sediment by SBT has merits to the downstream environment, the timing and size partition of sediment transport vary depending on the operation and the intake part of SBT. For example, if the gate of SBT is opened during the receding phase of hydrograph, bypass flow misses a peak of sediment transport in terms of quantity and particle size. If the tunnel intake is located in a section with a gentle channel slope, it can promote deposition and traps coarser particles at upstream and delivers finer portion of the sediment through SBT.

Studies of the effect of SBT on the downstream environment have increased recently [8] [9] [10] [11] [12]. These studies focused on bedforms, bed materials, and benthic invertebrates as a representative of the downstream environment. In this study, we reviewed these studies to clarify whether the operation of SBT has a positive effect on downstream environment, and in what aspect the SBT has such effect. We also discussed on the key features and operations of SBT that promote the environmental recovery of downstream reaches, which have been degraded for a long time after dam construction.

2. COMPARISONS AMONG DAMS WITH SBT IN TWO COUNTRIES

[12] and [13] conducted a pilot study of river environment by visiting 4 dams with SBT (Koshibu and Asahi in Japan, Solis and Pfaffensprung in Switzerland). In

each dam, 2 to 4 sites including upstream and downstream of dams were selected (Fig. 1). They surveyed bed materials, habitat composition, and invertebrate community of pools and riffles, and examined whether below-SBT reaches are more like upstream than above-SBT reach. In addition, the 4 dams varied in the years of SBT, from new (Koshibu: 0 yr, Solis: 2 yrs) to old (Asahi: 17 yrs, Pfaffensprung: >90 yrs), and they also examined whether the environmental recovery depends on the years of SBT. [14] also compared invertebrate community among 7 Swiss rivers including regulated (with dam) and unregulated rivers, and with SBT and without SBT for the former rivers.

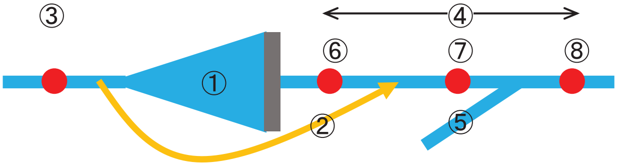
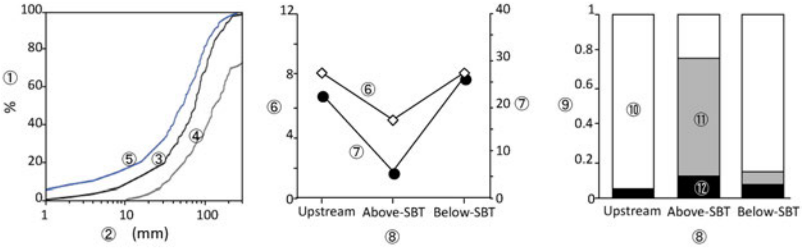


Fig. 1 (modified from [12] [13])
Schema view illustrating field sites
Schémas illustrant les sites d'étude

1	Reservoir	*1*	*Réservoir*
2	Sediment bypass tunnel (SBT)	*2*	*Galerie de dérivation des sédiments (GDS)*
3	Upstream	*3*	*Amont*
4	Downstream	*4*	*Aval*
5	Tributary	*5*	*Affluent*
6	Just upstream of the SBT Outlet	*6*	*En amont immédiat de la sortie de la GDS*
7	Just downstream of the SBT Outlet	*7*	*Aval immédiat de la sortie de la GDS*
8	Downstream of river-tributary confluence	*8*	*Aval de la confluence rivière-affluent*

2.1. DIFFERENCE BETWEEN ABOVE AND BELOW SBT

Bedform, bed material size, microhabitat composition (existence of 14 types of substrates), and invertebrate community differed largely between above- and below-SBT reaches, which located next to each other but differed in the supply of sediment through SBT, in the downstream of Asahi Dam [12] [13]. Riffle was more and pool was less, the bed materials were finer, microhabitat and invertebrate species richness (number of types/species occurred) were more in the below-SBT than above-SBT (Fig. 2). For all of these variables, the below-SBT was more like upstream of dam than the above-SBT. Such pattern was much pronounced for invertebrate community composition; the community of above-STB was dominated by limnophilics (= pool specialist), while the community of below-STB as well as upstream was dominated by rheophilics (= riffle specialists). These differences suggests that the sediment supply through SBT contributed to the environmental recovery of the downstream reach. Differences in bed topography and material size among sites were surveyed in more detail [15] [16].



(a) Grain size distribution
Distribution granulométrique

(b) Richness of habitat types and invertebrate species
Richesse des types d'habitat et espèces d'invertébrés

(c) Invertebrate community composition
Composition de la communauté des invertébrés

Fig. 2 (modified from [12] [13])
Changes in bed material and invertebrate species in Asahi Dam site
Modifications de la granulimétrie du lit et du peuplement d'invertébrés dans le site du barrage d'Asahi

1	Cummulative percentage	*1*	*Pourcentage cumulé*
2	Grain size	*2*	*Galeries de dérivation des sédiments (GDS)*
3	Upstream	*3*	*En amont*
4	Above-SBT	*4*	*En amont de la sortie de la galerie*
5	Below-SBT	*5*	*En aval de la sortie de la galerie*
6	Habitat type richness	*6*	*Richesse des types d'habitat*
7	Invertebrate species richness	*7*	*Richesse des invertébrés*
8	Survey sites	*8*	*Sites d'étude*
9	Proportion	*9*	*Proportion*
10	Rheophilics	*10*	*Rhéophile*
11	No-preference	*11*	*Pas de préférence*
12	Limnophilics	*12*	*Limnophile*

On the other hand, the difference in environmental variables between above- and below-SBT was small or less consistent among the variables in the downstream of Solis Dam. This may be due to a recent installation of SBT (2 years before) and a limited number of operations. In addition, they use the bottom outlet gates of dam to flush fine sediment during floods, which may supply sediment to the above-SBT as well as the below-SBT and obscured effects of SBT on the downstream.

2.2. SBT OPERATION YEAR AND DOWNSTREAM ENVIRONMENT

Bed material size (D_{60}, size at 60% of particles passing) of the upstream and downstream reaches of the 4 dams was well explained by channel conditions of the reach and the year of SBT [12] [13]. In Asahi and Pfaffensprung with old SBT, D_{60} was greater at the steeper channel between the up- and downstream (Fig. 3). In contrast, in Koshibu and Solis with new SBT, D_{60} was greater in the downstream reach despite the gentler channel. The downstream of Koshibu and Solis were also plotted close to downstream of dam without SBT (Fig. 3). Dimensionless shear stress (τ*) shows potential shear stress against actual bed material size, and thus, potential mobility of bed materials each reach. τ* is calculated as

$$\tau^* = \frac{HI}{SD} \qquad [1]$$

where H = water depth (m) of annual flood, I = mean channel slope (m/m), S = specific gravity in water, D = bed particle diameter (m). τ* of the downstream Asahi and Pfaffensprung was more like the upstream of dam (i.e., natural condition), while τ* of the downstream Koshibu and Solis was more like the downstream of dam without SBT.

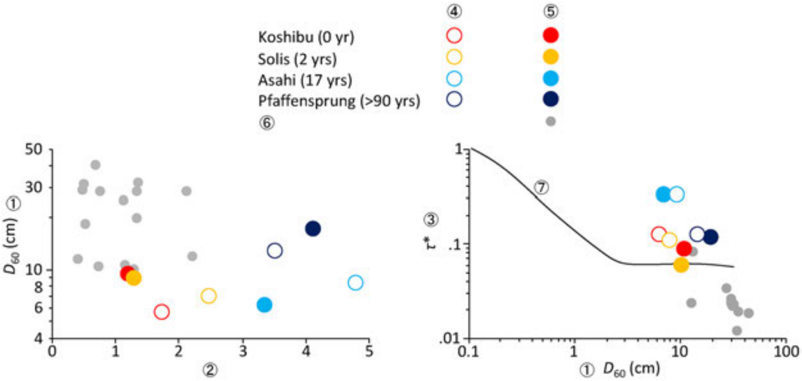


Fig. 3 (modified from [12])
Channel and bed grain size features for different field sites
Caractéristiques granulmétrique des différents sites d'étude

1	Riverbed particle size	*1*	*Granulométrie du lit de rivière*
2	Mean channel bed slope	*2*	*Pente moyenne du lit*
3	Dimensionless shear stress	*3*	*Contrainte de cisaillement adimensionnelle*
4	Upstream of dam	*4*	*En amont du barrage*
5	Downstream of dam	*5*	*En aval du barrage*
6	Dams without SBT (Japan)	*6*	*Barrages sans GDS (Japon)*
7	Empirical curve	*7*	*Courbe empirique*

As an index of the environmental recovery of downstream reaches, the similarity of the composition in microhabitats and invertebrate communities between upstream and downstream of dam was analyzed using the Bray–Curtis similarity (*BC*)

$$BC = \sum_i min\left(\frac{n_{iUP}}{N_{UP}}, \frac{n_{iD}}{N_D}\right) \qquad [2]$$

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. $BC = 0$ if no common type or taxon between the two sites was found, and $BC = 1$ if the two had the same composition.

Similarity of both microhabitat composition and invertebrate community tended to increase with the year of SBT among the 4 dams (Fig. 4). The increase of microhabitat *BC* was related to reduced coarse inorganic microhabitats (e.g. bedrock, cobbles) and organic microhabitats (e.g. moss mats, filamentous algae) in the downstream as in the upstream reach for the older SBT dams. The increase of invertebrate *BC* w was related to the increase of rheophilics over limnophilics. Based on these analyses, the environment of the downstream has recovered substantially to a previous state (i.e., before dam construction) for Asahi and Pfaffensprung and it is apparently improving for Solis.

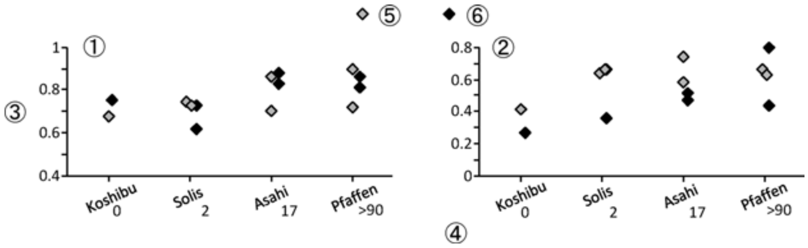


Fig. 4 (modified from [13])
Number of years of SBT operation and similarity between upstream and downstream of dam
Nombre d'années de fonctionnement des GDS et similitude entre l'amont et l'aval du barrage

1	Microhabitat composition	*1*	*Composition de microhabitat*
2	Invertebrate community	*2*	*Communauté d'invertébrée*
3	Bray-Curtis similarity (BC)	*3*	*Indice de dissimilarité de Bray-Curtis (BC)*
4	Dam and the number of year of SBT operation	*4*	*Barrage et nombre d'années de fonctionnement de la GDS*
5	Riffle	*5*	*Radier*
6	Pool	*6*	*Mouille*

2.3. DIFFERENCES IN INVERTEBRATE COMMUNITY AMONG NO-DAM, DAM, AND DAM WITH SBT RIVERS

[14] compared invertebrate community in 7 Swiss rivers, which were 2 unregulated (non-dam) rivers, 3 regulated rivers with SBT, and 2 regulated rivers without SBT. They selected 2-3 sites each river including upstream and downstream of dam for the regulated rivers. They conducted DNA metabarcoding analysis, which provides a rapid and reliable method of identifying organisms, and identified 131 species throughout the survey (almost 3-fold number of species identified by a classical manual method in [12] [13]). To examine the effect of dam and SBT on invertebrate community, they calculated Bray-Curtis dissimilarity (= 1 – similarity) between the sites each river. As expected, the dissimilarity was low (0.25-0.28) for unregulated rivers, while it was high (0.53-0.54) for regulated rivers without SBT, suggesting a negative effect of habitat fragmentation by dam. The dissimilarity varied largely among 3 regulated rivers with SBT from low (0.18) to high (0.52-0.75). Thus, a positive effect of SBT (i.e. recovery from habitat fragmentation) was suggested for a part of the dams, which may depend on SBT operation year or the size and amount of sediment supplied through SBT.

3. LONG-TERM MONITORING IN ASAHI DAM

3.1. OVERVIEW OF ASAHI DAM

Asahi dam (Kansai Electric Power Co., Inc.) is a hydropower dam constructed in 1978 in a tributary of the Kumano River in Nara Prefecture, Japan. The reservoir volume was 15.5×10^6 m^3. The mean annual inflow is 2.5 m^3/s and floods usually occur in the rainy season from June to September with an annual mean of 299 m^3/s. The catchment was 39.2 km^2 and mostly covered by forest. Turbidity in the reservoir substantially increased and lasted long after a heavy rainfall that induced several landslides in 1993. SBT was constructed because other measures were unsuccessful in reducing the turbidity. The operation of SBT began in 1998 [17], and 77% of the incoming sediment (average: 100,000 m^3/year) including gravel and cobbles were bypassed since then [18]. The gate of SBT was opened for sediment transport during floods several times a year and for clear water during normal flow.

An orifice at the intake limits SBT discharge when inflow exceeds 120 m^3/s for preventing sediment clogging inside tunnel. Peak of sediment transport through SBT occurs not at the peak of hydrograph but at the recession period when flood discharge is less than 70 m^3/s, because the orifice keeps low water surface slope upstream during greater discharge phase [9].

The upstream and downstream of Asahi Dam is a gravel-bed river flowing through steep canyons. Monitoring of river environment including water quality, cross-section topography, bed materials, and benthic invertebrates has been conducted every year since 1998. A routine survey of environment began and data have been accumulated since then. As shown in the following, the environmental changes occurred in the downstream of Asahi Dam is one of the most successful cases of sediment supply projects in Japanese rivers.

3.2. Changes in water quality by SBT

Due to slow deposition of very fine sediment, turbidity is usually higher in the reservoir than the upstream river especially after floods. Thus, such dam releases downstream a turbid water for a long period even if the inflow water gets clean soon after a flood ceases. In Asahi Dam, turbidity in the downstream river decreased after the start of SBT [8] [19]. For example, total number of days that exceeded 5 ppm per year was 50–130 before and less than 10 after the start of SBT, and yearly average turbidity was similar between upstream (1.8 ppm) and downstream (2.2 ppm). In addition, by comparing similar size of flood before and after SBT, turbidity of >10 ppm ceased shortly (1-2 days) after the SBT while it lasted more than 1 week before the SBT. Thus, SBT reduced inflow of sediment with fine particles into reservoir, which kept the turbidity of the reservoir low.

Because SBT bypassed not only sediment but also organic materials, eutrophication of reservoir also decreased [8] [19]. The occurrence of red tide (an algal bloom by dinoflagellates that colors the surface water into red or brown, depletes dissolved oxygen, and produce toxins) in the reservoir decreased from 5–10 before the SBT to less than 0–5 after the SBT despite an increase of water retention time in the reservoir.

3.3. Recovery of gravel-bars and pool-riffle by SBT

Dark colored sedimentary rocks were dominated the bed in the downstream of the Asahi Dam before the installation of SBT. However, light colored round stones have been increased in the downstream after the SBT as in the upstream. Fukuda et al. 2012 [9] compared aerial photos between 1994 (before SBT) and 2004 (after SBT) and showed that the amount of gravel-bar and distinct pool-riffle structure were more in the latter. Despite such changes, a yearly survey of cross-section profile suggested that both erosion and deposition occurred repeatedly in the downstream reach, and there was no consistent trend of bed level.

Changes of pool-riffle structure in the first 7 years since SBT were also reported by Takenaka et al. 2004 [20]. They surveyed for size (area), depth, bed grain size of each bed types (pool, riffle, run) occurred in a 2.1 km section downstream of the dam. Pools, which showed more conspicuous change than riffle and run, decreased in size and depth with years. Most of the changes occurred within 3 years after the start of SBT. Bed grain size also decreased sharply within the first 3 years; D_{50} was roughly 15 cm in 1998 and 1 cm in 2000 in pools, and it was 30 cm in 1998 and 10 cm in 2000 in riffles and runs. Grain size of riffles varied yearly, which may depend on the magnitude of flood each year.

3.4. CHANGES IN INVERTEBRATE RICHNESS AND SIMILARITY BY SBT

Surveys of benthic invertebrates were conducted every winter (less-flood season) for 17 years since 1998. The survey was conducted in an upstream reach and two downstream reaches. In each reach, a streambed of 0.5 m^2 was quantitatively sampled in each of 4 bed types (pools, riffles, runs, periphery). Invertebrate taxon richness and Bray-Curtis similarity were examined as indicators of community recovery [21].

Invertebrate taxon richness of the downstream reaches increased rapidly and was almost at the same level with the upstream reach by the third year (2000). Taxon richness of the downstream reaches tended to increase in the early half and decreased in the latter half of the 17-year period (Fig. 5). The taxon richness was the lowest in the fourth year (2001) and 16th year (2013), when a flood occurred within one month before the survey. Except for these two years and the first 3 years, the richness was negatively correlated with the annual maximum flood. Thus, the decreased richness in the latter half years was partly associated with the occurrence of floods each year.

Bray-Curtis similarity, which was calculated between the upstream and downstream reaches was less than 0.3 in the first year, while it increased sharply to around 0.6 in the second year, and it steadily kept around 0.6–0.8 for the following years except for the fourth year (Fig. 5). The similarity suggests that the recovery of invertebrate community took place rapidly within 2–3 years after the SBT, and less change toward an upstream state afterwards by 17th year.

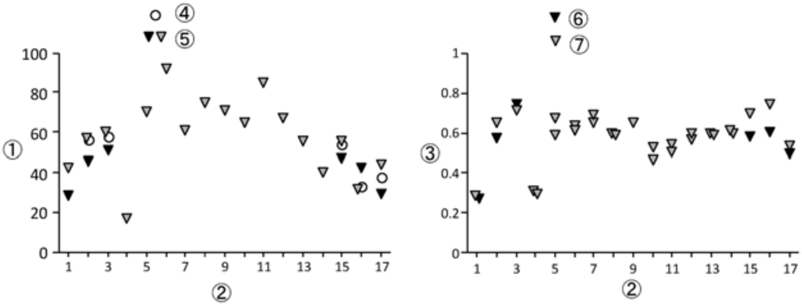


Fig. 5 (modified from [21])
Year since the start of SBT and invertebrate community (taxon richness, similarity between upstream- and downstream of dam)
Année depuis le début du SBT et de la communauté des invertébrés (richesse en taxons, similitude entre le amont en aval du barrage)

1	Taxon richness	*1*	*La richesse en taxon*
2	Year since the start of SBT	*2*	*Année depuis le début de la GDS*
3	Bray-Curtis similarity (BC)	*3*	*Indice de dissimilarité de Bray-Curtis (BC)*
4	Upstream of dam	*4*	*En amont du barrage*
5	Downstream of dam	*5*	*En aval du barrage*
6	Between upstream and downstream 1	*6*	*Entre l’amont et l’aval 1*
7	Between upstream and downstream 2	*7*	*Entre l’amont et l’aval 2*

4. ECOSYSTEM AND BEDMORPH DYNAMIC STUDIES IN SOLIS DAM

4.1. OVERVIEW OF SOLIS DAM

Solis Dam (ewz, Zurich) is a hydropower dam built in 1986 in the Swiss Alps, in the canton of Graubünden. The reservoir volume was 4.1×10^6 m^3. 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, and from upstream hydropower plants [22]. The mean annual flood is 131 m^3/s. The average annual sediment aggradation in the reservoir was 8.0×10^4 m^3 [22] [23]. Construction of an SBT was completed in 2012 and the operation began in the same year. The SBT is operated during floods with a frequency of 1–10 days/year.

Although tunnel intake is located upstream-end of reservoir for most SBTs, the intake of Solis locates at the middle of the reservoir. Thus, a drawdown of reservoir water level precedes before the operation of SBT.

The upstream and downstream of Solis Dam is a gravel-bed river flowing through steep canyons. Studies of bedforms and river ecosystems of the downstream have started after the completion of SBT in 2012 [10] [11]. A frequent field survey and numerical modelling clarified a short-term dynamic, bedform and ecosystem responses to individual floods, including an intense flood in August 2014 that exceeded the meteorological record of the river. About 80,000 m^3 of sediment passed through the SBT to the downstream [10]

4.2. ECOSYSTEM RESPONSES TO FLOOD AND SEDIMENT THROUGH SBT

[11] and [24] measured water quality, ecosystem metabolism (sediment respiration), periphyton biomass, and macroinvertebrate assemblages along a 5-km stretch in the downstream of Solis Dam several times in each of 2014 and 2015. Ecosystem metabolism, periphyton biomass, macroinvertebrate density and richness were reduced after each SBT event with the impact being correlated with the magnitude of the event. They also showed a quick recovery of these ecosystem variables after each event. They concluded that the SBT events act as a pulse disturbance, similarly to natural floods, followed by a recovery of ecosystem.

They also showed variation in the responses among sites along the 5-km stretch. Only large SBT events influenced ecosystem metabolism, suggesting small events lacked the competence to mobilize deeper sediment layers of the bed. Due to a constricted channel that enhance flow competence, existence of wide channel reaches that allows sediment deposition and formation of new habitats, and connected tributaries that act as source of colonizers to the disturbed main river may be keys for the ecosystem recovery after the events.

4.3. BEDFORM RESPONSES TO SBT SEDIMENT RELEASE

[10] compared before and after the intense event in August 2014, one of the first big events after SBT operation. Responses of the cross-section bed level to the event differed among 3 different sections downstream of SBT outlet (upper: a few-hundred meter downstream, middle: 3 km, lower: 6 km). The degradation tended to occur up to 1 m in the upper section, while the aggradation occurred in the middle section, and the aggradation was evident in the lower section. Although about 80,000 m^3 of sediment was transported through SBT in this event, much of the sediment seems to have been transported long distance and was not retained so much within a few-kilometer downstream of SBT outlet.

[25] identified realistic SBT-release scenarios in terms of water and sediment discharges, tested the impact of the different scenarios on the bed level and surface sediment grain size changes by numerical modelling, and examined the numerical results with field topographic survey data.

Numerical results showed that the downstream channel slope becomes steeper with scenarios of smaller water discharge, and the riverbed grain size distribution tends to be close to unarmored conditions for all the scenarios that release sediment. Thus, release of sediment through SBT has a positive outcome for alpine stream morphology, since they favor steeper channels that develop pool-riffle or step-pool structure as well as mobile bed conditions. According to the short- and long-term numerical analyses, while the change of bed level to reach equilibrium is slow and take long-time, the surface grain size distribution changes quickly even by one SBT release event that rework of the riverbed surface layer.

Field topographic survey by LiDaR (Light Detection and Ranging) before and after sediment release by SBT supported some of the numerical results. They also revealed upper-lower differences in the trend of deposition and erosion, which may show sediment wave, a time lag in the peak of sediment.

5. SBT TEST RUNS AND FIELD MONITORING IN MIWA DAM

5.1. OVERVIEW OF MIWA DAM

Miwa Dam (MLIT: Ministry of Land, Infrastructure, Transport and Tourism) is a flood-control and multipurpose dam built in 1959 in southern mountains in Nagano Prefecture (called south Japanese Alps), Japan. The reservoir volume was about 30×10^6 m^3. The mean annual inflow was about 13 m^3/s (average of 1993–2015) coming from the Mibu River (within the Tenryu River System) and its tributaries with catchment area of 311.1 km^2. Due to steep slopes and fragile ground formation associated with the Median Tectonic Line crossing the catchment, there are many large-scale collapses that activate sediment yield. The greatest reservoir sedimentation of 6 million m^3 occurred by large storm events 1982-83.

In order to solve reservoir sedimentation and flood control, dam redevelopment projects including excavation works and SBT installation have been implemented since 1989. The construction of SBT was completed in 2005. The SBT is one of the biggest in terms of tunnel size (diameter: 7.8 m) and discharge release capacity (300 m^3/s) in Japan and Switzerland. Test-runs of SBT have been done since 2005 and totally 548,000 m^3 of sediment has been transported through SBT by 14 runs in 12 years [26]. Because the inflow sediment is mostly silt and fine sand, the SBT is intended to transport mainly fine sediment. A check dam located upstream of SBT intake traps all of the coarse sediment and contributes to reduce a risk of SBT invert abrasion. To enhance sediment transport efficiency of SBT, a stockyard of sediment excavated in the reservoir was built at the upstream vicinity of the SBT intake.

Monitoring of downstream environment to clarify the effect of SBT has been conducted since before the first SBT test-run in 2005 [26]. One of the focus of the monitoring was the turbidity during and after the SBT operation.

5.2. EFFECTS OF SBT OPERATION ON TURBIDITY AND DOWNSTREAM BIOTA

A comparison of turbidity at dam outflow between before (October 2004) and after (July 2006, September 2007) SBT operation showed that the peak and average turbidity decreased after the SBT operation [24]. Reduction of turbidity to a level accepted by fishery (25mg/L) was faster after than before the SBT operation for more than 10 days. Deposition of washload on riverbed and vegetation was not evident after the SBT operation.

Attached algae (density of chlorophyll a), benthic invertebrates and fish have been monitored routinely several times a year since before the SBT run [26]. Although the density and growth of algae, invertebrates, and fish decreased soon after floods and SBT operation, they recovered in a similar manner before and after the SBT run.

5.3. INVERTEBRATE COMMUNITY AFTER SBT TEST RUNS

Benthic invertebrate community in the upstream and downstream of Miwa Dam has been monitored a 5-years interval as a national census on river environment (http://mizukoku.nilim.go.jp/ksnkankyo/). All of the data are available in the website. In Miwa the survey was conducted in 2007 and 2012 (2 and 7 years after the SBT run). [21] examined the difference in invertebrate taxon richness and Bray-Curtis similarity between upstream and downstream. Taxon richness was always higher in the downstream than upstream of dam every case except for spring 2012 (Fig. 6). In some cases, taxon richness of downstream was more than 1.5 times that of upstream. Bray-Curtis similarity was around 0.3–0.4 throughout the survey periods, which was apparently low compared to that of Asahi after 2–3 years of SBT operation. Thus, although in 2012 SBT test-runs have been conducted for about 10 times since 2005, the low values of Bray-Curtis similarity suggest that the downstream reach had not been recovered to a pre-dam state. Higher invertebrate richness below than above dam site is often the case in mountain rivers.

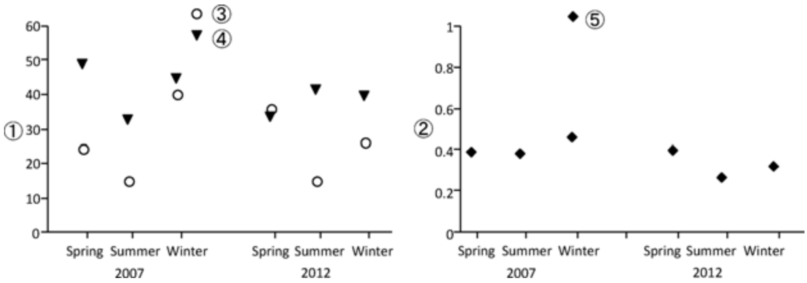


Fig. 6 (modified from [21])
Invertebrate taxon richness and similarity between up- and downstream of dam in Miwa Dam
Des invertébrés richesse en taxons et similitude entre le amont en aval du barrage le Miwa Barrage

1	Taxon richness	*1*	*La richesse en taxon*
2	Bray-Curtis similarity (BC)	*2*	*Indice de dissimilarité de Bray-Curtis (BC)*
3	Upstream of dam	*3*	*En amont du barrage*
4	Downstream of dam	*4*	*En aval du barrage*
5	Between upstream and downstream	*5*	*Entre l’amont et l’aval*

Limited changes in the downstream of Miwa despite of the SBT test-runs may be associated with a release of only fine sediment by SBT. Fine sediment is less likely to retain in the downstream reach. Even if it is retained, they may cause adverse effect on aquatic habitat by filling bed interstices. Further monitoring after the regular operation of SBT is needed to clarify this point.

6. CONCLUSION

Changes and recovery of downstream environment after the SBT operation are evident from the studies in Asahi, Solis and the pilot study of 4 dams (Koshibu, Asahi, Solis, Pfaffensprung). Relatively rapid (within a few years after the SBT installation) changes were observed for pool-riffle, surface bed materials, and invertebrate community. Thus, a certain recovery of the downstream environment toward an upstream state is expected within a short period associated with the changes of surface bed materials by sediment supply by SBT. On the other hand, recovery of bed level and environmental properties associated with bed level (e.g., channel slope, width, floodplain connection) seems to occur much slowly.

Although SBT releases sediment in recession period of a hydrograph in Asahi, and the intake of SBT locates at gentle slope section of reservoir in Solis, these SBTs seem to release sediment sufficient for the environmental recovery of downstream. It is still unclear how much transported sediment is trapped upstream of the intake, whether the upstream bed level increases by the deposition, and how much sediment transport efficiency by SBT is reduced. Because coarse fractions of bedload are also important component structuring bedforms [27], some adverse effects on downstream environment may occur if coarse bedloads are trapped upstream and finer bedloads are delivered disproportionately more through SBT.

Direction of the change and equilibrium state of the downstream by SBT operation seem to be affected by a balance of discharge and sediment that determines the trend of erosion/deposition. Certain magnitudes of floods are necessary to rework of armored-bed in the downstream of dam, while too intense flood with less sediment supply will only promote erosion in the downstream channel. Not only amount of sediment supply but also the grain size are important when considering the balance of erosion and deposition. Most of the reports showed a positive effect of SBT on downstream environment so far, though all of the reports focused on SBT that releases coarse sediment such as gravel and cobbles. Ongoing monitoring in Miwa and neighbor dams (Koshibu, Matsukawa) that release mainly fine sediment through SBT [28] [29] will provide us information about this point.

Turbidity of the downstream reaches is likely to decrease by operation of SBT that reduces sediment inflow to and turbidity of reservoir. Decline of turbidity after floods is expected to be natural (similar to that in the upstream of dam) and faster than that before the operation. In addition, supply of sediment by SBT and a development of gravel-bars in the downstream will increase filtering capacity of riverbed, which also contribute to decrease turbidity in the downstream direction. A frequent exchange of surface materials with a suitable grain size distribution by SBT may be important for increasing such filtering capacity

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