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Ecological effects of a long-term flood program in a flow-regulated river

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Introduction

- 1 Flow has been recognized as one of the most important drivers in the structure and functioning of river ecosystems (Poff et al., 1997; Hart and Finelli, 1999; Malard et al., 2006). The natural flow regime of many rivers is characterized by regular floods, which can strongly influence the distribution and abundance of aquatic organisms (Poff et al. 2002). For instance, algae have developed structural features related to flow (Biggs et al. 1998), benthic macroinvertebrates have evolved life cycles adapted to predictable seasonal floods (Robinson and Minshall, 1998), and fish have evolved various morphologies in response to flow properties of rivers (Poff and Allan, 1995).
- 2 The natural flow regime of most rivers in the world has been altered by regulation. There are more than 45,000 large dams (> 15 m high) worldwide that fragment rivers and influence their flow regime (Oud and Muir 1997, Jackson et al. 2001). The purpose of many dams is the storage of water for power production. It is well known that dams affect the physical and biological characteristics of downstream rivers in various ways (Ward and Stanford, 1979, 1995; Wallace, 1990; Vinson, 2001; Graf, 2006). Regulated rivers have an altered flow- and temperature regime and undergo changes in riverbed structure. In most cases, temperature becomes more constant (Vinson, 2001), flow is reduced and the flow regime differs from natural conditions (Poff et al., 1997; Vinson, 2001). Altered abiotic conditions lead to a shift in aquatic communities (*sensu* Southwood, 1988), favoring assemblages that are adapted to more stable environments (Armitage, 1976; Poff and Allan, 1995).

- 3 In recent years, the importance of restoring a river's natural flow regime to improve its ecological integrity has been emphasized (Sparks, 1995; Petts, 1996; Poff et al., 1997; Galant et al., 1998; Sparks et al., 1998; Dudgeon, 2000; Pringle et al., 2000; Robinson et al., 2003). The consideration of regime-based criteria such as temperature and flow regimes is a relatively new development in river management. In the past, river management was based on threshold-based criteria, which refers to the maximal concentrations of pollutants in waters below a certain risk level (Poole et al. 2004). The implementation of a regime-based river management is often difficult because of multiple interest groups involved in management decisions (Andrews and Pizzi, 2000; Patten et al., 2001).
- 4 The River Spöl is a good example of successful regime-based management that benefits most stakeholders. The Spöl flows through a confined valley in the Swiss National Park and has been used for power production since 1970. Water abstraction and absence of floods resulted in distinctive changes in riverine habitat and biota. The residual flow lacked the power to entrain and transport coarse sediments and allowed the riverbed to be clogged with fine sediments, which impaired the natural reproduction of the brown trout population (Ortlepp and Mürle, 2003) and enhanced the formation of large pools upstream of lateral debris fans (Mürle et al., 2003). The stable flows also resulted in dense algal mats, extensive moss beds, and a macroinvertebrate community atypical for an Alpine mountain river (Robinson et al., 2003; Uehlinger et al., 2003).
- 5 In 1996, Park authorities, the Engadin Hydroelectric Power Company, and the Cantonal and Federal governments agreed to implement a flood program to improve the ecological integrity of the Spöl. Fifteen experimental floods were released between 2000 and 2006 as part of this flood program. The main question of this paper was whether this flood management program has improved the ecological integrity of the flow-regulated river. Abiotic and biotic parameters were used as indicators of changes in river integrity. We expected little impact of the experimental floods on physical and chemical parameters because of the hypolimnetic water release. We hypothesized that the experimental floods would reduce periphyton biomass and macroinvertebrate richness, biomass and density, and cause a shift in the macroinvertebrate assemblage towards disturbance-resistant taxa. We predicted that habitat conditions for fish would improve and lead to better recruitment. Finally, we expected the initial floods to have a greater impact than later floods of similar magnitude because of the shift in assemblage structure.

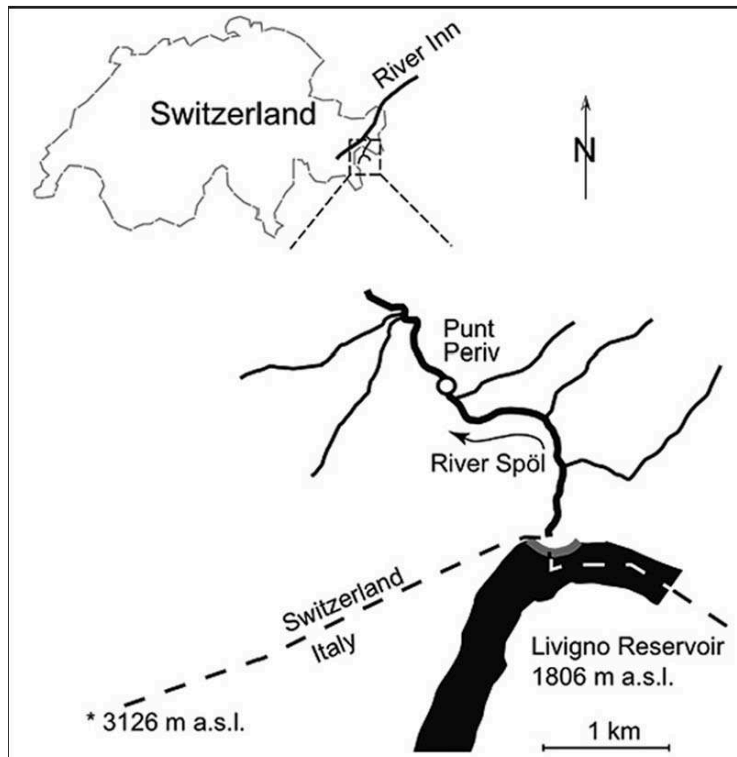
Methods

Site description and flood program

- 6 The study was carried out on the River Spöl in the central Alps (Fig. 1). The climate in this area is characterized by relatively low precipitation and high seasonal and daily variation in temperature (Barry, 1992). From the Livigno Reservoir in Italy, the Spöl flows through a confined valley and joins the River Inn in Zernez, Switzerland. Vegetation in the river valley is dominated by fir (*Picea abies*) and pine (*Pinus mugo*), whereas alder (*Alnus incana*) is common on riverbanks. The study site, Punt Periv (E10°11'22", N46°36'38"), is situated about 2,3 km downstream of the reservoir dam (Punt dal Gall). Elevation at the study site is 1660 m a.s.l., while the maximum elevation

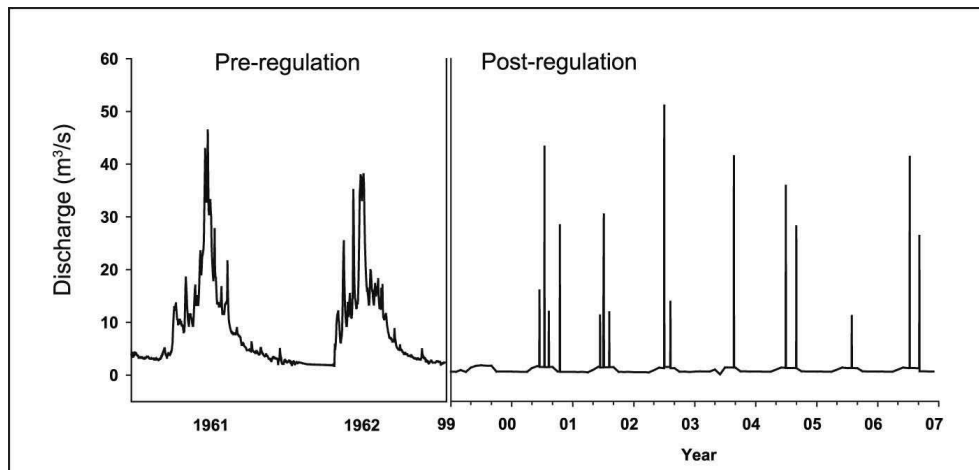
of the river at its headwaters is 3302 m a.s.l. The river at Punt Periv is 10-18 m wide and has a slope of 1-2%. The riverbed consists of alluvial cobbles, boulders and in some parts bedrock.

Figure 1. Map of the study area in the Swiss National Park showing the dam at Punt dal Gall and the long-term study site Punt Periv.



- 7 Before the river was used for hydroelectric power production, mean annual flows ranged between 6.6 and 12.5 m³/s and floods reaching 20-60 m³/s occurred regularly in summer and early autumn (Fig. 2). After dam construction was completed in 1970, annual average discharge decreased from 8.6 m³/s to 1.0 m³/s due to water abstraction for power production. The experimental flood program started in summer 2000 with the release of three floods ranging between 12 to 42 m³/s. One to three floods were released in subsequent years, leading to a total of 15 floods between 2000 and 2006. The flood regime was changed over time to reduce the frequency (1-2 floods/yr) but increase the magnitude (30-50 m³/s) of the floods to cause the ecologically desired changes in habitat conditions. Smaller floods were shown to have lesser impacts in the later years of the study as many of the transportable fines had been flushed from the system (Scheurer and Molinari 2003). A dry year in 2005 limited the amount of water available for floods, resulting in one small flood (~12 m³/s) being released that year. All floods were cost-neutral because residual flow was further reduced to compensate for the water released during the floods.

Figure 2. Flow regime of the Spöl before dam construction (1961 and 1962), after dam construction (1999) and during the flood program (2000-2006). The flow in 1999 represents the residual flow maintained below the dam with all excess water diverted downstream for power production.



Field protocols and data analysis

- 8 Field sampling began in 1999, one year before the flood program was implemented. Sampling at the 200-m long study reach took place 1-3 days before a flood, 1-2 days after a flood, and at periodic intervals between each flood. The Swiss Hydrologic and Geologic Survey provided discharge data. Temperature in the river was measured with temperature loggers (Vemco Inc., Nova Scotia, Canada) that were initially installed in 1999 and downloaded every 4-6 months. Turbidity (nephelometric turbidity units; NTU) (Cosmos, Züllig AG, Switzerland) and conductivity ($\mu\text{S}/\text{cm}$ at 20°C) (WTW LF340, Weilheim, Germany) were also measured in the field. In addition, nutrient concentrations (N and P) were measured following methods in Tockner et al. (1997).
- 9 Benthic macroinvertebrates were collected on each visit from riffle/run habitats using a Hess sampler ($0,045 \text{ m}^2$, $250\text{-}\mu\text{m}$ mesh) and preserved in the field with 70% ethanol. The organisms were hand-picked from each sample using a dissecting microscope at $10\times$ magnification, identified to lowest practical taxonomic level (usually genus) and counted. After removal of benthic macroinvertebrates, the samples were dried at 60°C , weighed, burned at 550°C and reweighed for estimates of benthic organic matter (BOM) as AFDM.
- 10 For periphyton measurements, 10 rocks (cobble-size) were randomly collected from the study reach, placed in a plastic storage bag and returned to the laboratory, and kept frozen at -25°C until processed. Before periphyton analysis, any moss was removed from each rock and measured as AFDM. Periphyton was removed from each rock by scrubbing the rocks with a metal bristle brush and rinsing. Aliquots of this suspension were filtered through two Whatman GF/F filters (pre-ashed at 450°C). One filter served for analysis of chlorophyll a, and the other for periphyton AFDM. The dimensions of each rock were measured (a-, b-, c-axis) for calculation of rock area, and periphyton biomass was expressed as grams per square meter (g/m^2) following Robinson et al. (2000).
- 11 Living conditions for brown trout in the Spöl were assessed by mapping the habitat structure in the study reach and by determining the sediment composition of the upper

layer of the streambed (8-12-cm depth). Information about the state of the brown trout population was collected by annual mapping and counting of spawning redds between Punt dal Gall and Punt Periv and by electro-fishing a 200-m reach about 600 m downstream of Livigno reservoir. Total fish stock was calculated following methods in DeLury (1947). The condition factor (size-weight relationship) of each captured fish was calculated.

- 12 ANOVA was used to test for effects of sequential floods on macroinvertebrates and periphyton. Data were grouped as preflood (PRE), years 2000-2003 (MID), and post 2003 (POST) for the analysis. Data were $\log(x+1)$ transformed to meet normality requirements (Zar, 1984). Post-hoc testing was done with Tukey's HSD test.

Results

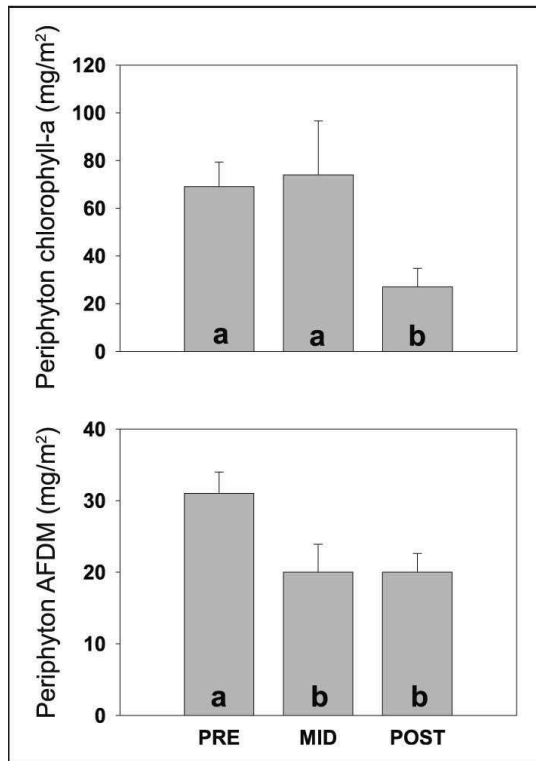
Physico-chemical characteristics

- 13 Average water temperature (7-8°C) did not change significantly from the floods due to hypolimnetic water release at all times. Values for specific conductance and turbidity between the floods did not differ from pre-flood values. Particulate-P and nitrogen constituents decreased after the floods, while other phosphorus constituents remained constant.

Flood effects on periphyton

- 14 Periphyton biomass was significantly reduced by the floods (AFDM: $F = 24.48$, $p = 0.0001$; chlorophyll-a: $F = 40.98$, $p = 0.0001$) (Fig. 3). However, high values were measured between each flood due to fast recovery by periphyton. The highest values were attained between floods in 2001 and 2003 (90 g/m² AFDM, 400-500 mg/m² chlorophyll-a). After 2004, periphyton biomass decreased to values lower than before the floods (2004: average = 20 g/m² AFDM, 27 mg/m² chlorophyll-a).

Figure 3. Means (± 1 SD) for periphyton chlorophyll-a and AFDM for samples collected before the floods (PRE), samples collected after the first flood in 2000 to those just before the flood in 2003 (MID), and samples collected after the flood of 2003 (POST).

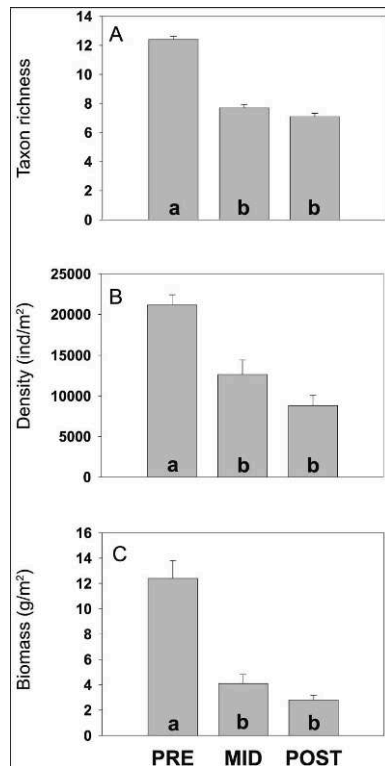


Letters indicate significant differences based on Tukey's test at $p < 0.05$.

Flood effects on macroinvertebrates

- 15 Macroinvertebrate richness ($F = 41.79$, $p = 0.0001$), density ($F = 7.77$, $p = 0.001$) and biomass ($F = 26.09$, $p = 0.001$) were significantly reduced by the floods (Fig. 4). Taxon richness decreased to 7 taxa during the flood program compared to an average richness of 12 in 1999. Average density decreased by a factor of ~ 2.6 from 22,700 in 1999 to 8800 ind/m² after 2003. Between each flood, macroinvertebrate density normally reached pre-flood values. The floods also reduced average biomass from 13.7 g/m² in 1999 to 3.2 after 2003.

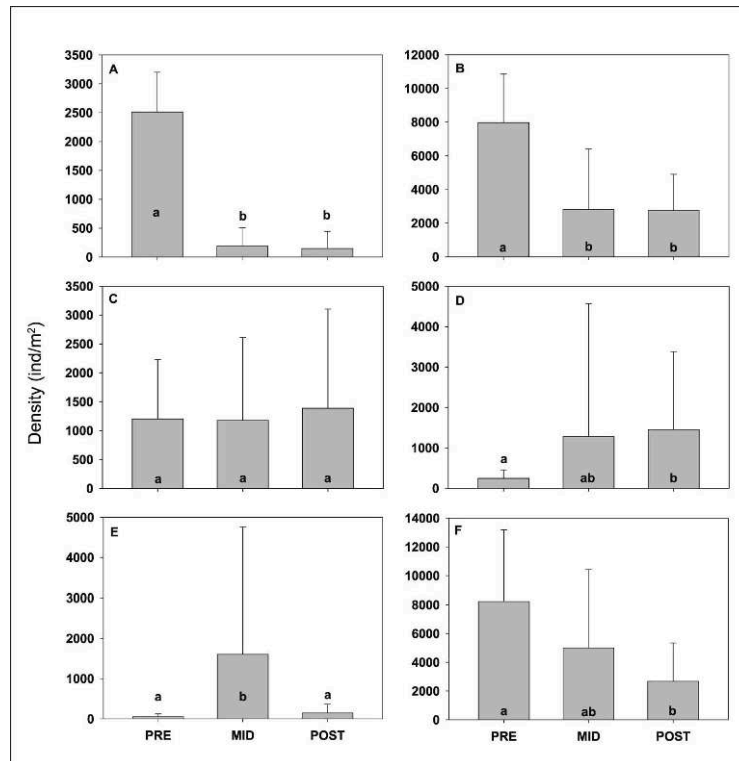
Figure 4. Means (± 1 SD) for macroinvertebrate A) taxon richness, B) density, and C) biomass for samples collected before the floods (PRE), samples collected after the first flood in 2000 to those just before the flood in 2003 (MID), and samples collected after the flood of 2003 (POST).



Letters indicate significant differences based on Tukey's test at $p < 0.05$.

- 16 Macroinvertebrate taxa in the Spöl reacted differently to the floods (Fig. 5). The densities of the gammarid *Gammarus fossarum* ($F = 5.85$, $p = 0.005$) and the turbellarian *Crenobia alpina* ($F = 13.22$, $p = 0.0001$) decreased in the course of the program. The floods reduced the average density of *G. fossarum* from 7000 ind/m² in 1999 to 2540 ind/m² after 2003. The average density of *C. alpina* was 2180 ind/m² before the floods and 132 ind/m² after 2003. Chironomids also decreased ($F = 5.29$, $p = 0.007$) from 8340 ind/m² in 1999 to 2360 ind/m² in 2003. *Baetis* spp. and *Protonemura* sp. on the other hand were favored by the floods. *Protonemura* density increased more than five-fold to 1360 ind/m² compared to 240 ind/m² in 1999 ($F = 4.61$, $p = 0.013$). *Baetis* spp. recovered fast after the floods and reached interflood densities of > 6000 ind/m², whereas the pre-flood density was only 1160 ind/m² ($F = 0.55$, $p = 0.579$). For *Simulium* sp. an increase in density was found in the first three years of the program (8000 ind/m²). After 2003, density decreased again to pre-flood levels (< 100 ind/m²) ($F = 12.03$, $p = 0.0001$). Trichoptera density was generally low in the study reach of the Spöl and remained so throughout the study. In some years, however, dense populations of the trichopterans *Rhyacophila* spp., *Allogamus uncutus* and *Drusus* sp. were found.

Figure 5. Means (± 1 SD) for density of A) *Crenobia alpina*, B) *Gammarus fossarum*, C) *Baetis* spp., D) *Protonemura* sp., E) *Simulium* sp., F) Chironomidae for samples collected before the floods (PRE), samples collected after the first flood in 2000 to those just before the flood in 2003 (MID), and samples collected after the floods of 2003 (POST).

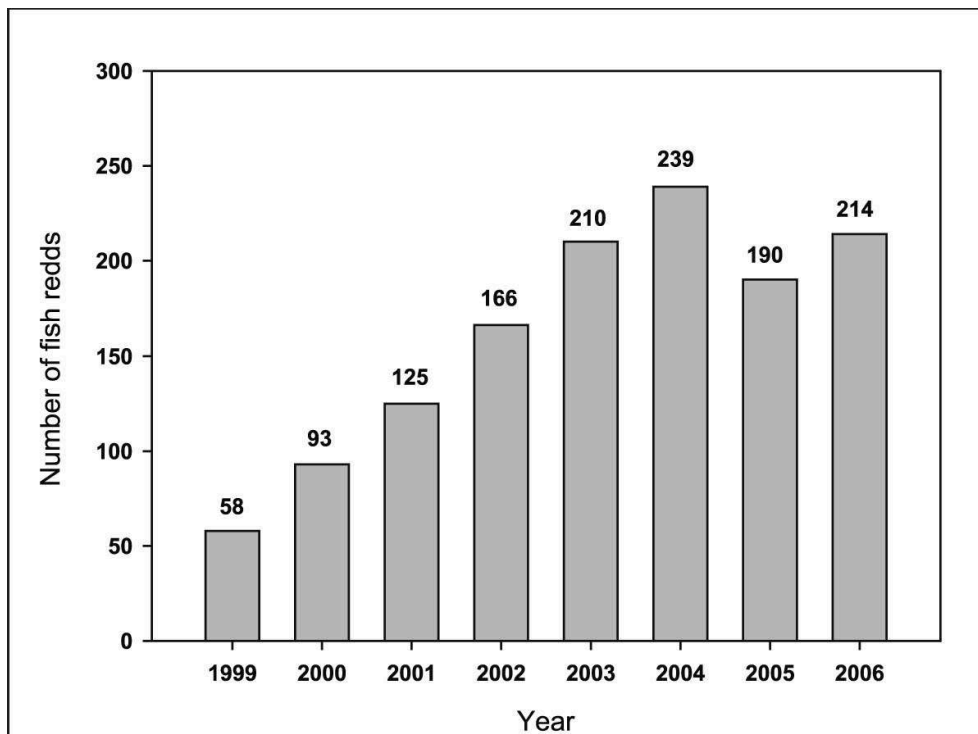


Letters indicate significant differences based on Tukey's test at $p < 0.05$.

Flood effects on brown trout

- 17 The floods increased the variability of water depth between the Livigno and Ova Spin reservoirs and reduced the degree of colmation observed before 2000 (Mürle et al., 2003). Fish abundance and condition remained fairly constant in the first three years of the study period. Less than 2% of the fish stock (> 5 cm) died during the floods due to stranding. The number of redds increased considerably in the 2,6 km long study reach below the Livigno reservoir. A total of 58 spawning redds were found in 1999 and a four-fold increase was noted in 2004 (Fig. 6). After 2004, the number of redds decreased slightly to 214 in 2006. Observations after the floods showed that there was not only an increase in redds but also in fingerlings.

Figure 6. Number of spawning redds counted each November from 1999 to 2006 in the Spöl between Punt dal Gall and Punt Periv (distance = 2,6 km).



Discussion

- 18 As predicted, the floods had little impact on measured physical and chemical parameters. Hypolimnetic reservoir water was used for the floods as well as for regular residual flow. Therefore, water temperature and nutrient concentrations remained almost constant during the floods. The decrease of particulate-P after the floods might have been caused by the flushing of fine sediments.
- 19 The floods reduced periphyton standing stocks as expected. Periphyton recovered between the floods but was scoured again by each new flood. Small floods (10-15 m³/s) had a greater impact on periphyton biomass in the initial years of the program than in later years. Thus, larger floods (30-50 m³/s) were used in later years to attain the same effect as the smaller initial floods. The results suggest that the long-term use of sequential floods can maintain low periphyton levels.
- 20 Macroinvertebrate richness, biomass and density were reduced by the floods as stated in our hypothesis. The main reason for the lower taxonomic richness was a loss of less common taxa; a conclusion supported by Rader et al. (2007). Taxonomic richness might increase again in the future due to colonizing by new taxa from other sources. The decrease in macroinvertebrate density and biomass is due to the loss of large-bodied organisms, especially gammarids. Later large floods (> 40 m³/s) caused a smaller change in biomass and density than earlier floods of the same magnitude. This leads to the conclusion that the species assemblage impacted by the later floods must have been more disturbance resistant than assemblages in the first years of the flood program.
- 21 The shift in macroinvertebrate composition became evident by changes in the abundance of individual species. Baetid mayflies and protonemurid stoneflies are well

adapted to disturbance and recovered rapidly after each flood. The gammarids and the flatworm *Crenobia alpina* on the other hand are used to more stable flows and were effectively reduced by the flood program. Simulium density increased in the first three years of the flood program, but decreased again in the following years. Simulium were not common before the floods. It seems that they benefited from the changed habitat conditions in the first years of the flood program but could not maintain a high abundance over the mid-term.

- 22 The quality of fish habitat, spawning grounds in particular, was noticeably improved as suggested by our hypothesis. The floods effectively removed fine sediments from the system, increased bed porosity and thereby improved spawning conditions for brown trout. After 2003, floods of higher magnitude were needed to mobilize the larger substrate in the Spöl. The improvement in spawning grounds was also evident in the more than four-fold increase in redds since the beginning of the flood program. Trout condition, however, remained relatively constant throughout the program. Gammarids are a main food resource for brown trout and the question remains if the decrease in gammarid density will have an influence on trout condition.
- 23 It has been recognized that a natural flow regime is important for sustaining river integrity (Stanford et al., 1996; Poff et al., 1997). The flood program of the river Spöl partly simulates a natural flow regime and has therefore the potential to enhance ecological integrity. The results of this study suggest that ecological integrity has indeed improved during the flood program: habitat heterogeneity increased, moss cover decreased, macroinvertebrate composition shifted towards disturbance-resistance taxa, and the spawning potential for fishes is higher than before the flood program. However, the actual flow regime still differs in many aspects from the natural flow regime of the river Spöl before 1970. The residual flow between floods lacks the variation of the original flow regime. Hence it is arguable if the biotic assemblages (periphyton, macroinvertebrates, fish) will change further towards pre-regulated conditions or if this development remains constrained by flow regulation.

Conclusions

- 24 Ecosystem properties of the River Spöl have considerably changed during the flood program. Periphyton, macroinvertebrates and fish habitat were significantly influenced by the experimental floods. The effects on biota were dependent on flood magnitude and flood history. The results highlight the importance of a river's flow regime for riverine flora and fauna. For example, Milhous (1998) suggested various different flows were needed to eliminate fines and maintain spawning habitat for squawfish in the Gunnison River, Colorado, USA. Flow regulation below dams significantly changes species composition in downstream receiving waters. More regular and frequent experimental floods (e.g., annual) below dams are required beyond the typical aperiodic flushing flows used in some rivers (Whiting, 2002). The Spöl project shows that a more natural assemblage can be attained by implementing multiple experimental floods. The natural dynamics of the river Spöl were only partly restored because residual flows between each flood were still regulated. This compromise between economy and ecology was necessary to achieve an agreement among all stakeholders. Nevertheless, the results from the river Spöl show that

incorporation of regime-based criteria in river restoration is feasible and an important step in attaining restoration goals.

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ABSTRACTS

The natural flow regime of many rivers on the globe has been altered by regulation, strongly influencing river morphology and aquatic biota. The incorporation of regimebased criteria such as flow and temperature regimes in restoration plans is an important step in river management. This paper summarizes the effects of a long-term flood program (15 floods over 8 years) on the river Spöl, Swiss National Park, on water physico-chemistry and river biota (periphyton, macroinvertebrates and fish). Due to hypolimnetic release, the floods had little impact on physical and chemical parameters. Periphyton biomass was reduced by the early floods and remained at low levels throughout the study period. Macroinvertebrate taxon richness, biomass and density were also significantly reduced and the macroinvertebrate assemblage shifted towards more disturbance-resistant taxa. The quality of fish habitat, especially for spawning, was noticeably improved by the floods. Further analysis suggested that the response of biota to floods of similar magnitude have changed over the study period in concert with the compositional shift in biotic assemblages.

Le régime hydrologique naturel de la grande majorité des rivières du globe a été modifié par une régulation artificielle, qui a profondément affecté la morphologie fluviale et la vie aquatique. L'intégration de critères hydrologiques comme le débit et la température dans les programmes de restauration constitue une étape importante pour la gestion de rivière. Cet article synthétise les observations, en terme de qualité physicochimique de l'eau et de biocénose aquatique, des

effets d'une programmation de crues sur le long terme (15 crues artificielles en huit ans) sur la rivière Spöl, dans le Parc National Suisse. Du fait des lâchers d'eau hypolimnétiques (issues des eaux profondes), ces crues ont peu d'impact sur les paramètres physiques et chimiques. La biomasse du périphyton a été réduite par les premières crues, puis s'est maintenue à des niveaux faibles pendant toute la période étudiée. La richesse spécifique, la biomasse et la densité de macro-invertébrés ont aussi été significativement réduites, et l'association de macroinvertébrés a évolué vers des taxons plus résistants aux perturbations. La qualité des habitats piscicoles, en particulier pour les zones de frai, a été sensiblement améliorée par les inondations. Une analyse plus approfondie a montré que la réponse de la biocénose à des crues d'ampleur similaire a changé pendant la période d'étude en parallèle avec la modification de la composition des associations biotiques.

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Mots-clés: crues artificielles, régime hydrologique résiduel, macroinvertébrés, périphyton, truite fario

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