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Feature Article

Effects of experimental flooding on riverine morphology, structure and riparian vegetation: The River Spöl, Swiss National Park

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Abstract. After the construction of two relatively large reservoirs in the late 1960s on the River Spöl, discharge was greatly reduced and regulated at a relatively constant flow. Following flow regulation in 1970, natural floods occurred only in the lower Spöl where the river is joined by a large tributary, the River Cluozza. Flow competence of the residual flow in the regulated river section was too low to transport downstream the input of inorganic and organic sediments from tributaries and side-valley scree (talus) slopes. Consequently, sediments accumulated on the riverbed, and alluvial fans from scree slopes extended into the river channel. The lack of flood disturbance also allowed woody vegetation to develop on previously exposed gravel banks, and the porous river bottom became clogged with fines. After the experimental floods in 2000, most alluvial fans in the channel were scoured downstream and bed sediments became less embedded due to the reduction in fines. The initial floods caused a rather broad accumulation of coarse sediments in wider reaches of the river, whereas the later floods mobilized/scoured these sediments and increased the variation in channel depth.

Key words. River management; controlled flood; sediment structure; lateral debris; colmation; Switzerland.

Introduction

Artificial floods have been used in many regulated streams and rivers to flush fine sediments, increase sediment porosity, improve morphological integrity, and enhance ecological conditions for instream fauna and riparian flora (Reiser et al., 1989; Petts, 1996; Milhous, 1998; Andrews and Pizzi, 2000). However, only recently has the importance of multiple sequential floods been emphasized for restoring the integrity of rivers downstream of reservoirs (Stanford et al., 1996), reflecting the premise of the natural flow regime as an inherent property of flowing waters (Poff et al., 1997). For instance, Kondolf and Wilcock (1996) suggested that two flood flows per year were necessary for maintaining habitat turnover of riparian areas. However, the implementation of a flood program appears to be highly system specific, as alluded to in flow models presently being used on different rivers (Milhous, 1998; Andrews and Pizzi, 2000; Downs and Thorne, 2000; Patten et al., 2001). The present study shows the results of multiple experimental floods over a three year period on the morphology of a canyon confined river downstream of a reservoir used for hydropower production. The floods were experimental in the sense that individual floods varied in magnitude depending on the particular needs at the time; an idea in line with adaptive management perspectives (Stanford et al., 1996).

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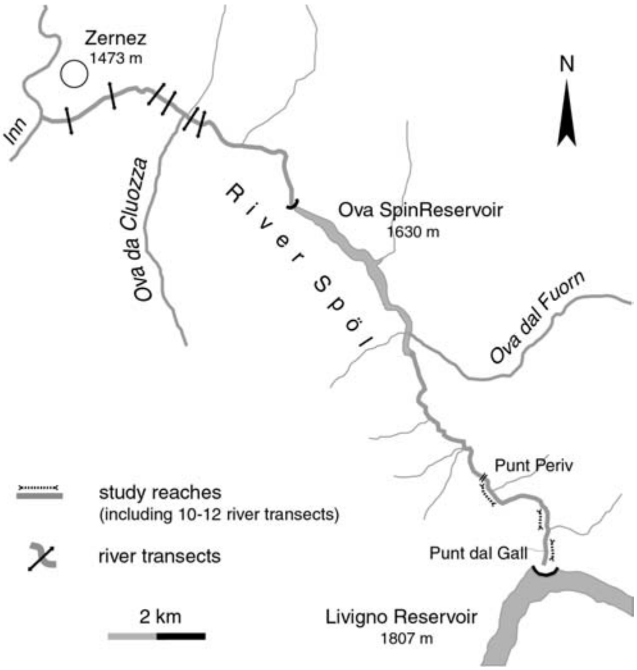

Figure 1. Map of the study area on the River Spöl, showing selected study reaches and transects used for the various morphological and structural measurements.

The actual flood program was developed following a number of earlier studies of individual flushing flows in the Spöl. After the flushing of safety release gates at the Livigno reservoir in 1990 (Fig. 1), Schlüchter et al. (1991) reported on the changes in sediment composition, Jäger (1991) on channel morphodynamics, and Kusstatscher (1991) on riparian vegetation. Changes of the riverbed resulting from the drainage of Ova Spin reservoir in 1995 are described in Ackermann et al. (1996). These studies showed that the riverbed was restructured by floods (with 70–90 m^3/s maximum discharge) and the accumulations of lateral sediments were removed, even though a considerable load of reservoir sediments were transported by the floods. Mürle (2000) then investigated the morphology and habitat structure of the river under the reduced flow regime from Punt dal Gall to Punt Periv before the beginning of the present controlled flood regime.

Due to the residual water situation and the absence of disturbance causing discharges by floods in the Spöl, sediment inputs from valley side-slopes are not mobilized and transported downstream. As reported in other studies (see references in Kondolf and Wilcock, 1996), debris fans from scree slopes protrude into the river channel, floodplains and gravel banks have become colonized by woody vegetation, and the coarse substrate of the river is embedded and clogged by fine material. The lack of flow disturbance also allowed river substrata to be thickly colonized by algae and bryophytes. In the hope of improving river habitat, a three year experiment using artificial floods was started in 2000 (Scheurer and Molinari, 2003). The primary objective of the present study was to determine the most optimal flood regime (duration, magnitude, frequency) to restore the morphological and structural integrity of the river using a given volume of water. It is hoped that the results will demonstrate a viable option for resource managers to better attain current regulations of the Swiss Federal Law for Water Protection (Scheurer and Molinari, 2003). Other papers in this series report on other changes in river ecology resulting from the floods (Uehlinger et al., 2003; Robinson et al., 2003; Jakob et al., 2003; Ortlepp and Mürle, 2003).

Site description

The study area (Fig. 1), geographical, and hydrological aspects of the River Spöl are described in detail in Scheurer and Molinari (2003). The natural mean annual discharge of 6–12 m^3/s was reduced to a constant discharge of 0.3/0.55/0.9 and 1.43 m^3/s depending on season and river section (Scheurer and Molinari, 2003). Primary flow is controlled by the outlets of Livigno and Ova Spin reservoirs. The only supply of importance is the River Cluozza, about 2.6 km upstream of the mouth of River Spöl.

River sediments originate primarily from dolomitic and calcareous scree from high gradient rocky side-slopes of the Spöl valley (Trümpy et al., 1997) and locally from remnant glacial moraines (Trachsel, 2001). A thin layer of sediments cover the bedrock in the canyon reaches. Significant alluvial deposits appear further downstream in the planal reach below the confluence with the River Cluozza (Fig. 1). Erosional properties downstream of the Livigno reservoir are mainly determined by the level of the lower Ova Spin reservoir and the River Inn. Locally, erosion is controlled by numerous rocky outcrops. After the Cluozza confluence the Spöl River flows through the alluvial valley of the Zernez Basin. Within this area, bedrock is evident in some places on the river bottom, again controlling erosion dynamics at a local scale.

The valley side-slopes of the Spöl between Punt dal Gall and Punt Periv are vegetated with sub-alpine coniferous forests (mainly *Erico-Pinetum mugo* (*arboreae*)) (Zoller, 1995). Where the bank is not wooded, *Agrostis gigantea* and herbaceous vegetation of sedges are present (Kusstatscher, 1991). In many places along the river, forest vegetation (*Pinus mugo ssp. uncinata, Picea excelsa*) have colonized riverbed gravel bars. Grassland also has developed at some places along the river bank, and is used for grazing by wild game animals. Typical floodplain vegetation that need clean, vegetation-free sand or gravel bars is strongly reduced. The roots of woody vegetation have stabilized river banks, further decreasing the riparian dynamics typical of free flowing rivers.

Material and methods

The effects of the floods on river character were examined at 3 locations up to 2 km downstream from Punt dal Gall (i.e., transects within study reaches; Fig. 1), and ca. 2.5 km of below the Ova Spin dam (individual river transects, Fig. 1).

The discharge is permanently measured at a gauging station ca. 600 m downstream of Livigno reservoir and controlled technically by the width of the opening of the reservoir outlets at Livigno and Ova Spin reservoirs.

Suspended sediment during the floods

Water samples were taken during the rise of each flood every 15 min, and later every 30 to 60 min. Surface samples (ca. 0.5 m depth) were collected from the Spöl directly below the Livigno dam, and at 0.3 km and 2.7 km downstream. Suspended sediments were determined from these samples using IMHOFF funnels (i.e., measuring the sediment volume after 30 min). This method allowed us to compare the measured sediment volumes with the limit of 20 ml/l aimed by the Cantonal authorities for reservoir flushing (Baumgartner and Lanfranchi, 1996).

Before the flood of 2 July 2002, substrata of 2 to 30 cm diameter were marked with paint in several reaches of the river. Following this flood, the painted substrata were relocated and used to determine substrate transport distances.

River morphology

Before the start of the flood program in 2000 and subsequently after the floods in 2000 and 2002, river morphology and substrate characteristics were mapped and photo-documented at 3 sites downstream of Punt dal Gall and at 6 transects below Ova Spin dam (each site was 200 m in length) (Fig. 1). Using a theodolite, we also measured 32 cross-sectional profiles (transects) below Punt dal Gall and 6 profiles below Ova Spin dam. In 2000, these transects were measured after each individual flood to evaluate the effects of floods of different magnitude. In 2001 and 2002, the transects were measured after the final flood in that year.

Riverbed structure and sediments

At selected transects (Fig. 1), we mapped the bottom substrata using a 1 m grid before and after each flood in 2000. In addition to characterizing the distribution of substrate types, the degree of colmation was categorized as (1) no colmation: substrate material loose, few or no fines around coarse grains; (2) low colmation: material loose, some fines around coarse grains noticeable; (3) moderate colmation: coarse grains clearly embedded with fines, a gap with clear edges remains after removing a stone; and (4) high colmation: coarse grains are embedded by a cohesive matrix of fines, stones are difficult to remove. Further, sediment samples were taken at 15 sites before and after each flood by means of a Surber sampler (mesh sizes of 190 μm and 63 μm) and the particle size distribution determined by sieving. Lastly, sediment freeze cores were taken to assess the sediment structure of deeper layers (Stocker and Williams, 1972).

Bank vegetation

Vegetation and substrate of 50 bank areas between Punt dal Gall and Punt Periv were photo-documented before and after the first two floods in 2000. From the photos, changes in the riparian bank as well as the riparian vegetation were assessed. In addition, standard vegetation transects (1 × 4–18 m) were mapped at 4 sites with special reference to substrate character. Bank vegetation measures were repeated after the last flood in September 2002.

Results

Suspended sediments

During the rise of the first flood (peak ca. 16 m^3/s) in June 2000, the highest concentrations of suspended sediments (12 ml/l) were measured (Fig. 2). Sediment volume was less than 4 ml/l during the following floods (some peak-

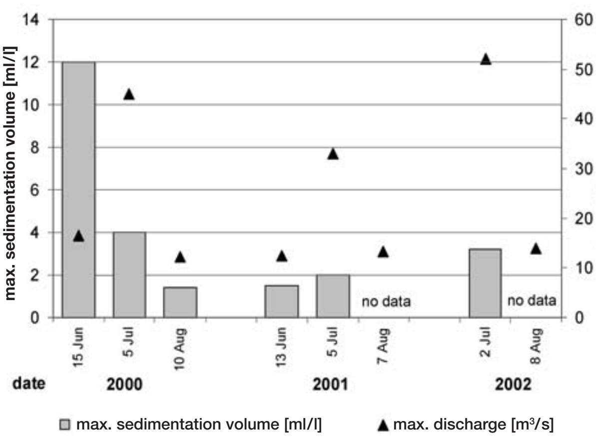

Figure 2. Maximum volume of suspended sediments (bars) and respective maximum discharge (symbols) of each flood from 2000 to 2002 at Punt Periv (see Fig. 1) ca. 2.5 km downstream of Punt dal Gall. Suspended sediments were not assessed for the 7 August 2001 and 8 August 2002 floods.

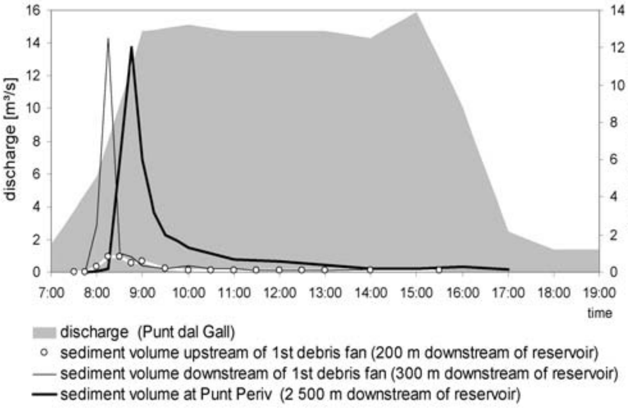

Figure 3. Temporal changes in suspended sediment concentrations (ml/l) at three sites downstream of Punt dal Gal dam during the flood on 15 June 2000. Note the importance of the first debris dam below the reservoir to suspended sediment levels during the flood.

ing at >30 m^3/s) through 2002. The maximum concentration in suspended sediments always occurred during the rising limb of each flood (Fig. 3). In addition to this temporal aspect, increasing concentrations of suspended sediments were observed progressively downstream. The concentrations of suspended sediment were quite low immediately below the Livigno dam, increasing substantially only after the first debris fan about 300 m downstream (Fig. 3). Some of the marked stones (up to 20 cm in size) were found up to 150 m downstream.

River morphology

The floods caused a significant removal of sediments at the foot of debris fans within the active channel. Debris fans were eroded approximately 0.5 m by the first flood (16 m^3/s) in 2000, and up to 1.5 m by the second (5 July) larger flood (peak flow ca. 45 m^3/s) (Fig. 4). Downstream

Figure 4. Photo of the erosion of a debris fan near Punt dal Gall (see Fig. 1) caused by the first flood on June 15, 2000. Photo: P. Rey.

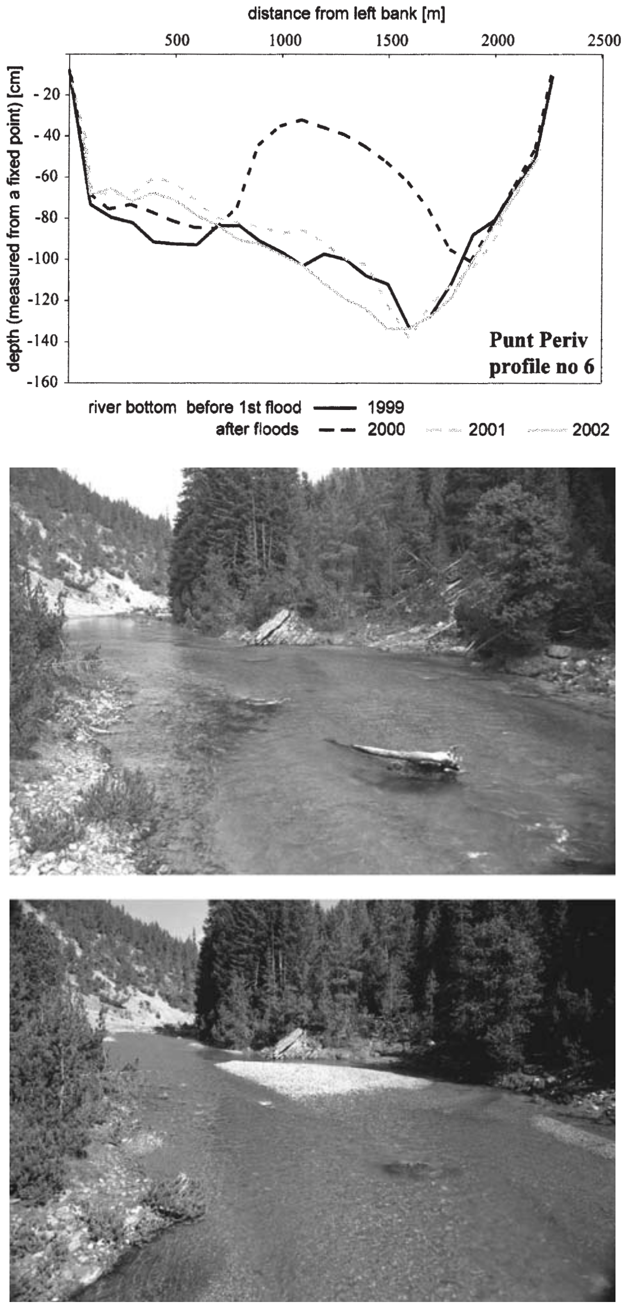

Figure 5. Selected cross-sectional profile (transect) near Punt Periv (see Fig. 1) measured before the floods in 1999 and then following each flood year from 2000 through 2002 (top). Photo-documentation of the effects of the 2000 floods: situation before first flood in August 1999 (middle) and after the second flood in 2000 (bottom) that resulted in the deposition of gravel and the formation of new gravel bars. Note that both photos are from the same location. Photos: U. Mürle.

of Punt dal Gall, fine materials on the river-bottom were mobilized with the first flood in June 2000, although the bed structure was only slightly modified. The second larger flood in July 2000 mobilized substantially more material from the debris fans, resulting in extensive accu-

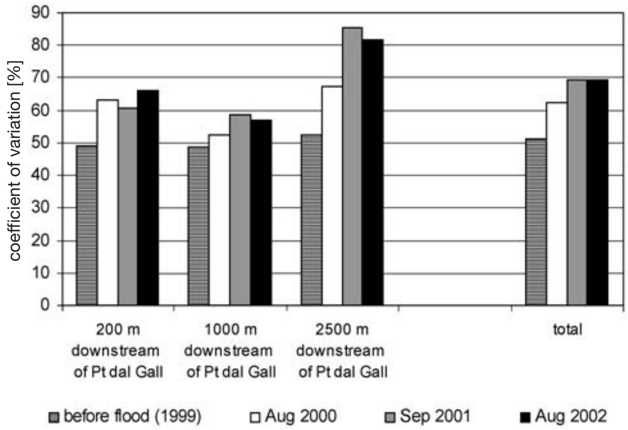

Figure 6. Coefficient of variation (CV as %) for water depth in the Spöl determined during 4 different periods under baseflow conditions (ca. 1.43 m^3/s) from 1999 through 2002.

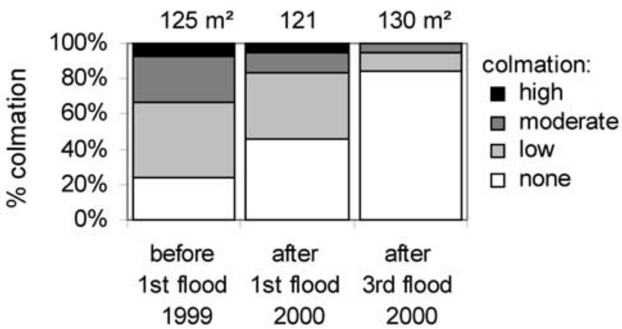

Figure 7. Colmation (clogging) of the riverbed between Punt dal Gall and Punt Periv (see Fig. 1) after the floods in 1999 and 2000. See methods for how the degree of colmation was determined)

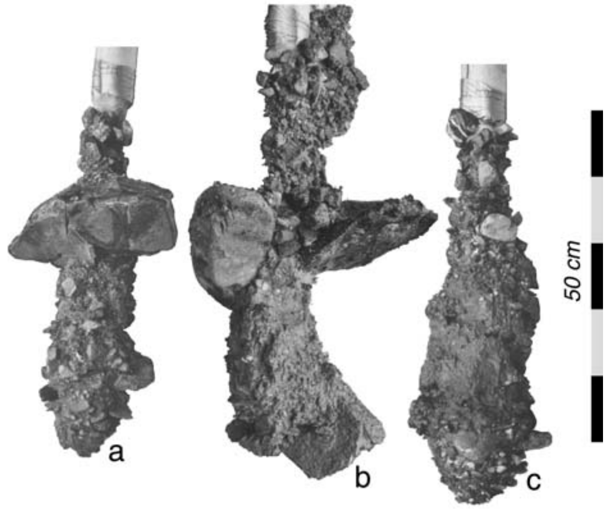

Figure 8. Photos of freeze cores taken after the floods in 2000. a) Core taken in a channel bar downstream of Punt dal Gall (see Fig. 1). The large stones show the surface layer, which was covered by gravel during the floods. Note that the substratum under the surface layer was not affected by the floods, as indicated by the high content of fine material. b) Core taken from a newly formed gravel bar near Punt Periv (see Fig. 1). The original bed surface (shown by the coarse material location) was buried at a depth of 35 cm, showing that the deeper layers were not disturbed by the floods before burial by gravel. c) Core taken from a formerly silty basin near Punt Periv that was not eroded but covered with a thick layer of gravel. Photos: J. Ortlepp

mulations of gravel and sand in the riverbed and adjacent floodplains (Figs. 5a–c). Following the first flood year, the floods in 2001 and 2002 scoured newly built gravel banks and further eroded benthic sediments. The floods also resulted in a greater variation (coefficient of variation in %) in water depths in the Spöl downstream of Punt dal Gall (Fig. 6), suggesting an increase in habitat variability.

Riverbed structure and sediments

Gravel and cobble are the predominant sediment classes in the Spöl. The average D_{50}-value before the floods was 62 mm, increasing to about 76 mm after the first flood year. The floods changed the substrate composition only by a small degree, increasing coarse sediments by erosion and gravel by deposition. The percentage of fine material (silt, sand) in the upper layer of substratum was reduced, as indicated by the reduction in substrate colmation already after first flood in 2000 (Fig. 7). Following the floods of 2000, benthic substrata were unembedded and, to a large extent, free of fine material. However, besides reducing the amount of fines in bed sediments, other colmated areas were covered with loose gravel, as shown in Figure 8. Bed sediments up to a depth of 0.5 m could be taken by freeze coring, although coarse sediment material in the upper-most layer was frequently lost when withdrawing the core in flowing water. Before and after the floods in 2000, the deeper layers of substratum contained a considerable fraction of fine material. Below 0.15 m in depth, fine material ($<$2 mm) reached 20% (by weight) of the fraction smaller than 63 mm. In part, the coarse sediments were embedded in a sticky clay-silt matrix (Fig. 8).

Bank vegetation

In only a few cases was the bank vegetation clearly affected by the floods. For example, some tree-covered banks were eroded and others remained flooded. Few young conifers were affected directly by the floods. Several banks of grass or wood were covered by deposited gravel or sand (Fig. 10). Based on the vegetation transects, there was only small shift in the species occurrence. For instance, *Carex maritima*, a typical but rare floodplain species in subalpine areas (Hegg et al., 1993), was found on a sand covered area that was quite densely covered by vegetation before the floods.

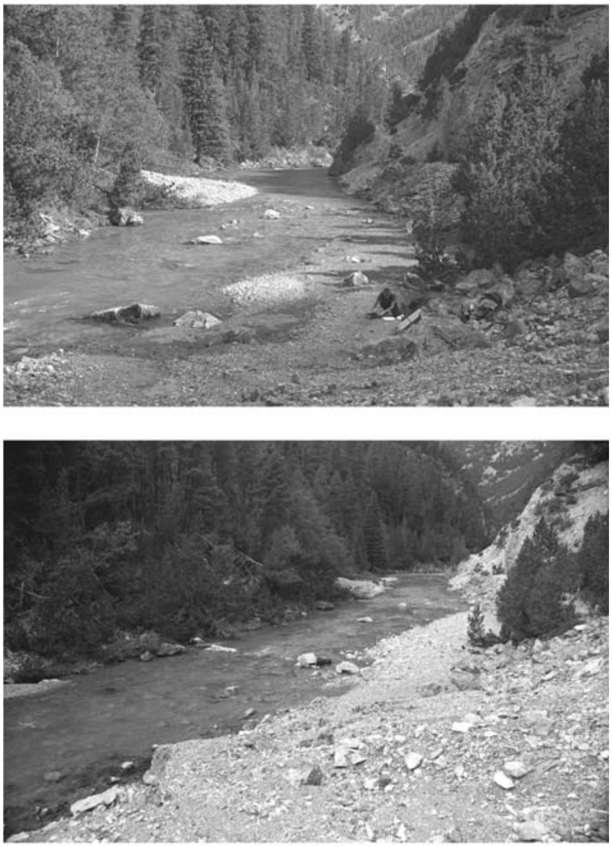

Figure 9. Photo-documentation of the rubble material from a debris fan covering a former vegetated area some 20 m downstream. Note the lower photo was taken some meters upstream of the upper photo (shown by the debris fan on the left side of each photo) to better present the accumulation of scree in the river channel. Photo: J. Ortlepp.

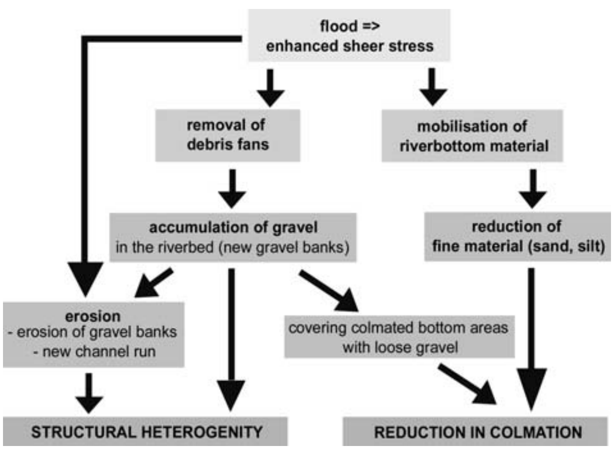

Figure 10. Conceptual diagram illustrating some of the more important effects resulting from the artificial floods during the study period.

Discussion

The construction of the reservoirs, and subsequent flow regulation, on the River Spöl caused the river to lose its mountain river character through drastic changes in hydrology and morphology. Discharge was regulated and remained essentially constant, except for the regulated flow change between winter and summer. Before reservoir construction, floods with discharges up to 40 m^3/s (max. 140 m^3/s; see Scheurer and Molinari, 2003) regularly occurred in the Spöl. Since 1970, natural floods are found only in the lower part of the river below the confluence with the Ova da Cluozza. Flow regulation has interrupted the dynamics of lateral inputs from valley side-slopes that were deposited and re-distributed in the river channel by floods. Since 2000, however, the hydrologic and morphologic characteristics of the Spöl have been changed by the artificial floods, with habitat conditions moving towards a more natural state.

Due to the substantial accumulation of fines over the years under regulated flows, the question arose whether a mobilization of the riverbed material and lateral debris inputs by flooding would cause ecologically detrimental sediment flows. However, suspended sediment volumes were always under the critical value of 20 ml/l (Gerster and Rey, 1994), and the highest value was 12 ml/l during the first flood in the year 2000. The accumulated fines in the river bed were mobilized already in the early phase of this flood at a discharge of 8 m^3/s. This pattern (i.e., hysteresis) is typical of suspended sediment patterns during floods in most streams (Lenzi and Marchi, 2000). The fine material was, to a large extent, transported downstream, before additional material from the debris fans was mobilized at higher discharges. Further, suspended sediment concentrations remained low in the later floods. The results suggest that the accumulation of fines in the river bed can be prevented using a regular flood release program, as no 'critical' suspended sediment loads should occur. A similar finding was presented by Milhous (1998), suggesting the use of flushing flows on an annual basis for sustaining both biological and hydrological needs of the river system. Lastly, the concentrations of suspended sediments immediately below the reservoir dam remained quite low during each flood, only increasing after mobilization of the first downstream debris fan. Thus, input of sediments from the reservoir was negligible during the flood experiment.

Questions regarding flood needs

Some questions were alluded to in the introduction regarding the flood program, and we now address some of those specifically. Concerning the question: how long must each flood be to transport the mobilized fine material? Floods of both 10 m^3/s and up to 40 m^3/s increased the concentration of suspended sediments with the initial increase in discharge with levels decreasing before reaching a constant flood discharge. Therefore, the duration of the maximum flood discharge could be reduced with future floods. However, to transport a large fraction of the fine material from the river, the duration of the maximum flood discharge should correspond to the flow time between Livigno reservoir and Ova Spin reservoir (ca. 40 min; after Schlüchter et al., 1991) or between Ova Spin reservoir and the River Inn.

As to the question: what discharge is necessary to remove the lateral inputs from side-slope talus fields? Here debris fans were scoured already at discharges of ca. 10 m^3/s, with an increase in discharge providing additional erosion of debris fans. Milhous (1998) also found that flows of different magnitude had different affects on sediment mobility.

As to the question: what discharge is necessary to mobilize bed substrates and restructure the river channel? Small flood discharges (10 m^3/s) had an evident effect on the river bottom only in the first year. Fine material deposited on the river bottom and material eroded from debris fans was transported and deposited downstream (an accumulation of over 1 m in some locations). The following larger floods distributed the new material from debris fans along the course of the river. Bed load transport and scouring of coarse sediments occurred only at flood discharges over 30 m^3/s, resulting in greater habitat heterogeneity (e.g., a higher coefficient of variation in water depth) (Downs and Thorne, 2000). Because the flood effects are noted on the rising limb of increasing discharge, several floods will be necessary for the transport and distribution of sediments in years with large inputs from lateral sources. These findings concur with other studies emphasizing the use of multiple floods over an annual cycle to meet both ecological and hydrological needs (Kondolf and Wilcock, 1996; Cooper et al., 1999; Downs and Thorne, 2000).

Regarding the question: what flood discharge is necessary to reduce the colmation of bed sediments? Colmation of the substratum was reduced in two ways by the floods (Fig. 10). First, material from the debris fans was deposited in the riverbed and, thereby, covered colmated areas with loose substrate. Second, colmated areas were scoured and loose sediments re-distributed by the floods. Similarly, diverse outcomes on channel morphology resulted during the Glen Canyon dam flood (Schmidt et al., 2001). Following the hydraulic computations of Mürle (2000), mobilization of the surface layer in the Spöl occurs at a discharge of 10–15 m^3/s with no larger scale erosion of the channel. However, as suggested by Milhous (1998), the flow needs vary depending on the individual stream system and the objectives of the flood flow.

Effects of the floods on riverbed habitats

In the Spöl, below the confluence with the River Cluozza in particular, the input of material from lateral sources causes a strong homogenization of the river bottom and a loss in channel structure. The increase in scouring with flooding increased the structural heterogeneity of the river channel and bottom. For example, depth variability, as a measure of structural diversity, increased after the floods in all parts of the river. In addition, the potential of interstitial habitats for benthic organisms was increased by the reduction in colmation, and the area suitable for trout spawning grounds increased by the removal of fines and the new formation of loosely packed gravel bars. Schmidt et al. (2001) also saw a revitalization of habitats used by the fishery in the Colorado River below Glen Canyon dam, although the effect decreased quickly after the flood.

Effects of floods on riparian vegetation

Young trees developing on the river bank were only slightly affected by the floods, suggesting colonization of trees on the bank will not be constrained with the present flood regime. Presently, the number and duration of floods were not sufficient to restore flood plains formerly free of trees. However, the coverage of grass areas by sand and gravel partially created locations for pioneer plants. It is expected that such locations can be created more extensively using floods in years with high lateral inputs of sediments. Schmidt et al. (2001) also noted little change in riparian shrubs due to the Glen Canyon dam flood as they were located in areas lacking substantial scouring. Nevertheless, a flood regime is likely to restore the hydrologic regime important for the establishment of pioneer riparian species (Cooper et al., 1999; Horton and Clark, 2001).

The numerous changes in the river character show that a flood regime program can mitigate the negative consequences of a reduced and regulated discharge. However, the desired effects occur only with a frequent number of relatively high magnitude floods. With each newly attained state in river bed character, the number and magnitude of future floods could be determined after assessing the sediment input from the side-slope tributaries and debris (talus) slopes in an adaptive management approach. Further efforts towards optimizing a dynamic discharge regime should consider, most of all, the biological effects of the residual water regime. For example, the substantial algal development (Uehlinger et al., 2003) and the rapid coverage of the stream bed with fines during residual water periods represent a relevant issue.

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