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Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from Glen Canyon Dam, Arizona

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The Swiss Experience with High-Flow Experiments—Implications for the Management of Glen Canyon Dam?

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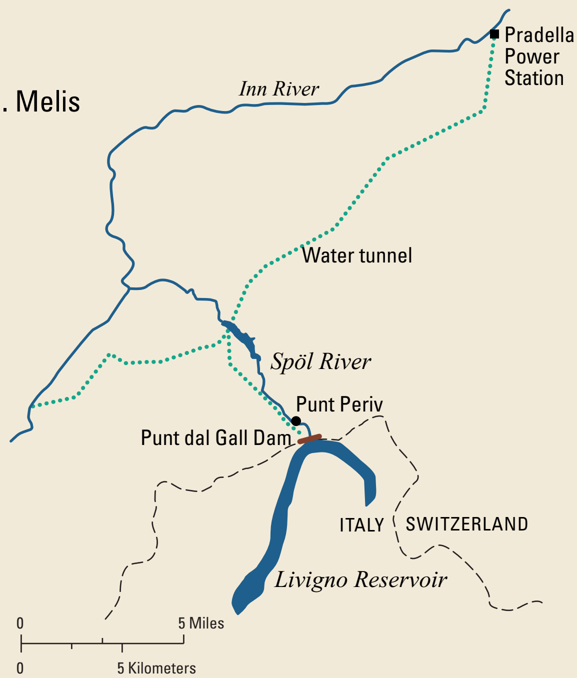
Planning is currently underway by the U.S. Department of the Interior's Bureau of Reclamation for a long-term experimental plan that will implement a structured, long-term program of experimentation at Glen Canyon Dam over the coming decade. The program will include criteria for triggering repeated high-flow experiments (HFEs) on the basis of relatively frequent sand inputs to the Colorado River from tributaries below the dam (see chapter 5, this volume). If the experimental triggering protocol suggested by sediment scientists is adopted, then the frequency of HFEs during a future Glen Canyon Dam experiment is anticipated to be annual or possibly more frequent in some years. In all likely cases, the HFEs intended to conserve limited sand supply below the dam will include flows from the dam's hydropower plant in combination with varying magnitude bypass releases. As planning continues, results from other experimental river programs where repeated high-flow dam releases have also been studied may be informative.

Nearly two-thirds of the electricity produced in Switzerland comes from hydropower. It is estimated that over 80 percent of Switzerland's hydroelectric potential has already been exploited. With few suitable dam sites remaining, developing the remaining 10 to 20 percent of hydroelectric potential will have increasingly greater environmental consequences and costs, although climate change is expected to increase precipitation in Europe and provide greater flexibility for hydropower production. The Swiss Federal Institute of Environmental Science and Technology (EAWAG) has developed criteria for "green labeling" hydropower production (Bratrich and others, 2004). The so-called "Green Hydro" concept establishes ecological criteria for certification that generally are consistent with the concept of "environmental flows," which are designed to sustain select or key ecological and societal values (Acreman and Ferguson, 2010). By 2004, 13 Swiss facilities had successfully passed the certification procedure, producing a total of 186 gigawatts (GW) of green electricity per year, which is sufficient to power almost 40,000 households. Although this green energy is produced by hydropower, it is important to know that hydropower causes other ecological effects on regulated rivers.

To test whether an annual artificial flood (hereafter, high-flow experiment or HFE) regime can improve the ecology of regulated rivers below dams, a program of experimental high flows was implemented on the Spöl River in southeastern Switzerland in



The study area on the Spöl River. The main study reach is located about 1.4 miles downstream from Punt dal Gall Dam. The dashed lines show the tunnel infrastructure for water transport for hydropower production. This infrastructure allows the frequently repeated high-flow experiments to be a no-cost management strategy for the hydropower company. Modified from Scheurer and Molinari (2003).

2000 (see map) in cooperation with the Swiss National Park and the Engadiner Kraftwerke Power Company (Scheurer and Molinari, 2003). The Spöl River flows through a confined channel surrounded by mountainous terrain (see photographs on opposite page). About 20 separate high flows have been released between 2000 and 2010 from Punt dal Gall Dam that forms Livigno Reservoir on the Swiss-Italian border (see figure at end of text block).

A comprehensive study of the ecological effects of these repeated HFEs on the Spöl River was initiated in 1999 (Robinson and Uehlinger, 2003). The study included aquatic food production (periphyton, stream metabolism, and benthic macroinvertebrates; Robinson and others, 2003; Uehlinger and others, 2003), brown trout (*Salmo trutta*; Ortlepp and Mürle, 2003), longitudinal patterns (Jakob and others, 2003), and river morphology and riparian vegetation (Mürle and others, 2003). A major finding from these studies that may be relevant to a long-term Glen Canyon

Dam HFE protocol was that one or two high-flow events per year can enhance and sustain the long-term ecological integrity of the river (Scheurer and Molinari, 2003) and that flow releases must be repeated on a regular basis (annually) to maintain their benefits (Robinson and Uehlinger, 2008).

The HFEs in the Spöl River scour and immediately reduce primary producer biomass, which then recovers quickly after each event (Uehlinger and others, 2003), similar to the effects of natural floods observed in unregulated rivers. Importantly, the high flows shifted primary aquatic food producers from a moss-dominated streambed to one of diatoms and filamentous algae. There was also a longitudinal downstream effect of scouring on periphyton and benthic organic matter as a consequence of the degree of disturbance with generally greater effects in the most upstream reaches (Jakob and others, 2003). After the first 3 years of HFEs, periphyton assemblages now resemble those of unregulated Alpine mountain rivers where a snow and ice-melt-driven flow pulse results in a typical seasonal pattern of low periphyton biomass in summer and high biomass in autumn.

The HFEs significantly reduced macroinvertebrate densities, although densities typically recovered to pre-experiment levels within a matter of weeks (Robinson and Uehlinger, 2008). Some taxa have decreased in abundance since beginning the experimental program, including amphipods (Gammaridae) and flatworms (Turbellaria), whereas others have increased in abundance, including mayflies (Baetidae), midges (Chironomidae), and stoneflies (Plecoptera, *Protonemoura*). Other taxa, such as blackflies (Simuliidae), caddisflies (Trichoptera), and mayflies (Heptageniidae) that were negatively affected by high flows in 2000, have subsequently increased in abundance. The sequence of annual high flows imposed on this regulated river revealed that the response of macroinvertebrates to repeated HFEs occurs over a period of years rather than months, as species composition shifts to the new and more variable habitat template. The Swiss results showed that the high-flow experimental regime must be maintained if resource managers wish to sustain the development of a more natural macroinvertebrate assemblage, especially if it is important in maintaining a food web to support native brown trout.

The flow experiments on the Spöl River were intended to improve the fisheries potential (brown trout) of the river within the Swiss National Park. Despite increased food resources after flow regulation, the reproduction and recruitment of brown trout had declined, primarily because spawning areas were greatly reduced by the clogging of coarse sediments (Ortlepp and Mürle, 2003). Trout abundance was not reduced by the high flows, and relatively few fish (less than 2 percent) were killed or stranded. The quality of fish habitat, spawning grounds in particular, has noticeably improved, even though food resources (macroinvertebrate composition) have changed since the experiments began. The results showed that the condition of trout in the Spöl River has remained relatively constant, but the number of redds have increased sixfold since initiation of the experimental program, which presumably translates to increases in fish recruitment.

One important finding of the high flows was the lack of extensive effects on riparian vegetation. Mürle and others (2003) found that a lack of flow disturbance on the Spöl River had allowed woody vegetation to develop on

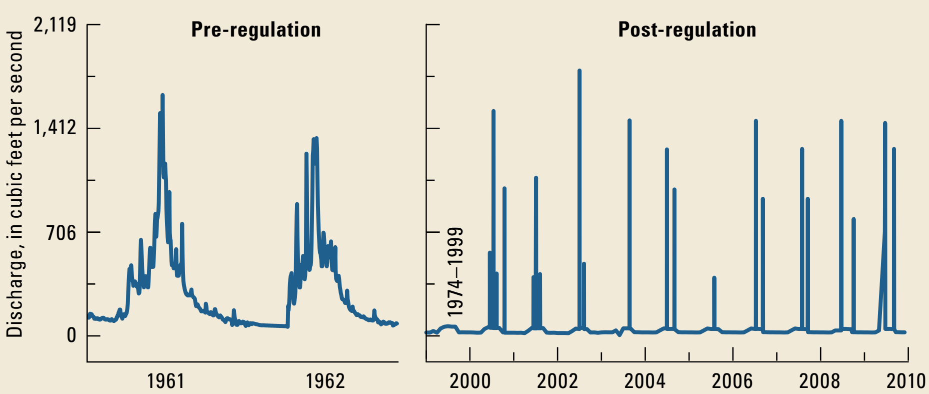
Left, the Spöl River at one of the study reaches (Punt Periv) under low-flow conditions (56 ft^3/s). Right, during one of the high-flow experimental releases (1,483 ft^3/s) on July 5, 2000. Photographs courtesy of Urs Uehlinger.

previously exposed gravel banks. Young trees developing on the river bank were only slightly affected by the high flows, suggesting that colonization of trees was not constrained by the experimental releases. Thus far, the number and duration of high flows have not been sufficient to restore former flood plains free of trees; however, the coverage (burial) of grass areas by sand and gravel partially created locations for pioneer plants. These effects on riparian vegetation may be related to the canyon-confined nature of the river valley in contrast to other rivers with more dynamic flood plains.

An evaluation of modified flow regimes worldwide (Murchie and others, 2008) and the experience of the Spöl River (Robinson and Uehlinger, 2008) reveal important issues in the evaluation of relatively frequent HFEs on river ecology. Study designs could include methods that target physical as well as all biological levels, including aquatic food producing organisms, fishes, and riparian vegetation. The most effective experimental designs also would provide sufficient data to allow for detailed statistical analyses to be performed. Rigorous study designs that include the use of appropriate controls and replicates are essential whenever feasible. Data on physical variables that respond to changes in flow can also be collected and examined to add explanatory power to results.

The HFEs on the Spöl River highlight some major effects of artificial floods on regulated river ecosystems. While the experiments affected the existing aquatic communities, recovery of primary and secondary producers (periphyton and macroinvertebrates) was rapid after each flood. Biotic assemblages have shifted to the new habitat template of the river, but these changes in slower variables have occurred over years as novel biological thresholds were passed and new ecosystem states were established. Whether biotic assemblages return to pre-dam levels is unknown, but the frequently repeated high flows have clearly increased the physical dynamics of the river, which has been translated to changes in biotic assemblages. It also is unknown, however, if repeated and continued high flows over time will eventually restore much of the ecosystem structure and function to those of a typical mountain river. Without consistent monitoring, the gradual nature and timing of this shift might not have been apparent.

The findings on the Spöl River may have general ecological application. Some of the learning that has occurred there is likely transferrable to the current Glen Canyon Dam HFE protocol planning process. However, it is clear that each river system is different because of its unique ecological setting and the specific manner in which each system is regulated. The Swiss experience clearly illustrates the benefits of cooperative efforts among stakeholders, especially power producers, water users, environmental groups, and State and Federal officials. The Spöl River experiment and other programs (Murchie and others, 2008) show how a good understanding of the relation of dam operations and resulting river flows to ecosystem components can help manage hydropower facilities to achieve large ecological benefits through relatively small modifications and costs.



The flow regime of the Spöl River (on the Swiss-Italian border) for 2 representative years before regulation, the year before the high-flow experimental program (1999) showing the typical seasonal regulated flow, and the flow after the experimental program, including each of the flow events. Data for 1999 and the years before regulation are daily values. Data are instantaneous values after 2000. Modified from Robinson and Uehlinger (2008).