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Hydropower production and river rehabilitation: A case study on an alpine river

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Abstract Despite the numerous benefits of hydropower production, this renewable energy source can have serious negative consequences on the environment. For example, dams act as barriers for the longitudinal migration of organisms and transport of particulate matter. Accelerated siltation processes in the receiving river reduce the vertical connectivity between river and groundwater. Hydropeaks, caused by short-term changes in hydropower operation, result in a negative impact on both habitat and organisms, especially during winter months when natural discharge is low and almost constant. In this study, we report the current deficits present in the River Rhone from two different scientific perspectives – fish ecology and hydrology. Potential rehabilitation solutions in synergy with flood protection measures are discussed. We focus on the effects of hydropeaking in relation to longitudinal and vertical dimensions and discuss local river widening as a potential rehabilitation tool. The fish fauna in the Rhone is characterized by a highly unnatural structure (low diversity, impaired age distribution). A high correlation between fish biomass and monotonous morphology (poor cover availability) was established. Tracer hydrology provided further details about the reduced permeability of the riverbank, revealing a high degree of siltation with K values of about 4.7×10^{-6} m s^{-1}. Improving the hydrologic situation is therefore essential for the successful rehabilitation of the Rhone River. To this end, hydropeaks in the river reaches must be attenuated. This can be realized by a combination of different hard technical and soft operational measures such as retention reservoirs or slower up and down ramping of turbines.

Keywords connectivity · fish biology · habitat stability · hydropeaking · hydropower · tracer hydrology · restoration

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1 Introduction

For centuries, man has modified running waters [51]. In alpine rivers, production of hydropower results in a wide range of environmental disturbances of river systems [66]. To date, two different types of power plants are commonly in use: (1) run-of-river power plants that continuously process the incidental discharge and the impoundment upstream of such dams provides only marginal storage capacity; and (2) huge reservoirs that were built in the alpine headwaters of many streams, storing a significant water volume during times of snowmelt and rainfall. These seasonal storage plants produce energy only when there is a demand and are brought online almost exclusively during periods of peak consumption.

Hydropower is an extremely important energy source in all alpine countries. With an annual production of 38 TWh, Switzerland's hydroelectric power plants provide 58% of the domestic energy production. Approximately 60% of this production is generated in the Alps [67, 76]. The two main Swiss hydropower production stations of the Grande Dixence hydropower scheme in the catchment of the River Rhone, for example, turbinated 611 millions m^3 of water in 2003, resulting in a total annual energy production of 2,877 GWh [24]. Peak production from storage reservoirs plays a key role in stabilizing the European power grid.

With an export of 7.1 TWh in 2000, Switzerland ranks third in the European electricity market [53]. Moreover, it has been suggested that until 2020, electric power consumption in Europe might rise by 40% [18]. With an increasing share of renewable energy sources, such as wind power, peak production by hydropower schemes will be in high demand to stabilize variable production rates.

Apart from the numerous positive aspects of hydropower, such as its renewability, it can also create serious environmental problems. On the one hand, all hydroelectric power schemes disrupt the river continuum [69]. Dams act as barriers for the longitudinal migration and drift of organisms [63] and they also trap sediment particles [21, 71]. Additionally, the river stretch between water diversion and release often has a reduced discharge, the so-called residual flow. The ecological consequences of this, such as a reduced persistence of habitat features [74] or a reduction of fish biomass [5], are well documented in the literature.

Dam operation has several far-ranging impacts on a river's natural flow regime [63, 52]. Reservoirs are mainly filled in summer during the snow and glacier melting period, whereas the stored water is used for hydropower production during the winter months. The effect on the tailwaters are twofold: (1) in comparison to natural conditions, river discharge increases in winter and decreases in summer; and (2) amplitude and frequency of large flood events decrease due to the additional retention volume of the reservoirs [39, 40, 44]. In Switzerland, for example, the 130 or so large reservoirs used for hydropower production can retain about 25% of the annual discharge of the main alpine watersheds of the rivers Aare, Reuss, Rhine, Rhone, and Ticino [76]. This impairs the flushing capacity of the connected river system [45]. Accelerated siltation processes [39] reduce the vertical connectivity between river and groundwater [57], affecting the benthic community and the spawning conditions for fish [8].

These seasonal effects are superposed by rapidly oscillating floods caused by daily hydropower operation. These so-called hydropeaks are not powerful enough to compensate for the lack of natural flood events removing the siltation of the riverbed [6]. Their regularity and high temporal frequency produce grave impacts on macroinvertebrates (catastrophic drift) [12], fish (stranding) [56] and their habitat [68]. In Switzerland, about 25% of the operating 500 hydropower plants with an annual production >300 kWh produce these hydropeaks, which in turn affect approximately 30% of all the country's rivers and streams [38].

In order to stabilize the bed of regulated rivers, hard structural measures like the construction of levees were used earlier. However, recently, a paradigm shift towards integrated river management has triggered efforts to reconcile economic, political and ecological interests [75]. In densely populated and economically intensively exploited river landscapes, conservation and rehabilitation measures are therefore facing many difficulties and constraints.

With a large installed capacity of storage reservoirs and hydropower plants [39], the River Rhone in Switzerland is presently an object of such conflicting interests. The main focus of the project for a third Rhone correction (consecutively called 3RC) is flood protection, although ecological and socio-economic improvements are also planned. In this context, local river widening is discussed. Being primarily an engineering measure for preventing incision, widening shows significant morphological and hydraulic potentials [55], such as gravel bank development and higher variability of depth and velocity, leading to increased shoreline length and a more diverse aquatic habitat. River widening represents an appropriate rehabilitation measure in formerly braided systems.

Many lessons can be learned for future flood protection and rehabilitation efforts by analyzing a large-scale project such as the 3RC. In Switzerland, approximately 25,600 km of streams and rivers (43% of the total stream/river length) are artificially deepened, dammed and straightened, and require rehabilitation [50]. With 60% of the Swiss river network lying in the alpine and high alpine region, the rehabilitation potential is especially pronounced there [49]. Therefore, the 3RC in its initial stages is accompanied by an interdisciplinary research project, namely the Rhone–Thur River Rehabilitation Project [50].

In this work, we document an interdisciplinary study within the framework of this project. Unifying two complementary perspectives – fish ecology and tracer hydrology – we analyze the actual distribution of environmental deficits in the River Rhone and assess their relative influence. Considering fish fauna in the longitudinal direction and river–groundwater interactions in the vertical dimension [73] allows the assessment of potential rehabilitation measures on a catchment scale [46]. The discussion is focused on the effects of hydropeaking and on the potential of local river widening as a rehabilitation tool.

2 Methods

2.1 Study area

The upper River Rhone (Fig. 1a) originates from the Rhone Glacier (1,763 m asl) and flows through the Rhone Valley into Lake Geneva (374 m asl). Along this 167.5-km stretch, it drains a catchment of 5,220 km^2 consisting mainly of forest and pastures (46%), rocks and glaciers (38%) and agricultural land (16%) [39]. Naturally, the system shows a nivo-glacial flow regime [39, 44].

Today, the River Rhone is highly channelized and reaches with a near-natural discharge regime are rare. Along 36 km (22%), the mean natural annual discharge volume is reduced

by more than 20%, and over a distance of 109 km (65%) hydropeaking is present (data from Gruppe fuer Hydrologie [26]). Areas with intact connectivity are virtually non-existent, mainly due to extensive use of the Rhone for hydropower generation [50].

The fish-ecological study sites were selected by means of stratified random sampling [37]. On the basis of topographical, hydrological and morphological data, the River Rhone was divided into 18 segments (strata). Within each stratum, points accessible with field equipment were determined randomly. Because of the difficult topography, seven shorter strata with a total length of 10.7 km (6%) could not be considered for the sampling. Altogether, 22 sites located in 11 strata were included into the investigation.

To investigate the water exchange in the vertical dimension (river–groundwater), the research focuses on the Rhone River near Martigny (Fig. 1a). The flood protection dike on both sides of the Rhone forms a clear interface between the groundwater and the river itself.

2.2 Fish ecology

2.2.1 Biotic parameters

The upstream part of every randomly determined point was electrofished via a semiquantitative approach along at least 100 m in length. The survey took place in February and March 2003. Generally, a stationary unit was used (EFKO, 8 kW, 150–300/300–600 V). Stretches difficult to access were fished with a backpack gear (EFKO, 1.5 kW, 150–300/300–600 V).

Fishing was conducted on strips of the riverbed: in the lower reaches, it was restricted to the bank strips; in stretches with minor discharge, a strip in the middle of the stream bed was also included. Narrow reaches in the headwaters were fished over the whole width. Over the 22 sites, 36 strips were fished in total.

Fishes were handled according to a standardized protocol [controlled conditioning, anesthesia with clove oil (0.5 ml diluted in 9.5 ml alcohol added to 20 L water)]. Wet weight (±0.1 g), body length (±1 mm), and presence and type of anomalies were determined. After recovery, all fishes were released along the fished stretch.

2.2.2 Environmental factors

For the survey of environmental factors, stretches were divided into 10 intervals of equal length. At four transects, substratum composition was estimated [3]. Substratum was assigned to one of nine classes using a modified Wentworth scale [14].

Between every two transects, hydraulic habitats [30] were mapped and their percentages visually estimated. Habitat

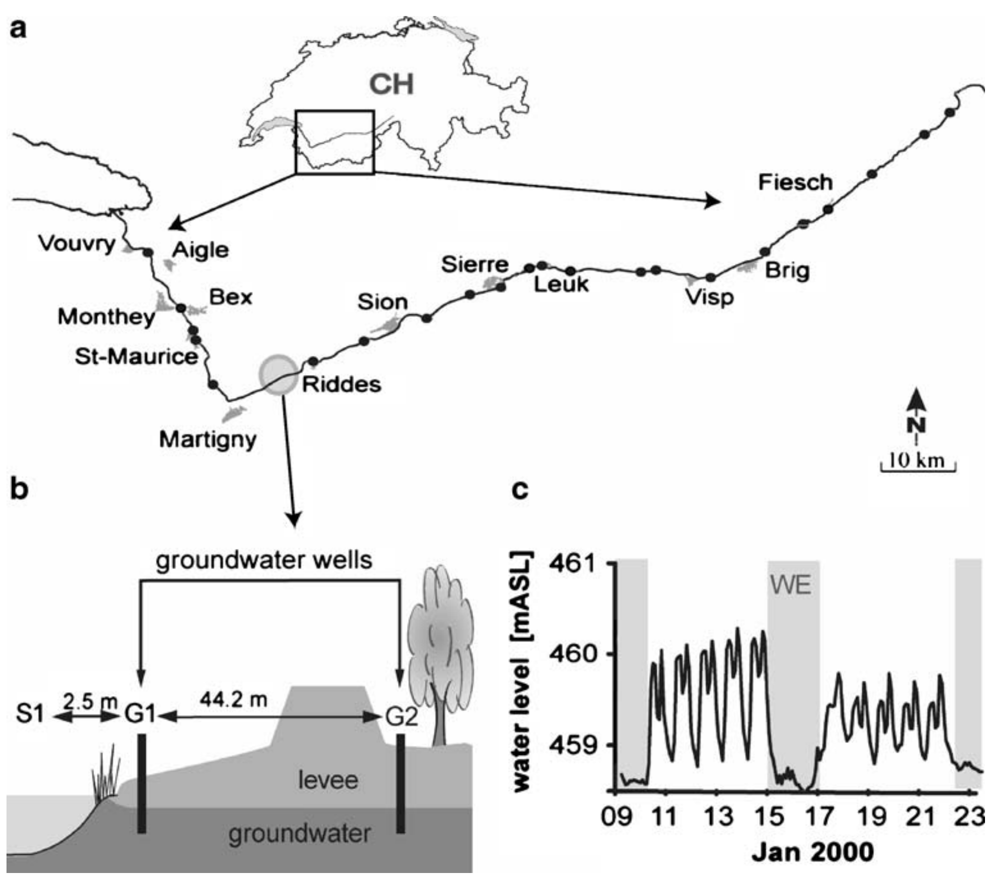

Fig. 1 (**a**) Area of investigation in the Valais (Rhone valley, Switzerland). The sampling points of the longitudinal approach are indicated in the schematic map of the river reach. (**b**) A schematic sketch of the groundwater–well transect within the levee near Martigny. The observation wells G1 (filtered between −5.5 and −6.5 m) and G2 (filtered between −2.5 and −3.5 m) are equipped with probes recording water level and temperature at 2-h intervals. (**c**) Graph showing a common hydropeaking regime in water level of the Rhone: daily water level variations up to 1.5 m from Monday to Friday are alternating with nearly constant water level during the weekend

diversity was determined using Shannon's index of diversity and evenness [2, 41]. In each interval, presence and type of suitable fish cover were determined visually, i.e., the area providing shelter from predators and high current velocities was identified. As according to Peter [48], overhead cover as well as slow water areas behind submerged objects were considered. For every interval, the shoreline composition regarding particle type and size was recorded.

Directly after fishing, water samples were taken at each site and immediately deep frozen in dry ice. Back in the laboratory, the samples were defrosted and analyzed for total phosphorous (T-P), NO_3-N, NO_2-N, NH_4-N, pH, alkalinity, dissolved organic carbon (DOC), total organic carbon (TOC) and suspended solids.

The remaining percentage of the mean natural annual discharge volume was determined on the basis of the hydrological atlas of Switzerland [26]. Based on this source, the impact of hydropeaking on the seasonal discharge regime was also quantified as a percentage increase in the natural winter flow.

2.2.3 Statistical analysis

To identify the environmental factors varying most between the stretches, abiotic factors were analyzed by means of principal components analysis (PCA). In this procedure, uncorrelated groups of intercorrelated variables are created, referred to as principal components. To determine the relationship between environmental factors and biotic parameters, all principal components with an eigenvalue >1 were compared with the fish-biological parameters in a mixed model procedure. This method allows us to consider the hierarchical structure of the data set given by the sampling of multiple strips at several sites. The analysis was conducted by the software package SPSS 11.0.1 for Windows. Before the analysis, all data were transformed using standard transformations (arcsin, log, square root).

2.3 Tracer hydrology

Based on transect measurements within the dam structure (Fig. 1b), the effects of hydropeaking across the dam were determined in the river and in two groundwater wells at a distance of 2.5 and 44.2 m from the river. The water levels and temperature were monitored over a period of 4 years using standard piezo-resistive pressure gauges and PT-100 thermometers, respectively.

2.3.1 Acquisition and evaluation of data

The data were taken in intervals of 2 h producing time series of data in the River Rhone itself and the adjacent groundwater. The analyzed data covered a period from October 1998 to September 2003, with about 21,200 values for each unit. The data set has been analyzed by using time series models to obtain an understanding of the basic processes. A common method for estimating the association between events in two time series is cross-correlation. The correlation coefficient obtained quantifies the match between the two quantitative time series [13, 29].

2.3.2 Interpretation of data

Water level and temperature signals provide different information: While water level may indicate the connection between wells, the temperature signal indicates heat transport in the groundwater. Old groundwater does not reflect significantly the sinusoidal seasonal temperature of the atmosphere. Young infiltrating groundwater, however, reflects these changes. The amplitude and the retardation of temperature minima or maxima with respect to the river are used to characterize the infiltration process [32, 62].

In infiltration flow systems, temperature variations are caused by heat transport (convection and thermal conduction) [7, 15, 58]. The temperature signal is retarded during transport in the groundwater due to heat transfer to the soil matrix. This means that the temperature signal as a tracer for water transport, as derived from the cross-correlations, must be corrected by a thermal retardation factor (R), which is a function of the porosity (n) of the soil matrix:

$$R = 1 + \beta \frac{(1-n)}{n} \quad (1)$$

where the nondimensional coefficient β describes the distribution of thermal energy between the fluid and the solid phase [15] and n reflects the porosity factor [–].

This simply means that the temperature signal will migrate through an aquifer in the same manner as a water parcel, but with a $1/R$ times slower velocity. The value for R for porosities between 0.1 and 0.2 lies in a range between about 3 and 5 [15].

3 Results

3.1 Fish ecology

3.1.1 Biotic parameters

The catches in the present study are highly dominated by the brown trout (*Salmo trutta fario*), amounting to 99.6% (714 individuals) of the total catch (717 individuals) (Weber et al., in preparation). In addition, three bullheads (*Cottus gobio*) were caught. Most brown trout were of medium

body size (median length 136 mm), and both large-size and young individuals were largely missing. Because of the dominance of the brown trout, the analysis was restricted to trout biomass.

Generally, low biomasses of brown trout were found, varying between 0 kg/100 m^2 (in four strips) and 1.54 kg/100 m^2, with a median of 0.06 kg/100 m^2. Between the different strips, the median weight of brown trout ranges from 6.2 to 191.6 g (median = 25.9 g).

3.1.2 Environmental factors

Values of all chemical parameters were within the tolerable range for brown trout [1]. In the PCA, the 28 original variables were reduced to nine principal components, accounting for 85.6% of the total variation. Every original variable showed a high loading only in a single principal component, therewith enabling a clear interpretation.

Based on this grouping of the original variables, the extracted components could be labeled. Component 6, for instance, could be referred to as presence of cover with variables like availability of cover, bigger-sized substratum and pools being the most important (Table 1). Additionally, the percentage of glides was negatively correlated with component 6.

3.1.3 Comparison between environmental and biotic factors

The mixed model procedure revealed a significant positive relationship between component 6 (cover availability) and total trout biomass per 100 m^2 (Table 1). Elevated biomasses of brown trout were found in stretches with a high amount of cover, a high percentage of pools, small amounts of glides and substratum bigger than 25 cm in diameter. No other components showed a significant relationship with the total trout biomass (Table 1).

Concerning the median weight of individual brown trout, no relationship with the investigated environmental factors could be found (Table 1). The plot of the individual weight against the impact of hydropower production (Fig. 2), however, showed a trend towards smaller weights in stretches with higher intensity of hydropeaking.

3.2 Tracer hydrology

Water temperature variations in rivers and streams are naturally mainly influenced by energy exchange with the atmosphere and the sediment as well as frictional heat [42]. Before construction of the main hydropower schemes, Uetrecht [16] measured average winter temperatures of 4.3°C and summer temperatures of 9.8°C in the Rhone River at Porte du Scex near Lake Geneva [43].

Today, this natural behavior is superposed by the influence of hydropeaks. In our area of investigation, the two hydropower plants, Grande Dixence and Mauvoisin, located with their outflow at ~11.5 and ~6 km upstream of the location of S1 (Fig. 1b), respectively, start normally in the early morning hours with the production of energy and the release of reservoir water to the river. This water release has a constant temperature of between 4 and 6.5°C [43], and leads to a significant increase in water level in the river (Fig. 1c). This hydropeaking modifies the seasonal temperature regime to an average of 5.5°C in winter and 9.1°C in summer at the

Table 1 Results of mixed model analysis (p values), testing the relationship between the nine principal components (PC) and the fish-biological factors

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
Mean weight, Brown trout (median)	0.546	0.764	0.698	0.256	0.164	0.416	0.420	0.851	0.531
Fish biomass/100 m^2	0.181	0.487	0.247	0.258	0.251	$\boldsymbol{p}$ **= 0.002** $\boldsymbol{F}$ **= 21.48 (+)**	0.815	0.291	0.210
Brown trout biomass/100 m^2	0.179	0.490	0.247	0.255	0.256	$\boldsymbol{p}$ **= 0.002** $\boldsymbol{F}$ **= 21.50 (+)**	0.814	0.281	0.209

Significant *p* values are in bold. (+) indicates a significant positive relationship.
Composition of the principal components (variables with loadings > 10.51):

PC1	$[NO_3]$ −, Residual flow +, Runs +, [Tot-P] +, Increased winter flow + , pH −, Alkalinity −,
PC2	Shannon index of diversity +, Evenness +, Number of habitat types +,
PC3	$[NO_2]$ +, $[NH_4]$ +,
PC4	DOC +, TOC +,
PC5	Substratum <8 mm +, Shoreline fine +,
PC6	Pools and deep edgewaters +, Substratum >256 mm +, Cover availability +, Glides −,
PC7	Substratum 8–64 mm +, Substratum 64–256 mm −,
PC8	Shoreline mixed −, Shoreline organic −,
PC9	Edgewaters shallow +, Shoreline coarse or rock +.
+ and −	indicate the sign of the loadings on the PC.

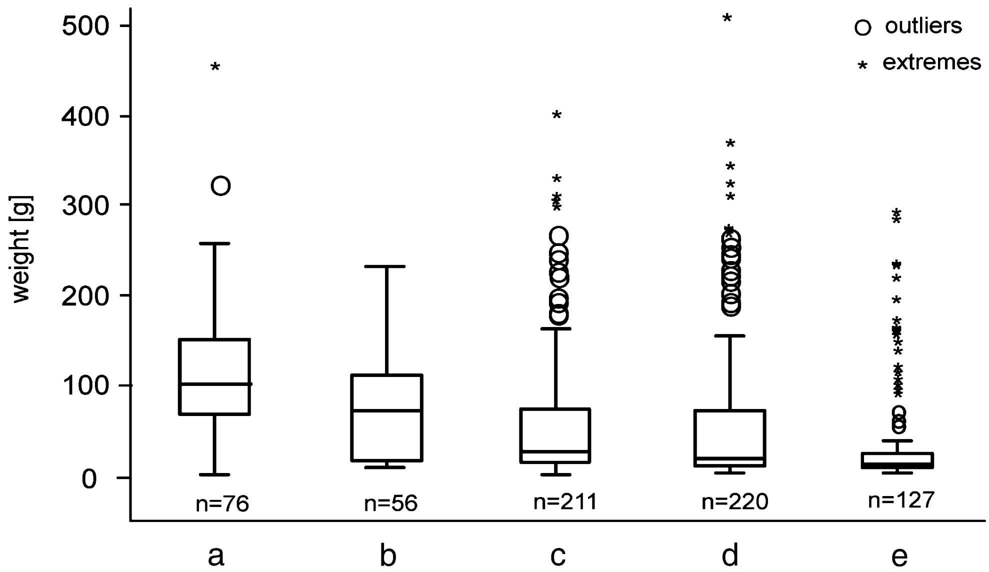

Fig. 2 Individual biomasses of brown trout in stretches differently affected by hydropower production. (**a**) Natural flow (<80% mean natural annual discharge, MNAD); (**b**) residual flow, moderate (41–80% MNAD); (**c**) residual flow, pronounced (0–40% MNAD); (**d**) hydropeaking, moderate (1–35% increase in natural winter flow); (**e**) hydropeaking, pronounced (>35% increase in natural winter flow). Circles and stars indicate outliers and extremes, respectively

monitoring station of Porte du Scex upstream of Lake Geneva [65]. This means that the construction of the hydropower plants generally led to winter warming and summer cooling of the river water. Raw temperature measurements at location S1 are shown in Fig. 3a.

Temperature records at the observation wells G1 and G2 (Fig. 3a) show comparable patterns. While the maximum water temperatures in the Rhone River are observed in August, the temperature in the groundwater reached its maximum with significant delay. This time lag can be determined more precisely by cross-correlation (Fig. 3b). The temperature signal is retarded by 732 h (~1 month) between the wells S1 and G1 and by 2,042 h (~3 months) between G1 and G2.

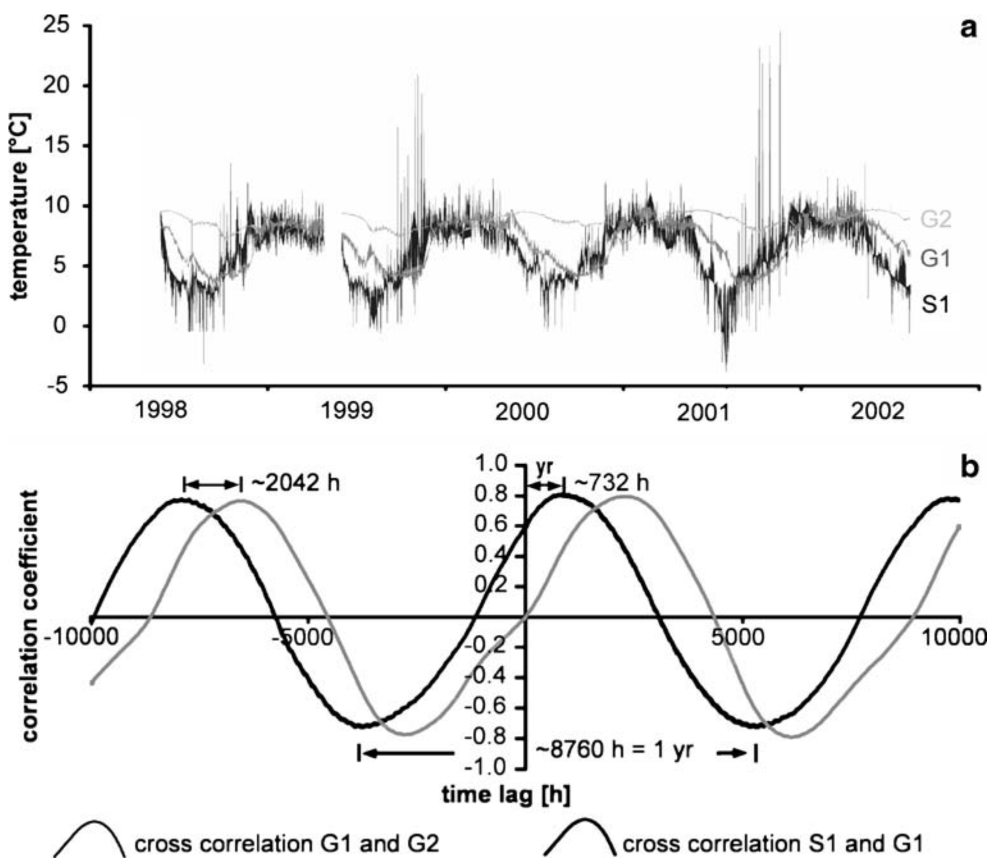

Fig. 3 (**a**) Raw data of temperature measurements in observation wells G1 and G2 (position is indicated in Fig. 1b). The three hydrographs show different time lags. (**b**) Quantification of the time lag by cross-correlating the data sets of S1/G1 and G1/G2

4 Discussion

4.1 Fish ecology

The fish fauna in the River Rhone showed a low species diversity. The assemblage was highly dominated by the brown trout, whose population structure clearly differed from that of undisturbed populations (Weber et al., in preparation).

Brown trout biomass varied considerably along the River Rhone. The highest values were found next to structured banks as those fixed by riprap. In the interstitial spaces between the large angular rocks, lower current velocities prevail and overhead cover is given. In exchange, in reaches with limited cover availability, like groyne fields with a high amount of fine sediments or unstructured instream strips, small biomasses were observed. The present data indicate a significant positive reaction of brown trout biomass to cover variables, and therefore, correspond well with results from previous studies (see Heggenes [31] for a review).

Despite this positive reaction on cover availability, the biomasses found in River Rhone are quite small. Comparable investigations in near-natural alpine rivers revealed biomasses between 12 and 100 kg ha^{-1}, ranging up to 270 kg ha^{-1} [49]. In two studies on Ontario trout streams, biomasses <12.5 [64] or 4 kg ha^{-1} [9] are considered to be low, whereas values above 50 [64] or 16 kg ha^{-1} [9], respectively, indicate high to very high biomasses.

Concerning the bank strips fished in this study, one reason for the low biomasses certainly is that riprap structures – although they offer cover – represent poor substitutes for the structural richness of a natural river shore (see Schmetterling et al. [60] for a review). Accordingly, results by Schiemer and Zalewski [59] indicate that in a reach with natural bank morphology, higher fish biomasses can be found than along artificially fixed shorelines. Habitat conditions in riprap banks are relatively monotonous, and current protected sections are limited to the immediate shoreline zone (embankment). Shallow areas with suitable habitats for young trout (and other fish species) are largely missing. As reported by Schmetterling et al. [60], riprap does not meet the habitat conditions required for different age classes of trout, explaining the low abundances of young-of-the-years and the dominance of medium-size animals. Moreover, spawning and rearing conditions in the River Rhone are highly unsuitable (Weber et al., in preparation). The observed medium-size fish therefore derived from tributaries or from stocking. Finally, in the instream sections of the River Rhone, the reduction in habitat heterogeneity is especially obvious. High current velocities dominate, and pool-riffle sequences are largely missing.

The question then becomes: Would rehabilitation efforts aimed at improving the shoreline and instream structures result in higher biomasses of brown trout and other fish-biological parameters? In the literature, most examples of river rehabilitation deal with measures like restructuring of banks, construction of instream structures or local widening offering a more diverse habitat situation. Not only structure-dependent species like the brown trout benefit in such rehabilitated river reaches, but also other taxa with more specialized habitat, spawning or trophic requirements. In many cases, positive effects on fish communities like higher species diversity [36] and the return of natural reproduction [27] are reported. Similarly, structural measures along the shoreline are of great importance for terrestrial organisms [19].

The central question in the case of a hydrologically impaired river like the Rhone is whether structural measures alone will be effective. Doubts are legitimate as low biomass values were also found in several riprap stretches, with the best available habitat structure. Some trends are obvious among the many possible explanations for this observation. As shown in Fig. 2, the individual trout biomasses in reaches strongly affected by hydropeaking are generally smaller than in residual flow stretches or hydrologically unaltered sections of the River Rhone.

Among the several impacts of hydropeaking on fish reported in the literature [5, 74], the discussion of habitat persistence is of special importance for the River Rhone, especially in its lower part. With rapid fluctuations of the water level of up to 1 m, riprap structures are not permanently covered by water. Because the cover is not constantly available, the structure-dependent brown trout are facing a serious reduction of habitat quality. Field [4, 61] as well as habitat modeling [20, 77] studies showed an increased habitat instability in hydropeaking reaches, especially affecting the availability of juvenile habitat.

The reaction of other aquatic organisms to hydropeaking is similar. Benthic organisms, for example, are massively disturbed by the scouring effects due to the higher flow velocities [12]. The aquatic invertebrate fauna living in the shoreline zone of hydropeaking-affected rivers is highly impaired compared with stretches of natural discharge regime [19]. Forming the nutritional basis for many species, such effects on the invertebrate community can also have an indirect feedback on the fish assemblage.

Due to the slow exchange between river and groundwater, the quality of the aquatic habitat is additionally degraded. In the highly clogged substrate of the River Rhone, natural reproduction of the lithophil brown trout is faced with additional problems such as impaired oxygen supply.

Probably, the rehabilitation of the fish community in the River Rhone can only be successful when structural improvements are linked with measures addressing the hydrological deficits such as hydropeaking and residual flow.

4.2 Tracer hydrology

The water causing the hydropeaks originates from the deep, temperature-constant sections of the high alpine reservoir. It is piped directly to the power stations in the Rhone Valley where it is discharged into the river. Hydropeaks strongly modify the seasonal, weekly and daily temperature regime in the Rhone. In winter, the river water is warmed up during hydropower production, while in summer it is cooled down. This results in an average water temperature in January 2000 of 2.64°C between Monday and Friday, but only 1.92°C during the weekend.

These temperature changes have an impact on, e.g., the invertebrate community [12]. However, it is unlikely that temperature is the only factor affecting size variation and the geographic distribution of aquatic insects [22, 70]. The frequent and intermittent variations in temperature [23] may act as an additional factor for lower density and biomass of invertebrates in hydropower-affected river reaches in comparison to unaffected sites [12].

These frequent temperature variations are transferred to the adjacent aquifer where they interact with the geological properties of the soil matrix of the levee structure. Egli [17] determined the hydraulic conductivity within the levees with two pumping tests. He studied two well transects about 1 km downstream of S1 (Fig. 1b). The pumping tests revealed high and varying values for the hydraulic conductivity K between 2.5×10^{-4} and 5.9×10^{-3} m s^{-1}, which can be classified between "permeable" and "very permeable" [33]. Calculations using Darcy's law, which are based on the displacement of seasonal temperature signals [Fig. 3b and equation (1)], between G1 and G2 confirm Egli's findings as the values for K range between 7.0×10^{-4} and 1.7×10^{-3} m s^{-1} (Table 2).

K values were determined by formulating Darcy's law as:

$$K = \frac{v_a n}{J} \tag{2}$$

where K stands for the hydraulic conductivity [m s^{-1}], v_a represents the average flow velocity [m s^{-1}], J denotes the slope of the groundwater surface and n reflects the porosity factor [–].

The flow velocity of the groundwater was calculated by the time shift of the seasonal temperature between probes S1, G1 and G2, and the rectangular distance in between (Figs. 1b and 3b). The resulting velocity value must be corrected by a retardation factor that is calculated according to equation (1). Parameters for calculation of the average flow velocities and the K values between S1 and G1 as well as G1 and G2 are summarized in Table 2.

The pumping test performed by Egli [17] can give information about the hydraulic conductivity of the material inside the levee, but not for the material of the riverbed. However, Table 2 shows that the hydraulic conductivity between S1 and G1 (riverbed material) is much smaller than that between G1 and G2.

Table 2 Results from cross-correlation between the observation wells S1, G1, and G2 (Fig. 1b)

	S1–G1	G1–G2
Time shift [h]	732	2042
Porosity, n [–]	0.1–0.2	0.1–0.2
Coefficient, β [–]	0.45–0.54	0.45–0.54
Retardation factor, R [–]	2.8–5.86	2.8–5.86
Slope, J [‰]	95–192	2–5
v_a [m day^{-1}]	0.2–0.5	1.5–3.0
K [m s^{-1}]	3.5×10^{-6}–5.8×10^{-6}	7×10^{-4}–1.7×10^{-3}
q [m^3 m^{-2} day^{-1}]	0.02–0.1	0.15–0.6

For an explanation of the parameters, see text. The values for v_a and K represent minimum and maximum values calculated with the extrema of the retardation factor R and porosity n, respectively.

To corroborate the small values of hydraulic conductivity of the riverbed, the value for the groundwater flow velocity v_a in [m s^{-1}] in Darcy's Law was transformed to the infiltration rate per unit area of riverbed q [m^3 m^{-2} day^{-1}] by multiplying v_a by the effective porosity n [32]:

$$q = v_a n \tag{3}$$

Hoehn [32] found specific infiltration rates for various rivers in Switzerland to be between $q = 0.05$ m^3 m^{-2} day^{-1} (Töss) and $q = 3$ m^3 m^{-2} day^{-1} (Rhine). The specific infiltration rates between S1 and G1 in the River Rhone of 0.02 m^3 m^{-2} day^{-1}< q < 0.1 m^3 m^{-2} day^{-1} (Table 2) are hence very low. The specific infiltration rates of 0.15 m^3 m^{-2} day^{-1}< q < 0.6 m^3 m^{-2} day^{-1} range near the lower end of the known infiltration rates of Swiss rivers.

The widening of the riverbed requires the dislocation of the current levee in order to secure the valley bottom against flood events. The rehabilitation will change the permeability of the reconstructed levee, and hence, the infiltration rate of river water into the groundwater. Additional sealing of new levees might be necessary to prevent rising water tables in the Rhone floodplain and to protect drinking water supplies.

4.3 Problem analysis and possible solutions

Currently, the performance of the River Rhone shows massive deficits. For example, the fish fauna is characterized by a highly unnatural structure. Furthermore, a high correlation between fish biomass and monotonous shoreline and instream morphology was established. Tracing the river–groundwater interaction revealed further evidence of the reduced habitat quality of the riverbank. A high degree of

siltation was found to strongly impede surface water–groundwater exchange.

Additionally, hydrological deficits were evident in both studies. In a longitudinal, system-wide view, the stability of fish habitat is massively affected due to poor cover availability and changing water levels. In a vertical and lateral perspective, the transient changes in water level are not limited to the river itself, but also measurable in the near-river aquifer. This type of disturbance is likely to produce more serious ecological effects if the lateral connectivity is improved by rehabilitation measures such as river widening.

Rehabilitation scenarios are therefore facing conflicting boundary conditions. The fishes' ecological situation can be significantly improved by effective rehabilitation of the longitudinal habitat structure. This success generally achieved by widening is also positive in terms of removing the siltation of the riverbank. River–groundwater interactions are reestablished, resulting in benefits for the epigean fauna [11, 72], spawning conditions for fish [35] as well as the replenishment of the adjacent aquifer for flood control [34]. In the river Rhone, as a formerly braided system widening is a rehabilitation measure that deserves special consideration.

Improving vertical connectivity, however, cannot be achieved without serious tradeoffs. During the summer months, the groundwater table in the Rhone Valley lies typically 0.5 m below the average water level in the Rhone River. If restoration measures increase the permeability, the water level in the river-near aquifer could rise and potentially damage the valley's agriculture, infrastructure [25] and public drinking water supply [54].

The boundary conditions are obvious: the River Rhone is heavily impacted by morphologic structures and intensively used for hydropower production. While the morphologic structures can be restored by widening the river, the status quo of the hydropower schemes is generally accepted because of the following reasons:

- The licenses for the operation of most of the hydropower plants in Switzerland are valid for 80 years.
- Hydropower plants play an important role in terms of regulating the European power grid.
- Hydropower is considered as a renewable energy with a favorable CO_2 balance in comparison with widespread fossil fuel electricity production.

Normalization of the hydrologic situation though is essential for the success of the 3RC. It will therefore depend on the effective attenuation of hydropeaks in the river reaches being subject to rehabilitation measures. This can be realized by a combination of different hard technical and soft operational measures:

- River widening should be planned as large, as long and as networked as appropriate [55]. The reconstructed levee constraining the wider riverbed should be sealed to prevent rising water tables in the urbanized valley ground [25].
- In order to attenuate the hydropeaks in the connected river, the turbinated water should be stored in retention basins or underground reservoirs before being continuously discharged into the river [47].
- Slower, more consistent powering up and down of the turbines could result in a more moderate hydropeaking rate [28]. Such "soft" methods are effective only in combination with the "hard" approaches outlined above [38].

Activities such as restoring a river while improving flood protection measures and adapting hydropower schemes for a more ecological operation require an integrated approach and considerable financial effort. The costs, however, will be acceptable if alpine hydropower is considered a "green energy" [10] requiring ecological investments instead of subsidizing other more expensive sources of electricity.

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