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Ecological impacts of small hydropower plants on headwater stream fish: from individual to community effects

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Abstract – Hydroelectricity is increasingly used worldwide as a source of renewable energy, and many mountain ranges have dozens or hundreds of hydropower plants, with many more being under construction or planned. Although the ecological impacts of large dams are relatively well known, the effects of small hydropower plants and their weirs have been much less investigated. We studied the effects of water diversion of small hydropower plants on fish assemblages in the upper Ter river basin (Catalonia, NE Spain), which has headwater reaches with good water quality and no large dams but many of such plants. We studied fish populations and habitat features on control and impacted reaches for water diversion of 16 hydropower plants. In the impacted reaches, there was a significantly lower presence of refuges for fish, poorer habitat quality, more pools and less riffles and macrophytes, and shallower water levels. We also observed higher fish abundance, larger mean fish size and better fish condition in the control than in impacted reaches, although the results were species-specific. Accordingly, species composition was also affected, with lower relative abundance of brown trout (*Salmo trutta*) and Pyrenean minnow (*Phoxinus bigerri*) in the impacted reaches and higher presence of stone loach (*Barbatula quignardi*) and Mediterranean barbel (*Barbus meridionalis*). Our study highlights the effects of water diversion of small hydropower plants from the individual to the population and community levels but probably underestimates them, urging for further assessment and mitigation of these ecological impacts.

Key words: water diversion; weir; fish condition; brown trout *Salmo trutta*; Pyrenean streams; Ter river basin

Introduction

Freshwater ecosystems are among the most altered ecosystems worldwide by multiple, interacting pressures including pollution, water abstraction and the construction of weirs and dams (Pires et al. 1999; Xenopoulos & Lodge 2006; Ayllón et al. 2012). The main purpose of weirs and dams includes irrigation for agriculture, water provisioning for human use and hydropower generation. Although most energy consumed worldwide currently is from fossil fuels and nuclear power plants, 10.5% comes from so-called renewable sources, of which hydropower is the most important (Habit et al. 2007; EIA 2011; Koç 2012). For instance, in Spain, about 8.1% of the total energy produced by 2008 came from hydroelectricity, and there are over 1300 hydropower plants (Espejo & García 2010). Increasing energy consumption in the next decades, combined with the need to reduce hydrocarbon-based energy production, has renewed the interest in hydropower generation (Koç 2012) and an increase in the number of hydropower plants that are being built or planned (Nilsson et al. 2005; Zhang et al. 2012). Nonetheless, with the potential to

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accommodate further large projects becoming limited, many countries are increasingly focusing on the development of small hydropower plants (<10 MW) (Santos et al. 2012).

Although the downstream effects of large dams on freshwater biota have been well investigated (e.g. Garnier et al. 2000; Gunkel et al. 2003; Xue et al. 2006), little attention has been paid to the effects of small hydropower plants. Although weirs of small hydropower plants are constructed in small and medium-size rivers, their water diversions provoke an alteration of the natural flow regime, with low flows in the reaches below weirs and hydropeaking downstream of the tailrace outlets (Santos et al. 2006; Schmutz et al. 2010; Rolls et al. 2012). The flow regime is viewed as a major factor governing stream ecology (Poff & Ward 1990), so its alteration may provoke significant influences on biota, ecosystem conditions and processes (Lake 2003). The main effects detected on freshwater fishes, in previous studies focusing on low flow due to water diversion of small hydropower plants, were reductions on density and biomass in impacted sites (Kubečka et al. 1997; Almodóvar & Nicola 1999; Mueller et al. 2011). Changes in species composition were also reported in some studies (Mueller et al. 2011), and Anderson et al. (2006) detected an increase in opportunistic species at impacted reaches in Central America. Similarly, Kubečka et al. (1997) showed that the dominance of brown trout (*Salmo trutta*) and other rather large-bodied fish was greatly reduced at impacted reaches and the fish community shifted to a system dominated by small-bodied species in Czeck streams. On the other hand, in Mediterranean rivers of Portugal and Spain, significant changes in fish abundance (Anderson et al. 2006; Santos et al. 2006) or species composition were not detected (Almodóvar & Nicola 1999; Santos et al. 2006).

Most of these previous studies have focused on the population and community levels and did not assess effects on individual features. It is widely known that exposure to environmental stressors causes the detrimental effects on important individual fish features such as metabolism, growth, resistance to diseases, reproductive potential and, ultimately, the health, condition and survival of fish (Rice 2001; Barton et al. 2002; Toft et al. 2004). Depending on the intensity and duration of stress exposure and species-specific features, these negative effects may be transferred from the individual to population or community levels (Adams & Greeley 2000). Therefore, studies integrating different fish organisation levels, from individual to community, are needed to understand the impact of water diversion of small hydropower plants.

In this study, we examine the effects of water diversion of small hydropower plants on fish populations in headwater stream, which has good water quality but a long series of small hydropower plants one after another. We compared control reaches (unimpacted for water diversion) with impacted reaches (downstream of weirs and impacted by low flows but upstream of the tailrace outlets and so not impacted by hydropeaking) in a Pyrenean stream. By comparing close-by control and impacted reaches, we aimed to assess the effects of water diversion of small hydropower plants on habitat features and fishes at three organisation levels (individual, population and community). Pyrenean streams are adequate study systems for this aim because they lack many other perturbations (large dams, significant water pollution or habitat degradation) much more intense in lowland reaches.

Methods

Study area

Sampling was conducted from July to September 2010 at upstream reaches of the Ter River (Catalonia, NE, Spain) (Fig. 1). The study area included the mainstream of Ter River and six tributaries: Rigard, Freser, Segadell, Ritort, Feitús and Riera Major (Fig. 1). The river basin is subject to a Mediterranean climate, although the headwaters are partially subject to a snow-fed regime (Boix et al. 2010). The Ter River originates in the Pyrenees Mountains and has a total drainage area of 2955 km^2, a mean annual water yield of 845 million m^3 and a mean discharge of ca. 10 m^3·s^{-1} (Benejam et al. 2010a). The Ter River and

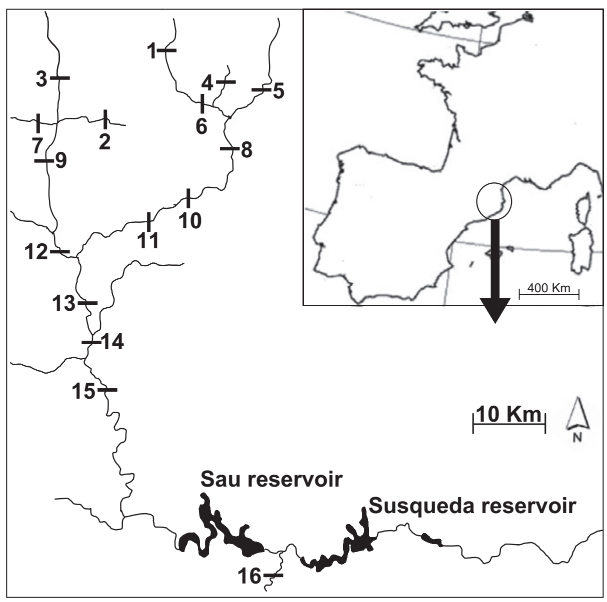

Fig. 1. Study area in the Ter River basin with the 16 hydropower plants studied (see sites codes in Table 1 for further details).

its flow regime are severely affected by two big dams (Sau and Susqueda reservoirs) located in the mid watercourse, which is thus split in the upper Ter basin (with a drainage area of 1799 km^2) and the lower basin (with a drainage area of 1156 km^2). Our sampling only considered the upper Ter basin, where during the 19th century dozens of small hydropower plants were constructed, as in many rivers of the Pyrenees, to produce energy for textile industries. Nowadays, although factories have closed, there are around 85 small hydropower plants in the upper Ter basin which are still operating to produce energy for the electrical grid (ACA 2010). In this study, 16 of these hydropower plants were studied (Fig. 1, Table 1), only two of them with fish pass facilities. We chose those hydropower plants that had previous data (streamflow of Table 1) and had good access for sampling. The water diversion of these hydropower plants causes an important reduction of streamflow below the weirs (Table 1; ACA 2010). The average features of these plants were 3.4 m of weir height (range of 1.1–7.0 m), 0.789 MW of power (0.02–2.8 MW) and 2 km length of the reach (0.5–5 km) affected by water diversion with reduction of streamflow. The region is rural and sparsely populated (26,393 residents living in an area of 956 km^2); the riparian habitat is well preserved and the predominant land cover is forest, with some agricultural and urbanised areas (Benejam et al. 2012). At half of the sampling reaches, brown trout was the only fish species present. In the other sampling reaches, in addition to brown trout, the fish assemblage consisted of Mediterranean barbel (*Barbus meridionalis*) and three non-native species: stone loach (*Barbatula quignardi*), Pyrenean minnow (*Phoxinus bigerri*) and common carp (*Cyprinus carpio*). Although brown trout is native to this river basin, many stockings have taken place during the past century and these populations are introgressed with foreign genetic stocks (Sanz et al. 2002). Nowadays, the study area is officially a so-called genetic reserve, and stocking is not allowed.

Experimental design and field methods

In this study, 36 reaches were sampled to study the effect of water diversion of 16 small hydropower plants (Fig. 1, Tables 1 and 2). Each site with one small hydropower plant was sampled upstream (hereafter, control reach) and downstream (hereafter, impacted reach or below impact) of the weir, where water diversion begins. Sampling reaches were at least at a distance of 200 m upstream or downstream to the weir. Impacted reaches were always below the weir but upstream of the tailrace outlet where water is returned after electricity production to estimate the effects of water withdrawal and avoid the effects of hydropeaking. Control reaches were always out of the direct influence of the weir to provide more natural stream features and avoid direct differences in habitat and flow. As weirs of hydropower plants are consecutively situated along the river, we also aimed at analysing the possible cumulative effect along the river, using site as an additional blocking factor to control for longitudinal variation (see details in *Statistical analyses*). In general, two sampling reaches (one control and one impacted reach) were sampled in each site. In some sites (when the length reaches were sufficiently long and the access at sampling site was possible), an additional reach was sampled to increase sample size and statistical power (see cases on Table 2). In these cases, the additional sampling

Table 1. Comparison of the upstream daily flow and flow diversion rates for each hydropower derivation point. Streamflow variables were calculated with 12 years of data series (1997–2009) from gauging stations. NA: in the case of Crous, there are no gauging data available.

Site code	Name of the hydropower plant	UTM coordinates (31 T)	Upstream maximum daily flow m^3 per s	Upstream average daily flow m^3 per s	Maximum legal flow diversion m^3 per s	Downstream average % daily flow diversion m^3 per s
1	Brutau 2	440621, 4679727	18.5	0.7	2.0	66
2	Pardines	435932, 4685451	8.6	0.2	0.6	99
3	El Molí Rialp	431581, 4684282	37.8	0.7	1.8	77
4	Feitús	447209, 4688528	18.7	0.4	1.8	86
5	Cruanyes	450723, 4687413	16.6	0.6	0.5	56
6	Brutau 1	445846, 4685673	46.8	1.7	1.5	76
7	Molí de Sart	430470, 4684704	54.4	1.0	0.8	71
8	Matabosch	447302, 4683230	81.9	3.0	2.5	76
9	Montagut	430915, 4682486	142.8	2.7	3.0	83
10	Molí Gran Pont Vell	442582, 4676858	101.5	3.6	2.5	51
11	Cal Gat	440117, 4675454	116.2	4.3	3.0	74
12	Surribes	431602, 4673434	211.8	4.1	3.0	27
13	L'Escala	434583, 4668204	269.7	8.7	6.0	77
14	La Cubia	434583, 4666412	269.7	8.8	6.0	77
15	Fàbrica Tomàs	434916, 4662331	269.7	10.0	8.0	81
16	Crous	451449, 4643648	NA	NA	10.0	NA

Table 2. Location, altitude and additional information of sampling reaches, including if they were control reach or impacted reach of water diversion of small hydropower plants and whether three-pass removals with block nets were applied (removal with 'yes').

Site code	Name of the hydropower plant	Date (dd/mm/yyyy)	UTM coordinates (31 T)	Altitude (m a.s.l.)	Control/impacted reaches	Removal
1	Brutau 2	30/07/2010	442652, 4693171	1340	Control	No
1	Brutau 2	25/08/2010	442601, 4691697	1249	Control	Yes
1	Brutau 2	23/08/2010	442413, 4691523	1226	Impacted	Yes
2	Pardines	10/08/2010	432702, 4684893	951	Control	Yes
2	Pardines	20/08/2010	436314, 4684974	1173	Impacted	Yes
2	Pardines	10/08/2010	434312, 4685083	1030	Impacted	Yes
3	El Molí Rialp	11/08/2010	431800, 4689717	1112	Control	Yes
3	El Molí Rialp	11/08/2010	431661, 4689512	1100	Impacted	Yes
3	El Molí Rialp	12/08/2010	431417, 4688476	1050	Impacted	Yes
4	Feitús	09/08/2010	447187, 4688551	1093	Control	Yes
4	Feitús	29/07/2010	447120, 4688377	1085	Impacted	Yes
5	Cruanyes	30/07/2010	450713, 4687465	1010	Control	Yes
5	Cruanyes	29/07/2010	448573, 4685254	950	Control	No
5	Cruanyes	25/08/2010	450791, 4687331	1004	Impacted	Yes
6	Brutau 1	22/09/2010	447293, 4685074	940	Control	Yes
6	Brutau 1	24/08/2010	446066, 4685636	962	Impacted	Yes
7	Molí de Sart	16/08/2010	430332, 4684701	951	Control	Yes
7	Molí de Sart	16/08/2010	430584, 4684641	920	Impacted	Yes
8	Matabosch	21/09/2010	447582, 4682361	900	Control	No
8	Matabosch	21/09/2010	447503, 4682556	902	Impacted	No
9	Montagut	20/09/2010	430973, 4682672	860	Control	No
9	Montagut	20/08/2010	430836, 4681029	840	Impacted	No
10	Molí Gran Pont Vell	22/09/2010	442805, 4677203	775	Control	No
10	Molí Gran Pont Vell	09/08/2010	441626, 4676774	758	Impacted	No
11	Cal Gat	23/09/2010	440413, 4675459	740	Control	No
11	Cal Gat	23/09/2010	440017, 4675602	730	Impacted	No
12	Surribes	20/09/2010	432883, 4672594	680	Control	No
12	Surribes	23/08/2010	431830, 4673131	690	Impacted	No
13	L'Escala	27/09/2010	434601, 4668471	640	Control	No
13	L'Escala	27/09/2010	434494, 4667601	630	Impacted	No
14	La Cubia	28/09/2010	434567, 4665242	610	Control	No
14	La Cubia	28/09/2010	434521, 4666201	615	Impacted	No
15	Fàbrica Tomàs	27/09/2010	434674, 4662704	570	Control	No
15	Fàbrica Tomàs	28/09/2010	434867, 4662116	560	Impacted	No
16	Crous	25/10/2010	451197, 4642860	445	Control	No
16	Crous	25/10/2010	451764, 4643893	420	Impacted	No

reach was located at least 1.5 km apart from the other reach to insure statistical independence.

Fish were sampled by electrofishing 100-m stretches (200–350 V, 2–3 A, fully rectified triphasic DC). Fishes stunned were collected with nets, identified to species, counted, measured (fork length in mm and total weight in 0.1 g) and then returned to the same reach. Following the CEN standard (CEN 2003), a single electrofishing pass without block nets was applied in general (Table 2). This method has been shown adequate to estimate species richness, species composition and fish abundance in some of the same tributaries of this study (Benejam et al. 2012). At ten sampling reaches, three-pass removals with block nets were applied to estimate population size and capture probability for each species (Table 2).

Several habitat variables were measured at each sampling reach: wetted width and depth (cm), geomorphology (percentage of pools, runs and riffles), substrate composition (percentages of boulder, cobble, gravel, sand and silt) and percentage of refuges (e.g. large boulders, wood and tree roots). Moreover, a modification (Sostoa et al. 2010) of the Rapid Bioassessment Protocol (RBA) (Barbour et al. 1999) was also applied at all sampling reaches; RBA scores variables such as habitat complexity, mesohabitat diversity, siltation, streamflow, sinuosity, margin stability and aquatic vegetation were calculated. The Riparian Habitat Quality Index (QBR index), which is officially used in the study region, was also estimated at all sampling reaches (Munné et al. 2003). The QBR index is a habitat quality index for riverine areas which considers riparian cover percentage, cover structure and cover quality of the river channel.

Statistical analyses

In the analyses, we aimed to detect changes on numerous fish attributes (from individual condition to species composition) and habitat features due to effects of water diversion of small hydropower plants, comparing control and impacted reaches (categorical factor). We used site as an additional blocking factor to control for longitudinal variation of the fish assemblage (see Table 1 for site code). We used generalised linear models (GLMs) with Poisson errors and log link functions to test for effects on fish abundance. We considered two measures of fish abundance: population size and catch per unit effort (CPUE). CPUE data were the total fish captured per 100-m stretch in a single electrofishing pass without block nets. We obtained CPUE data (fish/100 m) of all sampling reaches. Population size estimates were only possible at the ten sampling reaches where multiple passes were applied (Table 2) and for these we used program MARK 5.1 (White & Burnham 1999; freely available at http://warnercnr.colostate.edu/~gwhite/mark/mark.htm). We estimated population size using the multinomial model ('Huggins Closed Capture' in MARK), with recapture parameter *c* set at zero and constant catchability between different electrofishing passes (Cooch & White 2010). To describe the relationship between trout CPUE with altitude, we used quadratic regression because of clear nonlinear variation (see Carmona-Catot et al. 2010 for a similar pattern and approach).

To test whether control and impacted reaches differed in species composition, we used permutational multivariate analysis of variance using distance matrices (Anderson 2001), as implemented in function 'adonis' of 'vegan' (Oksanen et al. 2012), with Bray-Curtis distances and 999 permutations. 'adonis' seems to be less sensitive to dispersion effects than other more popular alternatives, such as ANOSIM, SIMPER and the multiple response permutation procedure (Oksanen et al. 2012). Because 'adonis' can anyway confound location and dispersion effects, we also tested for the latter using a permutation test of multivariate homogeneity of groups dispersions (Anderson 2006), as available in the function 'permutest.betadisper'. Both tests were performed constraining the permutations with sites, using the 'strata' option in 'vegan'. These analyses were computed with the 'vegan' package (Oksanen et al. 2012) in R (R Development Core Team 2012).

Two-way ANOVAs, with site as a blocking factor to control for longitudinal variation, were used to compare the average of length and total weight of fish between control and impacted reaches. Length and total weight variables were log-transformed because homoscedasticity and linearity were clearly improved. Analysis of covariance (ANCOVA) was used to compare the condition (total weight–length relationship) between control and impacted reaches to impact taking into account fish size (covariate). ANCOVA has several advantages over condition factors (e.g. weight length^{-3}) and similar indices (see reviews in García-Berthou & Moreno-Amich 1993; García-Berthou 2001). The adjusted or predicted means in ANCOVA are the means of values of the response variable adjusted for effects of covariates, typically length (García-Berthou & Moreno-Amich 1993); these adjusted means thus allow comparing groups or treatments for the response variable, after accounting for the effects of fish size.

To compare habitat features between control and impacted reaches, we used two-way ANOVA, with site as an additional factor to control for longitudinal variation. Moreover, multivariate analysis of variance (MANOVA) was also applied to the set of habitat features variables, to control for the overall rate of type I error. To reduce problems with analysing proportional composition data, some categories (e.g. boulder + cobble) were pooled and redundant variables (adding to 100%) were excluded from the analyses. These statistical analyses were performed with SPSS 15 (SPSS Inc., Chicago, IL, USA, 1989–2006).

Results

Effects of small hydropower plants on habitat features

There were significant differences in habitat features between control and impacted reaches for water diversion of small hydropower plants (Tables 3 and 4). In particular, impacted reaches were characterised by shallower water depth, lower presence of total refuges for fish, lower abundance of riffles and higher abundance of pools. (Table 3). The substrate composition was only marginally significant, with a trend of higher presence of boulders and lower of cobbles in the control reaches.

Moreover, the results of Rapid Bioassessment Protocol variables showed that impacted reaches had poorer habitat structure and lower presence of macrophytes (Table 4). The Rapid Bioassessment Protocol variables showed significant differences among sites

Table 3. Two-way ANOVAS of habitat features, with impact and site as factors (d.f. were 1 and 4 for all *F* statistics). Mean values of habitat features for control and impacted reaches are also given. QBR index is a Riparian Habitat Quality Index (Munné et al. 2003).

Habitat features	*F*	*P* value	Control reaches	Impacted reaches
QBR	1.80	0.25	79.69	76.88
% riffles	16.64	0.02	34.06	18.06
% pools	7.39	0.05	14.06	25.34
% boulder	4.75	0.09	32.03	24.69
% cobble	1.01	0.37	36.09	39.84
Total refuges %	8.07	0.05	77.50	70.62
Maximum depth (cm)	21.07	0.01	53.92	39.47

Table 4. Two-way ANOVAs of 'Rapid Bioassessment Protocol' variables, with impact and site as factors (d.f. were 1 and 4 for all *F* statistics). *R* (right side) and *L* (left side). Mean values of habitat features for control and impacted reaches are also given. All variables potentially range from 1 to 10.

'Rapid Bioassessment Protocol' variables	*F*	*P* value	Control reaches	Impacted reaches
Habitat structure	9.80	0.04	9.25	8.59
Habitat diversity	0.03	0.87	7.38	7.25
Channelling	0.01	0.91	8.56	8.50
Channel morphology	0.60	0.48	8.22	7.94
Streamflow	6.88	0.06	8.84	7.66
Margin erosion R	4.80	0.09	7.56	7.19
Margin erosion L	4.80	0.09	7.56	7.19
Macrophytes	8.07	0.05	2.41	2.06
Riparian vegetation R	0.24	0.65	8.06	7.88
Riparian vegetation L	0.24	0.65	8.06	7.88
Width of riparian vegetation R	0.00	0.96	7.66	7.69
Width of riparian vegetation L	0.19	0.68	7.50	7.75

in the set of variables (MANOVA Wilks' λ: $F_{60, 6.13}$ = 9.13; P = 0.005) and significant control-impact × site interaction (MANOVA Wilks' λ: $F_{60, 6.13}$ = 5.86; P = 0.015), indicating that the magnitude of impacts varied among sites.

Effects of small hydropower plants on fish populations

Fish abundance was higher at control than at impacted reaches for water diversion of small hydropower plants (Fig. 2). All species but common carp had significant site × impact interactions for catch per unit effort (CPUE) (GLM: Wald chi-square, all $P < 0.01$), suggesting that the impact of water diversion on abundance varies along the stream. Brown trout (GLM: Wald chi-square = 9.86, d.f. = 1, P = 0.002) and Pyrenean minnow (GLM: Wald chi-square = 5.72, d.f. = 1, P = 0.017) also had significant overall differences in CPUE between control and impacted reaches. The population size of brown trout, estimated using removal data multiple-pass and program MARK, was also higher at control reaches (GLM: Wald chi-square = 71.5, d.f. = 1, $P < 0.0005$) and displayed significant site × impact interaction (Wald chi-square = 60.3, d.f. = 1, $P <$ 0.0005). Brown trout abundance peaked at intermediate altitudes, but was lower at impacted reaches after controlling for this natural variation (Fig. 3). Moreover, the difference in brown trout abundance between control and impacted reaches slightly decreased along the river, from upstream to downstream (Fig. 3).

The average fork length (two-way ANOVA: $F_{1, 34}$ = 7.25; P = 0.011) and total weight (two-way ANOVA: $F_{1, 34}$ = 8.43; P = 0.006) of brown trout were significantly higher at control than impacted reaches (Fig. 2). Fish condition (weight after accounting for length) of brown trout was also significantly different between control and impacted reaches for hydropower plants (Fig. 4). After accounting for fish size (covariate in ANCOVA), condition of brown trout was lower in impacted reaches (ANCOVA: $F_{1, 1215}$ = 16.73; $P < 0.005$) (Fig. 4). This difference in fish condition between control and impacted reaches increased downstream (Fig. 4).

Control and impacted reaches also differed in relative species abundance ('adonis' function, P = 0.043). The 'permutest.betadisper' function showed that dispersions were not significantly different (P = 0.83), supporting the differences in average species composition. In the impacted reaches, the relative abundance of trout and minnow decreased and that of loach and barbel increased; common carp was only present in two of the sampled impacted reaches. See Appendix S1 for further information.

Discussion

Our results indicate that water diversion of small hydropower plants is affecting the habitat features and fish assemblages in Pyrenean streams. In the impacted reaches, we have shown a significant lower presence of total refuges for fish, poorer structure of habitat, lower frequency of riffles but higher of pools, shallower water levels and lower presence of macrophytes. We also detected lower values of fish abundance, average fork length, total weight and fish condition at impacted reaches. Moreover, species composition was also affected with lower relative abundance of trout and minnow at impacted reaches and higher presence of loach and barbel.

The detected impacts of low flow due to water diversion of small hydropower plants on habitat features agree with previous studies in contrasting regions (Kubečka et al. 1997; Anderson et al. 2006; Wu et al. 2009; Mueller et al. 2011). River discharge controls the diversity and availability of habitats, such as riffles, runs, pools, backwaters and floodplains. Low flows reduce volume, area and depth of aquatic habitat and change the instantaneous velocity of rivers (Rolls et al. 2012). For example, in headwater streams of West Virginia, USA, a 96% reduction in discharge resulted in a 52% reduction of riffle habitat area (Hakala & Hartman 2004). Anderson et al. (2006) observed similar results in the Puerto Viejo River, Costa Rica, where a larger percentage of the channel consisted of rapids and riffle habitats upstream from weirs of small hydropower plants, whereas pool or low water velocity habitats dominated at downstream, dewatered reaches. Comparable results were detected in different rivers of the Czech Republic, with higher abundance of pools and lower depth, water velocity and wetted surface area at sites

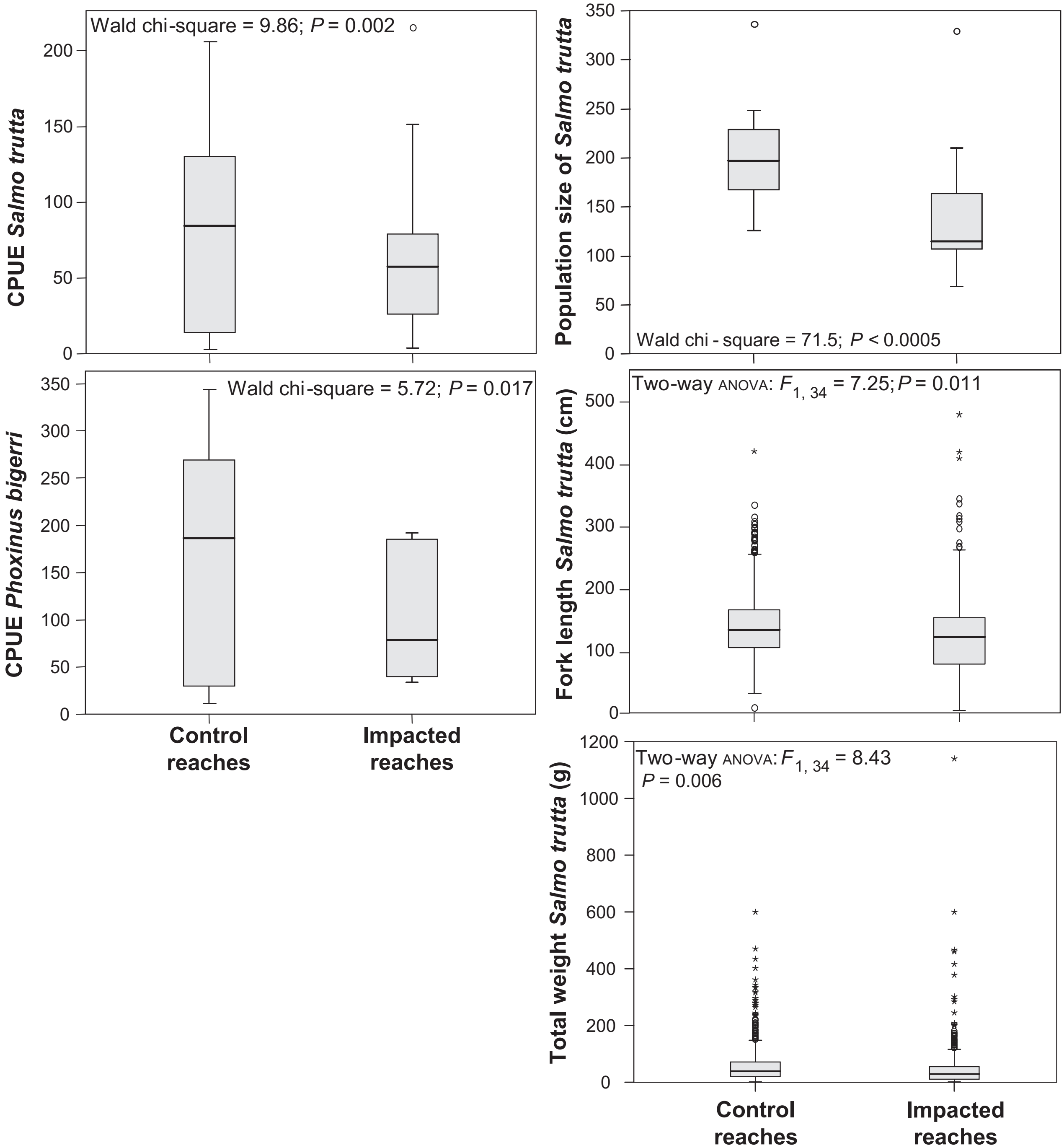

Fig. 2. Box-plots of fish abundances and fork lengths at control and impacted reaches. Only species with significant results are shown. Box corresponds to 25th and 75th percentiles; dark line inside the box represents the median; error bars show the minimum and maximum except for outliers (open circles and asterisks, corresponding to values beyond 1.5 and 3 box lengths, respectively, from the box).

impacted by water diversion of small hydropower plants (Kubečka et al. 1997). The overall differences detected in our study on habitat features between control and impacted reaches may be linked to changes on fish assemblages.

Brown trout was affected by the small hydropower plants analysed, with smaller mean size and lower abundance and condition at impacted reaches. Moreover, the cumulative impact of hydropower plants along the river was detected because the difference in condition between control and impacted reaches increased downstream. The condition or health of fish individuals is a measure of the physical and biological circumstances during recent life and is affected by interactions among food availability, physical factors and environmental conditions (Lloret & Rätz 2000; Vila-Gispert et al. 2000). Fish condition is particularly important because it has strong influences

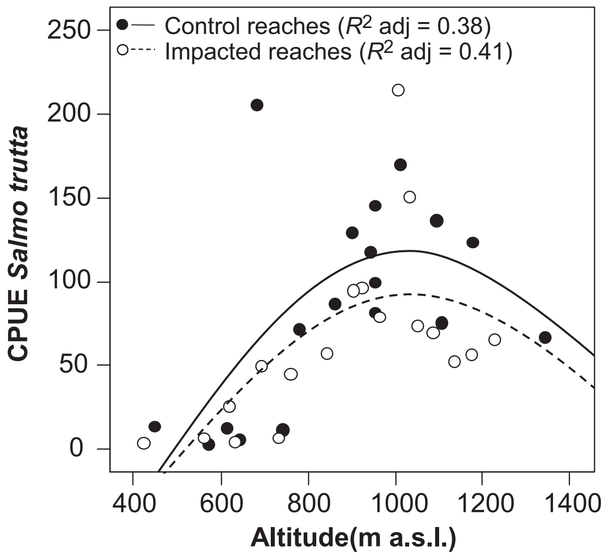

Fig. 3. Distribution of brown trout abundance (CPUE) by sampling sites ordered by altitude. Quadratic regressions per reach type (control and impacted) are also shown.

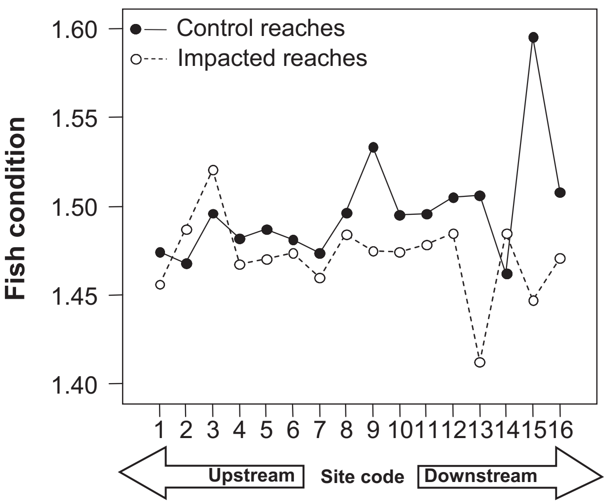

Fig. 4. Comparison of the condition of brown trout along sites between control and impacted reaches. Size-adjusted means (ANCOVA with fish length as covariate) of total weight are shown. Increasing site code indicates downstream direction (see Table 1).

on growth, reproduction and survival of individuals and thus affects other ecological levels, such as populations and communities (Lambert & Dutil 1997; Adams 1999; Marshall & Frank 1999). Although many studies have shown results of low fish condition in ecosystems with poor water quality in a range of species (Laflamme et al. 2000; Oliva-Paterna et al. 2003; Benejam et al. 2010b), as far as we known only Torralva et al. (1997) reported changes in fish condition almost entirely due to flow regime alteration. However, Torralva et al. (1997) studied the impact of two big reservoirs, not small hydropower plants, and they observed differences in condition but were not able to statistically test them.

The lower abundance of fish at impacted reaches detected in our study agrees with the results of other authors, who in some cases found four times higher biomass at control reaches (Kubečka et al. 1997; Almodóvar & Nicola 1999). Limited food resources and loss of preferred habitat have been attributed as causes of reduced densities of fish in sites affected by low flows (Hakala & Hartman 2004; Riley et al. 2009). Concretely, Lobón-Cerviá (2009, 2013) detected that low discharge and shallow water levels in March induced lower recruitment and survival rates of brown trout because it affected the emergence period and the earliest search stages for food. Nicola et al. (2009) also showed that the magnitude and duration of low flows during summer drought appeared to be a critical factor for survival of young brown trout.

Population size structure is considered a good health indicator in freshwater bioassessment, because it has the potential to inform us on whether disturbance is affecting populations (Karr et al. 1986; Murphy et al. 2013). Body size is a fundamental characteristic of organisms and arguably the most important trait affecting the ecological performance of individuals (Persson & de Roos 2007; Murphy et al. 2013). The implications of body size on growth, mortality and trophic interactions highlight the importance of size structure for populations (de Roos et al. 2003; Savage et al. 2004; Brown et al. 2007). In our study, we detected lower values of average fork length and total weight for brown trout at impacted reaches. Decreased average sizes have also been reported in various taxa as a response to anthropogenic perturbations (Dodson & Hanazato 1995; Jung & Jagoe 1995; Walters & Post 2008). In the same region of our study, Murphy et al. (2013) found opposite response of size structure for chub (*Squalius laietanus*), with increasing average size of populations under increasingly disturbed conditions. The authors suggest that this unusual pattern may reflect failure to recruit in disturbed conditions or growth at reduced densities, as increases in length appear to be related to a trend of decreasing abundance. However, in our study, fish abundance was higher in control sites where average fork length and total weight also increased, which seems a more expected response.

Overall, our results show that the response to environmental perturbation due to water diversion of small hydropower plants was species specific and brown trout was the species with the clearest effects on fitness-related traits at impacted reaches. It is widely known that brown trout is an intolerant species of poor water quality and habitat structure (Blanco & González 1992; Maceda-Veiga & Sostoa 2011). Consequently, brown trout seems more affected by small hydropower plants than Mediterranean barbel, stone loach or Pyrenean minnow. As a result, species composition was affected by water diversion of small hydropower plants with lower relative abundance of trout and minnow at impacted reaches and higher presence of loach and barbel. The alteration of natural flow regime provides a habitat more suitable to generalist and opportunistic faunas, giving these species a competitive advantage (Poff & Ward 1989).

Although the effects of water diversion of small hydropower plants on fish populations and habitat features that we detected seem logical, the impact may be underestimated because control reaches were not pristine sites and the impacts accumulate along streams. The weirs of hydropower plants are consecutively situated along the river, compromising connectivity; therefore, their impact accumulates downstream and many control sites have previous impacts upstream, as seen in our condition fish data and CPUE for trout. It is likely that other cumulative effects not detected in our study are occurring.

Adams & Greeley (2000) showed that the transfer of effects from individual to community levels depends on the intensity and duration of stress exposure. In our study, we detected effects of water diversion of small hydropower plants on fish assemblages at the three main organisation levels in ecology: individual (fish condition), population (abundance, average length and weight) and community (relative abundance of fish species). Therefore, despite the small size of these hydropower plants in headwater streams, their impact seems quite important, and these fish metrics could be used to evaluate ecosystem health during mitigation or restoration activities.

Some management tools might mitigate the negative effects of small hydropower plants. It is widely known that dams and weirs interrupt the longitudinal river connectivity, isolating fish communities (Santos et al. 2006). Longitudinal river connectivity is a basic requirement for fish community persistence, as it allows seasonal movements, enhances lifetime reproductive success and allows recolonisation of areas affected by disturbance (Ordeix et al. 2011). Therefore, the presence of effective fish passes in all weirs would allow connectivity along the river and would decrease their impact. However, recreating environmental flows as similar as possible to the natural flow regime is the main tool to reduce the impact of small hydropower plants, because flow regime is the major factor governing stream ecology (Poff & Ward 1990; Lake 2003). As a result of the requirements of the Water Framework Directive (WFD) (2000/60/CE), many European countries implement new regulations to restore the natural flow regime and improve ecological status of freshwater ecosystems. Many of the hydropower plants have old water rights, most of which expire in 2061, with few environmental obligations. Therefore, it is essential that hydropower plants apply environmental flows and other measures such as building effective fish passes to mitigate their impact on the freshwater biota and ecosystem services to achieve good ecological status according to the WFD requirements. Additionally, water authorities need to improve biological indices and suitable monitoring programs to properly detect flow regime alteration produced by hydropower plants, especially in clean waters and near natural headwaters where chemical quality is mainly good.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Fish individuals captured at each site.