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Moving waters to mitigate hydropeaking: A case study from the Italian Alps

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Abstract

We assessed the effect of a hydropeaking diversion mitigation measure that allows for additional hydropower production, which markedly reduced hydropeaking on a 10-km stream reach in the north-eastern Italian Alps. Hydropeaking, caused by a storage hydropower plant, affected the study reach from the 1920s to 2015, when a cascade of three small run-of-the-river plants was installed to divert the hydropeaks from the plant outlet directly into the intake of the RoRs plants, and hydropeaking was released downstream the confluence with a major free-flowing tributary. The flow regime in the mitigated reach shifted from a hydropeaking-dominated to a baseflow-dominated regime in winter, with flow variability represented only by snowmelt and rainfall in late spring and summer. The application of two recently proposed sets of hydropeaking indicators, the hydraulic analysis of the hydropeaking wave, together with the assessment of biotic changes, allowed quantifying the changes in ecohydraulic processes associated with hydropeaking mitigation. The flow regime in the mitigated reach changed to a residual flow type, with much less frequent residual hydropeaks; although an average two-fold increase in downramping rates were recorded downstream the junction with the tributary, these changes did not represent an ecological concern. The functional composition of the macrobenthic communities shifted slightly in response to flow mitigation, but the taxonomic composition did not recover to conditions typical of more natural flow regimes. This was likely due to the reduced dilution of pollutants and resulting slight worsening in water quality. Conversely, the hyporheic communities showed an increase in diversity and abundance of interstitial taxa, especially in the sites most affected by hydropeaking. This effect was likely due to changes in the interstitial space availability, brought by a reduction of fine sediments clogging. Besides illustrating a feasible hydropeaking mitigation option for Alpine streams, our work suggests the importance of monitoring both benthic and hyporheic communities, together with the flow and sediment supply regimes, and physico-chemical water quality parameters.

KEYWORDS

clogging, COSH method, hyporheic, macrobenthos, subdaily flow alterations, water diversion

1 | INTRODUCTION

Hydropeaking consists of sudden, artificial water releases by storage hydropower plants into rivers to address peaks of energy demand, thus affecting the subdaily flow regime through rapidly increasing and decreasing flow spates. A growing scientific and public awareness of the adverse effects of hydropeaking on stream ecology has developed in the last decades (e.g., Auer, Zeiringer, Fuhrer, Tonolla, & Schmutz, 2017; Bejarano, Jansson, & Nilsson, 2017; Bejarano, Sordo-Ward, Alonso, Jansson, & Nilsson, 2020; Bondar-Kunze, Maier, Schönauer, Bahl, & Hein, 2016; Boavida, Harby, Clarke, & Heggenes, 2017; Casas-Mulet, Alfredsen, & Killingtveit, 2014; Schülting, Feld, & Graf, 2016), leading to increasing attention to the study, design, and implementation of mitigation strategies, based on operational and structural measures (Barillier, Beche, Malavoi, & Gouraud, 2021; Bruder et al., 2016; Greimel et al., 2018; Hauer, Siviglia, & Zolezzi, 2017; Moreira et al., 2019). Operational measures rely on changes in the energy production schemes resulting, however, in a reduced flexibility of operations for the hydropower companies (Gostner et al., 2011), which may hamper their ability to profitably adapt to rapidly variable energy prices and peak requests from the grid. Structural methods imply large investment costs and are mainly based on the development of infrastructures (compensation basins, diversion tunnels, and so forth) that smooth or damp the hydropeaking waves, either within the hydropower scheme or in the affected downstream river reach. An example is the construction of re-regulation basins, which is very effective to dampen hydropeaking intensity and increase minimum flows, but in turn requires the availability of enough space in the river valley, where, however, the most sought-after land for productive activities in the Alpine area is also located (Geitner et al., 2017).

Studies on hydropeaking mitigation are quite recent (Barillier, Beche, Malavoi, & Gouraud, 2021; Bruder et al., 2016; Greimel et al., 2018; Hauer, Siviglia, & Zolezzi, 2017; Hayes et al., 2019; Moreira et al., 2019; Moreira, Schletterer, Quaresma, Boavida, & Pinheiro, 2020; Reindl, Neuner, & Schletterer, 2023) and only a few have assessed the ecological effects associated to already implemented measures (see review in Moreira et al., 2019; Hayes et al., 2022). Even fewer documented cases relate to the Alpine area (e.g., Moreira et al., 2020; Parasiewicz, Schmutz, & Moog, 1998; Schweizer et al., 2021). The limited information on the success of implemented measures hinders our ability to quantify specific thresholds and parameter ranges needed to target multiple species and life stages (Greimel et al., 2018; Hayes et al., 2019). Assessing the success or the shortcomings of implemented mitigation measures, therefore, represents an important step to develop future hydropeaking mitigation strategies, especially in view of the rapid worldwide expansion of hydropower (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015).

To this end, we investigated the biophysical effects of a recently implemented hydropeaking mitigation measure in the Upper Noce Stream (NE Italy), which also allows for additional hydropower production. The Upper Noce, a third-order gravel-bed stream in NE Italy, was affected since the mid-1920s by storage hydropower production and associated hydropeaking. The mitigation measure consisted in the diversion of most of the released hydropeaks into a sequence of three cascading run-of-the-river power plants, fed by penstocks running along the former hydropeaking reach. Combining hydropeaking mitigation with increased hydroelectricity production, and documenting the biophysical effects related to its implementation in the field represents a unique case so far for the European Alps, (i.e., Moreira et al., 2019; Hayes et al., 2022, and the designs by Premstaller et al., 2017 and Reindl et al., 2023, not implemented so far).

In the present work, we set up a comprehensive analysis of the hydraulic, ecological, and physico-chemical responses of river system to the hydropeaking diversion mitigation measure. We integrated the analysis of publicly-available datasets from environmental monitoring programs with field data collection and analysis focused on key biological data for the hydropeaking reach. We further complemented the analysis with publicly-available ancillary data collected by the manager of the new, diversion hydropower plants on a yearly basis to monitor the effects of the mitigation measure.

2 | MATERIAL AND METHODS

2.1 | Study area

The study area is located in the headwaters (1200–935 m a.s.l.) of the Noce Stream (Trentino, NE Italy), a first level sub-basin of the second longest Italian river (Adige River), which flows into the high Adriatic Sea (Figure 1a). The study area includes a shorter upper reach ('Noce Bianco', third order stream) and a longer lower reach, downstream the confluence with 'Noce di Val del Monte' at about 1,160 m a.sl. Both streams are permanent, fast-flowing gravel-bed streams with wetted width ranging between 4 and 20 m, mainly fed by glaciers in the upper courses, and with a mixed glacial-nival-pluvial regime downstream (Figure 1b).

2.2 | Hydropower schemes and the mitigation measure

The upper course of the Noce Stream has been used for hydropower production since the 1920s, with the construction and operation of the Cogolo-Pont storage hydropower plant, which uses water from two nearby catchments, feeding, respectively, the Careser reservoir-Malga Mare settling basin and Pian Palù reservoir. Hydropeaking affected the study reach only after a few decades following the initiation of the plant operation, because hydropower production was continuous in time in the initial years. Hydropeaking has been fairly regular in time since the 1970s, with daily hydropeaks mostly causing rapid discharge oscillations between 1 and 10 $m^3 s^{-1}$ occurring during daylight and working days and more frequently in winter. After the mid-1990s, when hydropower production started following a liberalized energy marked, hydropeaks have become more irregular, with oscillations occurring even more than once per day, and lasting for

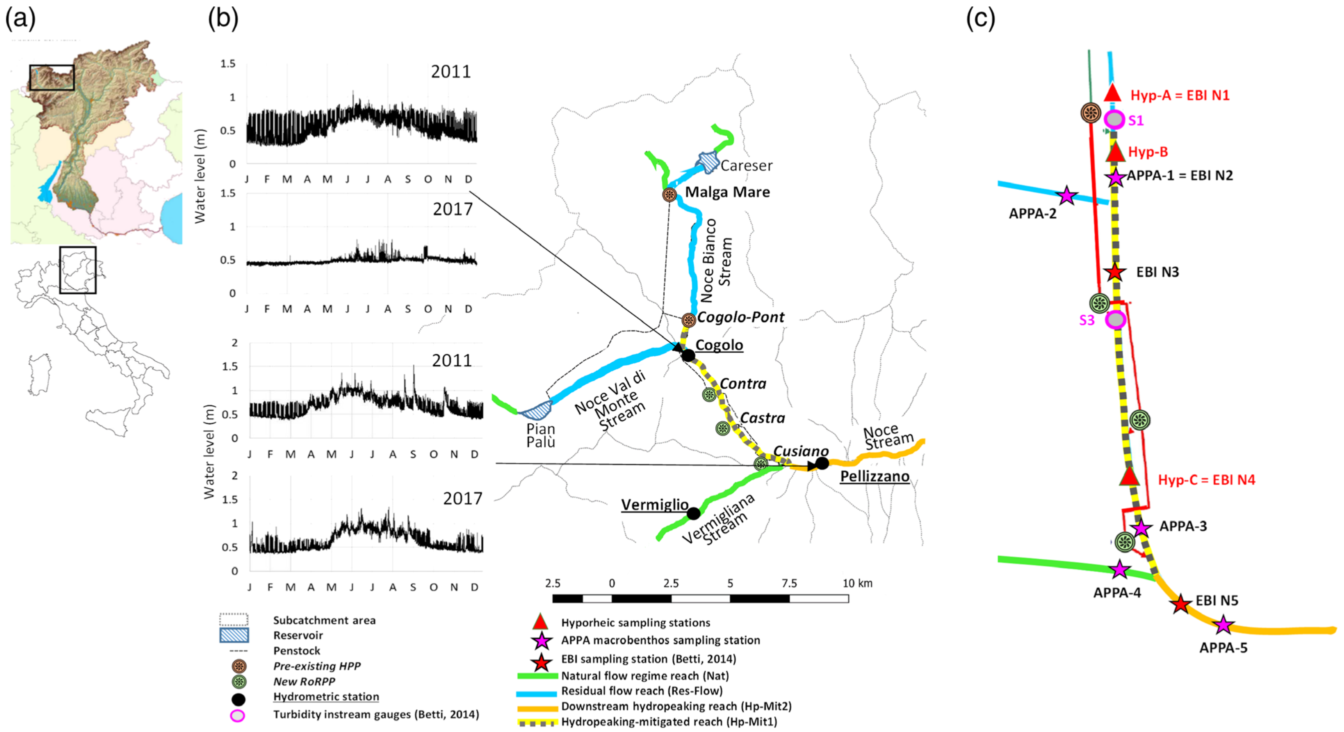

FIGURE 1 Details of the study area on the Upper Noce Stream. (a) geographical position of the studies watershed; (b) main waterbodies related to the studied hydropower scheme and location of the hydropower plants; flow regimes of the relevant reaches shown by different colours. Left inserts show illustrative examples of the annual flow regimes before (2011) and after (2017) the implementation of the mitigation measure at Cogolo (hydropeaking mitigated reach), and Pellizzano (downstream mitigated reach) hydrometric stations; (c) scheme of the position of the hydropower plants and of the sampling/monitoring stations for data used in this investigation (APPA, Hyp) and from ancillary data (EBI, S) [Color figure can be viewed at wileyonlinelibrary.com]

shorter periods (Figure S1). The mitigation measure was implemented in 2014–2015 and consists in a metal weir and diversion pipeline, built in the tailrace of a Cogolo-Pont hydropower plant (Figure S2). As a consequence, the hydropeaks are almost totally diverted through this pipeline to three cascading small run-of-the-river power plants (RoRPP, Contra, Castra and Cusiano) (Figure 1b). Each of the three RoRPPs has an installed capacity of nearly 3 MW and a maximum licensed discharge of 9 $m^3 s^{-1}$, which well matches the most frequent high discharge values of the previous hydropeaks (typically in the range 9–10 $m^3 s^{-1}$). As a result, hydropeaking is heavily reduced in a 10 km reach of the Noce Stream and is released 10 km downstream, near the confluence with a major, near-natural tributary (Vermigliana Stream, Figure 1b). Streamflow of the Vermigliana increases the base-flow of the Noce Stream, and was already attenuating hydropeaking before the mitigation was implemented. Further details on the hydropower systems and operation modes are provided in section S1 and Figure S2.

2.3 | Hydropeaking analysis

To analyse changes in the subdaily flow regime related to the diversion of hydropeaking into the three cascading RoRPPs, we used flow data measured at 15′ intervals at the hydrometric stations of Cogolo (flow-restored reach), Vermiglio (natural flow regime), and Pellizzano (downstream hydropeaking reach) (Figure 1b), recorded by the Hydrological Office of the Autonomous Province of Trento (Ufficio Dighe: data available at www.floods.it) between 2011 and 2019. Where an official discharge rating curve was not available (Cogolo and Pellizzano), discharge data were computed from water level recordings by reconstructing the rating curves, either through the interpolation of targeted discharge and water level measurements (Zolezzi & Bruno, 2013, for Pellizzano) or from hydraulic modelling based on a local normal flow approximation, which relied on available cross-sections surveys. A consistency check was finally performed to assess that the streamflow time series for Pellizzano was exceeding the sum of those for Vermiglio and Cogolo.

From the pre- and post-mitigation flow records, we computed two types of indicators to characterize hydropeaking modifications: the two hydropeaking indicators proposed by Carolli et al. (2015), and the COSH method developed by Sauterleute and Charmasson (2014). The two hydropeaking indicators are dimensionless measures of the hydropeaking magnitude (HP1) and the temporal rate of change of discharge (HP2). Three hydropeaking pressure classes (absent or low pressure, medium, and high pressure) were defined based on quasi-universal HP1 and HP2 threshold values. The COSH software (Sauterleute & Charmasson, 2014) processes long time series of water level or discharge, providing a set of indicators that characterize

TABLE 1 List of APPA biological monitoring stations/time periods included in each subset, each one corresponding to a different flow regime (see text for details). In parenthesis: pre/post = pre-/post-mitigation; number of samples

	Hp-Mit1	Hp-Mit2	Nat	Res-flow	Hp
APPA-1	2016–2019 (post, 6)				2010–2015 (pre, 3)
APPA-2				2010–2019 (pre + post, 6)	
APPA-3	2016–2019 (post, 7)				2010–2015 (pre, 5)
APPA-4			2010–2019 (pre + post, 6)		
APPA-5		2016–2019 (post, 3)			2010–2015 (pre, 3)

fluctuations of water level and discharge in rivers. The hydropeaking events are identified by an iterative, case-specific thresholding procedure, based on the analysis of the rate of change in the time series. Hydropeaking events can be subsequently described by up to 18 parameters, grouped into magnitude, timing, and frequency. These parameters were computed for Cogolo and Pellizzano stations for both the entire year and for January–March, when natural flow peaks (due to rainfall, snow and glacier melt) are nearly absent, which ensures that all peaks identified by the software actually corresponded to artificial hydropeaks.

2.4 | Environmental and ecological data

The ecological effects of the mitigation measures were assessed using three complementary data sources: (1) analysis of the benthic macroinvertebrates dataset collected by the local Environmental Monitoring Agency (APPA) as their institutional monitoring task; (2) analysis of data of hyporheic invertebrate communities that we collected before (Bruno, Maiolini, Carolli, & Silveri, 2009) and after the mitigation measure; (3) review of ancillary environmental data: the suspended sediment regime and the Extended Biotic Index (i.e., EBI, Ghetti, 1997) as reported in the environmental monitoring program prescribed to the RoRPPs owner by the APPA and conducted yearly from the year before the implementation of the mitigation measure (i.e., since Nov. 2014) (Betti, 2014, 2015, 2017, 2018, 2019, 2020a, 2020b).

2.4.1 | Benthic macroinvertebrates

We analysed the benthic macroinvertebrate data collected by APPA in 2010–2019 in five monitoring stations (named APPA-1, 2, 3, 4, 5 herein; Figure 1c). Sites were visited several times per year, primarily in spring (15 samples) and autumn (10 samples), for a total of 39 samples, 18 of which were collected before, and 21 after the entire system of the RoRPPs became operative. Sampling was performed according to the multi-habitat sampling approach defined in the AQEM (http://www.aqem.de) protocol: a total area of 1 m^2 was sampled with 0.05 m^2 20-replicates samples (net frame: 0.23 * 0.23 m; net mesh size: 500 μm) collected within a 20–50 m reach, in proportion to the observed micro-habitats (Hering, Moog, Sandin, & Verdonschot, 2004).

The dataset was divided into five subsets, corresponding to different flow regimes (Table 1): (1) Hp-Mit1, that is, fully mitigated reach: from hydropeaking to residual flow; (2) Hp-Mit2, that is, downstream hydropeaking reach: hydropeaking releases from the cascading RoRPPs system adding to the natural flow regime of the Vermigliana Stream; (3) Nat, that is, a natural reach with glacio-nival hydrological regime; (4) Res-F, that is, residual flow from Pian Palù Dam; (5) Hp, that is, hydropeaking reach: the same site as Hp-Mit1, but before mitigation.

2.4.2 | Hyporheic invertebrates

We collected hyporheic invertebrates from three sampling stations: Hyp-A, 0.25 km upstream from the Cogolo plant, at 1265 m elevation, in the residual flow regime reach (Res-F); Hyp-B (1,197 m a.s.l.) and Hyp-C (1,054 m a.s.l.) in the fully mitigated reach (Hyp-Mit1), 0.25 km and 6 km, respectively, downstream the Cogolo-Pont HPP (Figure 1c; more details in Bruno et al., 2009). The pre-mitigation dataset selected from a subset of the data used by Bruno et al. (2009) is comparable with the post-mitigation dataset (i.e., 13 months, from June 2007 to June 2008). The post-mitigation dataset was assembled from samples collected for 13 months, from June 2015 to June 2016. At each site, we installed two permanent instream steel piezometers of 115 cm length, 4.2 cm diameter, at about 50 cm from the bank, 2–4 m apart, inserted at the same depth into the riverbed to collect water 30–50 cm below the substrate surface.

Hyporheic invertebrates were collected by filtering 20 L of hyporheic water with a plankton net (mesh size 100 mm). Samples were fixed in the field in 90% ethanol; all organisms were sorted in the laboratory, counted and identified to the lowest possible taxonomic level. Identifications followed Campaioli, Ghetti, Minelli, and Ruffo (1994, 1999), Dussart (1967, 1969), Karaytug (1999), Pesce and Galassi (1987), Stoch (1998), Tachet, Bournaud, Richoux, and Usseglio-Polatera (2010). All identified taxa were functionally classified based on their degree of specialization to life in the hyporheic as stygoxene (organisms that have no affinities with groundwater systems where they occur only accidentally), stygophile (species that actively exploit the resources of the groundwater environment for part of their life cycle), and stygobite (specialized subterranean taxa that complete their whole life cycle exclusively in subsurface water), as defined by Gibert, Stanford, Dole-Olivier, and Ward (1994), based on the review of published specialized literature, and data on the distribution of Italian fauna (Stoch, 2000–2006).

We used a hand-held current meter (Global Water Flow Probe, Global Water Instrumentation, College Station, Texas, U.S.A.), and WTW handheld meters for oxygen, temperature, conductivity, and turbidity (WTW GmbH, Weilheim, Germany) measurements taken near each piezometer before sampling; hyporheic water temperature, conductivity and turbidity were measured twice: from the first 5 L sample, to assess the conditions of the riverbed (e.g., turbidity, to be used as a proxy for clogging), and from the 10–15 L sample, to measure the values of the interstitial water pumped from the surrounding sediment. We compared pre- and post-mitigation temperature and conductivity of surface and hyporheic water, the latter calculated by averaging the 0–5 and 10–15 L measurements, to compare with measurements of 2006–2008, which were taken from the first 10 L.

2.4.3 | Ancillary environmental data: Ecological status and sediment transport

The ecological status class was assessed with the Extended Biotic Index in five stations, three of which were located in proximity of the hyporheic sampling stations (Figure 1c). All data were retrieved from Betti (2017, 2018, 2019, 2020a, 2020b).

Suspended sediment regimes were monitored through continuous NTU turbidity readings and with three yearly suspended sediment transport sampling, in two stations (Figure 1c): station S1 is located upstream the Cogolo-Pont HPP outlet in the residual flow reach, and station S3 is downstream the syphon of Contra RORPP, in the mitigated reach Hp-Mit1. The potential mobility of the bed surface layer in the hydropeaking reach was also assessed by computing the largest sediment diameter corresponding to a critical dimensionless shields mobility parameter equal to the standard value of 0.047 (Shields, 1936), and assuming a reference condition of uniform sediment size and normal flow conditions with reach-averaged hydraulic parameters.

2.5 | Statistical analysis of ecological data

We retrieved information on the functional traits of each benthic macroinvertebrate taxon from www.freshwaterecology.info (Schmidt-Kloiber & Hering, 2015). The nine trait typologies chosen to assess the effects of hydropeaking mitigation are related to the habitat preference (zonal preference, current and substrate preference), saprobic preference, life- and body-related parameters (feeding habits, maximal size, locomotion type, locomotion, and substrate relation) (Table S1). Affinities of each taxon to each trait category were standardized between 0 and 1 using a fuzzy coding procedure (Chevene, Dolédec, & Chessel, 1994) and converted to community weighted means using the functcomp command from the FD R package. This procedure thus quantifies the proportion of each trait represented in each community.

We used the taxonomic and functional datasets to calculate the following community metrics: density (N. ind. m^{-2}), richness (expressed as total number of taxa), Shannon diversity, and functional dispersion (FDis, Laliberté, Legendre, & Shipley, 2014), and we tested for significant differences among and between flow regimes with non-parametric Kruskal-Wallis H-tests and Mann–Whitney *U*-tests. We compared taxonomic and functional composition among and, when significant, between flow regimes (Table 1) by applying a Permutational Multivariate Analysis of Variance (PERMANOVA - Anderson & Walsh, 2013) to the Bray–Curtis similarity matrix obtained from the log(x + 1) transformed abundance of taxa or proportion of traits. We visualized patterns of similarity in benthic community composition with a nonmetric-multidimensional scaling. To assess and visualize changes in the functional composition of communities, we run a Fuzzy Correspondence Analysis (FCA) (Chevene et al., 1994) on the dataset based on the community-level trait proportions.

For the hyporheic communities, we calculated the following community metrics from the pre- and post-mitigation datasets: density (N. ind. m^{-3}), richness (expressed as number of taxa), and Shannon diversity. Abundance and taxonomic richness were also calculated separately for communities of three faunistic groups: stygobiotic, stygophilic, and stygoxenic organisms. Differences pre-/post-mitigation in the metrics overall and for each of the three faunistic groups were tested with Mann–Whitney non-parametric *U*-tests. The effects of mitigation on the composition of hyporheic communities were analysed by applying a PERMANOVA to the matrix of Bray–Curtis dissimilarity after log(x + 1) transformation of original abundances, with 'pre-/post-mitigation' as fixed-factor, and 'site' as random factor to account for the repeated observations within site. Pairwise comparisons were run for significantly different factors. Patterns of similarity in community composition were visualized with a nonmetric-multidimensional scaling.

Statistical analyses were performed using the softwares R (version 3.6.2, R Development Core Team, 2019), PRIMER version 7 (Clarke & Gorley, 2015) with the PERMANOVA+ add-on package (Anderson, Gorley, & Clarke, 2008), Statistica ver. 13.3 (TIBCO Software Inc., 2017).

3 | RESULTS

To conduct our hydro-ecological assessment, we integrated the analysis of changes in the subdaily flow regime with analysis on the benthic (dataset provided by the Environmental Agency of the Autonomous Province of Trento, APPA) and hyporheic fauna collected before and after the hydropeaking mitigation measures (collection by our research group), supplemented with information on environmental variables (suspended sediment regime and Extended Biotic Index), retrieved from publicly-available Environmental Assessment reports, or provided by APPA.

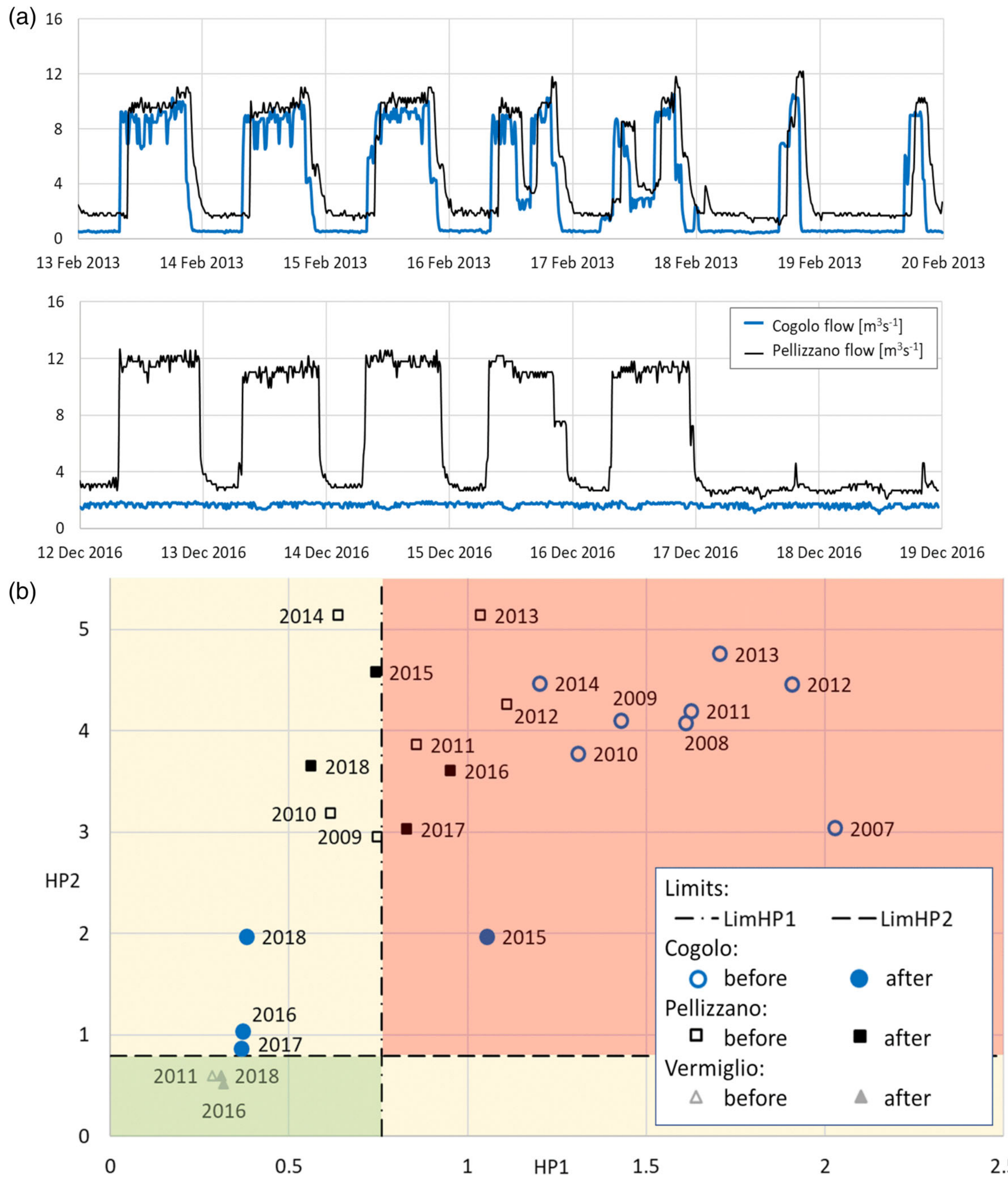

FIGURE 2 (a) Water level series at Cogolo and Pellizzano hydrometric stations in one exemplificatory week pre-mitigation (top) and post-mitigation (bottom); (b) Classification of Cogolo, Pellizzano, and Vermigliana stations based on the hydropeaking indices calculated following Carolli et al. (2015). Green: class 1: HP1 < TRHP1 and HP2 < TRHP2, low or no pressure; yellow: class 2: HP1 > TRHP1 or HP2 > TRHP2, moderate pressure; red, class 3: HP1 > TRHP1 and HP2 > TRHP2, high pressure [Color figure can be viewed at wileyonlinelibrary.com]

3.1 | Hydropeaking mitigation

Hydrographs for two typical winter weeks recorded in the mitigated reach (Cogolo) and in the downstream hydropeaking reach (Pellizzano; see Figure 1b) are reported in Figure 2a to illustrate changes in the subdaily flow regimes associated with the mitigation measure. Before mitigation (upper panel of Figure 2a), hydropeaking waves displayed a mean time lag of 85 min between Cogolo and Pellizzano, reflecting an average wave speed of 1.67 m s^{-1}. Pellizzano was characterized by a higher baseflow associated with the larger contributing catchment area; upramping rates were similar in both stations, while the downramping rates of the downstream station (i.e., Pellizzano) were smaller because of hydraulic diffusion (Hauer, Holzapfel, Leitner, & Graf, 2017; Toffolon, Siviglia, & Zolezzi, 2010). The lower panel of Figure 2a (post-mitigation) shows the absence of hydropeaking in the mitigated reach (Cogolo) and in Pellizzano, the hydropeaking pattern becomes similar to the pre-mitigation one, with the exception of slightly increased downramping rates.

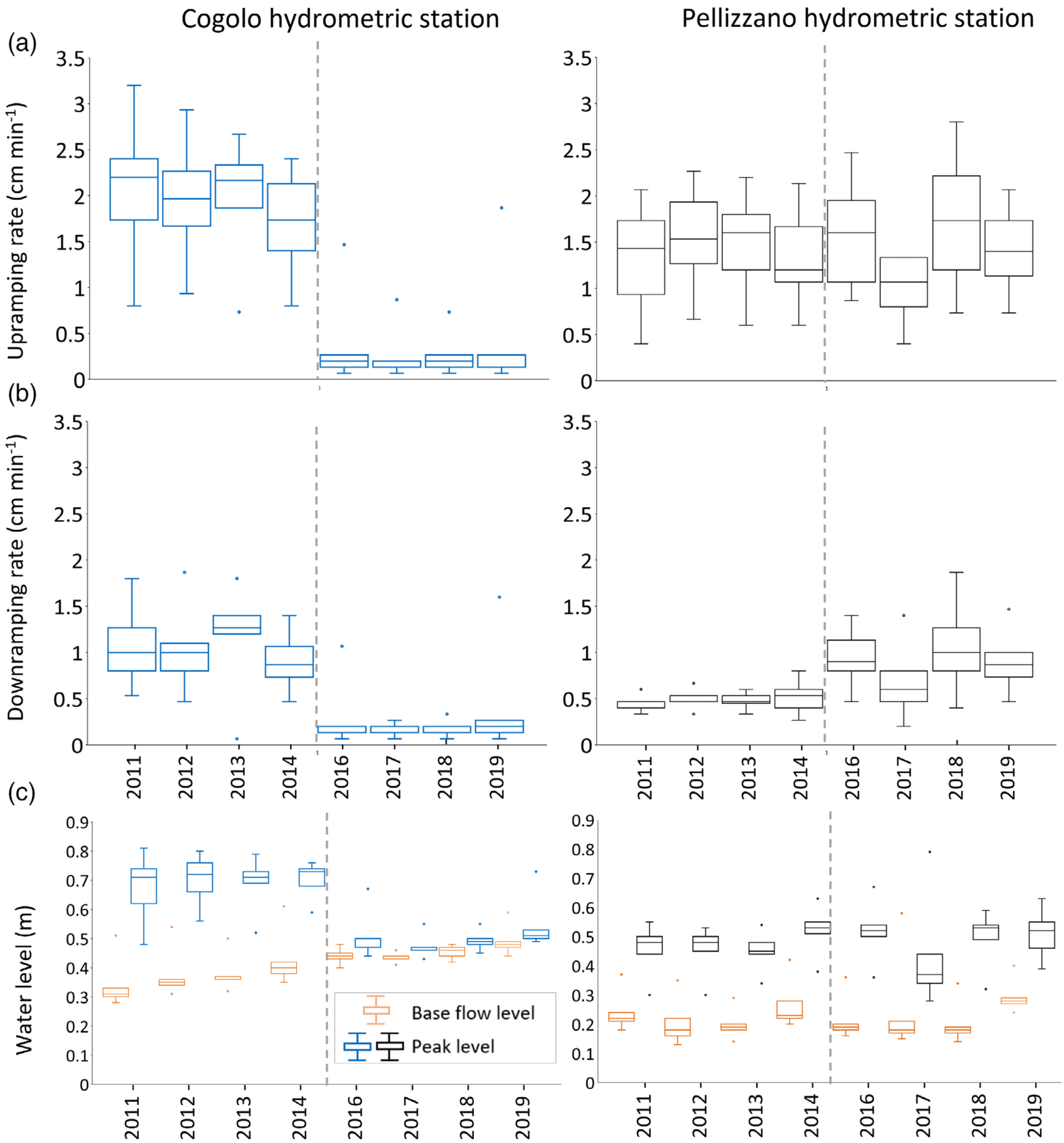

FIGURE 3 Results of the COSH analysis for Cogolo and Pellizzano hydrometric stations, for the first 3 months of the year. (a) Maximum rate of stage increases (upramping rate); (b) Maximum rate of stage decreases (downramping rate); (c) minimum (orange) and maximum (blue/black) water level. Line: median; box: 25%–75% interquartile, whisker: minimum-maximum values. The vertical dotted line separates pre- from post-mitigation data [Color figure can be viewed at wileyonlinelibrary.com]

The classification of the yearly hydrographs based on the HP1-HP2 indicators (Carolli et al., 2015; Figure 2b) shows a marked reduction of both hydropeaking intensity (HP1) and up/down ramping rates (HP2) for the mitigated reach (Cogolo), which moved from 'high hydropeaking pressure' (pre-mitigation, 2007–2014) to a region of the plot that falls below the HP1 threshold and very close to the HP2 threshold, still within the 'medium hydropeaking pressure' range (2016–2018). The downstream hydropeaking reach (Pellizzano) is almost unaffected by the mitigation measure, as its pre- and post-mitigation hydrographs group together in the plot, and do not show relevant shifts within the area identified by the two indicators (squares in Figure 2b).

The absolute values of pre-mitigation upramping rates exceeded those of downramping rates, as shown by the COSH analysis conducted for January–March (Figure 3a, b) both in the mitigated (Cogolo: average value of 2 vs. 1 cm min^{-1}) and in the downstream hydropeaking reach (Pellizzano: average value of 1.5 vs. 0.5 cm min^{-1}), as a result of the typical asymmetry of a propagating hydraulic wave in open channel flows. After mitigation, such rates were reduced to few mm min^{-1} in the mitigated reach, while in the downstream hydropeaking reach, the downramping rates increased in average from 0.5 to 1 cm min^{-1} (Figure 3b). Peak water levels (Figure 3c) coherently show a marked reduction in Cogolo after mitigation, becoming comparable to baseflow water levels: the flow

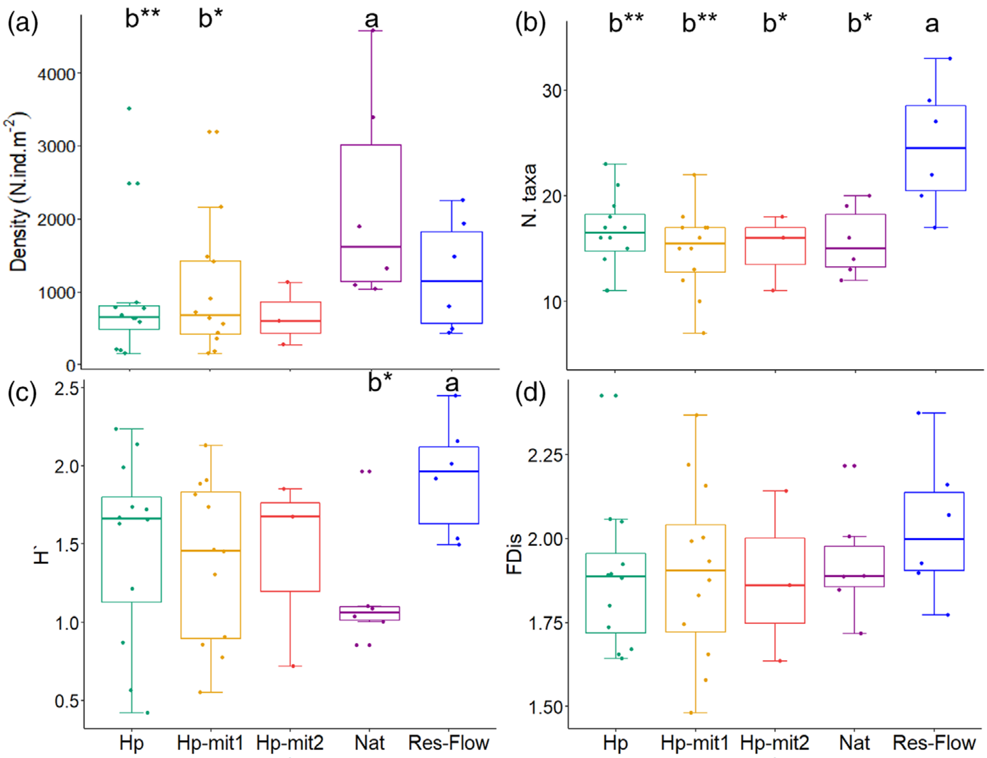

FIGURE 4 Boxplots of taxonomic and functional metrics of the macrobenthic communities. (a) total densities; (b) total number of taxa; (c) Shannon diversity; (d) functional dispersion. Line: median; box: 25%–75% interquartile, whisker: minimum-maximum values. Significant pairwise comparisons shown by asterisks (* if $p < .005$; ** if $p < .001$). Hp = hydropeaking reach; Hp-Mit1 = fully mitigated reach; Hp-Mit2 = downstream hydropeaking reach; Nat = natural hydrological regime; Res-F = residual flow reach [Color figure can be viewed at wileyonlinelibrary.com]

regime in the mitigated reach became a nearly constant baseflow in winter and late fall with some variability in late spring and summer resulting from a combination of snowmelt and residual hydropeaks that could not occasionally be diverted into the RoRPPs diversion system. The COSH analysis of the Cogolo time series also revealed (Figure S3) that an average number of 96.5 discharge peaks could be identified each year before mitigation (June 2010–2014), while only seven peaks per year could be identified after mitigation (June 2015–2018). Within the same periods, differences between maximum and minimum discharge values recorded in the same day, which are higher than 9 $m^3 s^{-1}$ (a value corresponding to the hydropeaks discharged from Cogolo-Pont HPP) occurred as average on 133.2 days per year before mitigation and for 2.3 days per year after mitigation.

3.2 | Benthic macroinvertebrates

Reaches with different flow regimes did not differ significantly in density, diversity and FD is of macrobenthic communities, whereas they differed significantly only in number of taxa (Kruskal-Wallis $p = .028$) (Figure 4). Community metrics remained similar in the hydropeaking and hydropeaking-mitigated reaches (i.e., Hp vs Hp-Mit1), where: (i) densities (Figure 4a) were lower than those of samples with natural flow regime (Nat) or residual flow (Res-F), significantly lower for HP-Mit1 and HP compared to Nat (Mann–Whitney $p < .05$ and $p < .01$, respectively); (ii) number of taxa (Figure 4b) was significantly lower than in the Res-F sites and similar to the Nat sites (Mann–Whitney $p < .05$ for all flow regimes compared to Res-F); (iii) Shannon diversity (Figure 4c) was higher than in Nat but lower than in Res-F; (iv) functional dispersion (Figure 4d) was similar to the one of the other flow regimes, but the median value was slightly higher in the Res-F samples. The macrobenthic community composition differed significantly among flow regimes: (PERMANOVA, pseudo-F = 1.9208; $p = .002$); specifically, Hp-mit1 differed significantly from Nat or Res-Flow (pairwise PERMANOVA, $p = .002$ and $p = .006$, respectively), Hp-Mit2 and Hp differed significantly from Res-F sites ($p = .015$ for both comparisons). The nMDS plot (Figure 5a) showed the group of communities of hydropeaking and mitigated reaches differing from those of residual flow or natural regime.

The FCA plot (FCA, Figure 5b) shows five flow regime groups which, however, did not differ significantly according to the PERMANOVA on the trait affinity Bray-Curtis distance. The macrobenthic community of the mitigated reach did not functionally shift towards the residual flow one: the mitigated reach (Hp-Mit1) was functionally more similar to the natural reach (Nat), and the Hp-Mit2 was functionally the most different from all the other reaches (Figure 5b).

The traits responsible for the similarity between the mitigated and natural flow regimes (Figure S4) were those related to: (i) the current preference of taxa, which were generally similar between the two flow types, except for rheophilic taxa which were more abundant in the natural flow regime; (ii) the substrate preference traits, with the abundance of taxa living on coarse substrate, sand and silt being similar between mitigated and natural regimes. Conversely, the saprobity preference traits were differently distributed, as the mitigated reach had proportionally less animals typical of clean waters and more animals typical of polluted waters. For the feeding groups, shredders and gatherers were proportionally less abundant, and passive filter feeders and predators similar or more abundant in the two mitigated reaches

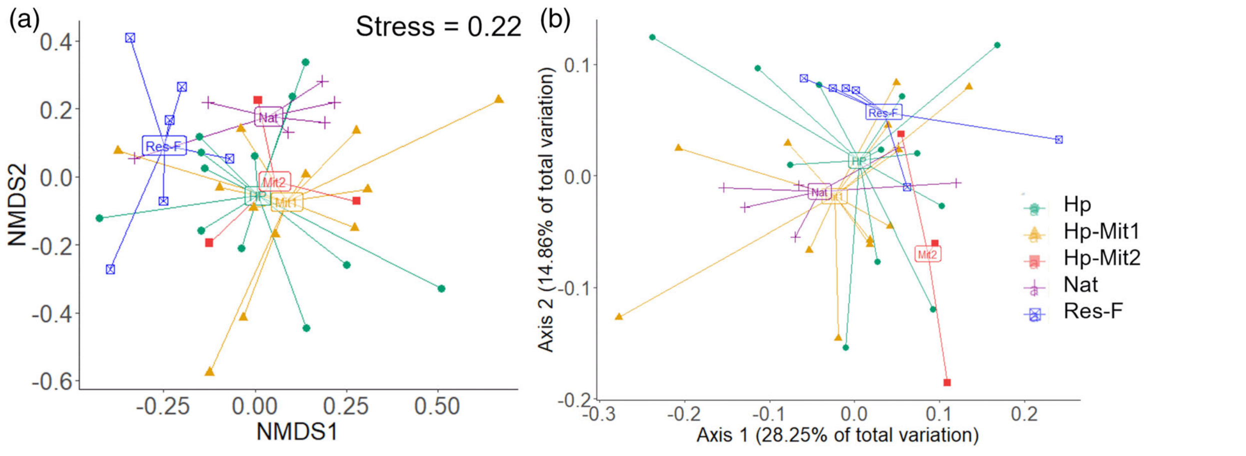

FIGURE 5 Macrobenthic communities: (a) taxonomic composition, nonmetric multidimensional scaling (nMDS); (b) functional composition, Fuzzy Correspondence Analysis (FCA). Station codes as in Figure 4 [Color figure can be viewed at wileyonlinelibrary.com]

than in the natural flow regime one; grazers were less abundant in Hp-Mit1 and more abundant in Hp-Mit2 than in the natural flow regime reach. The proportions of locomotion traits were similar between natural and mitigated reaches which, however, hosted less crawlers and more temporarily attached taxa (with proportion similar to those of the hydropeaking reach).

3.3 | Hyporheic invertebrates

The hyporheic communities were overall richer and more diverse after the mitigation measures (Mann–Whitney U Test, $p < .01$). Post-mitigation density was higher in the upstream-most mitigated site (Hyp-B, $p < .01$), but was lower elsewhere albeit not significantly (Figure 6a). Number of taxa and Shannon diversity (Figure 6b, c) was higher at all stations after mitigation, significantly only in the hydropeaking diversion-mitigated sites Hyp-B ($p < .05$ and $p < .01$, respectively) and Hyp-C ($p < .01$). The hyporheic post-mitigation density (Figure 6d) was significantly higher for stygoxenes and stygobites at Hyp-B ($p < .01$), whereas density was significantly lower for stygoxenes and styophiles and higher for stygobites at Hyp-C ($p < .01$). Post-mitigation richness (Figure 6e) was higher at all sites for all faunistic groups, significantly for stygoxenes and stygobites at Hyp-A and Hyp-B ($p < .05$), and for stygobites at Hyp-C ($p < .01$). Post-mitigation Shannon diversity (Figure 6f) was higher for all faunistic groups at Hyp-B and Hyp-C, and for stygophiles and stygobites at Hyp-A, significantly for stygophiles at Hyp-B ($p < .05$) and Hyp-C ($p < .01$), and for stygobites at C ($p < .01$).

The community composition (Figure 7) differed between pre- and post-mitigation within each site (nested PERMANOVA, Pseudo-$F = 2.8736$, $p = .001$); sites differed significantly from each other in composition in both pre- and post-mitigation conditions (PERMANOVA, $p < .05$ for each pairwise comparison), except for the first post-mitigation samples, which were more similar to the pre-mitigation ones for Hyp-B and Hyp-C. For the upstream site Hyp-A, where the flow regime was not influenced by the mitigation, the composition changed as well, but the shift in composition occurred 2 months after the mitigation. In post-mitigation condition, the composition of the hyporheic communities of the three sites became less variable over time than in pre-mitigation conditions, within-site similarity was higher for Hyp-B and Hyp-C (Figure 7). Average Bray-Curtis similarities between sites increased after mitigation (changing from 28.4 to 48.8 for Hyp-A vs Hyp-B; from 39.3 to 47.6 for Hyp-A vs Hyp-C, and from 22.2 to 51.9 for Hyp-B vs Hyp-C), that is the composition tended to converge. Six stygobiotic and 12 stygoxenic taxa were not collected in pre-mitigation conditions but were present in post-mitigation; conversely, two stygobiotic and five stygoxenic taxa were not recorded in post-mitigation (Table S2).

3.4 | Environmental variables

Descriptive statistics of the physico-chemical variables are listed in Table S3. Temperature and conductivity of surface of hyporheic water (Figure 8a, c) had similar values and increased along the longitudinal gradient both in pre- and post-mitigation. Differences between pre- and post-mitigation values of conductivity of surface and hyporheic water were always significant ($p > .05$, Wilcoxon matched paired test) for all stations: values were higher and more variable after mitigation (Figure 8c). Turbidity was higher in post-mitigation only at Hyp-A, and they were slightly lower at Hyp-B and lower at Hyp-C (Figures 8b). After mitigation, turbidity was higher and increased longitudinally from Hyp-A to Hyp-C for both the water inside or near the piezometers (i.e., litres 0–5) and the water pumped from the surrounding sediment (i.e., litres 10–15) although the latter was always less turbid (Figure 8d). Average turbidity of hyporheic water in the 0–5 and 10–15 L measurements at Hyp-A, Hyp-B, Hyp-C was 23, 30, 22, and 11, 15, 16 times higher than in surface water. In post-mitigation, mean

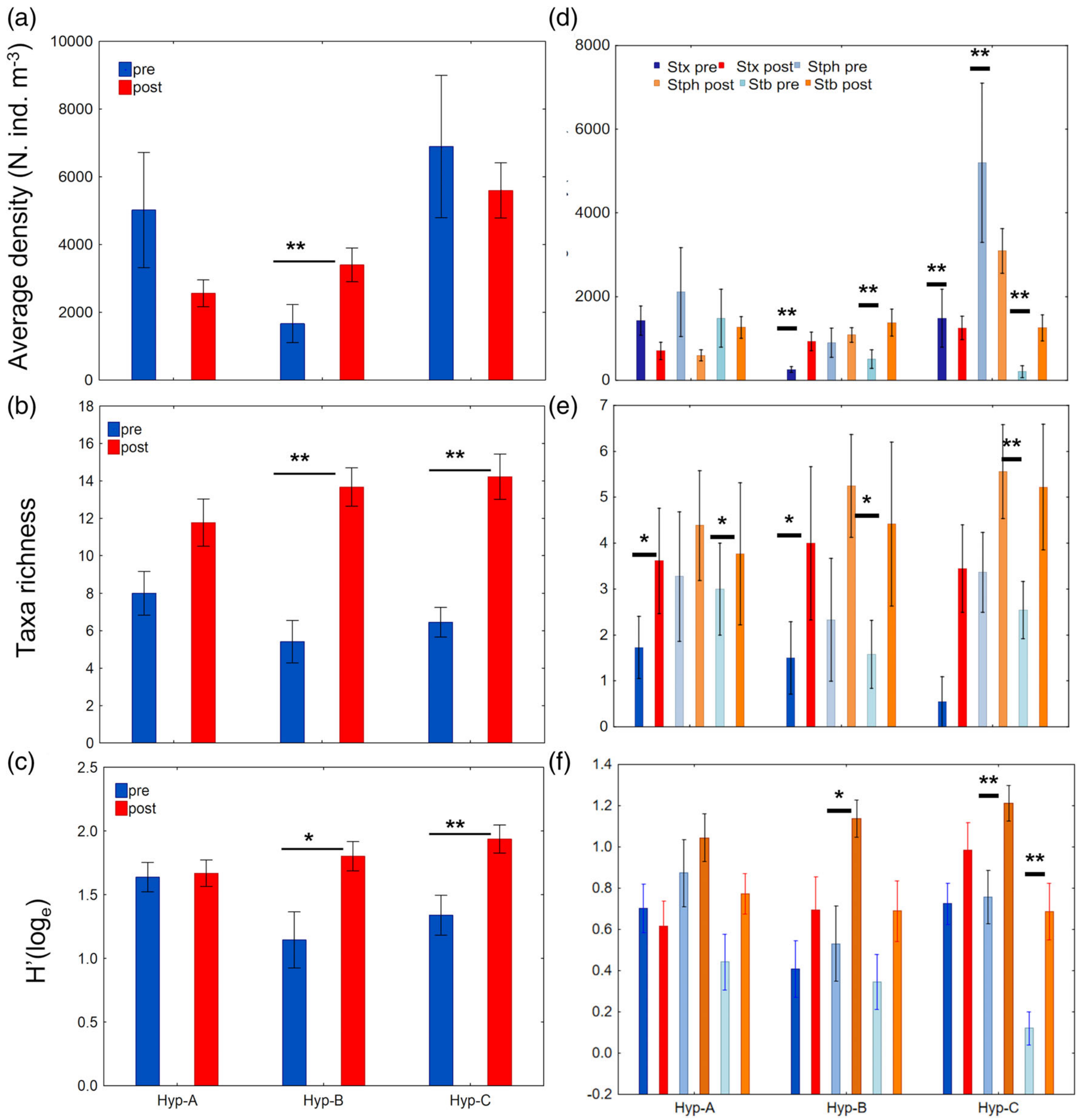

FIGURE 6 Community metrics of hyporheic communities calculated pre-mitigation (June 2007–2008) and post-mitigation (June 2015–2016) for the whole community (a–c), and for each of the different faunistic group (d, e). Pre = pre-mitigation; post = post-mitigation; stx = stygoxenes; stph = stygophiles; stb = stygobites. Horizontal lines mark significant pairwise comparisons, and the significance level is shown by asterisks (* if $p < .005$; ** if $p < .001$). Hyp-A: upstream, residual flow regime site; Hyp-B and Hyp-C: hydropeaking (2007–2008) or mitigated (2015–2016) site [Color figure can be viewed at wileyonlinelibrary.com]

surface water, oxygen concentration, and % saturation, water level, and velocity were highest at Hyp-B (Table S3).

3.5 | Dilution of contaminants and sediment transport

In the years following the mitigation and until 2018, the reduction in total discharge led to the increase of pollutants concentration originating from cattle effluents and civil wastewaters, followed by a reduction in water quality (Betti, 2020b). Nonetheless, from 2018, water quality improved due to the more efficient wastewater collection system and to the construction of septic tanks in most of the cattle farms adjacent to the stream. In fact, the ecological status assessed with the Extended Biotic Index (Table S4) generally decreased from high to good conditions (corresponding to 'none to moderate alteration') as recorded in the first post-mitigation year to moderate conditions in the second and third post-mitigation years in almost all the stations. From summer 2018, the EBI raised again to 'none to moderate alteration' class.

The suspended sediment regime in the fully mitigated reach changed after the mitigation measure (detailed description in S2), with likely effects on the riverbed sediment composition and clogging. Before mitigation, the hydropeaks released by the Cogolo-Pont HPP

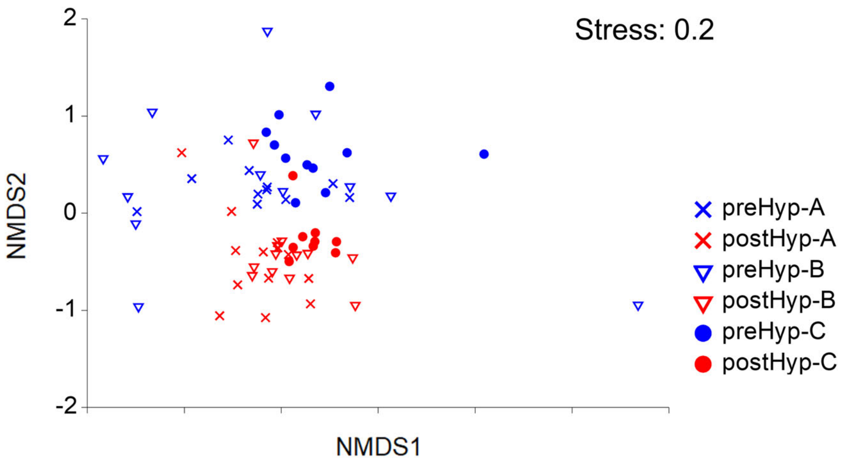

FIGURE 7 Ordination with nMDS of hyporheic communities. 1–13: sampling months, from June (2007 or 2015) to June (2008 or 2016). Station codes as in Figure 6 [Color figure can be viewed at wileyonlinelibrary.com]

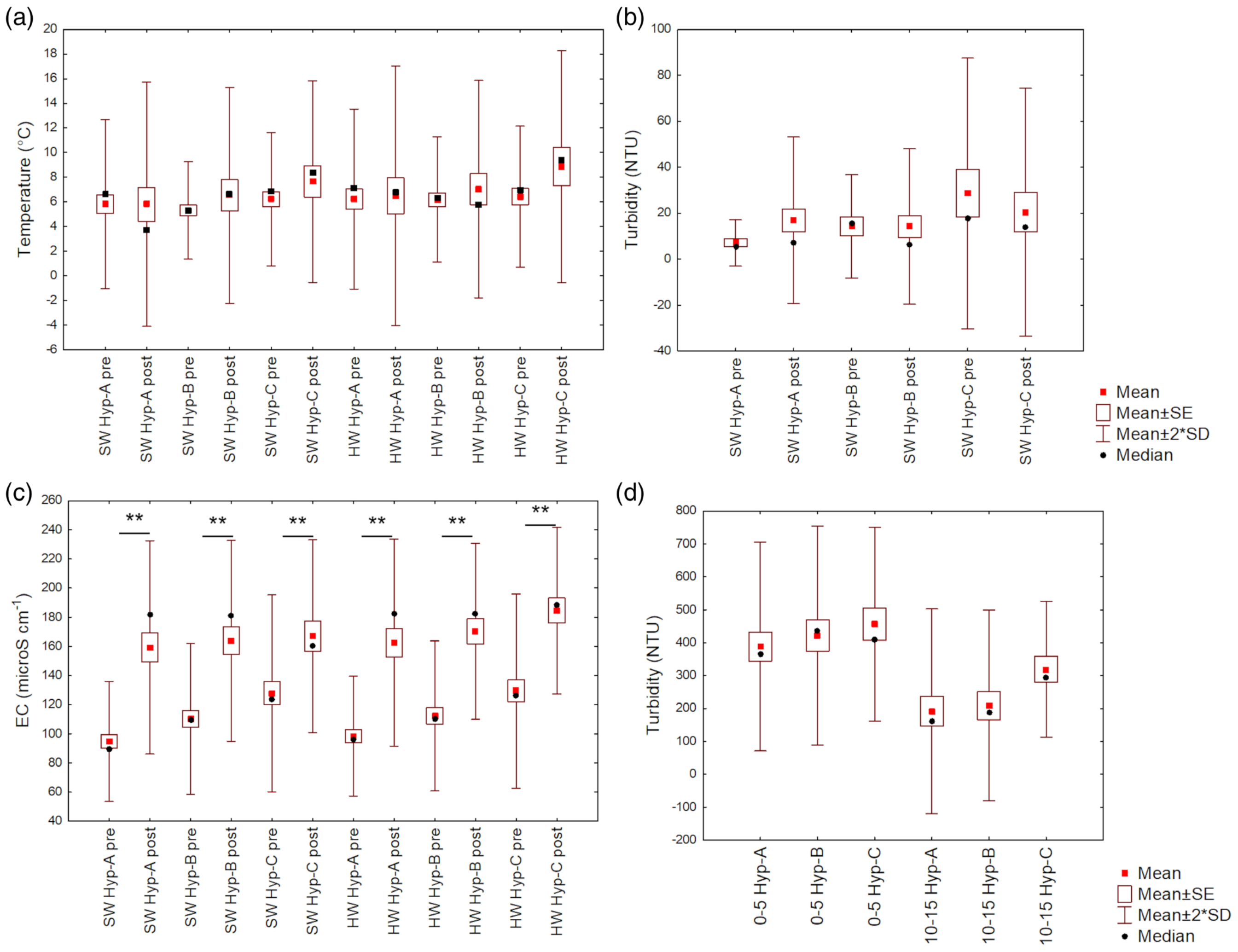

FIGURE 8 Boxplots of physico-chemical variables collected during the hyporheic sampling campaigns; (a, b, c) temperature, turbidity, conductivity measured in surface and hyporheic water pre (June 2007–2008) and post (June 2015–2016) mitigation ; (d) turbidity data as measured during post-mitigation in the hyporheic water, from the first 5 L (i.e., 0–5) and liters 10–15 (i.e., 10–15). SF = surface water; HW = hyporheic water. Horizontal lines mark significant pairwise comparisons, and the significance level is shown by asterisks (** = $p < .001$). Station codes as in Figure 6 [Color figure can be viewed at wileyonlinelibrary.com]

were systematically associated with turbidity peaks (e.g., Figure S5) during the entire year. Almost every hydropeak, therefore, determined a fine sediment input into the reach (e.g., illustration in Figure S2). After the mitigation, turbidity oscillations occurred almost exclusively in late spring and summer, when turbidity switched from very low values to peaks lasting few hours during daytime. These oscillations originated from occasional hydropeaks by Cogolo-Pont HPP during maintenance operations of the RoRPP pipelines or from natural sediment load during snowmelt periods. In early spring, autumn, and winter, suspended solids transport was low or absent (Figure S6D). After mitigation, in the investigated years, total yearly loads ranged from 3.7 * 10^3 to 13 * 10^3 to 16.8 * 10^3 ton in 2016–2017, 2017–2018, 2018–2019, respectively, corresponding to 54, 95, and 122 days with recorded solid transport (Figure S6).

Changes in riverbed clogging can also be related to disruption of the riverbed surface layer associated with bedload transport. The highest flow event on record occurred on August 13, 2014, (Figure S3) and corresponded to theoretical conditions of incipient mobility for the coarse sediment fraction of the riverbed (20 cm theoretical diameter). Such value well matches with the range of the coarser fractions of the riverbed sediments in the reach, which were estimated in previous studies (Zolezzi & Bruno, 2013), and that can be roughly and qualitatively assessed also from the images of the riverbed in Figure S2b, c.

4 | DISCUSSION

We provide one of the first comprehensive assessments of the hydro-ecological responses to a novel hydropower diversion measure, aimed at increasing hydropower production and at mitigating hydropeaking, implemented since 5 years in an Alpine river reach that was affected by hydropeaking for many decades. We first discuss possible interpretations for each ecohydraulic processes for which the most significant changes have been observed (4.1, 4.2), and then (4.3) synthesize the implications for the design and monitoring of hydropeaking mitigation measures. We remark that the possibility to directly compare our findings with the outcomes of monitoring programs in analogous contexts is highly limited by the paucity of implemented and monitored hydropeaking mitigation measures in Alpine streams (Greimel et al., 2018; Moreira et al., 2019; Premstaller et al., 2017; Reindl et al., 2023). To the best of our knowledge, two hydropeaking diversion mitigation measures similar to our case have been planned or are under construction in the Alpine area, though their implementation is not completed yet. Both consist of the construction of a new diversion hydropower plant fed by diverted hydropeaks, allowing to mitigate hydropeaking in reaches of considerable length on the Valsura Stream in South Tyrol (Premstaller et al., 2017) and on the Inn River in Western Tyrol (Reindl et al., 2023). The diversion in the Inn project is integrated a hydropeaking retention basin and represents the largest hydropeaking mitigation measure being presently implemented in Central Europe (Reindl et al., 2023). We have not found any further data on the ecological and hydrological monitoring of implemented diversion mitigation schemes similar to the one described in our study.

4.1 | Hydropeaking mitigation: Hydrology

Hayes et al. (2022) pointed out that the ecological outputs of hydropeaking diversion mitigation measures may be far from optimal, since the affected river reach can turn into a residual flow stretch, with hydropeaking only moved further downstream as it was the case in our study reach. In our study, the mitigated reach has moved from a 'strong' to a 'nearly absent' hydropeaking pressure (sensu Carolli et al., 2015; Figure 2b) and the number and rate of stage increases/decreases associated with the hydropeaks have been markedly reduced (COSH analysis: Figure 3; and Figure S3). The downstream hydropeaking reach (Hp-Mit2) was not substantially affected in terms of hydropeaking intensity, thanks to the input of a relevant free-flowing tributary (Vermigliana), that was already providing a higher baseflow before the mitigation measure.

In the same reach, hydropeaking rates of change were instead more affected by changes in the process of hydraulic diffusion brought by the mitigation measure. Hydraulic diffusion is a typical mechanism associated with the propagation of hydraulic waves in open-channel flow, related to friction, which dampens the wave peak and smooths the wave profile (thus, reducing the rate of change) while the wave propagates downstream (e.g., Chow, 1959). Such phenomenon usually occurs over large spatial scales (several tens of km) in the typical conditions of Alpine streams (Toffolon et al., 2010). Its effect is visible in the pre-mitigation downramping rates at Pellizzano (Hp-Mit2 reach, Figure 3b), being lower compared to ramping rates in the same hydropeaking wave at Cogolo. Once the mitigation measure has been implemented, hydropeaking waves propagate as pressurized flows into the penstocks of the three new RoR power plants. Hydraulic diffusion does not occur in the pressurized flow stretch, and the starting section of hydropeaking, therefore, shifts 10 km downstream the original section, being here still unaffected by diffusion. The distance from this point to the Pellizzano hydrometric station (downstream hydropeaking reach), where diffusion takes place is now much shorter (about 1 km), and insufficient to cause observable smoothing of the hydropeaking wave profile. This explains the increase in the downramping rates observed in Pellizzano after mitigation.

4.2 | Hydropeaking mitigation: Ecology

4.2.1 | Benthic macroinvertebrates

Benthic macroinvertebrates were investigated with a coupled taxonomic and functional approach. Compared to natural flow conditions, we recorded lower abundances and diversity in the mitigated reaches and similar composition for the HP and mitigated reaches persisting 4 years after the mitigation measure was implemented. This suggests that benthic communities had not yet recovered to a taxonomic composition typical of more natural flow regimes, although a partial shift in functional composition towards a more natural flow regime was detected, but characterized by low flows, and a poor water quality, as indicated in Figure S4 by the proportion of trait categories within each trait. However, the functional characteristics of an assemblage typical of hydropeaking sill persist, mainly in feeding traits, indicating that a shift towards foodwebs typical of a more natural flow regime, or even of a residual flow regime, have not yet fully occurred.

The most likely explanation for the observed changes in macrobenthic communities' composition is related to changes in benthic losses associated with drift. Although rapid changes in discharge can lead to drifting or stranding of benthic invertebrates (Greimel et al., 2018), stranding risk is rather low in straightened, homogenous channels with steep banks (Vanzo, Zolezzi, & Siviglia, 2016), such as the one investigated here. Therefore, the main and direct physical effect of the mitigation was the dramatic reduction of sudden increases in shear stress associated with each hydropeaking event, which reduced the rate of catastrophic drift (Bruno, Cashman, Maiolini, Biffi, & Zolezzi, 2016; Greimel et al., 2018). Considerable losses of benthic populations due to drift were reported by Bruno, Maiolini, Carolli, and Silveri (2010) following one single hydropeaking wave in the now-mitigated reach, and repeated high-flow events of similar magnitude can cause considerable losses of benthic populations to drift (Bruno et al., 2010). Changes in flow regime also bring about changes in the rate of behavioural drift, as animals leave or stay (i.e., increase or decrease their behavioural, active drift) according to the absence/presence of the optimal conditions of their habitat (Naman, Rosenfeld, & Richardson, 2016). However, behavioural drift in case of high flows is always lower than catastrophic drift (Naman et al., 2016, and references therein).

Differences in drift are determined by different morphological and behavioural traits which influence the exposure to flow: streamlined, swimming taxa are usually facultatively exposed to flow, whereas attached taxa, and case makers are obligatorily exposed to flow (Rader, 1997). Crawlers have various morphological adaptations that enhance attachment to the substrate, but they move actively to feed thus increasing the chance to be dislodged, and crawlers are usually poor swimmers. The likelihood of dislodgement and drift entry decreases from swimmers to crawlers, to temporarily attached to sessile taxa (Rader, 1997). In our study, traits associated with locomotion and substrate relation were similarly distributed across mitigated and hydropeaking reaches, although the former had proportionally more full water swimming and crawling taxa, and taxa temporarily attached to the substrate (i.e., less individuals with these traits were removed by drift in the absence of hydropeaks).

Because the mitigation of the daily hydropeaks caused a substantial reduction in catastrophic drift, other factors might be responsible for the limited recovery of the benthic communities, particularly the reported increases in organic pollution concentration from farming and civil wastewater as a consequence of reduced discharge (Betti, 2020b; and Section 3.5). In fact, the percentage of different saprobic groups in the mitigated reach was similar to the one of HP, in general with less taxa typical of unpolluted to slightly polluted water (i.e., xenosaprobic and oligosaprobic taxa) and more taxa typical of polluted water (a-mesosaprobic and polysaprobic taxa) than the flow types characterized by higher discharge (natural flow regime, downstream mitigate reach); moreover the percentage of taxa typical of polluted water taxa was slightly higher in the mitigated reach than in the hydropeaked reach, in agreement with the increase in pollutants concentrations persisting at least until 2018. High *Escherichia coli* concentrations during winter along the whole mitigated reach were recorded from the 2015–2016 mandatory monitoring campaigns, such microbic pollution originated from civil wastewater under the pressure of winter tourism (Betti, 2017), and persisted until winter 2017–18 (Betti, 2020b); from that year on, the peaks were recorded in summer but the recorded values are lower than in the previous years due to the extension of the wastewater collection system to the smaller municipalities. The improvement in water quality occurring from 2018, and recorded by the EBI index, did not apparently result in a taxonomic and functional recovery in the mitigated reaches, although our benthic invertebrates dataset covers only 1 year after the recorded improvement of water quality (i.e., 2018–2019).

4.2.2 | Hyporheic habitat

The investigation of the hyporheic communities, and their comparison with the pre-existing dataset assembled in 2008–2009, provided relevant information on the effects of mitigation on the quality of the hyporheic habitat. The main pre-existing habitat alteration was riverbed clogging (Bruno et al., 2009) by indirect evidence (mainly, by differences in faunistic composition) in the fully mitigated reach (Hp-Mit1), where deposition of fine sediments transported from the high elevation reservoirs and upstream glacial streams with each hydropeak (Figure S5) reduced the hyporheic habitat available to invertebrates. Because mitigation strongly reduced the hydropeaks in the reach (see section 3.1 and Figure S3), an important environmental effect of the mitigation was the change in suspended sediment regime, with turbidity oscillations occurring almost exclusively in late spring and summer.

After mitigation, the faunistic data suggest improved conditions/availability of the hyporheic habitat, as the taxonomic composition of the hyporheic communities changed and converged among mitigated sites, which became richer in taxa and more diverse already 1 month after the start of the operation of the three RoRPPs; moreover, the stygobiotic organism (i.e., exclusively living in the hyporheic habitat) increased in abundance, richness and diversity along the reach, suggesting more interstitial space and/or organic matter availability. This trend is the opposite of what recorded by Bruno et al. (2009) in the analysis of the two-year dataset for the same sites: before mitigation, the diversity and abundance of stygobiotic taxa declined along the upstream–downstream gradient in the impacted reach. This likely occurred because the suitable habitat for these specialized taxa was reduced, and the increase of abundance and diversity of benthic invertebrates (i.e., stygoxenes, which found shelter in the hyporheic during the hydropeaks).

Other studies have assessed the effects of clogging on hyporheic invertebrate assemblages and suggest the use of hyporheic invertebrates as indicators of sediment colmation and that the amount of interstitial space has a selective effect on invertebrates through their morphological traits. In fact, because clogging reduces the possibility of interstitial movements and between-zone exchanges, invertebrates which are small, cylindrical, or spherical, and with a highly flexible body are positively selected in streams with clogged interstitial space (e.g., Copepoda, Ostracoda and Cladocera) (Descloux, Datry, & Marmonier, 2013; Descloux, Datry, & Usseglio-Polatera, 2014; Gayraud & Philippe, 2001). In the previous study by Bruno et al. (2009), the most abundant stygobites collected in station Hyp-A were larger crustaceans or small vermiform invertebrates which require larger pore space, whereas smaller, cylindrical crustaceans which were favoured by clogging were dominant at Hyp-B; the relative density of these taxa was reversed after mitigation with invertebrates requiring large space becoming proportionally more abundant in the mitigated reaches. In contrast to what was recorded for hyporheic-specialist taxa, the use of the hyporheic as a refuge by epigean (stygoxene) fauna increased downstream of the hydropower plant before mitigation, as the high flow prompts the benthic invertebrates to penetrate into the hyporheic zone. However, sediment can act as a shelter only if enough space (porosity) is available (Bruno et al., 2009, and references therein). The most abundant stygoxene taxa collected in the hyporheic of the hydropeaking reach in pre-mitigation (Bruno et al., 2009) were taxa with cylindrical and flexible bodies and thus are able to penetrate into the fine sediment, and thus move through the interstices even if these are clogged. The abundance of these taxa decreased after mitigation at all sites, with the stronger effect recorded in Hyp-C, probably as a result of the reduction of shear stress on the sediment surface, which reduced the need for benthic fauna to seek shelter in the shallow hyporheic zone. These faunistic data suggest an increased interstitial space and hydraulic conductivity in the hyporheic zone of the mitigated reaches. Such changes call for a possible reduction of the riverbed clogging, for which a detailed mechanistic explanation can be hardly provided given the available hydraulic and sediment data for the case study.

Clogging of suspended sediment particles in gravel bed rivers is determined by a complex interaction among the concentration of suspended sediments in the water column, sediment size distribution, riverbed coarse sediment composition, which may eventually lead fine fractions to settle within the interstices (Schälchli, 1992; Wharton, Mohajeri, & Righetti, 2017). Clogging reduction in gravel bed rivers can be related to: (1) high flood events able to disrupt the surface (armor) coarse layer of the riverbed or, in their absence, to (2) alteration of the above complex dynamics leading to a net entrainment (instead of deposition) of the suspended fine sediments from the riverbed into the flow (Wharton et al., 2017). Our data suggest that a combination of both mechanisms is plausible, because the diverted hydropeaking spates were also characterized by turbid water. The reduction in the number and frequency of spates has, therefore, likely reduced the fine sediment input to the mitigated reach, where turbidity inputs have been limited to shorter rainfall events associated with summer storms or snowmelt in late spring–summer only. Turbidity inputs (originating from the glacial flour deposited in the Careser Lake) to the mitigated reach were instead happening regularly almost every day before mitigation. In fact, if hydropeaking water is rich in fines, the riverbed can become clogged when discharge rapidly decreases (Anselmetti et al., 2007; Blaschke, Steiner, Schmalfuss, Gutknecht, & Sengschmitt, 2003). Despite only few turbidity measurements available (Figure S7), these data support the hypothesis of seasonal reduction of suspended sediment input to the mitigated reach. Furthermore, theoretical hydraulic calculations on bedload transport initiation (Section 3.5) support the plausibility of a flood event causing at least partial disruption of the bed surface layer few months before hydropeaking diversion was implemented, thus potentially creating clogging-free riverbed conditions at that stage. Other site-specific factors may also play a role, given that an increase in riverbed hydraulic conductivity plausibly occurred in the same period also in the upstream, non-mitigated reach (Hyp-A) where an improvement of the hyporheic fauna has been observed as well.

The impact of high flows associated with the hydropeaks did not persist after mitigation except for natural events or the sporadic hydropeaking due to the maintenance activities of the RoRPPs. Hence, other factors might have co-occurred with the increased interstitial space availability to enhance the use of the hyporheic zone by benthic taxa. At the reach scale, because hyporheic processes are sensitive to hydropeaking with respect to rates of change, duration, and temperature (Casas-Mulet, Alfredsen, Hamududu, & Timalsina, 2015), the hyporheic habitat was less disturbed after mitigation, thus improving the ecological conditions for the hyporheic fauna. On the other hand, at smaller spatial scales, the lower discharge increased the risk of dewatering in the banks where the hyporheic samples were collected, and lowering of the water is a strong stress for surface taxa and the temporary hyporheos (stygoxenes + stygophiles), which respond by moving into the shallow hyporheic (Bruno, Doretto, Boano, Ridolfi, & Fenoglio, 2020, and reference therein). These taxa also exploit the available hyporheic space for the deposition and incubation of eggs and the growth of young instars, or for feeding due to the increased availability of organic matter accumulated with reduced flow. In fact, six of the 12 stygoxenic taxa collected only after mitigation in the hyporheic habitat were Ephemeroptera, or Plecoptera, or Trichoptera (i.e., *Baetis* sp., Leptophlebiidae, *Isoperla* sp., *Siphonoperla* sp., *Sericostoma* sp., Limnephilidae), which Graf et al. (2016) demonstrated to be taxa with preferences for coarse substrate types and highly sensitive to siltation; three taxa were large-sized copepod crustaceans (*Canthocamptus* cf *gauthieri*, *Eucyclops agilis*, *Mesocyclops leuckarti*) with benthic/planktonic life habits (i.e., they would require large interstitial spaces) and feeding on FPOM. Most of these taxa are known to occasionally use the interstitial and hyporheic habitat (i.e., *Siphonoperla*, *Sericostoma*, Limnephilidae, Leptophlebiidae, and all copepods; Stoch, 2000–2006; Schmidt-Kloiber & Hering, 2015). For insects, this is particularly true for the yearly larval stages, as it was the case of most of the organisms collected in the hyporheic after mitigation. The stygophilic taxa collected only after mitigation were represented by very early larval stages of the Ephemeroptera *Baetis* sp., which are often found in the hyporheos.

However, it must be noted that the hyporheic communities from the upstream, non-mitigated residual flow reach (Hyp-A) also differed before and after hydropeaking mitigation, mainly from the 2 months after the beginning of the mitigation although with a weaker shift and more temporal variability than in the downstream sites. Because Hyp-A was in a reach which did not change flow regime with the restoration (i.e., it was a residual flow even before the mitigation), it should have been affected by the mitigation only marginally, although the main high flow event that occurred in August 2014 possibly mobilized the substrate in this reach as well, promoting an increase in vertical connectivity (Boulton, 2007). At this site, changes in the taxonomic metrics overall, and for each faunistic group, were not always similar to those recorded in the mitigated sites, mainly the overall density, and the density of stygoxenes and stygophiles decreased from 2007–2008 to 2015–2016, while the density of stygobites remained almost unchanged. Conversely, as a result of the shift from hydropeaking to a residual flow regime, density of stygobites increased in the mitigated sites. After mitigation, five stygobiotic, one stygophilic, five stygoxenic copepods, and five stygoxenic insect larvae were collected only in the hyporheos of the mitigated sites; and four stygoxenic insect larvae only in the upstream, non-mitigated site.

The altered distribution of these newly-collected taxa accounts for most of the differences in the taxonomic metrics, and suggested ameliorated environmental conditions in the hyporheic habitat of the restored reaches, but also an increase of the overall diversity of the hyporheic communities of the Noce stream. The colonization source of these taxa is difficult to determine, nor it was in the scope of this work. We underline that stygoxenes and most of stygophiles colonize the hyporheic from the surface, and for taxa such as the recorded insect larvae and benthic copepods differences in distribution in the benthic habitat determine the taxonomic pool of possible colonizers, whereas for stygobiotic taxa, movements from one site to another must occur by movement within the substrate (Bruno, Bottazzi, & Rossetti, 2012; Robertson, 2000; Schmid-Araya, 2000), again suggesting higher space availability in the mitigated reaches. Finally, the value of water quality measured by EBI was usually higher in the upstream-most monitoring station (EBI N1), which corresponds to hyporheic site Hyp-A, and improved over time. The higher water quality might have contributed to support a more diverse and abundant community in 2015–2016 than in 2007–2008, when the wastewater collecting system was not fully developed and the input from cattle effluents was much higher.

4.3 | Synthesis: Effects of the mitigation measure on ecohydraulic processes

Integrating the analyses of multiple hydrologic and ecologic indicators allows the identification of the key processes that were affected by the mitigation measures. Our findings provide novel insights to support the design of hydropeaking mitigation measures and of the related environmental monitoring plans. First, structural measures based on hydropeaking diversion can determine an increase in downramping rates downstream of the location where the hydropeaks are returned to the river. This effect does not seem to be of particular ecological concern in our case study, because of the spatial scales, range of hydro-morphological conditions, and relevant ecological processes. However, it could be more pronounced in other cases, especially with an alternate bar, or a multi-channel morphology where rapid downramping rates may increase significantly the stranding risk for fish, an issue not relevant in the examined case study. Second, moving hydropeaks further downstream can determine a strong reduction of the overall flowing water volumes in the stream reach subject to the diversion-based mitigation measure. This can increase dilution of contaminants that enter the reach either in form of diffuse or point pollution. In our case study, organic and microbial pollution from livestock are a known concern in the catchment and the limited recovery in the condition of the benthic assemblages may be attributed to such reduced dilution. The design of hydropeaking diversion measures should be based on a comprehensive analysis of the different human pressures in the catchment to anticipate and balance possible undesired side effects. Third, the observed improvement in the hyporheic fauna seems to reflect an alteration of the fine sediment dynamics in the reach, which results from a delicate balance between multi-phase sediment transport processes. Direct quantification of sediment transport processes might pose operational challenges because of the high resources their monitoring requires, and the associated uncertainties can pose limitations to their interpretation, and may not be feasible in most cases. Observation on the hyporheic fauna, instead, can be a viable option to pursue when designing target monitoring programs especially in highly clogged hydropeaking rivers in which one of the main sources of turbidity is associated with the hydropeaks themselves (i.e., in glacier-fed basins). This, therefore, suggests the importance of monitoring both benthic and hyporheic communities, an approach not used so far in assessing the outcomes of hydropeaking-mitigation measures, together with the flow and sediment supply regimes, and physico-chemical water quality parameters. Such comprehensive monitoring approach might be advisable in selected contexts, especially where previous monitoring already suggested criticalities with vertical riverine connectivity.

5 | CONCLUSIONS

We assessed the hydro-ecological effects of 5 years of operation of a hydropeaking diversion measure. Such measure mitigated the effects of hydropeaking in a 10-km stretch of the Noce Bianco Stream, and allowed to produce 9 additional MW of hydropower. Overall, our analysis suggested that: (i) the recovery time scales of faunal communities composition from a hydropeaking flow regime may require several (>5) years, pointing at the importance of long-term monitoring plans for these mitigation measures; (ii) possible reduced dilution of contaminants has to be accounted for when designing hydropeaking diversion mitigation measures; (iii) a comprehensive monitoring that includes benthic, hyporheic communities, together with flow, sediment supply regimes, and physico-chemical water quality parameters is recommended, especially when issues with vertical connectivity were previously detected.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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