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Prioritizing reaches for restoration in a regulated Alpine river: Locally driven versus hydro-morphologically based actions

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Abstract

We discuss the prioritization of river reaches to be selected for restoration measures under the constraints of financial resource limitation. We propose and apply a simple approach based on the quantification of major hydro-morphological alterations and the critical comparison with locally proposed restoration actions. The available hydro-morphological and ecological data for the approach do not go beyond the requirements posed by the implementation of the EU Water Framework and Floods Directives. We describe an example that refers to a heavily regulated Alpine river (Sarca River, NE Italy). The results indicate hydropower facilities as a key source of hydrological alteration, with sediment retention and grade control structures on lateral tributaries playing an additional relevant role in reducing sediment supply. The frequency and duration of sediment-transporting floods have dramatically decreased, and the bed sediment composition has been markedly altered and become highly compacted. Habitat improvement has been achieved after the implementation of minimum environmental flows. The comparison between the results of the hydro-morphological indicators and the locally proposed restoration actions highlights that reaches with lower degree of hydro-morphological alterations do not coincide with the areas chosen for the locally planned actions, which often miss considerations of the relevant spatial scales. In a context of limited available financial resources and data compared to other flagship river restoration projects in the European Alps, the present work suggests viable options for the choice of target restoration reaches.

KEYWORDS
ecological flows, hydropower, regulated rivers, sediment transport

1 | INTRODUCTION

Most European rivers have been historically modified by human interventions, for example, flood protection, energy production and navigation (Habersack & Piégay, 2007; Hohensinner, Jungwirth, Muhar, & Schmutz, 2011; Klapper, 1990; Scorpio et al., 2018), which altered their hydro-morphology and led to ecosystems degradation and loss of biodiversity (Haines-Young & Potschin, 2018; Millennium Ecosystem Assessment, 2005). Hydro-morphology is scientifically (Frieberg, 2014) and legally (Water Framework Directive [WFD] European Parliament, Council of the European Union, 2000) recognized as a key supporting element for river ecosystem integrity, with flow regime and channel morphology affecting ecological processes, which, in turn, may feedback on channel morphology itself (Gurnell, 2014). To recover the ecological functioning of riverine ecosystems and their related services (Haines-Young & Potschin, 2018), and improve the ecological status of freshwater bodies as required by the WFD (European Parliament, Council of the European Union, 2000), hydro-morphologically based restoration has increasingly characterized river management strategies in the last decades (Buijse et al., 2002; Friberg et al., 2016). River restoration is a set of human interventions and measures aiming at improving river ecosystem functioning and restoring forms or processes that resemble near-natural conditions and dynamics. Restoring ecologically relevant components of the flow regime, removing barriers to improve ecological and sediment longitudinal connectivity, restoring bedforms and physical habitat at different scales are typical actions of hydro-morphological restoration (Friberg et al., 2016; Melis, Korman, & Kennedy, 2012; Olden et al., 2014; Roni et al., 2004). Such measures, which resulted in ecological improvements in some cases (Wohl, Lane, & Wilcox, 2015), are mainly publicly funded and entail important implications for local stakeholders, whose support is essential for their implementation (Carr, 2015; Comby, Le Lay, & Piégay, 2014; Logar, Brouwer, & Paillex, 2019; Tanaka, 2006). However, restoration actions have not systematically been based on scientific evidences (Friberg et al., 2016; Palmer, Menninger, & Bernhardt, 2010), and in Alpine rivers they take place mainly at reach-scale (Habersack & Piégay, 2007) without considering hydro-morphological processes occurring at larger spatial scales (i.e., the catchment or segment scale), which heavily affect hydro-morphology at the reach scale (Friberg et al., 2016; Gurnell et al., 2015). This hampers the measures' effectiveness, and the development of suitable, scientifically based methodological frameworks is relatively recent (Angelopoulos, Cowx, & Buijse, 2017; Beechie, Pess, Roni, & Giannico, 2008; Gurnell et al., 2015; Speed et al., 2016). Local stakeholders' participation is considered necessary for successful river restoration, although not sufficient to meet the projects' goals (Comby et al., 2014; Druschke & Hychka, 2015; Palmer et al., 2005), especially when bottom-up stakeholders' proposals do not rely on a comprehensive understanding of the relevant hydro-morphological processes. Participatory processes in river conservation and protection measures following the WFD (European Parliament, Council of the European Union, 2000) are increasingly common in several European countries, and an open issue is how to successfully harmonize locally desired restoration measures with the actual capacity of the river to sustain restoration measures, determined by its hydro-morphological functioning at different scales.

This paper critically examines the relationships between the hydro-morphological alteration level of a regulated Alpine river and the locally proposed restoration interventions, with the ultimate goal of providing support to the prioritization of reaches to be targeted by restoration measures. It proposes an indicator-based methodology that: (a) develops a comprehensive multi-scale characterization of the level of hydro-morphological alteration relative to pre-regulation conditions, and of possible ecological implications; (b) assesses each hydro-morphological element through a set of normalized and comparable indicators that quantify differences among reaches, to identify the less-altered ones; (c) uses the outcomes of participatory processes to detect the number, type and foreseen cost of proposed restoration measures in a spatially distributed fashion for every reach, and finally (d) compares the hydro-morphological alteration level with stakeholder-proposed restoration investments and interventions at the same spatial scale. We discuss observed mismatches and suggest possible ways forward that can combine feasibility and potential success in the context of limited available financial resources. The application of this approach is illustrated with reference to a case study in the Italian Alps, which has similarities with other regulated river systems in the same region in terms of degree of regulation, WFD ecological status, data availability and local interest for the improvement of the river environmental integrity.

2 | METHODS

A key underlying assumption of the proposed methodology is that a higher hydro-morphological alteration might correspond to a smaller potential of successful restoration efforts, following concepts of non-linear system behaviours proposed in the wider field of restoration ecology (Suding, Gross, & Houseman, 2004). The assumption of higher alteration, implying fewer chances of success in river restoration projects, moves from the observation that many ecological systems behave as non-linear systems with conditions that can rapidly shift towards a new, stable, and degraded state when threshold levels of external stressors are exceeded (Scheffer, Carpenter, Foley, Folke, & Walker, 2001; Suding et al., 2004). However, such new state may be relatively stable, thus hampering the restoration of a more natural state even if the level of the external stressor is reduced below these thresholds (Balke, Herman, & Bouma, 2014).

The methodology is structured along the following main components. The study area needs to be first segmented into homogeneous reaches by means of a geomorphologically-based hierarchical method (see, e.g., Rinaldi, Surian, Comiti, & Bussettini, 2015). Then, a quantitative assessment of the hydro-morphological and ecological status from the catchment to the reach scale is developed, together with the assessment of the level of alteration compared to pre-regulation conditions. Afterwards, one or more sets of normalized indicators are proposed to quantify these levels of alteration and possibly related ecological effects. Next, locally proposed restoration actions are mapped through participatory surveys and are suitably analysed at the relevant spatial scales. Finally, the spatially distributed information on hydro-morphological alteration, resulting from the chosen indicators' sets, and the proposed interventions, are compared at the same spatial scale, and critically examined.

2.1 | Multi-level assessment of hydro-morphological conditions and potential ecological implications

After performing the spatial segmentation procedure, the analysis aims to quantify which are the most altered hydro-morphological processes and at which spatial scale. Characterization of the hydro-morphological conditions can be made at two partially related levels:

level 1 the level of hydro-morphological and ecological status indicators, which typically provide a rather general, synthetic assessment;
level 2 the hydro-morphological process level, which provides a deeper knowledge of the actual system alteration and conditions, compared to level 1.

Level 1 includes indicators of flow regime alteration, morphological alteration and overall ecological status, as they are routinely required for assessing the ecological status of water bodies in EU countries, according to the EU WFD.

When daily streamflow data are available, a widely used method to analyse flow regime alterations is the Indicators of Hydrologic Alteration (IHA) method (Richter, Baumgartner, Powell, & Braun, 1996). The IHA quantifies flow regime alterations from the comparison between pre-impact and post-impact daily flow records. In the case of Italy, it is the core of the IARI method (ISPRA, 2011), which offers a viable approach also for data-poorer catchments.

The Morphological Quality Index (Rinaldi et al., 2015,b) is the indicator used at the national level in Italy to assess the morphological quality. It is based on three main elements: geomorphological functionality (e.g., longitudinal and lateral continuity, channel patterns, river bed structure and substratum, riparian vegetation), artificiality (e.g., presence of local and remote sources of hydro-morphological alterations, such as weirs, bridges, levees and embankments, dams) and (only for rivers wider than 30 m) observed recent adjustments.

The ecological quality has been assessed using the Star_ICMi index (Buffagni & Erba, 2008). This method is officially adopted by the Italian legislation as the Biological Quality Element to guide the classification of running waters in the WFD context. It is based on six metrics (Buffagni et al., 2006), and includes taxonomic richness and diversity, as well as taxa sensitivity to organic pollution.

Level 2 indicators provide more detailed information on the causes of alteration and on the actual system conditions that can be collected with typically available information for Alpine rivers. With reference to the recently proposed framework by Gurnell et al. (2015), the following hydro-morphological process-level elements have been considered in the present study:

1. Alteration of longitudinal sediment connectivity;
2. Alteration of bedload-transporting events (with potential to drive morphological change);
3. Historical evolution of the active river channel
4. Alteration of bed sediment composition;

Level 1 indicators are not fully independent from level 2 indicators. For instance, alteration of longitudinal connectivity (level 2) contributes to the overall assessment of the MQI, (level 1) and the flow regime alteration (level 1) has implications for the alteration of flow events that can potentially drive morphological change (level 2).

The historical evolution of the active river channel at multidecadal time reflects the river response to human-related modifications to the flow and sediment supply regimes (Surian & Rinaldi, 2003), which have relations to level-2 elements, n. 2 and 1, respectively. It can be quantified through system trajectories extracted from aerial/satellite images and historical cartography, in terms of key planform and/or bed elevation parameters (Kondolf & Piégay, 2005).

As the ultimate target of river restoration is the entire ecosystem functioning, or at least some of its components, it might be useful to quantify also potential ecological implications of the detected hydro-morphological alterations. For example, the changes in channel morphology have a close correlation with the spatial habitat availability for target species, especially in rivers where hydro-morphology represents the strongest alteration source, like in most Alpine streams (Poff & Zimmerman, 2010). Such ecologically relevant indicators with high dependence on hydro-morphological parameters might be included as well in level-2 assessment.

2.2 | Normalized indicators and spatially explicit synthesis

The obtained information on hydro-morphological alteration has to be standardized to obtain comparable indicators at coherent spatial scales. For each assessed hydro-morphological element ($i = 1, \ldots, n$) and typical spatial unit at the scale at which the methodology is applied ($k = 1, \ldots, n$) a generic indicator, x_i^k, of the chosen hydro-morphological process alteration elements (Section 2.1) has to be derived from the outcomes of the hydro-morphological analysis. Afterwards, a normalized indicator, z_i^k, has to be developed from the original indicators, x_i^k, that were not normalized yet (especially level-2 indicators), by scaling them in the range (0, 1) referring to the minimum ($min_k[x_i]$) and maximum ($max_k[x_i]$) values for the entire study area, as follows:

$$z_i^k = \frac{x_i^k - min_k(x_i)}{max_k(x_i) - min_k(x_i)}, \tag{1}$$

All normalized indicators, z_i^k, therefore, range between 0 (maximum alteration level for the study area) and 1 (minimum alteration).

An overall assessment of the system alteration at the spatial scale of interest can be done both through level-1 and level-2 indicators, but not by combining the indicators from the two levels into a single synthetic indicator, because of the several mutual dependencies between the two levels. Moreover, the choice of the specific indicators (especially level-2) can change among different study areas to better reflect specific local conditions. Several scenarios can then be developed corresponding to analogous indicator choices at the chosen spatial scale.

2.3 | Spatial identification of river restoration actions

A set of locally desired river restoration actions must be established to identify which are more relevant, beneficial and sustainable. Such locally-proposed actions might be identified in various ways: through expert opinion, conducting studies, through participatory process and literature review (Wohl et al., 2015). A key step to link this part of the analysis with the hydro-morphological assessment is to then classify the proposed actions according to: (a) the dominant hydro-morphological or ecological element, coherently with the adopted level-1 and level-2 indicators; (b) the spatial unit (reach, segment, etc.) to which they were referred to. Finally, it can be assessed whether the proposed actions consist of a practical intervention or a supporting study.

3 | APPLICATION TO THE SARCA RIVER CATCHMENT

3.1 | Study area

The Sarca River (Trentino, NE Italy) is the main tributary of Lake Garda, one of the largest pre-Alpine glacial lakes in Europe. It has been chosen because it offers an example of a heavily modified Alpine stream, where a considerable local interest for river restoration has emerged in the last 10 years, and which is characterized by data and financial resources availability that is well below that of catchments where major "flagship" restoration projects have been implemented (e.g., Szałkiewicz, Jusik, & Grygoruk, 2018), and thus may reflect a more widespread situation in the Alpine area. It conventionally sources at Pinzolo (770 m a.s.l.) at the confluence between Sarca di Campiglio, which sources from the dolomitic Brenta group, and Sarca di Genova, which sources from Lago Scuro Lake at 2668 m a.s.l. in the granitic Adamello-Presanella group. The Sarca River (Figure 1) runs north–south until the confluence with one of its main tributaries, the Arnó Creek. Downstream this confluence, it turns west–east and flows into the Ponte Piá artificial reservoir (4 Mm^3, 463 m a.s.l.). After flowing eastwards for 10 km, it takes an approximate North-Northeastern to South-Southwestern direction in its lower course, finally entering in Lake Garda after further 22 km. The natural flow regime of the Sarca River is nivo-glacial, although it is heavily impacted by hydropower production. As in several Alpine rivers of comparable size (e.g., Zolezzi, Bellin, Bruno, Maiolini, & Siviglia, 2009), most hydropower regulation in the Sarca River has been developed during the 1950s. A complex system of tunnels and artificial diversion canals withdraws the water from the river's major tributaries in the entire catchment (see black dotted line in Figure 1). The diversion canal runs at about 900 m a.s.l. for 43.5 km and it collects the water from 41% of the catchment area. Further downstream, the Ponte Piá

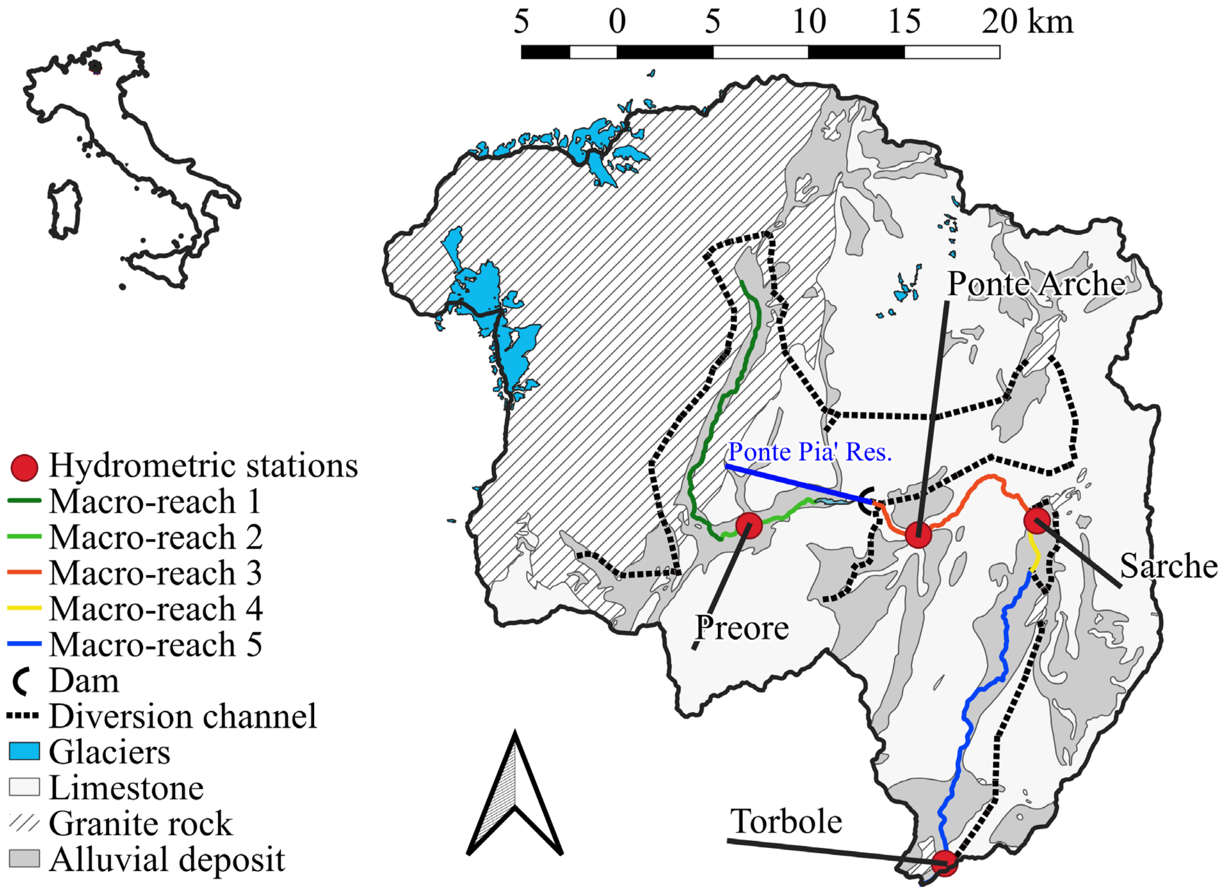

FIGURE 1 Map of the Sarca River catchment (main stem, coloured lines) with indication of the key elements of the complex hydropower system (red dotted line), of the hydrometric gauging stations and of the main geological formations [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Main characteristics of the five macro-reaches in which the study area has been partitioned for the hydro-morphological analysis

Macro-reach	From - to	Length (km)	Hydrometric station	Slope	Width (m)	d_{50} (m)	Qmob (Θ_{cr0}) (m^3/s)
1	Pinzolo to Arnó confluence	16.2		0.0105	25	0.08	26
2	Arnó confluence to Ponte Piá reservoir	6.5	Preore	0.0089	25	0.13	100
3	Ponte Piá reservoir to Limaró canyon	11.7	Ponte Arche	0.0074	30	0.098	93
4	Limaró canyon to Pietramurata	3.5	Sarche	0.0032	25	0.062	95
5	Pietramurata to Torbole	20.4	Torbole	0.0049	25	0.087	104

Note: The columns denote: starting location, ending location, length, reference hydrometric station, down-channel slope, average width, median surface sediment size (d_{50}), estimated streamflow threshold for incipient bedload transport(Q_{mob}).

reservoir disconnects macro-reaches, 2 and 3 (Table 1). The most important hydropower plant in the system is Santa Massenza (105.3 MW), which releases water in the Santa Massenza-Toblino Lake. From these lakes, an artificial channel flows into the Cavedine reservoir, which stores water for the Torbole hydropower plant, located close to the river mouth into Lake Garda.

Hydro-morphological analyses have been conducted for the entire catchment with focus on the main river channel (coloured lines in Figure 1). We have performed a hierarchical segmentation of the study site. We called the five main resulting partitions of the study area "macro-reaches," because they correspond to an aggregation of several homogeneous river reaches, but they are smaller than river segments (following Rinaldi, Belletti, et al., 2015). The segmentation has been conveniently made according to the main hydrological discontinuities of the Sarca River's main course, both natural (main tributaries) and artificial (dams and large check-dams), to meet hydrological and hydraulic modelling requirements. The main characteristics of every macro-reach are reported in Table 1. All information was available in publicly accessible archives and databases at the regional institutions, except for the sediment grain size information that was collected through a dedicated field campaign.

3.2 | Level 1 indicators

We collected spatially distributed data about level-1 indicators for the Sarca River from the WFD-related monitoring program of the Trentino Environmental Protection Agency (APPA Trento). The MQI is assessed at the reach spatial scale (Rinaldi, Surian, et al., 2015), while the Star_ICMI is assessed at the "water body" scale, a WFD-related definition that does not necessarily result from the same morphologically based segmentation process at the base of the MQI.

The IHA method has been applied to daily averaged streamflow records from four hydrometric stations, quite homogeneously located along macro-reaches, 2,3,4,5: Preore, Ponte Arche, Sarche and Torbole (Figure 1a). Available data for these stations only refer to post-regulation conditions. Historical, pre-regulation (before 1950) daily streamflow data were not available and have been reconstructed through the hydrological GEOTRANSF model (Bellin, Majone, Cainelli, Alberici, & Villa, 2016), which can account for man-made water abstractions and releases, as well as for the presence of artificial reservoirs and their operational rules. Simulation of realistic pre-impact flow series has been performed using the 1994–2014 meteorological data and present land use–land cover information as model inputs. The parameters were calibrated on a 6 years time interval (2001–2006) in which the data on water uses in the catchment were also available. The simulated daily flow record has been assumed representative of what would have occurred in the same period (1994–2014) in the absence of any man-made flow alteration. Both simulated and measured daily averaged flow records refer to a 20 years interval (1994–2014), except for Ponte Arche (macro-reach 3) where only 9 years were available (2006–2014). Data from Torbole in macro-reach 5 (Table 1, Figure 1) could be used to quantify high flow conditions, but are not reliable enough for representing actual low-flow conditions in the reach, because of a backwater effect related to the release from the lowest hydropower plant in the system. *HA*, the "Hydrological Alteration" parameter as computed by the IHA method, has been used as the normalized indicator for the flow regime alteration.

For the purposes of this study, MQI, Star_ICMI and IHA normalized indicators have been eventually aggregated at the macro-reach scale.

3.3 | Level 2 indicators

For every macro-reach, four indicators of hydro-morphological process alteration have been computed and normalized as described in Section 2.2. In addition, assessment of the degree of alteration in hydraulic habitat conditions has been performed as key ecological parameter affected by hydro-morphological alterations.

3.3.1 | Longitudinal sediment connectivity

Alteration in the longitudinal connectivity has been measured on the basis of the most recent orthophotographs in the absence of an updated inventory of lateral structures, such as weirs and check-dams. Each observable lateral barrier in the image has been mapped and georeferenced. A related number n per unit channel length (or density, $x_1^k = n/km$) has been computed for every macro-reach, k.

3.3.2 | Alteration of bedload-transporting events

For every macro-reach, we computed the streamflow value corresponding to the incipient motion of the highest d_{50} value between the sediment sample collected on the bar and the sample collected on the permanently wet channel bed (see Section 3.3.4 for details). The cross-sectional average near-bed shear stress, τ, was computed from the application of the 1D HEC-RAS hydraulic model (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2002; see Section 3.4 for details of its application on the Sarca River). Incipient bedload motion was assumed to correspond to the following condition:

$$\theta = \theta_{cr}; \quad \theta = \frac{\tau}{(\rho_s - \rho) g d_{50}}, \tag{2}$$

where θ denotes the Shields' sediments mobility parameter, (ρ_s = 2,650 kg/m^3, ρ) denote sediment and water density, and g denotes gravity acceleration. Two values of the critical Shields parameter θ_{cr} were used: a standard reference value equal to 0.047 (Meyer-Peter & Müller, 1948), and a value arbitrarily increased by 20% to account for the high level of bed compaction that was invariably observed in all sampled reaches. The two corresponding streamflow values were used as thresholds to calculate the number and duration of bedload-transporting events in every macro-reach, for both simulated pre-impact and measured streamflow series. The chosen (non-normalized) indicator has been $x_2^k = 1 -$ percentage decrease in the frequency of bedload-transporting events.

3.3.3 | Historical evolution of the river channel

We reconstructed the morphological trajectories of the river reaches that were laterally unconfined by natural obstacles in the first available aerial image. The available aerial images for the region were taken in 1954 (flight of the Gruppo Aereo Italiano, source: Istituto Geografico Militare Italiano, see for details Gobbi et al., 2018), 1973 (flight of E.I.R.A. source: P.A.T.), 1988 (source: Geoportale Cartografico Nazionale), 1994, 2000, 2006 (source: Geoportale Cartografico Nazionale) and 2015 (source: Google Satellite). Three land cover classes have been used to classify the active river corridor: wetted channel, bare sediment bars, vegetation. The classes were visually recognized on the images and manually digitized, and areas occupied by each class have been computed for every macro-reach in each image. As indicator of channel adjustments, we chose the active corridor width, computed as the ratio of the wet channel plus bare sediment areas to the macro-reach length. The chosen indicator is $x_3^k = 1$ $-$ percentage reduction of the active corridor width compared to a reference 1973 orthophotograph having enough resolution for this analysis.

3.3.4 | Alteration of bed sediment composition

In the absence of publicly available data on the riverbed sediment composition, two bed surface sediment samples were collected in every macro-reach on an emerged bar and in the adjacent wet channel. We use the Wolman count method (Wolman, 1954) to compute grain size distributions, from which we calculate the values of the relevant percentiles (d_{50} and d_{90}). The alteration of bed sediment composition has been estimated by comparing the riverbed sediment size onto the exposed bars and into the adjacent, permanently wet channel. The rationale behind this choice is that in an alluvial channel with an alternating bar pattern both field (Ferguson & Werritty, 2009) and numerical (Cordier et al., 2019) studies indicate the natural tendency of the coarser sediments to be found at bar tops, with bed sediments in the permanently wet low-flow channel being of smaller size. Reversal of such difference could be associated with a more pronounced tendency to armouring of the low-flow channel, as typical of river reaches downstream of dams (Kondolf, 1997). The chosen indicator is x_4^k = difference between the surface d_{50} on bars and the surface d_{50} in the adjacent low-flow channel, divided by the surface d_{50} on bars.

3.4 | Potential ecological implications: Temporal alteration in hydraulic habitat availability

The implications of flow regime alterations for the temporal availability of hydraulic habitat have been assessed with reference to two representative sub-reaches nearby the hydrometric stations with the longest flow records (Preore and Sarche in macro-reaches 2 and 4, respectively). We applied the 1D HEC-RAS fixed bed hydraulic model to compute spatially distributed flow depth and velocity at low-flow conditions (most relevant for fish habitat suitability). Cross-sections, spaced nearly 100 m apart, were available for the study site. Model parameters, especially the Gauckler–Strickler roughness coefficient, k_s, have been calibrated using the wetted area extracted from aerial images at known flow conditions, yielding nearly homogeneous k_s values of 35 $m^{\frac{1}{3}}s$ in macro-reaches 2–5 and a k_s values of 25 $m^{\frac{1}{3}}s$ in macro-reach 1. For habitat modelling, we targeted the adult stage of the marble trout (*Salmo trutta marmoratus*), a salmonid endemic species of the Southern Alps. We applied univariate preference curves developed for an adjacent river catchment (Noce River; Carolli, Geneletti, & Zolezzi, 2017). Although the mesoscale is ecologically more consistent to describe the spatial scale of actual usage by fish (Parasiewicz, 2007), hydraulic habitat suitability has been modelled using the micro-scale habitat model, CASiMiR (Schneider, Noack, Gebler, & Kopecki, 2010), because mesoscale habitat surveys were not available.

Habitat rating curves (Weighted Usable Area [WUA]–streamflow curves) have been obtained by weighting the area of each wet computational cell with its modelled suitability value, a parameter in the range 0–1. Because of the similar, single-thread regulated channel morphology, habitat rating curves computed for reach 2 (4) could be also considered representative for reach 1 (3 and 5). The relatively homogeneous, single-thread morphology of the Sarca River in most of the study area reduces the simplifications that are inherent in the use of a 1D instead of a 2D hydraulic model. Streamflow series have been converted into habitat time series through the habitat rating curves. Simulated pre-impact flow time series was used to set a representative threshold for habitat stress events, chosen as the Q_{355} in near-natural hydrological conditions, that is, the value statistically exceeded 355 days a year (Vezza et al., 2015). Habitat stress events have then been defined as those in which the habitat time series falls below the WUA value corresponding to Q_{355}. Increase of the continuous duration and frequency of such events are considered as a limiting factor for the fish fauna (Benejam, Angermeier, Munné, & García-Berthou, 2010).

Three different flow scenarios have been analysed: a first one when no release of any minimum environmental flow (MEF) was foreseen (1994–2000); a second one when MEF release was established (2001–2006), and a third idealized scenario corresponding to the simulated pre-impact flow using meteorological data for the 2007–2014 period. For each scenario, uniform continuous under threshold curves (Parasiewicz, 2007) were obtained using as threshold the available habitat at the pre-impact Q_{355} streamflow value.

The used indicator has been $x_5^k = 1 - d_c$, with d_c average increase of the continuous duration of habitat stress events compared with the pre-impact, simulated flow regime.

3.5 | Synthesis of hydro-morphological alteration and proposed restoration projects

To reduce subjectivity resulting from the choices of the specific alteration indicators (especially level-2), four different scenarios have been developed by combining the described indicators at the macro-reach (k) scale as follows:

Scenario 1 MQI, HA (level-1, only hydro-morphology);
Scenario 2 MQI, HA; Star_ICMI (level-1, hydro-morphology and ecology);
Scenario 3 $z_1^k, z_2^k, z_3^k, z_4^k$ (level-2, only hydro-morphology);
Scenario 4 $z_1^k, z_2^k, z_3^k, z_4^k$ and z_5^k (level-2, hydro-morphology and hydraulic habitat).

A participatory process aiming at improving and restoring the river ecosystem started before 2010 (Trentini et al., 2010) with focus on the lowermost macro-reaches, 4 and 5; since 2015 such process also included macro-reaches 1, 2 and 3. It involved local fishermen and conservation organizations, regional river authorities, the main hydropower company, municipalities and the managers of a natural protected area of national relevance (Parco Naturale Adamello Brenta). Eventually, a new public entity was established (Parco Fluviale della Sarca) in charge of continuously promoting the environmental values of the river system. The process consisted of a series of facilitated workshops, public meetings and focus groups where an initial list of more than 200 proposed projects was refined into 98 actions, of which 35 were actual restoration measures (20 interventions, 15 technical support or feasibility studies). Such final list was included in the river management plan for the 3 years after 2016.

4 | RESULTS

4.1 | Level 1 indicators

A considerable length of the main channel (39% of the study area) is in poor or bad morphological status (Figure 2a). These low values are due mainly to the presence of flood protection and grade control structures (weirs, levees). Moreover, the morphological quality is altered by the presence of hydropower production system, including dams and artificial reservoirs. The MQI index values for the tributaries are considerably higher, mostly because tributaries flow in lateral valleys that are less populated and less subjected to human pressure. The STAR_ICMi index (Figure 2b) shows that the ecological quality of the Sarca River is “high” or “good” in the upper and Inter mediate parts of the catchment. In the lower catchment, the index value falls in the “moderate” class due to the higher anthropic pressure, resulting from human settlements and agricultural activities. The application of the IHA methodology quantifies the heavy alteration of the flow regime in all the four considered hydrometric stations. The illustrative example of Figure 3a suggests that, after hydropower regulation, the streamflow is nearly constant for the whole year, with values between 2 and 4 m^3/s and is only interrupted by few high flow or flood pulses that cannot be completely controlled by the water abstraction system. The hydrograph of monthly mean flows is almost flattened in all examined reaches, as most of the water abstracted from the river network by the complex hydropower system is returned back to the river just 1 km upstream the river mouth in Lake Garda. Each of the 33 IHA parameters (Richter et al., 1996) is heavily affected in all reaches: the number of high pulses strongly decreased (Figure 3b,c), while the magnitude and duration of low-flow pulses markedly increased (Figure 3d) as it happened for the rise rates of flow events (Figure 3e). While the hydrological alteration was qualitatively consistent among all macro-reaches, macro-reach 2 (upstream of the dam) showed slightly less quantitative alteration compared to the downstream macro-reaches, 3, 4 and 5. The complete output of the IHA application is reported in the Supporting Information.

4.2 | Level-2 indicators

4.2.1 | Morphological alterations and longitudinal connectivity

The channel morphology has been markedly simplified along the entire study area, with the active river corridor width being progressively reduced in most reaches, where the morphology shifted from

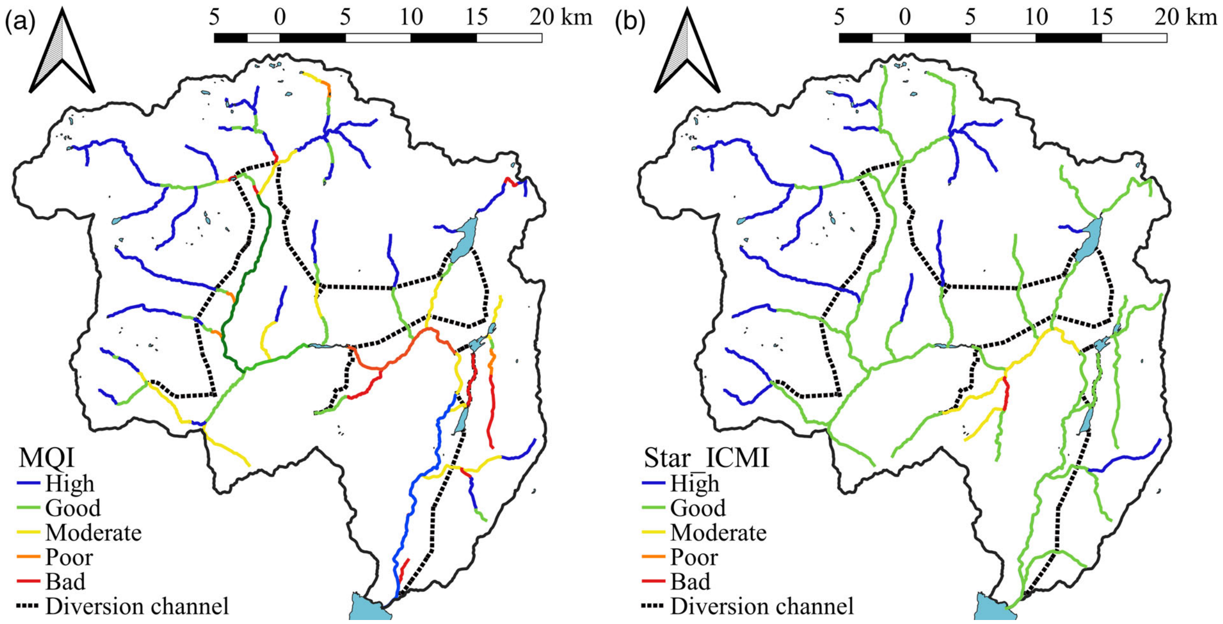

FIGURE 2 (a) Present-state spatial distributions of the morphological quality index (MQI) and (b) of the WFD Italian indicator of river ecological quality (STAR_ICMi) for the main stem and for the main tributarie [Colour figure can be viewed at wileyonlinelibrary.com]

wandering/transitional to channelized, single-thread. Two illustrative examples of variations in the active channel area are reported in Figures 4a,b, where the active corridor extracted from orthophotographs dated 1954, 1973 and 2015 are compared. In addition to the generalized narrowing associated with the constructions of embankments, evidence of riverbed incision has been documented in previous studies (Trentini et al., 2010). The morphological simplification is associated with a progressive stabilization of the riverbed, whereby bars have been gradually over-topped by a layer of fine sediments, which has been further consolidated by riparian vegetation sustained by the constant low flow occurring most of the year. This progressive stabilization process has been affecting the river trajectories shown in Figure 4c,d for macro-reaches located above (c) and below (d) the Ponte Piá reservoir. Currently, bare sediment bars can be found more frequently in the upstream macro-reaches (especially 1 and 2), while they are almost absent in macro-reach 3, located immediately below the Ponte Piá reservoir.

Reduced morphodynamics is also associated with the presence of lateral barriers and weirs built along the main stem for hydraulic safety purposes. The mapped weir density is higher in the upper part of the catchment, particularly in macro-reaches, 1 and 2, which suffered the strongest reduction in longitudinal connectivity (Table 2).

4.2.2 | Alteration of bed sediment composition and formative discharges

In reach 2, having higher sediment size, the frequency of bedload-transporting events reduced from 1 every year to 1 every 3 years (Figure 5a and Table 2), but may further decrease to once every 10 years if bed sediment compaction is accounted for. Such reduction rate is comparable for the macro-reaches downstream the dam, where the frequency decreases from three times a year to once every nearly 2 years if accounting for sediment compaction. The difference between the d_{50} and d_{90} is reversed for reaches downstream the artificial reservoir (Figure 5b): upstream the dam sediment diameter is larger on the bars, while the opposite occurs downstream the reservoir, suggesting that the higher flow alteration in macro-reaches 3, 4 and 5 has also resulted into a progressive armouring of the low-flow channel, causing an alteration of the bed sediment composition.

4.3 | Potential ecological implications: Temporal alteration in hydraulic habitat availability

The habitat–streamflow rating curves presented a common pattern in the two assessed macro-reaches. It is characterized by a maximum value of suitable habitat for intermediate streamflow values (Figure 6a,b,c), with highest WUA values at 12 m^3/s in macro-reach 2 and at 10 m^3/s in macro-reach 4. This shape is related to the similar, channelized single-thread morphology of both macro-reaches, with alternate or lateral bars, and to macro-reach 4 being slightly wider. Given the very frequent low-flow values in the range 2–4 m^3/s, most frequently the Sarca River in the study area falls in the rising limb of the habitat rating curve, where an increase in streamflow corresponds to an increase in the available habitat. For this reason, habitat time series showed a clear increase in their minimum values following the introduction of compulsory MEF from major water intakes in the region in 2008 (Figure 6d).

UCUT curves, computed using the Q_{355} of the simulated flow record as threshold (Figure 6e), indicate higher frequency and a longer duration of habitat stress events when closer to the upper right-side

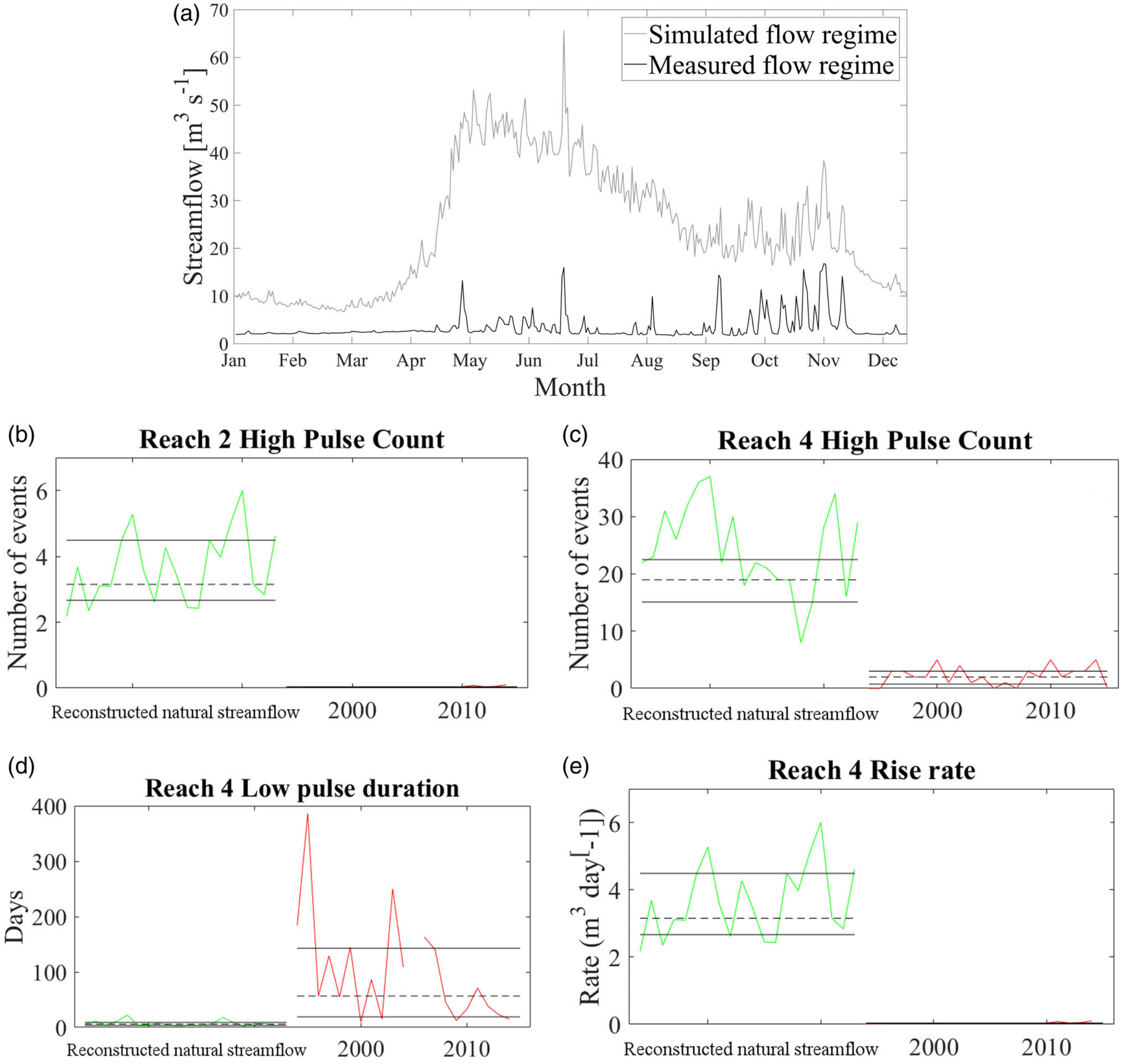

FIGURE 3 (a) Illustrative example of the flow regime alteration of the Sarca River in macro-reach 5, close to its mouth before entering the Garda Lake. (b–e) Main outcomes of the IHA analysis. (b and c) High Pulse count for reaches 2 and 4, showing slightly less alteration in reach 2. (d and e) Heavy alteration of low pulse duration and rise rate in reach 4. The three horizontal lines plotted with each series refer to the 75th, the 50th and the 25th percentile of the series, and are used to assess hydrological alteration through the RVA methodology [Colour figure can be viewed at wileyonlinelibrary.com]

of the graph. The worst habitat conditions occurred in the period 1994–2000 (blue curve), when major water intakes, including dams, were not prescribed to release a MEF. After an initial test phase (2001–2006), the release of the MEF became compulsory since 2008. This is reflected in the leftward shift of the corresponding UCUT curve (black line) in Figure 6e, and can be also visually inferred from Figure 6d. As an idealized benchmark, the red UCUT curve in Figure 6e refers to the reconstructed natural streamflow series for the same period (2007–2014), and may be viewed as the lowest limit that could be achieved with flow restoration given the present channel morphology.

The most important difference between macro-reach 2 and macro-reach 4 in the UCUT analysis is that the latter is affected by very long continuous stress event (up to 1 year), associated with the higher regulation imposed by the upstream dam.

4.4 | Synthesis of hydro-morphological alteration and of proposed restoration projects

Spatially explicit values (per macro-reach) of the normalized alteration indicators, z_i^k, are reported in Table 2, which also reports

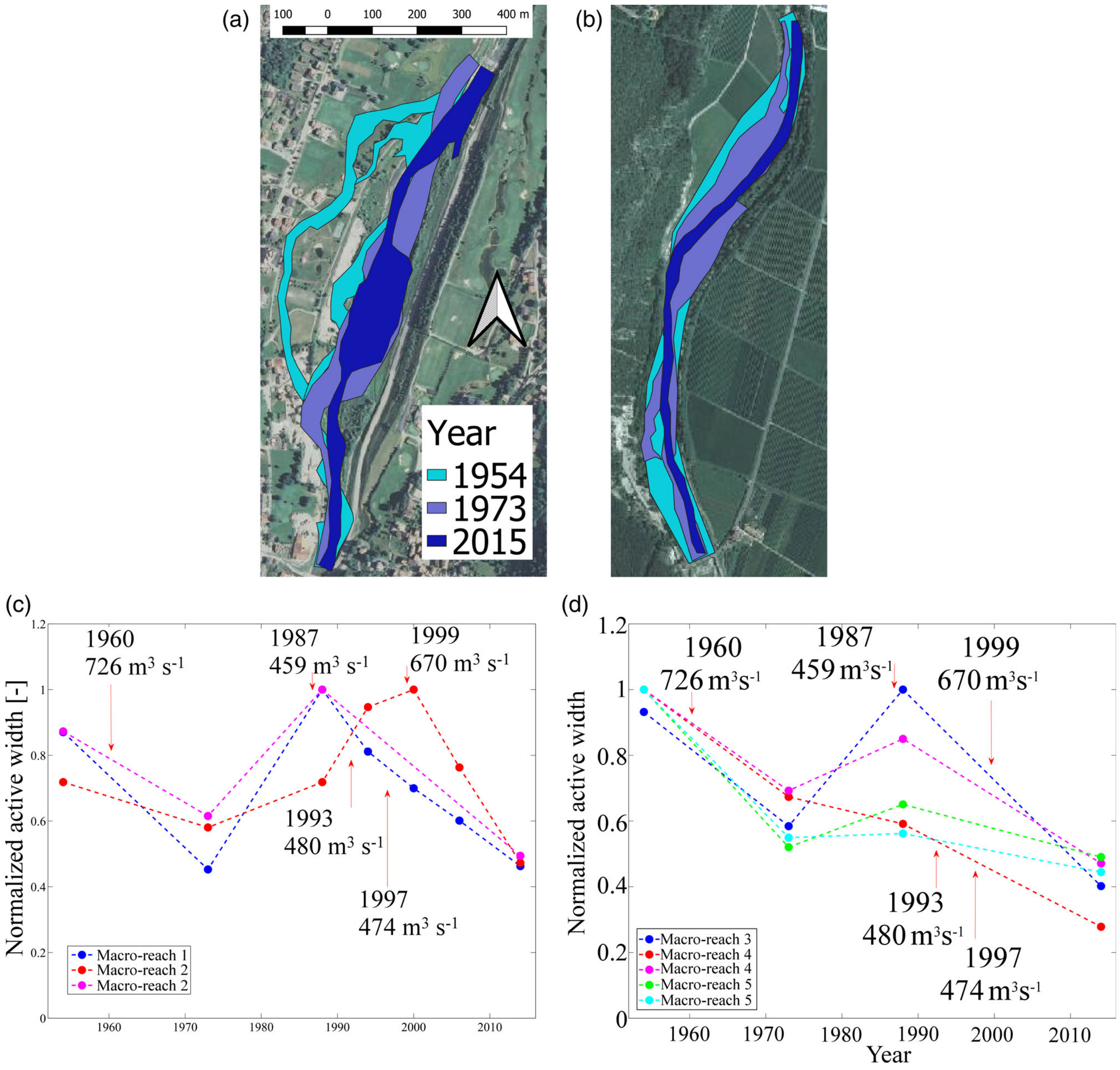

FIGURE 4 Changes in the active riverbed area occurred in sub-portions of macro-reaches 1 (a) and 4 (b). Trajectories of the reach-averaged active width for reaches included in macro-reaches 1 and 2, upstream the Ponte Piá reservoir (c) and 3, 4, 5, downstream the reservoir (d) [Colour figure can be viewed at wileyonlinelibrary.com]

the costs of the proposed restoration actions, on the basis of the main hydro-morphological element they address and their location.

Overall alteration scores for every macro-reach have been computed by averaging indicator values according to the four scenarios described in Section 3.5. Figure 7 shows that, regardless of the chosen scenario (combination of indicators), macro-reaches 1 and 2, are, in general, less altered, with higher ecological and morphological quality compared to downstream ones (3, 4 and 5). The only element that shows higher alteration in the upstream macro-reaches, 1 and 2, is the reduction in longitudinal connectivity (Table 2). Habitat alteration for the target fish species and alteration of the bedload-transporting events shows essentially little or no differences between the upstream and downstream groups. Proposed ecological restoration actions mainly focus on riparian vegetation management and on the control of different invasive species, besides few actions related to the control of waste management and wastewater inputs. Proposed habitat improvement measures mainly consist of displacing large boulders in the stream to enhance local hydraulic diversity and potential refugia, and in reshaping existing concrete bank protection structures through the use of boulders and woody material. Morphological restoration measures consist mainly of localized interventions aimed at creating new, often artificial, geomorphic units that can keep stable over

TABLE 2 Upper panel: (0–1, with 0 indicating maximum alteration and 1 indicating minimum alteration) values z_i^k [Equation (1)] of the normalized indicator for every analysed hydro-morphological and ecological element and for every macro-reach (levels 1 and 2); Lower panel: cost (€) of the proposed restoration actions separately computed for every hydro-morphological and ecological element which they address and for every macro-reach

Score Alteration parameter	Level 1				Level 2				
	Overall	STAR_ICMI	MQI	HA	Connectivity	Incip. Bedload	Channel adjustment	Bed sed.	Habitat
1	0.63	0.9	0.62	1	0	1	0.46	0.9	0.24
2	0.67	0.7	0.66	1	0.12	1	0.47	1	0.24
3	0.42	0.42	0.71	0.03	1	0	0.4	0.85	0.24
4	0.23	0.7	0.32	0	0.93	0	0.38	0	0.24
5	0.21	0.6	0.44	0	0.57	0	0.47	0.23	0.24
Proposed actions	Total				0				
1	110,000	0	0	0	50,000	0	0	0	60,000
2	400,000	30,000	330,000	0	25,000	0	0	0	15,000
3	25,000	5,000	0	0	0	0	0	0	20,000
4	165,000	0	160,000	0	5,000	0	0	0	0
5	768,000	25,000	730,000	0	10,000	0	0	3,000	0
Total		800,000	1,220,000	0	90,000	0	0	3,000	95,000

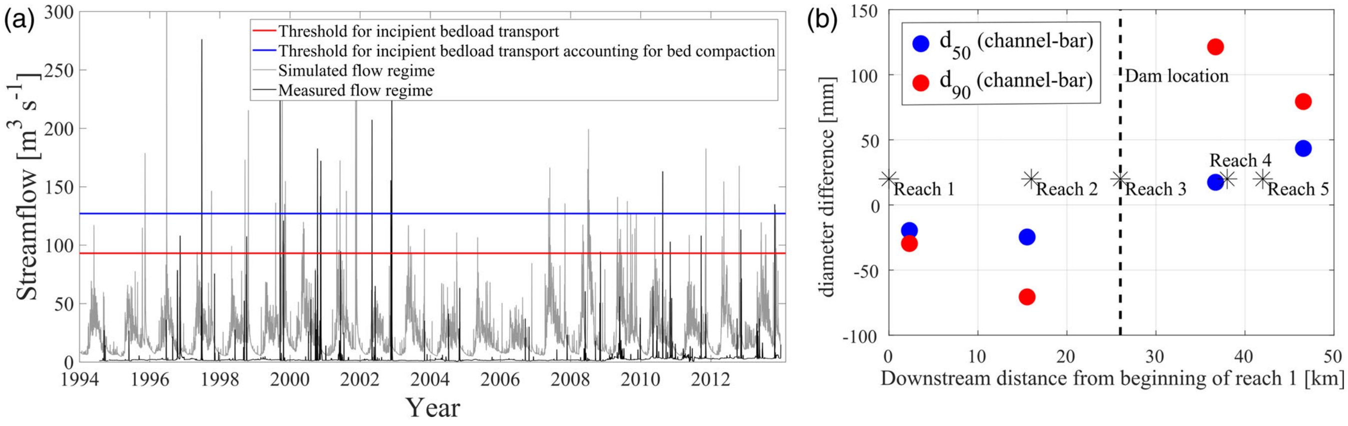

FIGURE 5 (a) Natural reconstructed and measured streamflow series (Sarche hydrometric station, reach 4) with two different thresholds for the initiation of bedload transport. (b) Difference between sediment size on the permanently wet channel and the adjacent exposed bar, computed for two percentiles (d_{50}, d_{90}) of the grain size distributions in different reaches upstream and downstream the Ponte Piá reservoir. Asterisks denote the location of the upstream section of every macro-reach [Colour figure can be viewed at wileyonlinelibrary.com]

time and can locally increase hydraulic and sedimentary diversity. Only one action, although of investigation type, is proposed in relation to sediment management. The largest share of the budget is for morphological restoration actions, which aim mainly to restore "static" morphological heterogeneity but not morphological processes (e.g., sediment transport, sediment continuity). In macro-reaches, 4 and 5, the removal of several weirs was proposed, mainly to restore the longitudinal continuity with the downstream Lake Garda for fish species. In one area, the proposed action is a restoration of the buffer zone, to improve physico-chemical water quality. Restoration actions already implemented by the regional government consist of artificial habitat improvement through the construction of small ponds or stable secondary channels that are fed through a backwater mechanism from the permanently wet channel, and that can be used also for recreational purposes.

Figure 7 presents the spatially explicit connection between the hydro-morphological analysis and the proposed restoration action. It shows that the score for each scenario and for every macro-reach, and the planned restoration actions do not precisely correlate. The largest number and amount of estimated costs are in macro-reach 5, where the alteration is the highest for each scenario. However, the second targeted macro-reach is number 2, characterized by the lowest alteration.

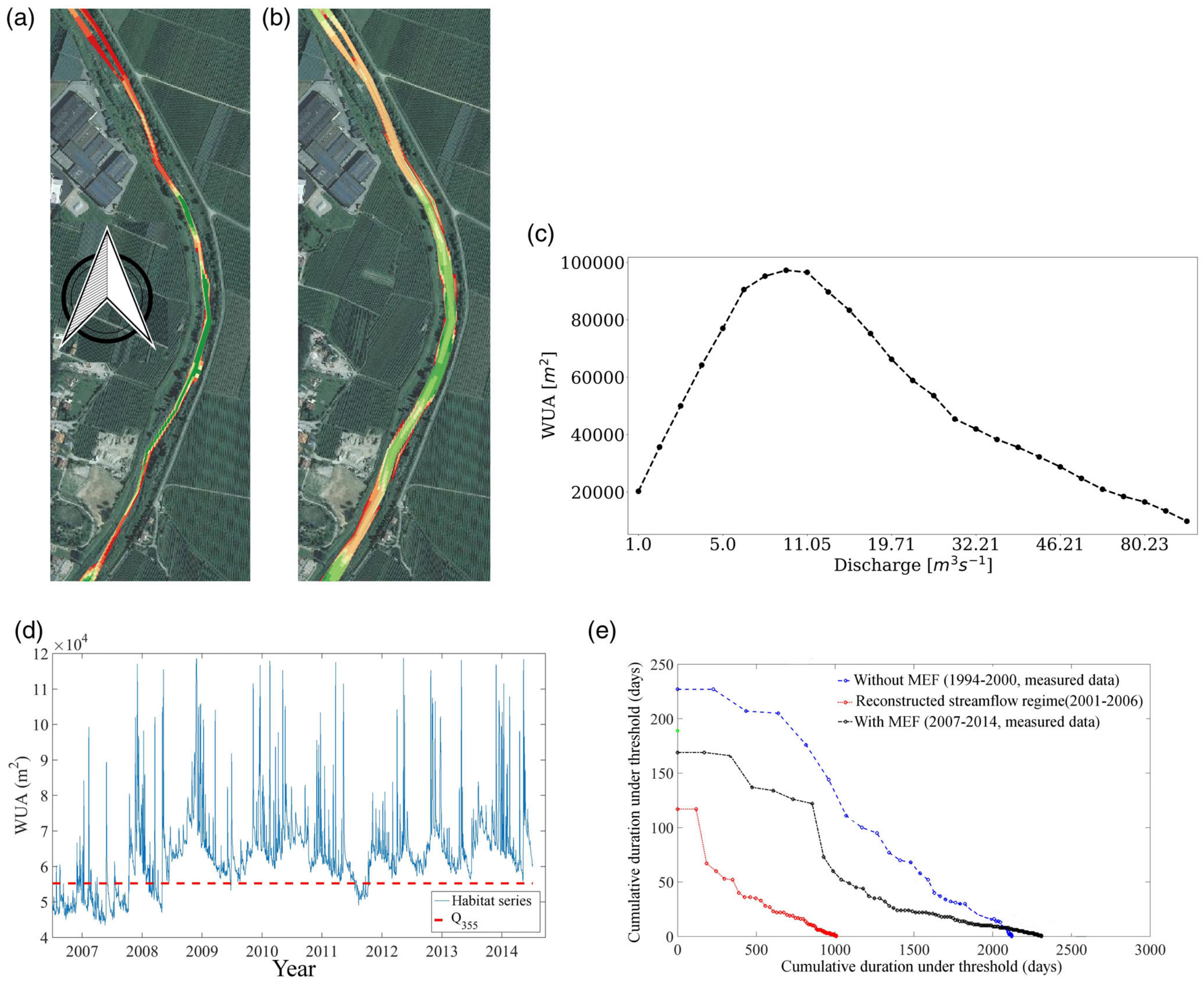

FIGURE 6 Illustrative steps of the habitat modelling analysis in macro-reach 4. (a and b) Maps of micro-scale habitat suitability at two different streamflow values in a portion of macro-reach 4. (c) Habitat–streamflow rating curve (WUA: Weighted Usable Area). (d) WUA time series for years 2007–2014, showing habitat improvement after change in regulation of minimum flow release. The red dashed line corresponds to the available habitat for the Q_{355} calculated from the reconstructed streamflow series. (e) Uniform continuous under threshold (UCUT) curves obtained by setting a threshold on the habitat time series corresponding to different streamflow scenarios (see legend) with the Q_{355} of the simulated pre-impact flow record [Colour figure can be viewed at wileyonlinelibrary.com]

5 | DISCUSSION

5.1 | Synthesis of hydro-morphological alterations and implications for river restoration

The Sarca River is an example of a heavily regulated Alpine river system, because of the alteration of the flow and sediment supply regimes. The most perceived alteration by the local stakeholders is related to the flow regime. Our analysis indeed confirms that all its components (magnitude, frequency, duration, timing, rate of change) are severely altered, and quantifies how the seasonal variability typical of Alpine, glacier-fed streams is essentially lost (Figure 3a). The present streamflow pattern consists of an almost constant low streamflow value, interrupted by few floods of short duration associated with major rainfall events, which cannot be fully controlled by the existing hydropower infrastructure. In some cases, the largest floods could still reactivate some morphological dynamics by disrupting the stable vegetated bars, as observed in other systems (Ziliani & Surian, 2016). However, after these rare floods, the system invariably tends to a new rather stable state characterized by much less diversity compared to pre-regulation conditions. Overall, the system morphological adjustment has qualitative analogies with the theory of alternative stable states that characterize some dynamical environmental systems (Scheffer et al., 2001). Flow (and likely also sediment) regime alteration has reached a significant stressor level, bringing the system to a new, dynamically “stable” state characterized by an active river corridor that is 40% narrower (Figure 6c,d) compared to the original, dynamical stable state that characterized

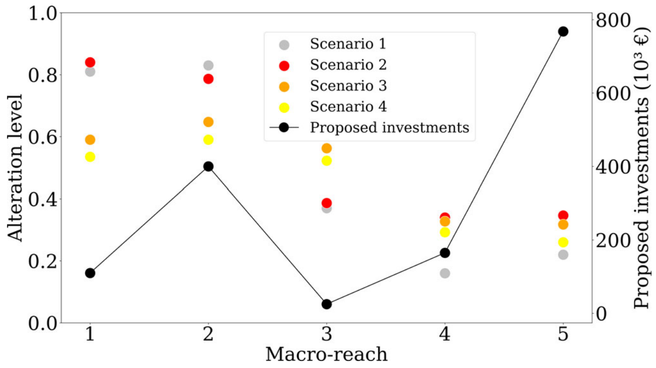

FIGURE 7 Spatially distributed (macro-reach) alteration scores for the four indicator scenarios and corresponding proposed investment for river restoration; (0, 1) indicate maximum and minimum alteration, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

pre-regulation condition. Sediment-transporting flood events, able to drive morphological change, still occur, but at such reduced frequency. The system under the present regulation condition therefore tends to such a new state, also after the rare large floods able to temporarily shift the system to the pre-regulation state only for a few years. Besides the river morphological dynamics, such altered flow pattern heavily affected the availability of hydraulic habitat for a target autochthonous fish species and, likely more indirectly, might have also contributed to alter the bed sediments' composition.

The second source of alteration relates to artificial changes in the river morphology that affect the sediments' supply regime: besides embankments and bank protection structures, the presence of many weirs and lateral structures decreases the longitudinal connectivity and the down-channel slope of the whole river segment. Although they were not analysed with the same detail in the present study, grade control structures are also widespread in most lateral tributaries. Overall, this heavily reduces the upstream sediment supply and the transport capacity of the Sarca River in the five macro-reaches. The detected alteration in the bed sediment composition (Figure 5b) can also be related to such alteration of the upstream sediment supply. Local fishermen organizations also report a strong decrease in the spawning sites, which is consistent with the observed paucity of the corresponding sediment size (fine to medium gravel) in the measured sediment samples.

Flow restoration has already shown its potential,, thanks to the implementation of compulsory MEF releases after 2007, which clearly improved the physical habitat for the target species (*Salmo trutta marmoratus*), decreasing the continuous duration and frequency of stress events (Figure 6e). MEF has also been reported by local stakeholders to be beneficial for the degraded thermal regime of most of the river system, although no data are available to quantify such improvement. The potential of reactivating self-formed morphodynamics, as done in many other restoration projects in Alpine streams (Rhodes, Closs, & Townsend, 2007), is highly limited (though not cancelled, Figure 4c,d) by the strong reduction of bedload-transporting flow events, and by the alteration of the riverbed composition. Riverbed alteration indeed implies that even higher than ordinary natural floods might be required to mobilize the bed sediments because of the high degree of compaction in the permanently wet channel, the presence of stable riparian vegetation on formerly bare gravel bars, and of the reduced channel slope due to the high density of lateral in-stream structures.

5.2 | Comparing locally proposed restoration measures and hydro-morphological alteration

The detected system shifts towards a new eco-morphological, dynamically stable state (Figure 6c,d) provides some support to the assumption that a higher hydro-morphological degree of alteration may correspond to a reduced likelihood to self-sustain river restoration action, as we implicitly assumed when developing the proposed methodology (Section 2). This is also supported by recent studies, which suggest that less-impacted streams can respond better to rehabilitation (Langhans, Hermoso, Linke, Bunn, & Possingham, 2014; Stranko, Hilderbrand, & Palmer, 2012). Such underlying reasoning guides the comparison between the present hydro-morphological alteration degree and the locally proposed restoration measures at the macro-reach scale in the application of the methodology to the Sarca River (Table 2 and Figure 7), which highlights three main issues.

The first issue relates to the spatial scales of the interventions. Locally proposed restoration mainly consists of very localized actions, even at the scale of geomorphic units, which represent the hierarchical geomorphological level just below the reach scale (Belletti et al., 2017). Thus, they have limited the capacity for affecting ecological or hydro-morphological processes at the hierarchically higher reach scale (Muhar et al., 2016). River processes acting out of a river restoration project's spatial and temporal horizons may limit the project success and hinder the achievement of the project goals (Wohl, 2018). River restoration projects are more likely to be effective and successful if framed into a higher catchment-scale context (Wohl, 2018; Wohl et al., 2005), a perspective which was not raised during stakeholders negotiation. Therefore, restoration actions should be planned by grouping them at a higher scale (e.g., macro-reach in the Sarca River case study), and be prioritized accounting for the hydro-morphological conditions, as less-impacted reaches may respond better to rehabilitation (Langhans et al., 2014; Stranko et al., 2012). More than half of the locally proposed actions are located in the macro-reaches with least hydro-morphological and ecological alteration, but such correlation is not reflected in the overall related budget (Figure 7). Moreover, the WFD requires actions on rivers with low ecological status to restore a good ecological status (or potential), and requires member states to take into account the cost-effectiveness of the measures (Klauer, Schiller, & Bathe, 2015). In our case study, the available budget is only 37,000 € per km, or 13,000 € ha^{-1}, well below the average value of 310,000 € (195,000 € without outliers) for other documented restoration projects in Europe (Szałkiewicz et al., 2018), and well below the budget of “flagship” restoration projects as the Thur River in Switzerland (3.7 Million € per km) and the Drava River 1999–2002 project in Austria (900,000 € per km). In this context, macro-reaches upstream the dam (macro-reach 1 and 2), which yields the second-least and the least hydro-morphological alteration, respectively, are more likely to sustain restoration actions within the constraints of a limited budget.

The second issue relates to the feasibility of the ideal restoration measures emerging from the hydro-morphological study. Flow regime restoration would be a prerequisite for reactivating morphological dynamics and sustaining higher diversity, which highly reduced in the last 60 years. While MEF implementation has already shown benefits in terms of habitat improvement, increasing the frequency of bedload-transporting events would be desirable but at the same time problematic because of the high costs for hydropower management and given the present regulatory framework. Regulatory improvements should shift from "threshold-based" to "regime-based" concepts (Poole et al., 2004), to ensure the necessary flow variability that sustain ecological dynamics, following the lead of few existing flow restoration examples worldwide that include artificial floods as integral part of a temporally variable ecological flow regime (Melis et al., 2012; Olden et al., 2014).

Finally, the critical comparison of the two complementary approaches to restoration design provides a template on which novel options, which were not previously considered, could be developed, representing trade-offs between feasibility and potential effectiveness. One of these is the release of recreational flows (kayaking, sport navigation), which may also be competent to transport the fine gravel fraction that can contribute to the regeneration of spawning sites. These artificial releases require much smaller water volumes compared to those needed to reactivate morphological dynamics, especially considering bed compaction and the hardly movable vegetated/fine sediment cover on the previous bare sediment bars (Carolli et al., 2017; Rood & Tymensen, 2001; Scheurer & Molinari, 2003; Serlet et al., 2018), but may well serve different purposes.

5.3 | Transferability of the approach

The methodology proposed in this work can be of interest and has enough flexibility to be applied to other regulated Alpine river systems, especially where restoration measures are constrained by relevant limitations in the available financial resources, and where complex, more detailed decision support systems (e.g., Klauer et al., 2015; Linke et al., 2012) are not applicable. The Sarca River case study presents similar pressures and data availability to other Alpine rivers (e.g., see Carolli et al., 2017). In particular, indicators for the ecological and the hydro-morphological quality are required by the WFD and usually available by the local agencies (column 3 and 4, Table 2), hydrological data for IHA analysis are available in national or regional databases (e.g., Italian, Austrian, Bavarian databases), although the length of historical series may be limited in time (column 5, Table 1). Aerial orthophotographs and data used to calculate the connectivity score (e.g., weirs and dykes) are often available by public bodies, not always freely accessible (column 6, Table 2). Analysis of bed sediment composition is based on field campaigns not requiring large resources. Perhaps, the most critical issue is the availability of sufficiently spaced river cross-sections and biological preference models for target species to perform habitat modelling. Preference models often suffer from subjectivity in the judgement from local experts, and require improvements in their transferability (Vezza, Parasiewicz, Calles, Spairani, & Comoglio, 2014).

6 | CONCLUSIONS

The work has proposed an indicator-based methodology to integrate and critically discuss two complementary approaches to design river restoration measures in a river catchment at a coherent spatial scale: an analysis of hydro-morphological alterations, together with some ecological implications, and a participatory synthesis of locally proposed restoration actions by relevant stakeholders. The methodology has been applied to the highly regulated Sarca River, in north-east Italy, representative of other Alpine streams in terms of hydro-morphological pressures, data availability and local interests towards restoring its environmental quality. The analysis used available data by public bodies, integrated with few targeted field measurements, and is, therefore, repeatable on other Alpine rivers with similar data availability.

The comparison shows relevant mismatches between the possible restoration options suggested by the two compared perspectives. Locally proposed actions are not conceived within a hierarchical spatial scale framework, which is instead crucial in determining hydro-morphological processes that control the sustainability of the restoration measures. On the other hand, proposals solely based on a hydro-morphological analysis without a direct relation with the local context may result in idealized and hardly feasible measures under present regulatory frameworks and local perception on the river system. Besides supporting the prioritization of the reaches to be targeted for restoration measures, the comparison also allows novel restoration options to emerge, which consider the relevant spatial scales and may represent a good trade-off between effectiveness and feasibility.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study were derived from public regional river management bodies or collected in the field by the authors; they are available on request from the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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