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Response of stream benthic macroinvertebrates to current water management in Alpine catchments massively developed for hydropower

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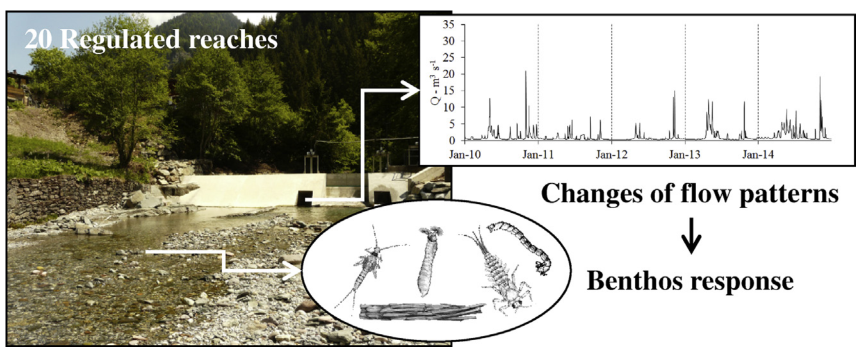
HIGHLIGHTS

- Minimum flows are currently implemented in the study area as environmental flows.
- 5-years monitoring of streamflow and benthos was performed at 20 regulated reaches.
- Differences of benthic communities were found at sites with different flow patterns.
- According to the current Italian standards, stream quality was on average good/high.

GRAPHICAL ABSTRACT



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ABSTRACT

The present work focuses on evaluating the ecological effects of hydropower-induced streamflow alteration within four catchments in the central Italian Alps. Downstream from the water diversions, minimum flows are released as an environmental protection measure, ranging approximately from 5 to 10% of the mean annual natural flow estimated at the intake section. Benthic macroinvertebrates as well as daily averaged streamflow were monitored for five years at twenty regulated stream reaches, and possible relationships between benthos-based stream quality metrics and environmental variables were investigated.

Despite the non-negligible inter-site differences in basic streamflow metrics, benthic macroinvertebrate communities were generally dominated by few highly resilient taxa. The highest level of diversity was detected at sites where upstream minimum flow exceedance is higher and further anthropogenic pressures (other than hydropower) are lower. However, according to the current Italian normative index, the ecological quality was good/high on average at all of the investigated reaches, thus complying the Water Framework Directive standards.

1. Introduction

The effects of climate change on the environment is a major topic in current ecological research. In Alpine catchments, receding glaciers and snowfields, combined with altered precipitation regimes, are driving shifts in hydrology and thus in biology (Hotaling et al., 2017). Frequently, these changes are superimposed upon anthropogenic hydrological alterations. Most of the Alpine streams are massively exploited for hydropower generation and their flow regime is highly regulated (Schinegger et al., 2012; Bruno et al., 2013; Premstaller et al., 2017). Due to the steep slopes typical of the Alpine areas, hydropower systems

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often induce severe water depletion in long river reaches, also in case of run-of-the-river projects (Lazzaro and Botter, 2015), which are widely recognized to impact river environments to a much smaller extent than reservoir systems (Bilotta et al., 2017).

Despite the huge efforts of the scientific community to define proper streamflow standards in regulated rivers, ecohydrological science still needs future investigation to provide the necessary knowledge and tools for policy development and distribution of sustainable water allocation (Acreman et al., 2014). Moreover, the management of flow releases to better meet both human and ecosystem needs is a complex societal challenge involving not only scientists but also water resources managers, policy makers and the public (Acreman et al., 2014; Acreman, 2016).

The Water Framework Directive (WFD, 2000/60/EC) is the main legislative reference for the European Union (EU) countries regarding water-related issues. Despite not using the term environmental flow (hereafter e-flow) explicitly, the WFD requires the achievement of "good ecological status" (GES, i.e. a slight deviation from a type-specific reference condition) for all water bodies in the EU context. Within the WFD, it is accepted that ecologically appropriate hydrological regimes are necessary to meet GES (Acreman and Ferguson, 2010) and a relevant guidance document provides detailed recommendations for considering e-flow in the WFD implementation (WFD CIS, 2015). This document prompts the EU countries to provide biologically-derived e-flows based on the requirements of the instream biota. However, the implementation of e-flows still remains a major issue in most of the EU countries.

Flow management in many Alpine streams is currently based on the early e-flow approach focused on quantifying a single minimum flow (MF) sufficient to maintain aquatic species during crucial low-flow periods (Tennant, 1976). This approach however is based on historical hydrological data series, without properly considering the requirements of the aquatic communities. E-flow recommendations based on simple hydrologic rules (McKay, 2015; Acreman, 2016) have been widely recognized to be inadequate for sustaining the biological structures and the functionality of aquatic ecosystems (Poff et al., 1997). Current state-of-the-art approaches (e.g. Poff et al., 2010; Richter et al., 2012; Yin et al., 2012; Yarnell et al., 2015) specifically advocate that flow recommendations should be based on the mechanistic relationships between flows and ecological outcomes. Nevertheless, the limited availability of hydrological and ecological data for Alpine streams often prevents their applicability (Vezza et al., 2012, 2014).

Benthic macroinvertebrate monitoring is widely used to characterize river quality, also from a normative point of view, and also in the WFD framework (Birk and Hering, 2006). The impact of the streamflow alteration on the biota has been frequently quantified through stream benthos sampling and analysis (e.g. Carlisle et al., 2014; Eddy et al., 2017). Also in the Alpine environment, where streamflow alteration can frequently be associated to hydropower, there are several studies available concerning stream quality assessment through benthos monitoring (Bona et al., 2008; Brown et al., 2015). The specific subjects of these studies range from quality assessment at a regional level (Yoshimura et al., 2006), to analysis of invertebrate drift induced by hydro/thermo-peaking (Bruno et al., 2010; Bruno et al., 2013), to restoration effects of artificial flooding in water depleted reaches below large reservoirs (Robinson et al., 2004; Robinson, 2012). However, current water management based on MF release below water diversion structures is surprisingly poorly investigated, both in terms of ecological response and hydrological alteration.

In this study, we present the results of a field investigation concerning the benthic macroinvertebrate response to the current water management practices in the central Italian Alps, where strategically important hydroelectricity at the National scale has longly been generated. Hydrological and biological monitoring was carried out in twenty regulated stream reaches for five years. Since 2009, MFs have been implemented in the study area, ranging from 5 to 10% of the mean annual natural flow estimated at the intake section.

We tested the basic hypothesis that stream reaches characterized by a relatively minor streamflow alteration would provide a better habitat, supporting richer and more diverse benthic macroinvertebrate communities. As a proxy of hydrological alteration in a regulated stream reach, we adopted an index relating the actual streamflow and the MF released at the upstream diversion structure.

2. Materials and methods

2.1. Study area

Our investigation was carried out in the central Italian Alps, in the catchments of Mera, Adda, Oglio, and Caffaro rivers (Fig. 1).

The Adda and Mera rivers are the main tributaries of Lake Como, with drainage areas of 2600 and 760 km^2, respectively. Both catchments are transboundary, with Swiss quotas of approximately 480 and 100 km^2. The Oglio (1400 km^2 basin area) and the Caffaro (140 km^2 basin area) drain into the Iseo and Idro lakes, respectively.

These catchments share common traits, typical of Alpine areas. Maximum elevations range from 3000 to 4000 m asl (except for the Caffaro basin, where maximum elevation is 2500 m asl). Water surface elevations at the receiving prealpine lakes range approximately from 200 m asl (Lake Como and Lake Iseo) to 350 m asl (Lake Idro). Maximum runoff is observed during late spring-early summer due to snowmelt. Flood peaks can also occur in autumn, due to heavy rainfall. With the exception of valley bottoms, the land is generally scarcely anthropized, with prevailing activities related to mountain tourism; several areas of high naturalistic interest are also present.

However, water resources in the area are massively exploited for hydropower. Around 50 GW hydropower are currently installed in the entire Alpine region (approximately 190,000 km^2 area shared by eight countries), providing renewable electricity of strategic importance on a European scale. In particular, peak-energy supply as well as grid-energy storage (i.e. pumped-storage hydroelectricity) is granted by Alpine reservoirs, providing about 12 km^3 capacity overall (Permanent Secretariat of the Alpine Convention, 2009; Gaudard et al., 2014). The Italian Alps account for 28% of the Alpine region in terms of area. There, over 210 large reservoirs (e.g. storage $>$1 Mm^3 or dam height $>$ 15 m) can store approximately 2.2 km^3 of water. According to the available estimates concerning the five-year interval 2011–2015 (Terna Rete Italia SpA, 2011, 2012, 2013, 2014, 2015), the overall hydropower capacity installed in the Italian Alps amounts to 15 GW, and is mostly subdivided into 170 large plants (i.e. larger than 10 MW). The related production exceeds 35 TWh per year, satisfying $>$10% of the National electricity demand. In the investigated catchments, hydropower pervasivity is even greater: for instance, the overall installed power in the catchments of the Adda and Mera rivers above Lake Como (including the Swiss quota of the Mera basin) currently exceeds 2.4 GW, giving an average productivity of approximately 6 TWh per year. Accordingly, the ratio between installed power and catchment area (0.7 MW km^{-2}) is more than double than the Italian Alpine region (0.3 MW km^{-2}).

Hydropower development in the area dates back to the beginning of the 1900′s, and, as it commonly occurs in the Alps, it is mostly performed through complex "cascade" systems, where water abstraction takes place at intakes of different size (Fig. 2 and Table S1 in the Supplementary Material). In particular, according to the water storage available at the withdrawal section, we have classified intakes with negligible storage, small reservoirs (e.g. available storage allows daily to weekly regulation), reservoirs (available storage allows seasonal regulation).

In order to obtain widespread exploitation of the available potential, the investigated catchments are overspread by several intakes (Fig. 1 and Table S1), located both on the mainstem of the rivers and on the tributary streams of different order. As mentioned above, in order to mitigate - at least partly - the impact of the off-stream diversion on