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A review of hydrological and chemical stressors in the Adige catchment and its ecological status

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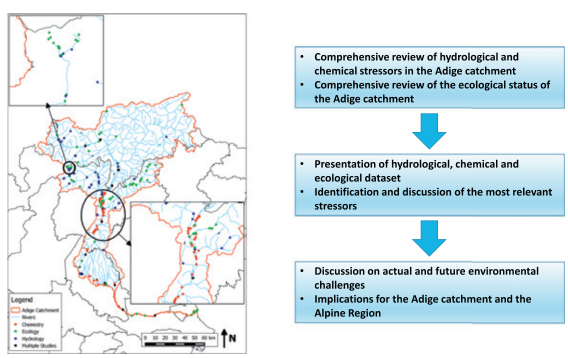
HIGHLIGHTS

- Comprehensive review of hydrological and chemical stressors in the Adige catchment.
- Comprehensive review of the ecological status of the Adige catchment
- Future challenges to characterize the feedback between stressors are discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

Quantifying the effects of multiple stressors on Alpine freshwater ecosystems is challenging, due to the lack of tailored field campaigns for the contemporaneous measurement of hydrological, chemical and ecological parameters. Conducting exhaustive field campaigns is costly and hence most of the activities so far have been performed addressing specific environmental issues. An accurate analysis of existing information is therefore useful and necessary, to identify stressors that may act in synergy and to design new field campaigns. We present an extended review of available studies and datasets concerning the hydrological, chemical and ecological status of the Adige, which is the second longest river and the third largest river basin in Italy. The most relevant stressors are discussed in the light of the information extracted from a large number of studies. The detailed analysis of these studies identified that hydrological alterations caused by hydropower production are the main source of stress for the freshwater ecosystems in the Adige catchment. However, concurrent effects with other stressors, such as the release of pollutants from waste water treatment plants or from agricultural and industrial activities, have not been explored at depth, so far. A wealth of available studies address a single stressor separately without exploring their concurrent effect. It is concluded that a combination of extended experimental field campaigns,

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focusing on the coupled effects of multiple stressors, and modeling activities is highly needed in order to quantify the impact of the multifaceted human pressures on freshwater ecosystems in the Adige river.

1. Introduction

The anthropogenic pressure on water resources is growing worldwide, and reducing its effects on the ecosystem is one of the major societal challenges to address in the near future (Ludwig et al., 2011; Navarro-Ortega et al., 2015; Vörösmarty et al., 2010; Kolditz et al., 2013; Barceló and Sabater, 2010). Knowledge of the complex feedback existing between hydrological (e.g., hydropeaking, water scarcity, flooding), geochemical (e.g., chemical pollution and erosion) and ecological (e.g., occurrence of invasive species, decrease in biodiversity) stressors in large river basins (e.g., 10,000 km^2 or more) is still patchy and additional research is needed to support informed decisions about water resources management at the catchment scale (Rodríguez-Iturbe et al., 2009; Ceola et al., 2014; Aristi et al., 2012; Widder et al., 2014). Even more complex can be to prioritize appropriate intervention strategies, considering economical and societal constraints (Boithias et al., 2014; Valle et al., 2014). For example, climate and land use changes are expected to impact the hydrological cycle to an extent that depends on the resilience of the catchment and on the spatial distribution of these changes (Botter et al., 2013; Destouni et al., 2013; Santos et al., 2014).

Furthermore, additional effort is required to better understand and quantify the fate of contaminants at the river basin scale (Grathwohl et al., 2013; Rinaldo et al., 2006; Botter et al., 2010). In the same way, the investigation, within a coherent framework, of the impact of micro and emerging pollutants (Medina et al., 2007), diffused sources of pollution (e.g., nutrient fluxes as shown in Rinaldo et al. (2005)) and particle facilitated transport (Rügner et al., 2014) on freshwater ecosystems, is a challenging task.

Modeling the impact of hydrological (e.g., water scarcity as described in Acuña et al. (2014) and chemical stressors (Holmstrup et al., 2010) on freshwater ecosystems is also an open issue for large river basins. In particular, the inclusion of the feedback mechanisms, which relate ecosystem functioning and anthropogenic activities to water resources management and chemical fluxes (Heathwaite, 2010), represents a challenge.

In order to investigate these three issues, i.e., changes in the hydrological behavior of large scale catchments, the fate and transport of pollutants in the environment and the interaction with the ecosystem (comprising human activities), it is important to have access to all available information. In particular, it is beneficial and in some cases absolutely necessary, for gaining a global perspective, to integrate data collected by water authorities and environmental protection agencies operating in the river basin, with results published in both peer-reviewed journals as well as in technical reports and other types of gray-literature (e.g., Uhlemann et al., 2013).

In the present work, we provide a review of available hydrological, chemical and ecological data for the Adige catchment, a large Alpine catchment located in Northeastern Italy (Fig. 1). The location of the sites targeted in the peer-reviewed studies are reported in the map shown in Fig. 2 with additional details provided in the Supporting Information. The Adige catchment has been selected as a case-study in the FP7 project GLOBAQUA (Navarro-Ortega et al., 2015), because representative of the variety of stressors encountered in the Alpine region: i) hydropeaking and thermopeaking caused by hydropower production (Zolezzi et al., 2009, 2011); ii) emerging and regulated pollutants released by waste water treatment plants (WWTPs) effluents, which are expected to show significant temporal variations due to seasonal touristic fluxes; iii) climate change, which is expected to impact the hydrological cycle by reducing winter snowfall with the consequent reduction of late spring and summer runoff (Majone et al., 2015; Carturan et al., 2013; Beniston and Stoffel, 2014); iv) pollutants transported by atmospheric circulations and stored in retreating glaciers which are released at low concentrations as an effect of increasing temperatures as observed in the Italian Alps (Villa et al., 2006a) and in other Alpine regions (Bogdal et al., 2010).

The structure of the paper is as follows: the second section provides a general description of the catchment, while the third focuses on the main hydrological stressors. The fourth section reviews the available data on the chemical status of the catchment. The fifth section deals with the ecological investigations focusing on macro-invertebrates. In the sixth section, identification of the most relevant stressors is discussed, and finally, the last section delineates the major scientific challenges in assessing hydrological functioning and water quality dynamics beyond the requirements of the Water Framework Directive.

2. Study site

2.1. Hydrology

The Adige river rises from a spring in proximity of the Resia lake at the elevation of 1586 m a.s.l. and after 409 km it ends in the Adriatic

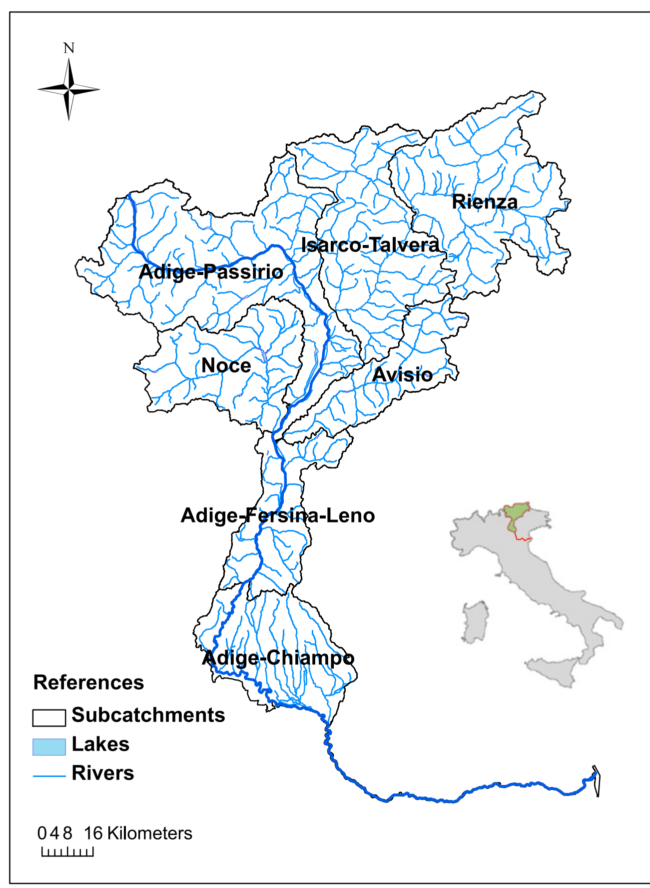

Fig. 1. Map of the Adige basin. Black polygons indicate the main sub-basins, the dark blue line highlights the Adige River, whereas the light blue lines represent the tributaries. The lower right inset shows the location of the Adige catchment within the Italian territory.

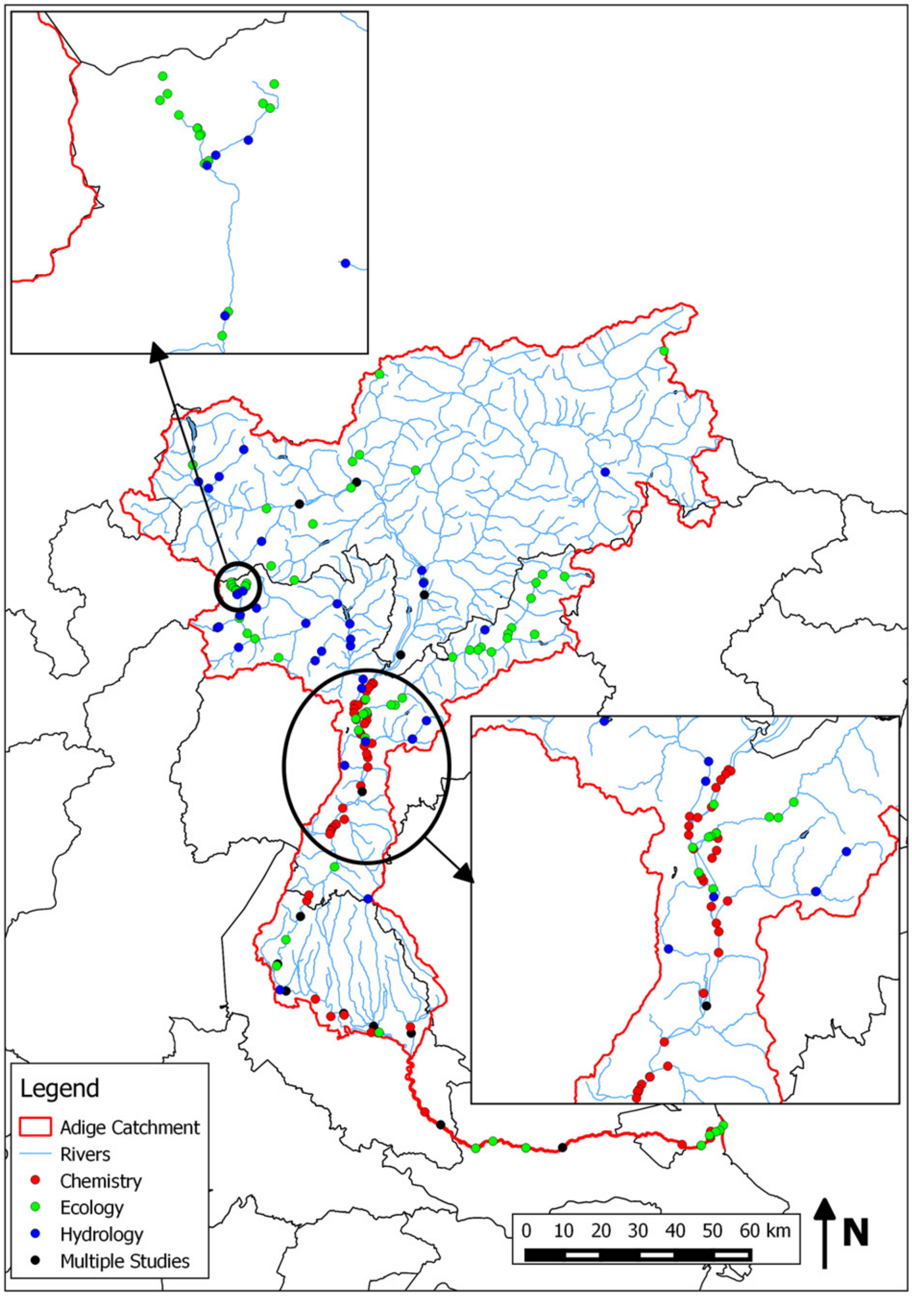

Fig. 2. Location of the peer-reviewed studies collected in this work. Red dots indicate studies related to the chemical status of the Adige River and its tributaries, while green and blue dots refer to ecological and hydrological studies, respectively. Black dots refer to interdisciplinary studies.

sea at Porto Fossone between Brenta estuary and Po river delta. With a contributing area of 12100 km, the Adige is the third largest Italian river (after Po and Tiber) and the second longest (after Po). The mean water discharge registered at Boara Pisani gauging station (see Supporting Information for the location) is about 202 m^3/s (Autorità di bacino del fiume Adige, 2008), with peaks usually registered in the period from June to September (Piovan, 2008), showing the typical behavior of Alpine catchments.

The Adige river flows through the territories of the Province of Bolzano (62% of the overall river basin surface), the Province of Trento (29%) and the Veneto region (9%). From the source to Merano the Adige flows east through the Venosta valley (with a drainage area of 1680 km^2). Then, it turns south and crosses the valley that holds its name. The Adige receives the contribution of the Isarco river, close to Bolzano, and the contributions of both the Noce and Avisio rivers just upstream of Trento, where the drainage area of the Adige river rises, thanks to these contributions, to 9810 km^2. Finally, it crosses the Lagarina valley until Verona (drainage area of 11100 km^2) and then it turns east again and flows through the Padana plain without receiving other significant contributions. Because of the lack of significant contributions in the lower reach, hydrological studies have been conducted chiefly in the northern part of the catchment (i.e., Province of Trento and Province of Bolzano). The river basin is divided into 7 main subbasins: Adige-Passirio, Isarco-Talvera, Rienza, Noce, Avisio, Adige-Fersina-Leno and Adige-Chiampo (see Fig. 1).

The river basin contains 550 lakes, most of which have a surface smaller than 1 ha and of glacial origin (Autorità di bacino del fiume Adige, 2008). The biggest natural lake is Caldaro, followed by Anterselva, Braies and Carezza in the Province of Bolzano, Lake Tovel and Terlago in the Province of Trento.

Glaciers are carefully monitored within the catchment (Autorità di bacino del fiume Adige, 2008), since they strongly influence the annual flow regime and due to the increasing concern related to the observed acceleration in melting caused by rising air temperatures. Analysis of land cover changes as retrieved by CORINE (//www.eea.europa.eu/publications/COR0-landcover) products in 1990 and 2006 (Swen Meyer, personal communication) showed that glaciers have reduced their surface extent with a negative trend of about 2.3 km^2/year. According to the last report from the basin authority (Autorità di bacino del fiume Adige, 2008), glaciers cover an area of 212 km^2, corresponding to 1.9% of the catchment's area at Verona.

Climate in the Adige river basin is characterized by dry winters, snow and glacier-melt in spring, whereas it is humid during summer and autumn. Annual average precipitation values range between 500 mm in Val Venosta and 1600 mm in the southern part of the basin.

2.2. Geology

The geological characteristics of the Adige basin were defined during Alpine orogeny, with the overlapping of different rock complexes. As a consequence of this overlapping process, it is possible to distinguish three main groups or zones: Pennidic, Austroalpine and Southern Alps (Autorità di bacino del fiume Adige, 2008; Piovan, 2008).

Rocks of the "Tauern Window" characterize the north-eastern sector of the Province of Bolzano. They represent the group of minor tectonic extension that remained at greater depths during the Alpine orogeny. This has led to a high metamorphosis due to high pressure and temperature. Although gneiss and schists dominate, quartzites, amphibolites, serpentinites, schists and marbles are also present. The Pennidic area (between Valle Isarco and Valle Aurina) can be subdivided in some complexes, which are ordered from the bottom to the top as: complex of Tux-Gran Veneziano (granitic gneiss with subordinate paragneiss, micaschists, quartz and marbles); complex of Greiner-Picco dei Tre Signori (prevalent micaschists granatifer, with interpositions of quartz and marbles) and complex of Calcescisti with ophiolites.

The rocks of the Austroalpine group are mainly metamorphic and cover most of the Bolzano Province. Among these rocks prevail gneiss (orthogneiss, paragneiss), schists and mica schist, encountered in Val Venosta and Val Passiria and in part of Val Pusteria. There are also phyllites, amphibolites, quartzite, dolomite and marble.

The formations of the Southern Alps have overlapped other rocky complexes during the Alpine orogeny, and present three different geological formations: sedimentary rocks of the eastern and southern Province of Bolzano (Dolomites and Mendola complex); phyllites, which are low-grade metamorphic rocks; and igneous effusive rocks (porphyries) from the volcanic Atesino complex. In the stratigraphic sequence of the Southern Alps, including the dolomitic groups of Gardena, Badia, Fassa e Non valleys, the Lagorai chain and the calcareous–dolomitic mountainous groups of the Adige valley as well as the volcanic–sedimentary of the Lessini Mounts, it is possible to distinguish the different competent units (compacted, massive, and coherent) from that incompetent (very stratified, with clay, and erodible).

Moreover, more recent deposits can be found in the valley floor, which can be defined as "loose sediments" and whose nature is related to the transport capacity of the Adige river and its tributaries. These sediments contribute to alluvial fan formation. Additionally, in these formations it is also frequent to find evidence of detritus, glacial and fluvio-glacial deposits.

2.3. Land use

The main agricultural areas in the northern part of the catchment are located in the Adige, Noce and Venosta valleys, and the cultivation comprise mainly fruit trees and grapes (Cassiani et al., 2015). Land use at high elevations is dominated by grass, grazing and forest. In the Veneto Region, the catchment area is very small and the stream is mainly suspended: in the Province of Verona agriculture is a very important economical activity and is supported by a large irrigation consortium. Mountains cover an area of around 9700 km^2, with very wide forest, pioneer vegetation and exposed rocks. The largest urban areas are located in the main valleys where land use is more heterogeneous.

Summarizing, the analysis of land cover map, as retrieved by CORINE product for 2006, indicates that 56% of the catchment area is covered by forest (i.e., coniferous forest, mixed forest, vegetation areas and agroforestry), with meadows and pastures occupying 17.9% . The remaining area is subdivided as follows: 12.35% is destined to agricultural purposes (i.e., fruit trees and berry plantations, vineyards, orchards, and non-irrigated arable land); 8.85% is covered by bare rocks; 2% is water (i.e., water courses, glaciers and perpetual snow); 2.2% is urban areas with the remaining 0.6% destined to other uses (e.g., industrial and commercial areas, roads).

2.4. Water use and economy

The Adige river provides water to 34 large hydropower plants (average nominal capacity larger than 3 MW) with a total effective power of 650 MW (Autorità di bacino del fiume Adige, 2008). Water management for hydropower production is performed with 28 reservoirs, 15 in the Province of Bolzano and 13 in the Province of Trento, with an operational total storage of 560.59×10^6 m^3. The two largest reservoirs are Resia and Santa Giustina, with a storage of 116×10^6 m^3 and 172×10^6 m^3, respectively; 11 reservoirs have a storage between 10×10^6 and 50×10^6 m^3; 11 between 1×10^6 and 10×10^6 m^3, whereas the remaining 4 have storage smaller than 1×10^6 m^3 (Autorità di bacino del fiume Adige, 2008) (see Fig. 3). In addition to the aforementioned large hydropower plants, about 1050 small hydropower plants are distributed within the river basin (Provincia Autonoma di Trento, 2006; Provincia Autonoma di Bolzano, 2010).

We notice that aggregated values relative to hydropower production are reported differently depending on the information provided by the two managing authorities (Provincia Autonoma di Trento, 2006; Provincia Autonoma di Bolzano, 2010). In the Province of Bolzano, the mean annual hydropower production amounts to 6940.45 GWh, while total average nominal licensed water discharge for hydropower production in the Province of Trento is about 404.4 m^3/s (subdivision for each of the main tributaries of the Adige river is reported in the Supporting Information).

Besides the presence of hydropower the basin is intensively exploited with a large number of small withdrawals associated to a variety of water uses: agricultural, civil and industrial. Average nominal licensed water discharge is lower than 0.5 l/s for 70% of the derivations, percentage that increases to 90% for a thresold of 1 l/s.

Fig. 4 shows the licensed water uses in the northern part of the catchment. In the Province of Bolzano the second highest water demand, after hydropower, is for irrigation, followed by industrial and other uses, and finally for drinking water supply (Provincia Autonoma di Bolzano, 2010). Similarly, in the Province of Trento, the largest licensed average annual volume is for hydropower, followed by irrigation, domestic and livestock, and industrial uses (Provincia Autonoma di Trento, 2006). Moreover, 153 water withdrawals from the Adige main stream, its tributaries and channels connected to the river network in the portion of the basin within the Veneto region. In this case the main water uses are for agriculture, with the rest being distributed between civil (i.e. drinking), industrial and other uses.

3. Hydrological status

In this section we refer mainly to the hydrological information available in the northern part of the catchment. Data from about 200 meteorological stations are available with a variable extension of the time series of precipitation, temperature, wind speed and direction, humidity, and atmospheric pressure (data available at http://

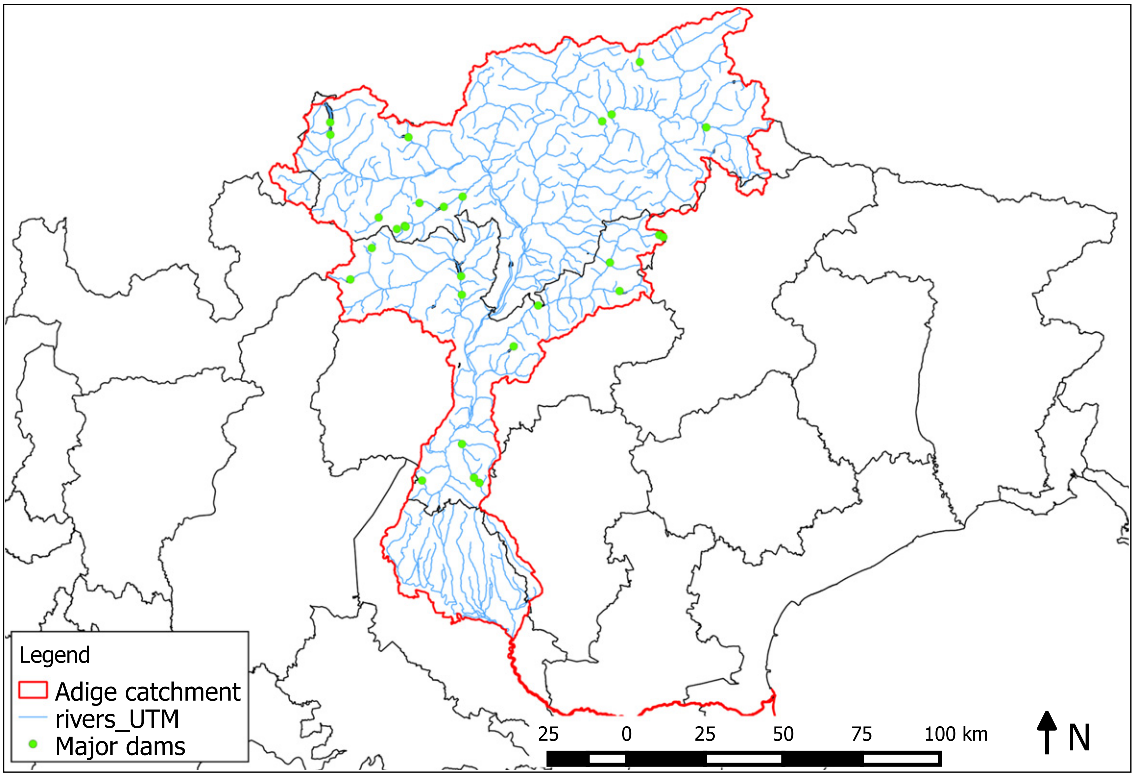

Fig. 3. Location of reservoirs within the Adige river basin.

www.meteotrentino.it for the Province of Trento and http://www.provincia.bz.it/meteo/home.as for the Bolzano Province). Long term daily historical precipitation and temperature data are available starting from 1930, while data with 5 min and 15 min resolution for precipitation and temperature, respectively, are available since 1980. About 70 snowfields are also available recording snow depth, density and surface temperature. In addition, groundwater levels at hourly resolution, with a variable extension of the time series, are available at 130 locations. Streamflow data are registered continuously at 69 gauging stations. Several of them record daily historical data for at least two decades, while others (e.g., the gauging station in Trento which has a drainage area of about 9700 km^2) operate continuously since 1920. High-resolution data are also available with a maximum resolution of 10 min. Streamflow shows a typical Alpine regime with two peaks, one in spring due to snow melt and the other in autumn due to cyclonic storms, which are the main cause of flooding events.

Despite its intrinsic difficulty, identification of the main contributions to runoff and of the hydrological interactions between melt water, streamflow and groundwater is crucial for effective water resources management in mountain river basins, and the Adige is not an exception. A number of studies have investigated this issue at the local scale. Groundwater flow was investigated at the confluence between Adige and its tributary Isarco by means of stable isotopes and gas tracer experiments (Leibundgut et al., 2009, ch. 7.5.1). The outcome of the study indicates a contribution of infiltrating river water ranging from %1 to 2%. A detailed hydraulic model of the surface–groundwater interaction between Adige river and regional aquifer was performed by Carneglutti et al. (1999) and Castagna et al. (2015) in order to assess aquifer exploitability. Norbiato et al. (2009) analyzed the effect of climate, geology, land use, flood types and initial soil moisture conditions on event runoff coefficients focusing mainly on medium size mountainous catchments located in the Adige catchment. Other hydrological

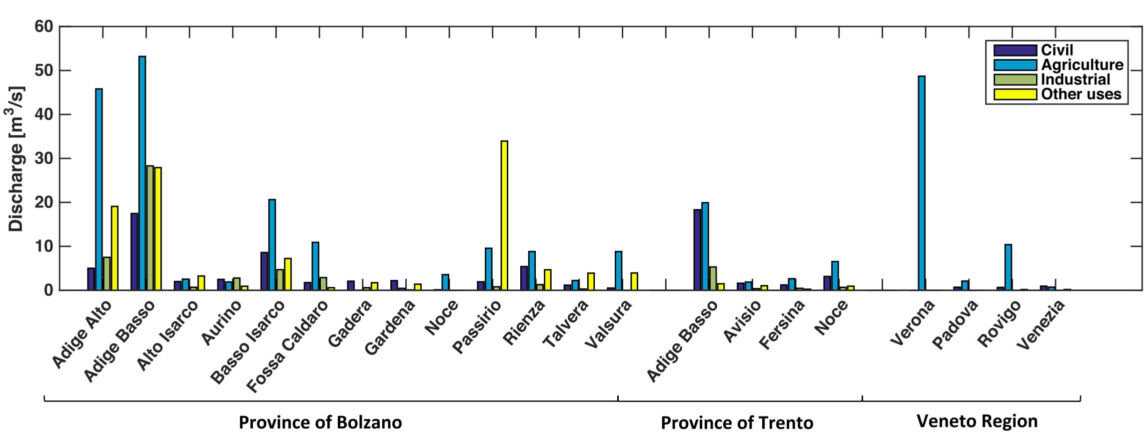

Fig. 4. Average nominal licensed water discharge [m/s] according to the different water uses in the Adige catchment. Notice that for the data referring to the Province of Bolzano civil use corresponds only to drinking water.

studies investigated spatial and temporal variability of runoff water sources in the San Vigilio (Van de Griend et al., 1986), Saldur (Penna et al., 2013; Penna et al., 2014) and Vermigliana (Chiogna et al., 2014) catchments by means of stable isotope ratios of oxygen and hydrogen. In particular, Penna et al. (2014) found that snow melt contribution to groundwater storage was significant and in the range between 58% and 72% during 3 years of observations. Chiogna et al. (2014) evidenced for the Vermigliana the significant contribution of the tributaries, whose streamflow originates mainly from snow and glacier melt. Average contribution is 44% and 75% for Presanella and Presena creeks, respectively. Other studies focused on the analysis of the streamflow generation process in karst systems (Majone et al., 2004; Majone et al., 2010), while stable isotope records retrieved from stalagmite samples in caves have been used as proxies for climate change variability (Miorandi et al., 2010; Scholz et al., 2012). This background shows that local studies are available for the hydrological characterization of some tributaries of the Adige river. However, a comprehensive framework to integrate the different sources of available information (water stable isotopes, snow and groundwater data, availability of streamflow data

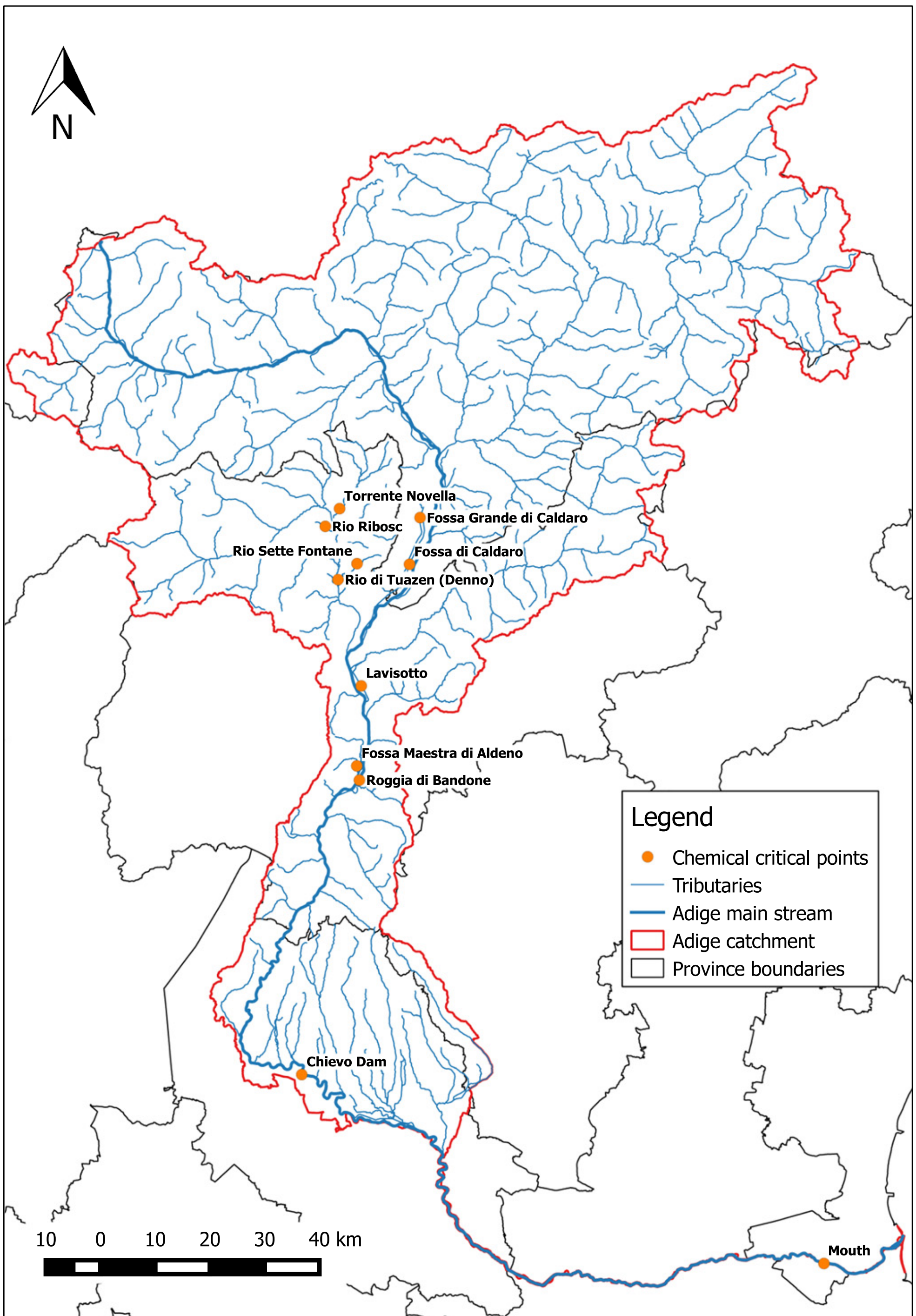

Fig. 5. Location of chemical critical points in the Adige catchment.

in several nested sub-catchments) into hydrological models to reduce uncertainty and improve their predictive capability, is still lacking at the river basin scale.

4. Chemical status

The chemical status in the Adige River basin is classified as good in the majority of the sites routinely monitored by the environmental protection agencies of the Province of Trento, Province of Bolzano and Veneto Region (Autorità di bacino del fiume Adige, 2002). The status of 3270.4 km of the river network, which counts for 82.7% of the total length, is classified as good, 154.8 km (3.9%) as poor and 531.4 km (13.4%) as unknown or non-scheduled (Distretto idrografico delle Alpi Orientali, 2014). Water bodies classified in poor conditions, in terms of the chemical status, are shown in Fig. 5.

In this section, we focus on available data present in the scientific and gray literature. Another important source of data is the database of the environmental protection agencies operating in the Adige River catchment, collected to comply with the European Water Framework Directive (WFD). Literature studies related to the chemical status of the Adige River catchment can be divided into three groups: the first group includes nutrients (e.g. N, P and their compounds), the second concerns with inorganic pollutants such as metals and heavy metals and the third group contains organic pollutants such as persistent organic pollutants (POPs), hydrocarbons and pesticides. An overview of all sampling campaigns performed in the basin is presented in Table 1. In the Supporting Information we provide a comprehensive overview of the data available such as sampling locations, measured compounds and measured concentrations found in the collected literature.

Table 2
Concentrations and legal limits for human consumption of nitrogen and phosphorus species.

Chemicals	Concentrations	Legal limits for human consumption
NH_4^+	0.253 mg/L	0.5 mg/L
NH_3	0.003 mg/L	0.5 mg/L
N-NH_4^+	0.167 mg/L	0.5 mg/L
N-NH_3	0.001 mg/L	0.5 mg/L
NO_2	0.071 mg/L	0.5 mg/L
Ptot	0.062 mg/L	–

4.1. Nutrients

Benfenati et al. (1992) identified in the stream Coste, an effluent of Adige in Rovereto area, the highest values of organic matter (COD, BOD, TOC and ethereal extract). However, in the lowest reach of the Adige river the concentrations of organic matter seem to decrease significantly probably due to the positive influence of water treatment plants. Braioni and Salmoiraghi (2001), Braioni (2001a) and Braioni (2001b) performed a systematic sampling campaign along the Adige river in the northern part of the catchment. These studies report a mean concentration of nitrogen species and total phosphorous for the sampling period and for sampling areas summarized in Table 2; further details relative to this study (e.g., measured concentrations and sampling points), are reported in the Supporting Information.

Peripoli (2008) analyzed water samples of the Adige river collected every 15 days in the period March–September 2008 in five sampling stations (see Table 1). The comparison of this work with the results of Braioni and Salmoiraghi (2001) evidences a slight reduction in the

Table 1
Summary of all the chemical sampling campaign in the Adige catchment.

Year	Pollutants	Sampling sites	Source
5/11/1984	Ni, Cr, Pb, Cu, Zn, Cd	Adige river estuary (Busiola, Portesine and Laghetti + two in the sea)	Juračić et al. (1987)
05/06/1982–22/02/1983	ΣDDT, PCBs	Ceraino (Adige river), Villa Buri (Adige river), Final track Fibbio (Adige tributary), Final track Alpone (Adige tributary), Villa Bartolomea (Adige river)	Pavoni et al. (1987)
05/06/1982–22/02/1983	Hg, Cd, Cu, Zn, Pb, Cr, Ni, Co, Fe	Ceraino (Adige river), Villa Buri (Adige river), Final track Fibbio (Adige tributary), Final track Alpone (Adige tributary), Villa Bartolomea (Adige river)	Duzzin et al. (1988)
01/04/1990–01/07/1990	Dichlobenil, lindane, seazine, atrazine, metolachlor	Northern tract of Adige river	Befenati et al. (1990)
01/05/1989–01/10/1989	Ammonium ion, nitrite, nitrate, chloride, sulfate, Al, As, Ba, Be, B, Cd, Cr III, Cr IV, Cu, Fe, Hg, Mn, Ni, Pb, Se, Sn, Zn, Ptot, COD, BOD, TOC, ethereal extract, anionic, surfactants, methylisobutylketone, p-xylene, m-xylene, o-xylene, 4-methyl-2-pentanol, naphtalene, indole, phthalates, BHT, coliforms-total, fecal coliforms, streptococci	14 points on the Adige river + 5 points on the tributary	Benfenati et al. (1992)
1997–1998	BOD5, NH_4^+, NH_3, N-NH_4^+, N-NH_3, NO_2, Cl^-, Ptot, MBAS, Pb	Ponte San Lorenzo, Ponte San Giorgio	Braioni (2001a,b)
14/02/2004–25/03/2004	HCO_3, F, Cl, NO_3, NO_2, NH_4, PSO_5, SO_4, Na, K, Ca, Mg, As, Al, Sb, Ag, Ba, Cd, Co, Cr, Fe, Li, Mn, Mo, Ni, Pb, Cu, Se, Sn, Sr, V, Zn	Fiume Adige A1, Torrente Avisio AV, Torrente Noce N, Torrente Fersina F	Fuganti et al. (2005)
December 1997–April 1998	Ag, Ba, Bi, Cd, Co, Cr, Cu, Fe, Mo, Mn, Pb, Sb, Ti, U, V, Zn, Cl^-, SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, K^+, Na^+	Tarlenta, Prarodont, Viote, Tonale pass, Folgarida, Mount Presena, Pampeago (TN)	Gabrielli et al. (2006)
2006–2007	TEL, TREL, DEL, TOL	North of Trento	Andreottola et al. (2008)
March–September 2008	Na, Mn, K, Ca, Cl^-, SO_4^{2-},NO_3^-, NH_4^+, Ptot, SiO_2	Bolzano, Cortina all'Adige (BZ), Besenello (TN), Pescantina (VR) e Boara Pisani (PD)-Badia Polesine (RO)	Peripoli (2008)
25/7/2010–9/8/2010	Carbamazepine, fluoxetine, diazepam, lorazepam, bromazepam, lormetazepam, codeine, morphine, 6-acetylmorphine, benzoylecgonine, (Â±)-amphetamine, (Â±)-methamphetamine	Influent Verona's WWTP	Repice et al. (2013)
04/05/2011–24/10/2012–30/04/2013	PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFBS, PFHxS, PFOS	Cavarzere VE, river Adige, San Bonifacio VR, tributary Alpone	Valsecchi et al. (2015)

dissolved oxygen concentration and a general reduction of nitrates between 2008 and 2001. Ammonia displays the same concentration gradient in both studies from upstream to downstream (ammonia concentration decreases from Bolzano (north) to Boara Pisani (south) by 50%). Moreover, phosphorus concentrations oscillate without a clear spatial trend. No significant temporal variations can be identified comparing the studies of Peripoli (2008) and Braioni and Salmoiraghi (2001). Furthermore, Di Lorenzo and Sartori (2007) define the area between Gardolo and Mezzocorona as a not exposed zone to nitrates from agricultural origin.

Comparing the Adige river with other North Italian rivers such as Brenta, Piave, Livenza, Isonzo etc., it is possible to conclude that the catchment presents the lowest values of NO_3, moderate values of NO_2, NH_4 and PO_4 (Cozzi and Giani, 2011). Moreover, available data indicate that nutrients are not a critical stressor within the catchment.

4.2. Inorganic pollutants

An overview of the literature describing inorganic pollutants within the Adige catchment is provided in Table 1, while in the Supporting Information measured concentrations and sampling locations are also provided. Metals and heavy metals have been monitored in the Adige estuary by Juračić et al. (1986) and Juračić et al. (1987). Presence of Ni, Cd, Zn and As has been also reported for the upper part of the catchment, while Cr, Pb and Hg have never been detected (Provincia autonoma di Bolzano, 2006). Duzzin et al. (1988) indicated as possible sources for heavy metals (in particular Cr) an important leather production district, tanneries and paper industries in the southern part of the catchment. More recently Fuganti et al. (2005) detected considerable concentration of Cr in water samples (0.4 μg/L). In the last years (2010–2012) the chemical status of the final course of the Adige River (Veneto region) and its tributaries (Fibbio and Alpone) has improved: in fact, referring to the latest published data of the environmental protection agency of the Veneto Region, no metals or heavy metals have been detected and the chemical status is defined as good and even high at the confluence of Alpone stream and Adige river (www.arpa.veneto.it/dati-ambientali).

Benfenati et al. (1992) identified the presence of Mn and Cu (see Supporting information), although the concentrations are below the Italian legal limits (50 μg/L for Mn and 1 mg/L for Cu).

Another metal detected in the basin is As (Fuganti et al., 2005): the highest values (up to 56 μg/L) are found in water that leaches volcanic rocks and in the water of the deep aquifer of the Adige Valley. The reason of arsenic accumulation only in deep water is determined by the lack of oxygen. The only exception is in the *Roverè della Luna* aquifer where considerable concentration of arsenic is found also in the shallow aquifer (concentrations up to 32 μg/L in water samples, hence above the legal limit of 10 μg/L).

Gabrielli et al. (2006) reported atmospheric deposition of heavy metals in shallow snow samples (see Table 1 and the Supporting Information). The study noticed the reduction of concentrations values at high altitude: sites locate at higher altitudes are less influenced by anthropogenic emissions originating from the adjacent Alpine valleys and the higher snow accumulation causes dilution. An exception of this behavior is *Passo Tonale*: higher concentrations than in the other sites are observed probably due to the proximity of anthropogenic sources. Possible sources of atmospheric trace elements may be activities related to winter tourism: in the Province of Trento, Pb and Cd can be associated to the intensive automobile and truck traffic in the valleys, NO_x emissions are mainly due to road transportation and SO_x emissions (minor importance) are mainly due to agriculture and industry (Provincia Autonoma di Trento, 2003; Gabrielli et al., 2006).

It is also worth mentioning the contaminated site named *Trento nord* (included as an area of national interest in the decree n. 468 of September 18th, 2001). It is characterized by an intense contamination both in the soil and in the groundwater (Provincia Autonoma di Trento, 2003). The chemicals of concern in this case are Hg, organic and inorganic Pb along with polycyclic aromatic hydrocarbons (PAHs), aromatic solvents, phenols, oil and organolead compounds (Andreottola et al., 2008).

4.3. Organic pollutants

With respect to the third group of pollutants, Pavoni et al. (1987) showed that the most relevant concentrations of both DDT and PCBs are detected close to the Adige river mouth and mainly in the Fibbio and Alpone tributaries and in higher percentage in macrobenthos rather than in sediments (see Supporting Information). Benfenati et al. (1992) measured along the Adige river in the Rovereto area higher concentration of polycyclic aromatic hydrocarbon than in other areas probably due to chemical plants at the exit of the Province of Trento. The concentrations are, however, always below the regulation limits.

Villa et al. (2006b) studied the release of POPs from several Alpine glaciers: the highest concentrations of DDTs and HCBs are found in Italian western Alps glaciers, while the *Careser glacier*, located within the Adige basin, is characterized by lower values.

Pesticides are constantly monitored, since some areas of the catchment are characterized by intense agriculture (vineyard and apple orchard). Benfenati et al. (1990) performed a simultaneous analysis of 50 pesticides in water samples from the Adige river and the screening revealed the presence of dichlobenil, deethylatrazine, lindane, atrazine, simetryne and metholachlor at low levels. The concentration of the main pesticides is between 0.1 and 10 ng/L, which indicates a low level of contamination, at least 10 times below the limits for drinking water. Mean annual concentration of pesticides (<1 μg/L) in the surface water samples of the Adige river at *Ponte Adige* and at *Roveré della Luna* were reported by Provincia autonoma di Bolzano (2006). Notice that in the Province of Trento the number of sites where the chemical status is poor due to the presence of pesticides doubled between 2010–2012 analyses and the 2015 report (APPA Trento, 2015). The impact of agriculture, yet in term of organic pollutant load other than pesticides, is noteworthy in the lower reach of stream Ram, an effluent of the Adige situated in the Province of Bolzano (Distretto idrografico delle Alpi Orientali, 2014). Recent analyses (2005–2006) indicate a deterioration in water quality compared to the period 1996–2001. This is probably due to organic pollutant load from agriculture (Distretto idrografico delle Alpi Orientali, 2014).

Chemical pollution deriving from WWTPs (in total about 100 WWTP are present in the Adige catchment, which can treat about 2.58×10^6 inhabitants equivalent) and municipal solid waste (MSW) incineration plants leads to the occurrence of carbamazepine and codeine in the Adige river water. These persistent and recalcitrant pollutants have been detected in the proximity of Verona (Repice et al., 2013), while polychlorinated dipenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) have been measured both in air (mean total PCDD + PCDF approximately equal to 958 fg m^{-1}) and soil (mean total PCDD + PCDF approximately equal to 45.3 pgg^{-1}) samples in the proximity of municipal solid waste incinerators in the Province of Bolzano (Caserini et al., 2004). However, the occurrence of these contaminants in soil and air is not only due to the MSW incineration plant but also to the presence of motorway and the city area itself.

Finally, surfactants have been investigated by Valsecchi et al. (2015) and their concentrations are very close or below the detection limit; however, a peak in the concentration has been detected in the Alpone creek, which drains the Chiampo valley. As already mentioned, this area hosts one of the most important Italian tannery district, which can explain the occurrence of these compounds.

5. Ecological status

In this section, we refer mainly to the ecological information available on the northern part of the catchment, with special reference to

Table 3
Study categories of the main literature concerning the River Adige. Fig. 6 summarizes the sites (where coordinates are available) referred to each category below described.

Sites category	Biological component	Study category
1	Zoobenthos	"Lake Effect" in the upstream–downstream invertebrate distribution (high altitude reaches)
2	Hyporheic and benthic fauna	Overview on the quality of the River Adige
3	Hyporheic and benthic fauna	Characterization of high altitude river ecosystems
4	Hyporheic fauna	Longitudinal zonation within the river discontinuum
5	Zoobenthos	Ecological and chemical studies
6	Zoobenthos	Lowland ecological studies
7	Zoobenthos	Ecological studies in Mountain Springs (coordinates not available)

headwaters (Table 3) and macro-invertebrates. Indeed, almost 80% of the Adige River catchment is located at altitude higher than 1000 m a.s.l., with the knowledge on the ecological status of headwaters (streams and springs) limited to scientific papers published in the last 15 years and mainly taking into account benthic invertebrate fauna (zoobenthos and hyporheic fauna) as biological element. Public data from the three environmental agencies involved in the Adige ecological monitoring (Environmental Protection Agency of the Province of Bolzano, of the Province of Trento and of the Veneto Region) refer only to stream reaches lower than 1700 m a.s.l. (e.g., the highest sampling point in the Province of Trento is the Vermigliana creek, 1300 m a.s.l). In addition, biological (mainly zoobenthos and hyporheic fauna) and ecological studies have been conducted in low elevation reaches of the Adige River since the 1970s (Braioni, 1994). This is a consequence of the general belief that headwaters are pristine and in high ecological status. For example, the European Directives concerning the protection of aquatic environments and related organisms (e.g. the Water Framework Directive WFD 2000/60/EC) have not included them as habitat to be regularly monitored.

However, the scientific interest is increasing towards habitats in which freshwater biodiversity is under threat, like glacier-fed reaches experiencing a reduction of meltwater contribution due to the effect of climate change (e.g., Bizzotto et al., 2009b; Jacobsen et al., 2012). Moreover, these habitats provide many ecosystem services, such as the provision of resources that will benefit lowland populations (e.g., drinking water, irrigation), ecosystem production (e.g., crop, grazing) and support services (e.g., soil as store of water and carbon, protection from erosion). Such habitats are now endangered by the accumulation of contaminants transported by wind (from currently used pesticides to emerging contaminants such as personal care products) and released in the rivers at the thaw, posing a threat for wildlife and finally human health (Villa et al., 2006a).

A large effort was spent to develop a biotic index for benthic macro-invertebrates in rivers, but to date a method for headwaters monitoring is still lacking. The actually accepted bio-monitoring methods in Italy based on invertebrates, such as Biotic Index (Ghetti, 1997) and STAR_ICMi (Buffagni et al., 2006), were in fact developed with reference to different habitats like large rivers, Mediterranean streams, lowland springs etc. Macro-invertebrates are useful and convenient indicators of the ecological health of a water body. Furthermore, the abundance and richness of macro-invertebrates enables an objective judgment of the ecological condition and their tolerance values are commonly used to assess water pollution (Chang et al., 2014). Bizzotto et al. (2009b), for example, evidenced how they respond very rapidly to concentration changes of chemicals in their host catchments. Specifically, in the Adige river, Duzzin et al. (1988) and Pavoni et al. (1987) highlighted that zoobenthos preferentially bioaccumulate some metals (Cu, Zn) and helped in detecting acute contamination by showing concentrations higher than sediments for some metals (Hg, Cr). On the basis of data provided by the three regional environmental agencies, reports (e.g., Braioni, 2001a) and peer reviewed publications (e.g., Braioni et al., 2002), the ecological status of the Adige river is good. By applying the Fluvial Functional Index (FFI) (Siligardi et al., 2000), river reaches with high ecological and functionality value, which do not need restoration, reaches moderately impacted, and reaches severally compromised, i.e., almost impossible to restore, have been highlighted (Negri et al., 2004; Braioni, 2001b). However, these studies always focus on altitudes below the treeline.

Indexes applied to lowland rivers are not directly applicable on headwaters due to the natural low biodiversity that characterized pristine reaches, especially those fed by ice-melt. Due to the stressful environmental conditions characterizing glacier-fed rivers, they host extremely simplified communities, highly sensitive to environmental changes (Brown et al., 2003). Only few species highly specialized to survive cold temperatures, high turbidity, low channel stability, high discharge and low amounts of nutrients colonize the fish-less glacier-fed rivers (Lencioni et al., 2007b). The studies based on macro-invertebrates carried out on Alpine area of the Adige River (e.g., Lencioni et al., 2011) provided a base knowledge about the structure and functional properties of zoobenthos, in relation to altitude (e.g., Lencioni et al., 2007a; Maiolini et al., 2005), stream origin (e.g., Boscaini et al., 2004; Lencioni and Spitale, 2015), water temperature and other environmental variables (Lencioni and Rossaro, 2005), and the presence of natural lakes and artificial dams (Maiolini et al., 2007), etc. Spatial and temporal gradients have been analyzed (e.g., Lencioni et al., 2002; Lencioni and Spitale, 2015), highlighting that (i) richness and biodiversity increase with distance from the source and decrease in presence of hydrological and physical natural stress, (ii) biodiversity is higher in the winter period even under snow cover, (iii) in highly disturbed habitats (kryal reaches) the hyporheic zone has an important role of refuge area for zoobenthic taxa, (iv) streams fed by groundwater, even at high altitude, host a more diversified community being characterized by transparent and less turbulent waters than glacier-fed streams. Zoobenthos and hyporheic fauna were studied also in relation to hydroelectric power generation and consequent hydropeaking in the Noce river basin (e.g., Bruno et al., 2009; Bruno et al., 2010; Maiolini et al., 2007; Silveri et al., 2008) and in the Avisio river (Di Lorenzo et al., 2013). In both cases, composition of macro-invertebrates and hyporheic fauna changed according to geomorphological and physical–chemical stream longitudinal discontinuities. Grazing livestock and hydrological disturbance have been evaluated also in mountain springs (Lencioni et al., 2011; Lencioni et al., 2012; Bottarin and Fano, 1998) highlighting that biodiversity decreases with decreasing water quality and habitat integrity. Finally, springs are also extremely sensitive to environmental changes, thus they are good proxies to monitor changes in groundwater quality induced by human activities (Cantonati et al., 2006).

6. Identification of the most relevant stressors

6.1. Hydrological stressors

The most important stressor within the Adige catchment is undoubtedly the streamflow alteration due to hydropower exploitation, occurring mainly in the northern part of the catchment. Because of the large elevation range and humid climate, the river basin is in fact well suited for hydroelectric production with 34 major power plants using the water of the river basin (see Section 2.4). This leads to a significant streamflow alteration in the basin, particularly at intermediate and low flow regimes (Zolezzi et al., 2009). As a consequence substantial alterations in stream velocity, turbidity and water temperature (Zolezzi et al., 2011), and stress to the benthic invertebrates communities (Bruno et al., 2013) have been observed.

Droughts are more frequent in the southern part of the river basin (particularly in summer), and increase the risk of salt water intrusion (Autorità di bacino del fiume Adige, 2008). Such drought events often generate conflicts between stakeholders of the hydropower and agriculture sectors. In 2007, for the first time and for about one month, imposed water releases from hydropower plants were not able to counterbalance the drought, and saltwater intrusion propagated well upstream the artificial barrier located 4.2 km upstream the river mouth (Autorità di bacino del fiume Adige, 2008). This evidence suggests that for certain periods of the year, and despite the releases from the upstream reservoirs, streamflow may be too low to guarantee both agricultural water uses and ecological functionality of the river.

Despite hydrological stressors have been clearly identified, there is an impelling need for finding suitable water management solutions to alleviate their effects on the ecosystem. Although a pulsating hydropower production is in fact economically rewarding, streamflow alterations is substantial and long-term health of the riverine ecosystem is only partially taken into account in reservoir optimization schemes. Harmonizing the often conflicting water uses is a major societal challenge in the Adige catchment, due to the complexity of the institutional architecture with fragmented competences and conflicting water uses.

6.2. Actual and future water management stressors

The variety of water uses in the Adige (see Fig. 4) causes increasingly conflicts in spring and summer between irrigation water demand, hydropower, recreational activities and drinking water needs (see the work of La Jeunesse et al. (2015), for the Noce tributary). Competition is likely to increase in the future as a consequence of the observed negative trends in precipitation and streamflow time series, which showed a reduction of water availability in the last two decades.

Fig. 7b shows trend analysis conducted on the time series of annual water yield (Q) at the Ponte S. Lorenzo stream gauging station in the city of Trento (see Supporting information for its location) and mean annual precipitations (P) of the contributing catchment (9800 km^2). The spatial mean of precipitation is obtained by interpolation of the measurements at the available rain gauges by means of Kriging with External Drift algorithm (see e.g. Goovaerts, 1997). Mann–Kendall test (Hirsch and Slack, 1984) with a significance level of 5% has been applied to 30-years overlapping time windows of precipitation (P) and streamflow (Q) (see Fig. 7a). The analysis shows for the annual water yield a trend of −7 mm/year, which starts from 1974, whereas the negative trend of precipitations is statistically not significant (see the open symbols in Fig. 7a). This negative trend of Q at Trento is in agreement with the findings of

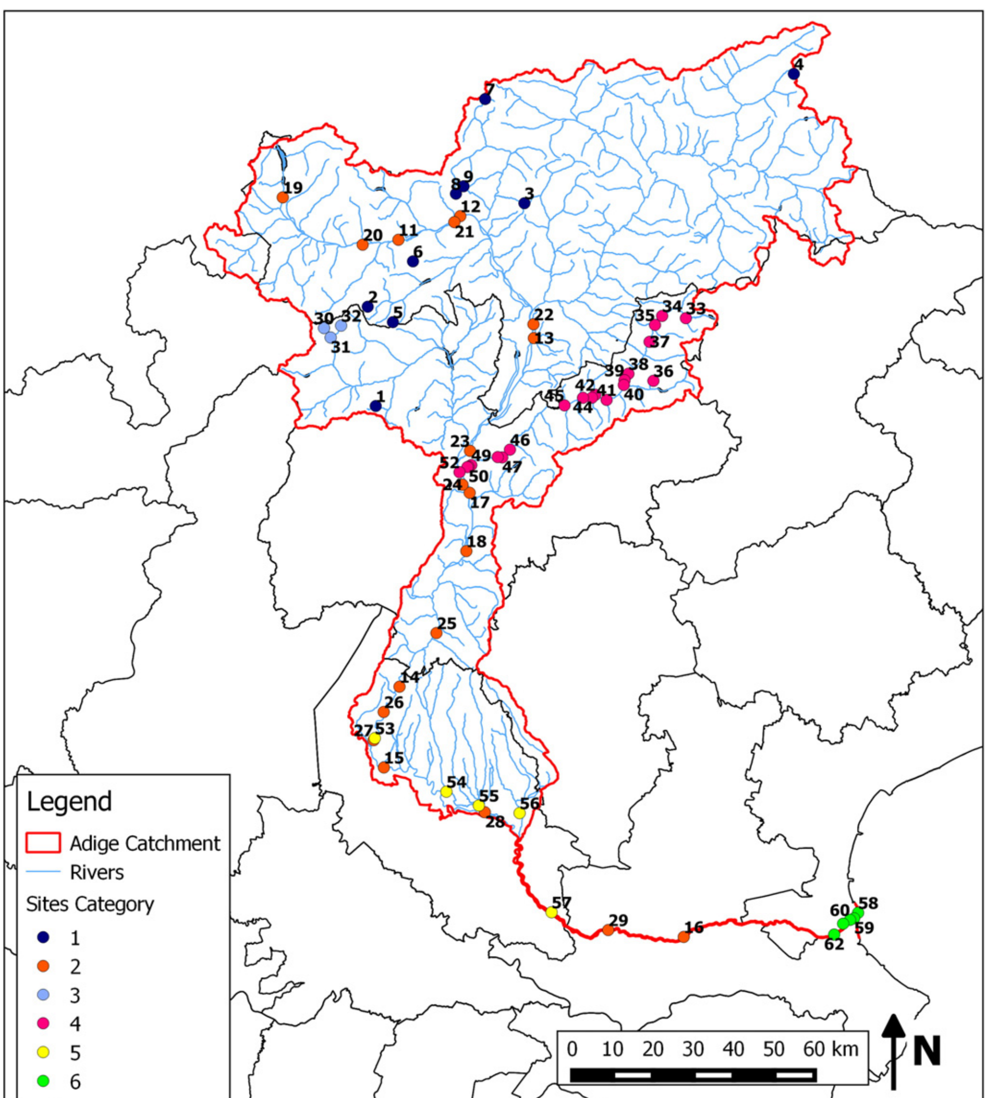

Fig. 6. Sites of the principal ecological studies concerning the River Adige. Colors refer to the categories in which studies have been subdivided, according to Table 3.

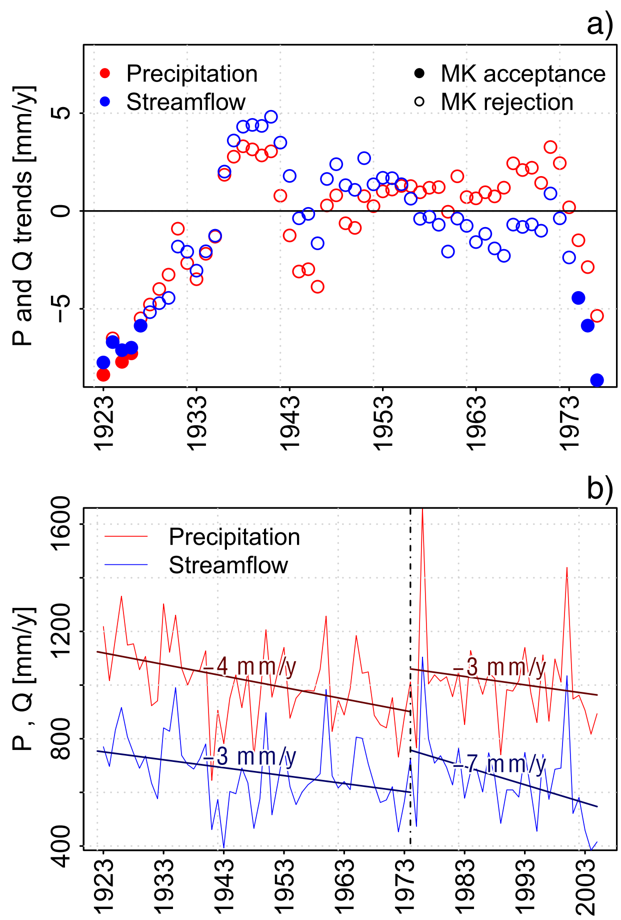

Fig. 7. a) Trends and Mann–Kendall significance test for time series of annual precipitation (P) and water yield (Q) computed over 30 years of overlapping time windows; b) time series of average annual Q registered at Trento and catchment-averaged P. Linear regressions are computed separately for the two variables during the periods pre- and post-1974 (starting year of the negative and statistically significant trend for Q).

Alvisi et al. (2006), who observed also larger negative trends for both water and sediments yields at Boara Pisani gauging station (southern part of the Adige river basin, see Supporting information) in the period 1922–2000.

According to current projections, climate change may impact significantly the hydrology of Alpine catchments and its ecosystem (Viviroli et al., 2011; Beniston, 2012a,b). In a recent contribution, Majone et al. (2015) highlighted that, in the next decades, warming will lead to changes in the seasonality of streamflow for the Noce catchment as a consequence of less winter precipitation falling as snow and melting of winter snow occurring earlier in spring. Furthermore, a moderate reduction of snow and ice storage is projected for 2020–2050 in the entire Alpine region, with a more drastic change in the second half of the century (Farinotti et al., 2012). The reduction of snowfall accumulation due to the increase of winter temperature will likely reduce streamflow in late spring and summer, while an increase is expected in winter as snowfall elevation is projected to increase. These result are confirmed by a recent analysis conducted by Meteotrentino (2011), which estimated for the glaciers of the Province of Trento a reduction of surface by almost 40% in the last 50 years. Changes in the evapotranspiration regime will also affect lower elevation streams due to the combination of increasing temperatures and longer vegetative season, thus leading to higher water demands (Della Chiesa et al., 2014) and likely exacerbation of conflicts among different and often-competing water uses.

Projected impacts on streamflow and water resources availability are expected to significantly affect the hydropower sector. Therefore, actual water management strategies will need to adapt to the changing climatic conditions. Recent studies conducted in the Noce tributary (Majone et al., 2015) evidenced that changes in water availability are reflected in hydropower potential of the catchment, with larger changes projected for the hydropower plants located at the highest altitudes. Another interesting result is that the introduction of prescriptions for Minimum Ecological Flow may reduce hydropower potential by 8–9% with respect to the situation in which only the effect of climate change is considered.

As highlighted in a recent commentary by François et al. (2014), integration of hydropower with other renewable energies, and the need of a shared and not conflicting use of water resources with other important water uses (like e.g., agriculture, recreational activities, ecological functionality preservation), pose new challenges to the hydrological community. Available studies conducted in the Adige river basin cover however limited areal extensions and they analyze only individual aspects of the land use–climate change–energy nexus (e.g., Majone et al., 2015). An integrated environmental assessment of the linkages between these compartments, including effects relevant at different temporal scales, and their impacts on socio-economic sectors is therefore needed.

6.3. Chemical stressors

Available literature studies and data collected by the environmental protection agencies show a positive situation of the Adige catchment with significant pollution by compounds included into national and European regulations limited to a few, chiefly local, spots. Moreover, considering all sampling campaigns carried out since 1982, we can observe that contamination occurs mainly along the tributaries of the Adige river. This is due to the fact that the concentration of industrial and agricultural areas along the tributaries is higher than along the main river. Furthermore, significant dilution of the contaminant concentrations occurs in the main river.

Nonetheless, two potential chemical stressors are worth to be investigated within the Adige catchment: POPs released from snow and glacier melting and emerging pollutants released from WWTPs. Despite the increasing release of POPs from glaciers has attracted the attention of many researchers (Villa et al., 2006b; Villa et al., 2006a; Villa et al., 2003; Gabrieli et al., 2010; Bizzotto et al., 2009a; Tremolada et al., 2008; Tremolada et al., 2009), it has not yet been investigated through systematic sampling campaigns and the available data are scarce and discontinuous both in time and space. Therefore, it is difficult to evaluate possible trends and contaminant dynamics, which may alter fragile headwaters ecosystems. Due to the rise of temperature in the catchment, chemicals (in particular organochlorine compounds), previously trapped in the glaciers, are now progressively volatilized and released both to the air and the surface water of the streams. Long term projections of contaminant release are not yet available.

Except the work of Repice et al. (2013), very little is known about the fate and transport of emerging and micro pollutants in catchments located at high elevation and subject to significant fluctuations in the contaminant load due to touristic fluxes. The results shown in Robinson et al. (2014) indicate that spatial distributions of macro-invertebrates in Alpine catchments at high elevations are related to spatial relationships among environmental attributes like land-use, habitat, and water quality (e.g., presence of WWTP) that depend also on river network complexity.

Furthermore, even low contaminant loads may become relevant for the ecosystem when it is subject to additional hydrological stressors, like in the Adige basin. Fig. 8 show the STAR.ICM index classification. Five quality classes identify the ecological status of a reach: 1 (very good status) to 5 (very bad status). According to this classification, the data collected by the Environmental Protection Agency of the Province of Bolzano (Provincia Autonoma di Bolzano, 2006) show the highest quality values. Proceeding downstream in the Province of Trento

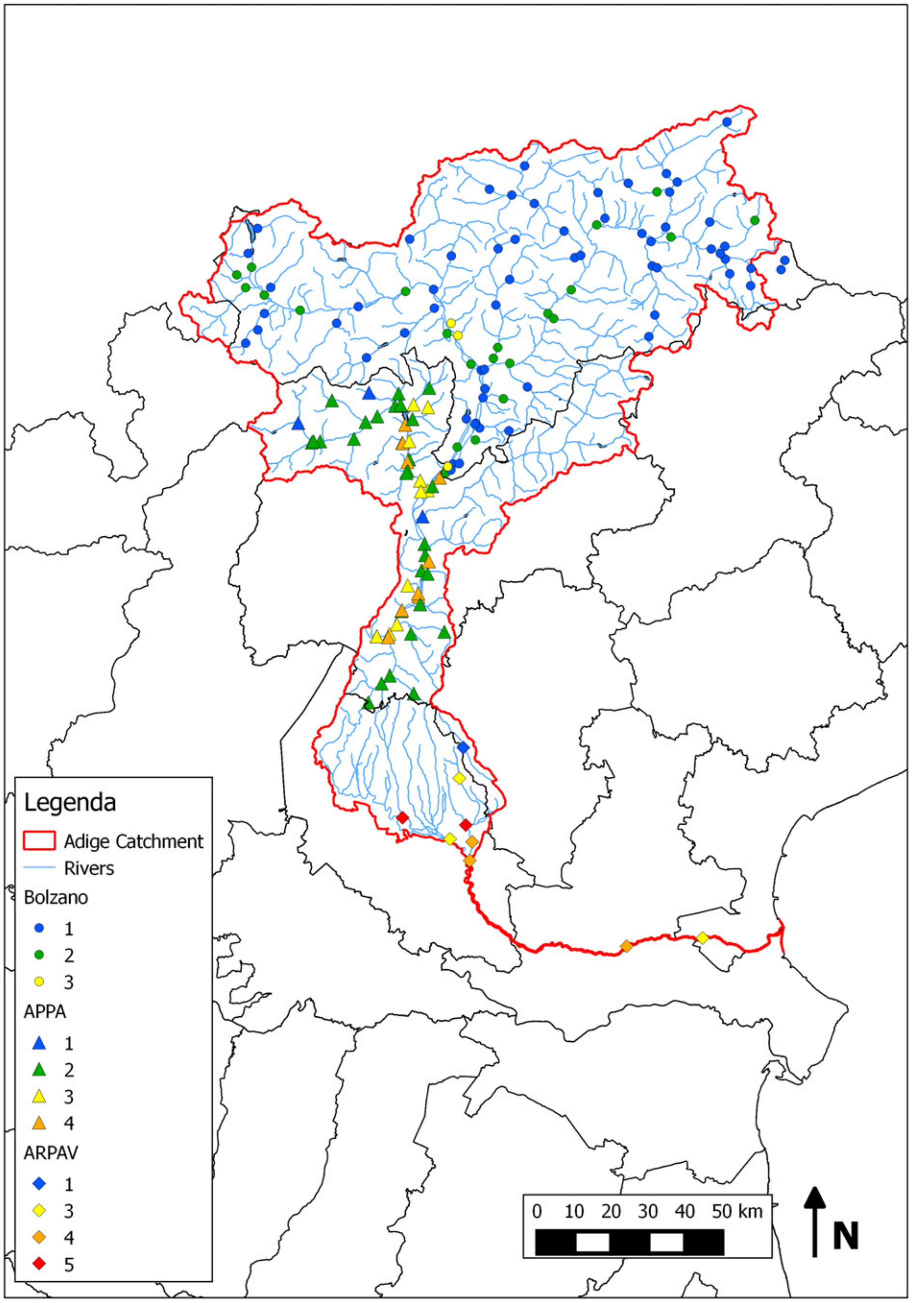

Fig. 8. Map of the ecological status of the Adige catchment. Sites refer to data available from the Environmental Protection Agency of the Autonomous Province of Bolzano (circles), the Province of Trento (triangles) and the Veneto Region (diamonds). Colors concern the ecological status they refer to: "blue" corresponds to the highest level (1 — "very good status"), "red" is related to the worst status (5 — "very bad status").

(APPA Trento, 2013) and in the Veneto Region (ARPA-Veneto, 2006) the ecological status deteriorates. According to this classification, therefore, the ecological status of the Adige river clearly indicates a north–south gradient. Such gradient seems to contradict the evidence that hydropeaking has in general a negative effect on the ecosystem. Indeed, the worst ecological status occurs where the effects of hydropeaking are negligible. This apparent paradox can be explained with the increase of the anthropogenic pressure and the occurrence of multiple stressors related to the combined effects of agricultural and industrial activities, as well as geomorphological alterations, all increasing along the river. Again, this points to the fact that both water quality and the ecological status of the catchment are influenced by stressors whose effects are relevant at multiple spatial and temporal scales.

6.4. The need for integrated studies

As shown by the available literature, the Adige catchment is an extremely complex environment, where multiple stressors act simultaneously to alter the ecological status. However, as shown in Fig. 2, very few studies provide a comprehensive approach investigating multiple stressors in a specific location, and practically no studies addressed the complex interaction of different stressors throughout the entire river basin.

As already mentioned, the Adige catchment is characterized by many hydropower plants, which regulate the river flow. As a consequence, aquatic ecosystems can be altered by changes in flow related to hydropeaking. However, disturbances are not only related to variation in discharges. Flow regulation affects also water temperature and sediment transport and deposition (Hart and Poff, 2002). According to measurements within the Noce Bianco basin performed by Bruno et al. (2009) and Bruno et al. (2010), such alterations increase the instability of the benthic and hyporheic habitats and reduce abundance and diversity of those organisms dwelling in the streambed. On the other hand, benthic invertebrates react to this stress by using the hyporheic zone as a refuge from the imposed hydrological alteration. Such effects are detectable 10 km downstream the power plant (Maiolini et al., 2007). It has been evaluated also the time-response of the benthic communities, which can be estimated of the order of about 5–10 min after the hydropeaking wave. Moreover, these measurements highlighted the abundant presence of *Nematoda*, which is usually found in polluted habitats (Zullini, 1976).

Along the Adige river, it has not been investigated, however, the effect of flow regulation on important contaminant fluxes, such as particle fluxes carrying sorbed compounds and the concurrent effect of hydropeaking and contaminant loads deriving from different possible sources (e.g., POPs from snow and glacier melting, micro and emerging pollutants from overloaded WWTP). This calls for an improved understanding of the coupled hydrological, chemical and geochemical system functioning, which requires long-term sampling with a high temporal resolution distributed throughout the catchment in which multiple parameters are monitored.

6.5. The Adige catchment as a benchmark for testing models in the Alpine region

The amount of data collected and organized in this work, some of them available in the Supporting Information, some of them contained in public databases, makes the Adige catchment a rich large-size catchment, in terms of data availability. Furthermore, it shows a significant variability in terms of land use, water use and hydrological driving forces. Water management is also differentiated throughout the catchment and different climatic conditions (from Alpine to subcontinental) lead to a considerably high invertebrate biodiversity. This allows using this basin as a benchmark for testing and validating models of ecosystem functioning, pollutants cycling, including their penetration in the food chain, as well as the effects of new water policies and water management strategies on the ecosystem.

In addition, the stressors relevant for the Adige catchment are common to most Alpine catchments. The impact of hydropower production on the hydrological cycle is a common issue throughout the Alps (Zolezzi et al., 2009; François et al., in Press). The concern related to the impact of POPs and of micro and emerging pollutants released by glaciers and WWTP, respectively, is also shared in the Alpine region (Steinlin et al., 2014; Pavlova et al., 2014; Ort et al., 2009). Therefore, the presented data can be used for further comparative studies between Alpine catchments.

7. Conclusions

In this work, we have provided a comprehensive review of the available hydrological, chemical and ecological studies performed in the Adige catchment. Hydrology in this catchment is strongly influenced by snow and glacier melting dynamics in the headwaters, while rainfall and groundwater become relevant in the valleys and in the southern portion of the basin. Furthermore, water management and water policies are particularly relevant due to the exploitation of water resources for agriculture and energy production. Streamflow both in the tributaries and in the main river is therefore significantly affected by anthropogenic alterations driven by economical decisions.

In such complex socio-economical and hydrological situation, pollution may have dramatic adverse effects on the freshwater ecosystem, even at low concentrations. Although the Adige river does not show significant chemical contamination, fragile headwaters catchments, influenced by hydrological stressors, such as hydropeaking, may be affected by the release of old pollutants stored in glaciers and by the occurrence of micro and emerging pollutants. In particular, areas in the Alps, characterized by strong fluctuations in the population due to touristic fluxes, may be particularly impacted by such chemicals. In addition, the southern portion of the catchment is exposed to releases of chemicals from dismissed (e.g. the contaminated site of national interest in Trento) and active industrial activities. Once again, it becomes clear the relevance to couple socio-economic drivers (e.g., tourism activities, industrial areas) with monitoring and modeling activities to improve our understanding of system functioning and resilience of the system to the pressure of anthropogenic activities.

The analysis provided also a solid base of knowledge for future studies dealing with the impact of multiple stressors on aquatic ecosystems. In particular, it pointed out the necessity to investigate more in detail the impact of pollutants dynamics on macro-invertebrates communities in headwaters. Systematic sampling campaigns within the Adige catchment with the aim of analyzing ecological parameters in association with chemical and environmental stressors have not been extensively performed and the feedback of climate change, pollutants release, tourism activities and hydropower have not been yet investigated simultaneously.

Despite the available studies provide a detailed outlook on the environmental status of the catchment, they generally focus on specific aspects of the system: hydrology, chemistry or ecology. Furthermore, despite the amount of the experimental data collected, few systematic modeling studies have been performed within the catchment. The analysis of the available information calls for a more comprehensive investigation of the way these stressors combine. In fact, it is important to consider also constraints introduced by water policies and water uses which require the development of innovative and adaptable management strategies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.06.149.

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