Long term (1921–2011) hydrological regime of Alpine catchments in Northern Italy

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1. Introduction

Global warming is impacting water resource distribution in temperate regions, tampering water and food security [3,5,50,51]. Changes in precipitation and temperatures as expected under transient climate change conditions will likely have considerable fallout upon stream flow regimes worldwide [7,9,15,26,29,30,34], including the impact of modified seasonal snow cover upon hydrology in the Alpine environment [30,52]. The Italian (and European) Alps are a complex and extremely sensitive ecosystem and they are often called the "water towers" of Italy (and Europe). Northern Italian rivers Springs from the Alps and thawing of snow and glaciers comprises a large part of hydrological fluxes [1,2,48]. Over the last 4 decades significant warming was observed within the European Alps, cascading into decreased snow cover and glaciers' extent [10,23,24,35,38]. Within the Alps temperature is increased twice as much as compared against global trends, with

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an estimated increase in temperature of 2 °C, and no significant trend in the total amount of precipitation, but with an important decrease in snowfall and snow cover [6,12]. On the other hand, Alpine rivers of Italy provide water supply for the Po Valley of Northern Italy, among the most productive agricultural areas within Europe (viz. for rice, wheat, maize etc. [27]).

The combined effect of increasing population density and prospective enhancement of heat waves, droughts and extreme weather events will put at stake water security in this area, falling out upon agriculture and crop yield, and thus upon food security of population therein [14,53]. Therefore, assessment of the latest trends of stream flows, and of their future evolutions within Alpine rivers seem warranted. While recent studies explore potential variability of stream flows in the Italian Alps, and potential impact upon water resources management [3], a comprehensive investigation of either recent or long term trends of observed hydrological fluxes seems lacking. Further on, the presence of flow regulation, as given by the construction of large reservoirs within Alpine catchments in Italy during the XX century may also have led to noticeable changes in flow regime therein, possibly improving water resources management, at the cost of hampering water biodiversity [25,28,46,54,57]. Whenever large modification of hydrological regimes is given by flow regulation, one may erroneously charge such variability to other drivers, including climate. Therefore, one needs separate changes arising from flow regulation from other changes, possibly related to climate drivers. Accurate assessment of flow regulation effect within largely regulated catchments effect would require ideally reconstruction of “natural” flows, maybe using inverse reservoirs flow routing [19] within each reservoir. However, this may be cumbersome given the large number of reservoirs in some cases, and especially the lack of the necessary data, i.e. pool level, and flow release (including hydropower, and in stream release), that are considered sensitive ones, and rarely distributed. For instance, within the considered area here, in the Alps of Italy ca. 180 large (i.e. with either 10 m or more altitude, or 10^6 m^3 or more storage) reservoirs are present [39], and most with unavailable data, so making this calculation very difficult. Here, long term (1921–2011, with variable length of data series) changes of yearly and seasonal discharges of 23 Alpine rivers in Northern Italy, spanning a wide range of catchments area (ca. 10^2–10^4 km^2) are investigated. First, the issue of flow regulation is addressed, to assess its relative weight at the yearly and seasonal level, to highlight its potential bearing upon flow trends.

For unregulated, or little regulated catchments, the presence of non stationarity, and trends, is detected using linear regression, including variable slope analysis, and Mann Kendall test, traditional and progressive. The observed trends are investigated against descriptive physiographic variables of the selected catchments, to highlight geographic and topographic patterns of changes of the hydrological cycle. Then, the relationship between the observed trend intensity and global thermal and NAO anomaly is analysed to highlight potential impact of large scale climate drivers against regional hydrological regimes. Global temperature and NAO display control upon precipitation, snowfall, and snow and ice melt patterns in Northern Italy [e.g. [10,23], possibly cascading upon hydrological regime. The response to drivers of general circulation is also investigated against geographic coordinates and altitude. Also, the correlation between stream flows, precipitation and temperatures in nearby stations is investigated, to highlight local climate trends potentially driving hydrological changes, and potential changes in the nexus between climate and hydrology.

Eventually, based upon this joint analysis, a judgment is provided as to whether (i) the evidence of modified hydrological cycles within some of the considered catchments need be sought for by separating the effects of flow regulation, or (ii) modified hydrological cycles is observed, and investigation is needed to unravel the physical underlying patterns of variability.

2. Case study

2.1. Italian Alpine rivers

Hydrological fluxes at 23 river stations were studied here, evenly spread from East to West upon the Italian Alps (Fig. 1). The data base covers rivers within Piemonte, Lombardia, Trentino, and Veneto regions, while the necessary data from Val D’Aosta (West) and Friuli Venezia Giulia (East) could not be gathered. Mean catchment altitude (Table 1) ranges from 2246 m a.s.l. (Rabbies river closed at S. Bernardo) to 942 m a.s.l. (Brenta at Borgo Valsugana), with an average value of 1628 m a.s.l. thus giving a sample of high altitude Alpine catchments, with considerable snow feeding, including ice cover in some cases. Drainage area ranges from 101 km^2 (Rabbies at S. Bernardo) to ca. 9763 km^2 (Adige at Trento, with mean altitude 1709 m a.s.l.), with an average of 1615 km^2. In Table 1 it is also reported the yearly average discharge for the period of available data, also specific to drainage area. The data base of either daily or monthly average discharges, precipitation and temperatures used here were retrieved from different sources, including the data base of ARPA Lombardia and ARPA Piemonte, Lombardia Region authority (via PTUA, the program for use and protection of water), Hydrographic Service of Italy (ex-SIMN), Regione Trentino Authority, all of which the author kindly acknowledges. Climate series from Piemonte region come from [20]. The period of observation (and actual available years of data) for each river is reported in Table 1.

2.2. Climatological and hydrological regime

The climate regime of Northern Italy according to the Köppen-Geiger climate classification ranges from temperate dry, with hot/warm Summer (Csa/b) in the Po valley, to temperate wet with warm Summer (Cfb) in the piedmont belts, temperate cold with warm Summer (Dfb) especially in the Eastern Alps, and to polar cold and glacial (ET, EF) in highest areas of central and Western Alps [[47], Table 1, and Fig. 8]. The precipitation in this area shifts from sub-littoral Alpine regime in the North West, displaying a bimodal shape, with a first maximum in Fall and a second one in Spring and a minimum during Winter, to a mainly continental or close-to-continental regime in the North Eastern part, displaying unimodal behaviour, with maximum in Summer and minimum in Winter [17,22]. Precipitation here is in the order of 1000–1500 mm per year or more, with frequent snowfall from October to May, and seasonal continuous snow cover above 1000 m a.s.l. ca. Runoff is influenced by snow melt, and later ice melt in Spring and Summer, the latter especially in the North Western area [23,24]. Several recent studies indicate consistent evidence of climate warming within the Italian Alps during the last few decades, resulting into decreased snowfall during Winter, and decreased snow covered area and snow water equivalent at thaw, potentially resulting into down wasting of permanent ice bodies [e.g. [10,40], and into increase of Winter flows, at the expenses of Spring and Summer flows [13,30].

3. Methods

3.1. Linear regression against time LR

Linear regression of the considered variables is carried out with respect to time (i.e. years). Significance of the regression is given using the *p-value* ($\alpha = 5\%$, e.g. [24]). All the calculation for LR, and

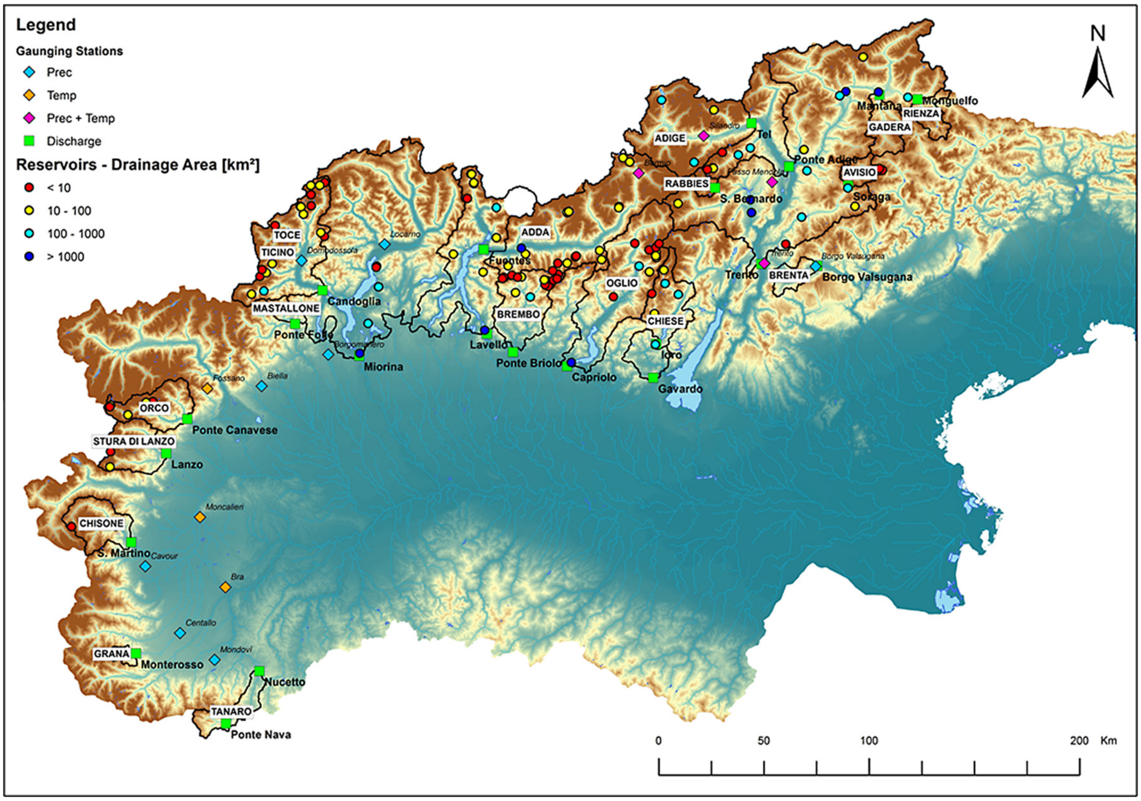

Fig. 1. Study area and investigated stream sections.

Table 1
Investigated catchments. Coordinates of the outlet section, catchment area S, mean (A_m) and outlet (A_o) altitude reported. Also reported period of observation, and available years N_y, and average yearly flow, absolute Q_{av} [m^3 s^{-1}], and specific to area Q^*_{av} [m^3 s^{-1} km^{-2}]. Total volume of large reservoirs V_{Tot} reported. **Bold** values of V_{Tot} means that large regulation started before the observation period.

River	Station	Lat. [°]	Long. [°]	S [km^2]	A_m [m a.s.l.]	A_o [m a.s.l.]	Period	N_y	Q_{av} [m^3 s^{-1}]	Q^*_{av} [m^3 s^{-1} km^{-2}]	V_{Tot} [E^6 m^3]
ADDA	Fuentes	46.15	9.41	2498	1870	204	1926–2011	73	87.5	0.035	358
ADDA	Lavello	45.79	9.43	4572	1531	196	1971–2011	41	153.5	0.034	655
ADIGE	Ponte Adige	46.48	11.30	2642	1893	238	1926–1971	42	57.2	0.022	202
ADIGE	Tel	46.67	11.08	1675	2108	512	1927–1972	43	33.3	0.020	175
ADIGE	Trento	46.07	11.12	9763	1709	191	1921–2011	83	208.5	0.021	538
AVISIO	Soraga	46.39	11.67	208	2068	1209	1926–2011	71	5.6	0.027	17
BREMBO	Ponte Briolo	45.71	9.59	765	1154	225	1937–1979	39	31.4	0.041	25
BRENTA	B. Valsugana	46.05	11.46	214	942	386	1956–1999	40	4.6	0.022	–
CHIESE	Idro	45.74	10.46	589	1502	373	1960–2003	42	25.1	0.043	**76**
CHIESE	Gavardo	45.59	10.44	934	1220	204	1970–2011	35	30.4	0.033	**110**
CHISONE	S. Martino	44.89	7.28	580	1732	424	1937–2011	44	12.9	0.022	0.11
GADERA	Mantana	46.78	11.88	387	1856	826	1926–1965	38	8.3	0.021	–
GRANA	Monterosso	44.41	7.32	102	1564	738	1934–2011	50	2.6	0.026	–
MASTALLONE	Ponte Folle	45.83	8.26	149	1326	481	1933–1965	32	7.5	0.050	–
OGLIO	Capriolo	45.65	9.92	1842	1386	173	1933–2011	74	56.5	0.031	**262**
ORCO	P. Canavese	45.42	7.61	617	1927	440	1928–1976	45	20.5	0.033	103
RABBIES	S. Bernardo	46.40	10.84	101	2246	1080	1968–2011	30	2.9	0.029	–
RIENZA	Monguelfo	46.75	12.11	273	1881	1101	1930–1971	38	6.5	0.024	–
STURA DI LANZO	Lanzo	45.27	7.48	582	1761	467	1930–2011	60	19.7	0.034	1
TANARO	Ponte Nava	44.12	7.87	148	1580	712	1931–2011	44	4.9	0.033	–
TANARO	Nucetto	44.34	8.06	375	1225	825	1947–1979	31	10.7	0.028	–
TICINO	Miorina	45.70	8.65	6599	1286	190	1960–2002	42	293.7	0.045	**600**
TOCE	Candoglia	45.97	8.42	1532	1673	201	1935–2010	60	66.6	0.043	**162**

Mann Kendall, traditional and progressive have been carried out using appositely developed algorithm in MATLAB®, and with EXCELS®. LR coefficients were first evaluated for all catchments, and used to benchmark flow regulation, as reported in Section 3.2 below. Subsequently, for those catchments displaying little effect of flow regulations, LR results were retained, and further investigation was carried out. To assess the presence of multiple trends, i.e. of modified hydrological behaviour in time, multiple trend detection is carried out [49], using iterative change point detections [40,42], carried out with *Segmented* R® package (provided by Muggeo [41]). The package implements segmented (i.e. with different slopes) linear fitting of a data sample with a given number of break points, by way of an iterative algorithm for break position search, and parameter estimation based upon Maximum Likelihood. Initial values for number and position of potential break points were detected by visual analysis of the series, and fed to the iterative break point search algorithm of the *Segmented* package. By iteratively changing the number and initial position of the break points, a final significant ($\alpha = 5\%$) configuration was found (i.e. a number of points where a new trend starts, or where substantial stationarity is attained instead). Whenever one (or more) significant breaking point was found, the corresponding year and new slope was taken.

3.2. Assessment of flow regulation

The issue of flow regulation is tackled, to highlight those catchments were hydrological trends, if present, may be masked by reservoirs' operation. Using information of the Italian *RID* (Registro Italiano Dighe, Italian register for dams, see [39]) of Italy data base, and of Ministero dei Lavori Pubblici (Ministry of Public Works) of Italy, a number of pertinent data concerning Italian dams was gathered, including date of construction, position, catchment area, altitude, impounded volume, and other features of large dams (i.e. higher than 15 m, more than 10^6 m^3 in volume). In our study area there are 175 large dams included within the data base. Of these, 94 were built during 1923–1950, having all the others been built before 1991. The total volume of such dams is of 3.3 E^9 m^3. As a comparison, the largest river here, Adige at Trento (9763 km^2), has an estimated average (1921–2012) yearly flow volume of ca. 6.6 E^9 m^3. The potential effect of flow regulation from these reservoirs upon the assessment of hydrological changes was investigated here by way of two approaches, namely (i) assessment of the percentage regulation volume stored by reservoirs $Reg_\%$, and (ii) assessment of modified mean flow regimes pre and post reservoirs' installation $DA_\%$, against percentage change as highlighted by LR, $Var_\%$.

The coefficient $Reg_\%$ was quantified as follows. For each dam within a catchment it was calculated the volume that could be retained or released either yearly or seasonally, and the effect this would have at the catchment scale. For a given reservoir one can call V_{Max} the maximum storage that can be used for flow regulation. Generally, this is a share of the total volume of the impoundment V_{Tot}, compatible with the possibility of modifying the pool level safely. For instance, in those reservoir where almost constant pool level is maintained, V_{Max} may be very small with respect to V_{Tot}. If one considers a given time interval T, the difference between the water volumes ingoing and outgoing from the reservoir, V_{in}, V_{out}, as depending upon input and output hydrograph (Q_{in}, Q_{out}), may be evaluated by integration of the continuity equation for reservoirs [19], and it is at most

$$|V_{in} - V_{out}|_{Max,0-T} = \left| \int_0^T (Q_{in}(\tau) - Q_{out}(\tau)) d\tau \right| = \left| \int_0^T \frac{dV}{d\tau} d\tau \right| = V_{Max}, \tag{1}$$

i.e. ingoing and outgoing volumes may differ at most by $\pm V_{Max}$, for either filling or emptying of the reservoir. Therefore, if one may calculate the ratio between the ingoing volume V_{in} and V_{Max} in a given period

$$\begin{aligned} Reg_\%(T) &= \frac{|V_{Max}|}{V_{in}(T)} = \frac{|V_{in} - V_{out}|_{Max,0-T}}{V_{in}(T)}, \\ |V_{in} - V_{out}|_{Max,0-T} &= V_{in}(T) \cdot Reg_\%(T), \end{aligned} \tag{2}$$

he would have a perception of the largest possible changes as given by flow regulation downstream a reservoir, i.e. the largest difference between V_{out} and V_{in}, given by a share of V_{in}. Clearly, the smaller $Reg_\%$, the smaller the regulation effect upon downstream flows, and the larger $Reg_\%$ the vice versa. Notice that by definition $Reg_\%$ depends upon the regulation period T, given that V_{Max} is a constant value (because the reservoirs geometry remains constant), while V_{in} changes (increases) with T. Therefore, over longer periods $Reg_\%$ will be smaller, so that regulation effect will be larger during shorter periods, and the vice versa for longer periods. At the seasonal scale, considerable reservoirs filling (or emptying) may occur, so one may expect larger values of $Reg_\%$. Further, in the hypothesis that within a given river a constant hydrological regime is present, and in a given period reservoirs are built and operated, the difference of seasonal (and yearly) flow volumes $V_{in} - V_{out}$ before and after the installation period could be on average no more than V_{Max}. Also, whenever a trend would occur in the stored volume, e.g. whenever the yearly, and seasonal filling or emptying of the reservoir would increase regularly in time (say from zero, i.e. for no regulation, to V_{Max} for largest regulation), the average percentage difference $V_{in} - V_{out}$ between the start and the end of the considered period could not exceed V_{Max}, and $|V_{in} - V_{out}|/V_{in}$ could not exceed $Reg_\%$. For each catchment here it was calculated a value of $Reg_{\%,r}$ for each reservoirs r of the n_r within the catchment, and all these values were summed, by weighting against the ratio of the volume of water delivered by the area S_r regulated by the reservoirs $V_{in,r}$, to that delivered by the whole catchment with area S, V_{in}. This stems from the rationale that a reservoir that can store a given volume $V_{Max,r}$ and closes only part of a catchment, will have an overall effect on the larger catchment which is proportional to the ratio $V_{r,in}/V_{in}$. Therefore the overall basin $Reg_\%$ is calculated as

$$Reg_\% = \frac{\sum_{r=1}^{n_r} Reg_{\%,r} V_{in,r}}{V_{in}}. \tag{3}$$

To accurately assess $Reg_{\%,r}$ one would need to know for each reservoir pool level dynamics in time (and characteristic level-volume curves of each reservoir), which is unfeasible for the area here as reported, so one needs a working hypothesis about reservoirs' dynamics. It was made here the hypothesis that in each season (and in a year) each reservoir can change its water content by 100% of its volume, or $V_{Max} = V_{Tot}$, meaning that all the volume can be indeed used for regulation. Notice that this is a very strong hypothesis for a number of reasons. First, at the yearly scale as reported reservoirs tend to remain constant in level (i.e. all water in needs to go out), so yearly regulation should ideally be close to zero, or small anyway. Second, at the seasonal scale the level of some reservoirs may indeed oscillate, say for irrigation release, or flood dampening, but in large reservoirs emptying and filling in the order of 100% seems unlikely, and possibly dangerous given the large oscillations of reservoir's pool level, so actual regulation would be likely smaller than that. Likely, not all reservoirs will simultaneously act in the same direction (i.e. all releasing, or all storing at the same time), and therefore the actual flow modification would be smaller than $Reg_\%$. For calculation of $Reg_\%$ it was used the average volume of ingoing discharge $E[V_{in}]$, estimated using the yearly, and seasonal average discharges along the Y years, in the hypothesis that over periods of multiple years such values are representative of the actual natural flows (i.e. that regulation over several years is negligible in calculating average volumes). Notice that use of $Reg_\%$ ignores by-pass flows, i.e. flows diverted from the study catchments to nearby rivers or consumed, flows supplying agriculture or municipal uses, and flows that are simply released back to the river downstream of the selected outlets. However, use of $Reg_\%$ may be considered as a reasonable first guess to assess the potential impact of flow regulation within a catchment. Here $Reg_\%$ was calculated at yearly and seasonal scale. A threshold was set of $Reg_\% \leqslant 10\%$ to regard the basin as relatively pristine, i.e. to make the hypothesis that stream flow within the catchment is substantially unaltered by reservoirs' operation. Thus, all catchments with $Reg_\% > 10\%$, either seasonally or yearly, were discarded for the subsequent trend analysis. The choice of such a threshold is clearly arbitrary, however it should be small enough that one may assume substantially undisturbed flows in the catchments, and carry out a hydrological trend analysis also in rivers that are little regulated.

As a second approach to the assessment of reservoirs' effect, in all cases when relevant regulation was introduced during the study period (i.e. in a period, or year included within the period of the available flow data series) it was evaluated the effect of regulation upon flow changes. This was done by visually analysis of the flow series, which may display dates when some modification occurred. From this joint analysis, those catchments were labelled where effect of regulation may potentially provide changes, that may then not be attributable to other processes. Also, whenever it was possible, it was estimated the difference between the seasonal (and yearly) averages of ingoing flow volumes before, and outgoing flow volumes after the construction of noticeable reservoirs, $V_{in,bef}$, $V_{out,aft}$, scaled on $E[V_{in}]$, namely $DA_{\%}$

$$DA_{\%} = \frac{E[V_{in,bef}] - E[V_{out,aft}]}{E[V_{in}]}. \tag{4}$$

$DA\%$ was then compared against an index providing the extent of the estimated changes in seasonal (and yearly) flows as from the LR analysis, as

$$Var_{\%} = \mathrm{LR_V} \cdot Y/\mathrm{E}[V_{in}], \tag{5}$$

where $\mathrm{LR_V}$ is LR slope, expressed in $\mathrm{m^3\ y^{-1}}$, and Y is the number of years when data were available for LR analysis. Whenever $DA_{\%}$ would be smaller than $Var_{\%}$, besides the potential effect given by flow regulation, some other type of non-stationarity would be present. Based on the joint analysis of $Reg_{\%}$, and $DA_{\%}$ as reported, those catchments were regulation is supposed to play a large role, and hydrological trend analysis would be hampered were excluded. Upon the remaining catchments, a number of tests as explained below were carried out.

3.3. Mann–Kendall test, MK

Mann Kendall test is widely adopted to assess significant trends in time series [8,31,36,56]. It is a non parametric test, less sensitive to extreme sample values, and independent from the hypothesis about the nature of the trend, either linear or not. Within the Mann Kendall test the hypothesis of stationarity is evaluated by building a statistics considering the number of times any given value is exceeded when moving sequentially forward within the series, and by comparing this with a normally distributed function with known mean and variance. Whenever the sample statistic falls within the boundaries of the normal distribution (with a given level of probability, or significance α), one may assume stationarity of the series, and the vice versa when it falls outside. Let consider a sample of a random variable, e.g. P_m, $\{P_{m,y},\ y = 1,2,\ldots,Y\}$ with Y length of the series in years. Let denote with p_y the number of elements of the sample with $j < y$ and $P_{m,j} < P_{m,y}$, while with τ one indicates

$$\tau = \sum_{y=1}^{Y} p_y. \tag{6}$$

One can show that τ is asymptotically normally distributed with the mean and standard deviation

$$\mu(\tau) = Y(Y-1)/4; \quad \sigma(\tau) = \sqrt{Y(Y-1)(2Y+5)/72}. \tag{7}$$

The variable $u(\tau) = (\tau - \mu(\tau))/\sigma(\tau)$ has a standard normal distribution, so one can build the associated confidence interval. The Mann–Kendall test verifies the assumption of stationarity by ensuring that $u(\tau)$ is included within the confidence interval for a given significance level (for $\alpha = 5\%$, range from -1.96 to 1.96). In the progressive form of the Mann–Kendall test MKP, the variables τ_j and $u(\tau_j)$ are calculated for each element of the sample j, by trading Y for j in Eq. (1) ed Eq. (2). The value of τ defines the direction (positive/negative) and magnitude (modulus) of the trend. The same procedure is applied by starting from the most recent values and backward. In this case, p_i' indicates the number of elements of the series of $P_{m,y}$ with $j > y$, and $P_{m,j} > P_{m,y}$. By p_y' one gets τ_j' e $u(\tau_j')$. If no trend is present, the chart of $u(\tau_j)$ and $u(\tau_j')$ against time (i.e. years) shows several crossing points. Contrarily, the crossing period is unique, and allows to approximately locate the starting point of the trend. Here the MK test was applied to raw data, without pre-whitening, according to [55].

3.4. Linear regression against with NAO and global thermal anomalies DT_G

The link between stream flows and (i) the anomaly (vs. long term average) of the Northern Atlantic Oscillation, NAO index [e.g. [32,33,44,45], (ii) the Global temperature anomalies $\mathrm{DT_G}$ [e.g. [16], Had-Crut [4]] during 1921–2012 was investigated. To do so, the regression slope of discharges against NAO and $\mathrm{DT_G}$, $\mathrm{LR_{NAO}}$ and $\mathrm{LR_{DT}}$, respectively, and its significance were assessed.

3.5. Correlation against physiographic and climatic features

The observed trends in time and against drivers of general circulations of stream flows, were studied depending upon descriptive physiographic variables of the selected catchments. To do so, it was assessed the correlation between the values of LR slopes of stream flows (regardless of their level of significance) against basic physiographic variables, namely geographic coordinates (latitude Lat., longitude Long.), contributing area S and mean catchment and outlet section altitude, A_m, A_o [e.g. [11]. Also, it was assessed the correlation between the values of $\mathrm{LR_{NAO}}$ and $\mathrm{LR_{DT}}$ slopes (again, regardless of their level of significance) against the same physiographic properties. They were considered trend of discharge LR, $\mathrm{LR_{NAO}}$ and $\mathrm{LR_{DT}}$ made specific to contributing area S (i.e. in $\mathrm{m^3\ s^{-1}\ km^{-2}}$), to allow a comparison between homogeneous values, otherwise being their values clearly dependent upon contributing areas.

3.6. Correlation against local climate variables

A historical climatic data base was retrieved, including precipitation P, and temperature T from a number of stations close as possible to the considered catchments (Fig. 1). Given the considered time window for flow trend assessment, dating back in some cases until 1921 or so, historical series of climate data could be retrieved in few sites. Linear correlation was calculated between seasonal stream flows and the corresponding precipitation, and temperatures. The closest precipitation and temperature station was used, and in case more close stations were available, the one displaying the highest correlation was adopted. The aim here was not to investigate variability of climate *per se*, but to highlight (i) the link between stream flows and climate, and (ii) the potential presence of climate trends, subsequently leading to flow variability. Therefore, it was carried out a procedure as follows. First, significant linear correlation between stream flows, and seasonal (cumulated) precipitation, or (average) temperature was labelled. For the sake of simplicity, it was considered correlation of stream flows with climatic variables in the same season (or yearly), with no lag (i.e. not Winter to Spring correlation, etc.). Second, for regulated catchments (among those retained for trend analysis, as explained above) where flow data were available before and after reservoirs' construction, seasonal flow correlation before and after were compared. Specifically, those cases were highlighted where prior to regulation start significant correlation was seen, and not significant correlation was found after regulation. This would imply that the introduction of regulation modified the pre-existing natural link between climate and hydrology, thus making hydrological modification less likely linked to climate. Third, from among the rivers where a significant correlation was found between climate and stream flows (bold values in Table 6), they were analysed more specifically those where significant stream flow trends were seen (Table 2). It was checked whether the (significantly correlated) climate series would display any significant trend (using linear regression analysis). The direction of the trend (positive/negative), if any, was highlighted, and it was tested whether this direction was concordant, or discordant with the stream flow trend (e.g. if discharge had an increasing trend, and it was negatively correlated against temperature, a decreasing trend of temperature was labelled as concordant, while a negative trend of temperature was labelled as discordant, etc.). The results from this analysis were used jointly with those from the other tests above, to formulate a judgment as to whether (i) hydrological behaviour may be visibly influenced by (i.e. correlated to) climate, (ii) flow operation may have disrupted the link between climate and hydrology, and (iii) visible trends of climate variables can be highlighted, that may have led to trends in stream flows.

4. Results

4.1. Effects of flow regulation

In Fig. 2, they are reported yearly, and seasonal values of $Reg_{\%}$, $DA_{\%}$, and $Var_{\%}$. Whenever $Reg_{\%}$ is larger than 10% either yearly or seasonally, it was assumed that flow regulation affected too much stream flows, and the corresponding catchments were discarded from further analysis. It is stressed that the presence of hydrological trends in these catchments needs to be investigated by means of more complex approach, possibly filtering reservoirs' operation effects.

In several cases within little ($Reg_{\%} \leqslant 10\%$) regulated catchments, the absolute value of $Var_{\%}$ was larger than that of $DA_{\%}$, possibly indicating that changes of the average stream fluxes before, and after the construction of large reservoirs are smaller than changes given by the highlighted LR trends. Whenever the vice versa case occurred ($DA_{\%} > Var_{\%}$), the related catchments were also discarded for further analysis. The retained catchments (11) for subsequent analysis are reported in Table 2, where the results of LR and MK test are shown.

4.2. Hydrological trends

In Table 2, the results of LR and MK analysis are reported, and in Fig. 3 the seasonal LR coefficients specific to area LR [$m^3\ s^{-1}\ km^{-2}\ y^{-1}\ E^4$] are represented spatially. LR analysis displays somewhat different results depending upon the scale of investigation, from yearly to seasonal.

During Winter (JFM, January February March), some variability is seen, with either increasing (3 cases) or decreasing (8 cases) values, only two significantly. The MK test displays substantially consistent results, finding significant non stationarity for the two catchments with significant linear trends. Generally speaking, in Fig. 3a increasing values (orange to red) are seen mostly in the Eastern Alps, while substantial stationarity (yellow to light green) is seen in the central and western Alps. In Spring AMJ (April May June) 1 catchment displays (not significant) increase, while 10 catchments display decrease (and 3 significantly). Decrease is mostly seen everywhere (Fig. 3b), more homogeneously at the Eastern most edge of the investigated area, but with larger values in some catchments in the West (Tanaro, Grana). In Summer JAS (July August September) 1 only catchment display (not significant) increase, with 10 catchments undergoing decrease (5 significantly). Visually (Fig. 3c), everywhere consistent decrease is observed. During Fall (OND, October November December) one river has increasing discharge, and the remaining have decreasing fluxes (one significantly), mirrored in Fig. 3d. Eventually, at the yearly scale, 1 catchment displays increasing trend of discharge (not significantly), whereas 10 catchments display negative trend, and 3 significantly. The MK test display substantially consistent results, finding significant non stationarity for 2 of the 3 catchments with significant linear trends, and stationarity otherwise. Fig. 2e displays a pattern of mostly decreasing yearly stream flows, with significant values both in the Eastern and Western Alps.

In Table 3, catchments displaying significant change of slope in time according to slope break analysis are reported. Also, it is reported the results of progressive MK test MKP, that is the year when a trend onset may be clearly detected visually. This latter test was carried only for those catchments and seasons when significant non stationarity was detected, according to the results in Table 2, and clear onset date could be detected for a subset of these catchments. Comparatively few cases display (detectable) slope break, and in the North-Eastern area a number of catchments display complex pattern. Avisio at Soraga displays decrease of yearly discharge during 1926–1945, with constant values thenceforth (Table 3). During JFM stationarity is detected until 1973, with increase thereafter (and MKP indicates onset of increasing trend in 1992). For OND, discharge seemingly decreased during 1926–1949, and then increased significantly. Rabbies at San Bernardo

Table 2
Results of LR and MK tests. In **bold** significant ($\alpha = 5\%$) slope of linear regression (LR) in [$m^3\ s^{-1}\ km^{-2}\ y^{-1}\ E^4$], and significant *p-val* for non stationarity (MK), dimensionless. Flag of regulation is reported.

River	Station	Reg.	LR Y	MK Y	LR JFM	MK JFM	LR AMJ	MK AMJ	LR JAS	MK JAS	LR OND	MK OND
AVISIO	Soraga	X	−0.37	0.23	**0.53**	**0.00**	−**1.03**	**0.05**	−**1.25**	**0.00**	0.28	0.27
BRENTA	B. Valsugana	–	−**1.50**	0.10	−0.91	0.38	−1.40	0.21	−**1.85**	**0.02**	−1.83	0.33
CHISONE	S. Martino	X	0.11	0.96	0.03	0.69	1.59	0.47	−0.30	0.36	−0.81	0.21
GADERA	Mantana	–	−0.84	0.24	−0.25	0.20	−1.71	0.21	−0.25	0.70	−1.17	0.29
GRANA	Monterosso	–	−0.68	0.23	−0.05	0.64	−1.56	0.33	−0.29	0.34	−0.79	0.43
MASTALLONE	Ponte Folle	–	−1.31	0.42	−1.94	0.50	−3.49	0.58	−0.70	0.38	1.03	0.62
RABBIES	S. Bernardo	–	−**4.77**	**0.00**	−**1.19**	**0.03**	−**6.57**	**0.01**	−**8.41**	**0.00**	−**2.86**	**0.04**
RIENZA	Monguelfo	–	−0.36	0.48	0.29	0.65	−1.52	0.41	0.06	0.72	−0.25	0.55
STURA DI LANZO	Lanzo	X	−0.68	0.10	−0.18	0.52	−0.54	0.61	−1.32	0.33	−0.67	0.33
TANARO	Ponte Nava	–	−2.04	0.04	-0.62	0.96	−**2.82**	**0.02**	−**1.66**	**0.00**	−0.99	0.80
TANARO	Nucetto	–	−**3.94**	**0.04**	−3.23	0.33	−6.17	0.38	−**2.73**	**0.02**	−3.57	0.43
	Mean		−1.49	–	−0.68	–	−2.29	–	−1.70	–	−1.06	

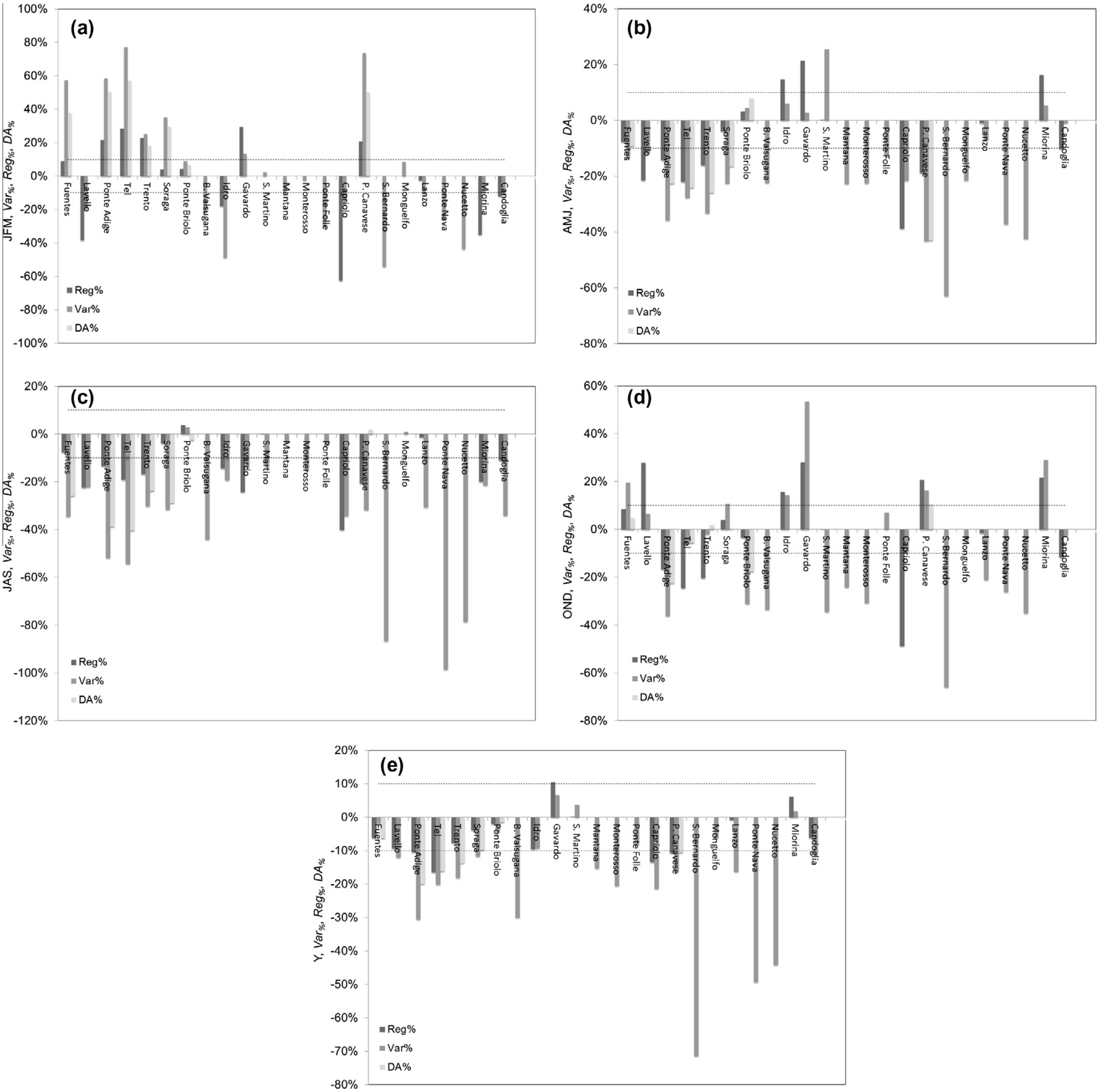

Fig. 2. Percentage regulation volume stored by reservoirs $Reg_{\%}$, modified mean flow regimes pre and post reservoirs' installation $DA_{\%}$, and percentage change as highlighted by LR, $Var_{\%}$. The dashed line indicates 10% threshold of $Reg_{\%}$, for retaining the catchment for trend's analysis. (a) JFM. (b) AMJ. (c) JAS. (d) OND. (e) Year.

had yearly discharges increasing during 1968–1977, and decreasing during 1978–2011 (Table 3). In Spring season AMJ stationarity is found until 1977, with significant increase thereafter. During Summer JAS discharge increased until 1977, with decrease thereafter. In Fall OND stationarity is found until 1976, with significant decrease thereafter. Brenta at Borgo Valsugana has yearly discharges stationary until 1979, decreasing thereafter, and similarly during AMJ and JAS, with decrease after 1985 and 1976, respectively. Tanaro at Ponte Nava displays onset in AMJ (1951, decreasing after then with net decrease during 1931–2011), and in JAS (1952, decreasing after then with net decrease during 1931–2011). Tanaro at Nucetto downstream (data set covering 1947–1979) has consistently an MKP onset of JAS season in 1956, and a slope break in 1966 (from stationary to significantly decreasing), with net decrease during the observation period. Stura di Lanzo river in Lanzo displays onset period for JAS flows around 1941, but not significant decrease during 1930–2011.

4.3. Linear regression against NAO, DT_G, and physiographic attributes

In Table 4 it is reported linear regression slope of flow discharge against NAO anomaly and global thermal anomaly DT_G. At yearly, and seasonal scale some catchments display negative correlation against NAO, and slope (7 out of 11 at yearly scale, 4, 11, 6, and 10 for JFM, AMJ, JAS, and OND, respectively), albeit in few cases significantly (1 for JFM, 2 for AMJ), and significant positive correlation is found in one case only. Concerning DT_G, some of the catchments display negative correlation and slope (7 out of 11 at yearly scale, 9, 9, 8, and 5 for JFM, AMJ, JAS, and OND, respectively), with 8 significant cases. Of those cases with positive slope, only 1 is

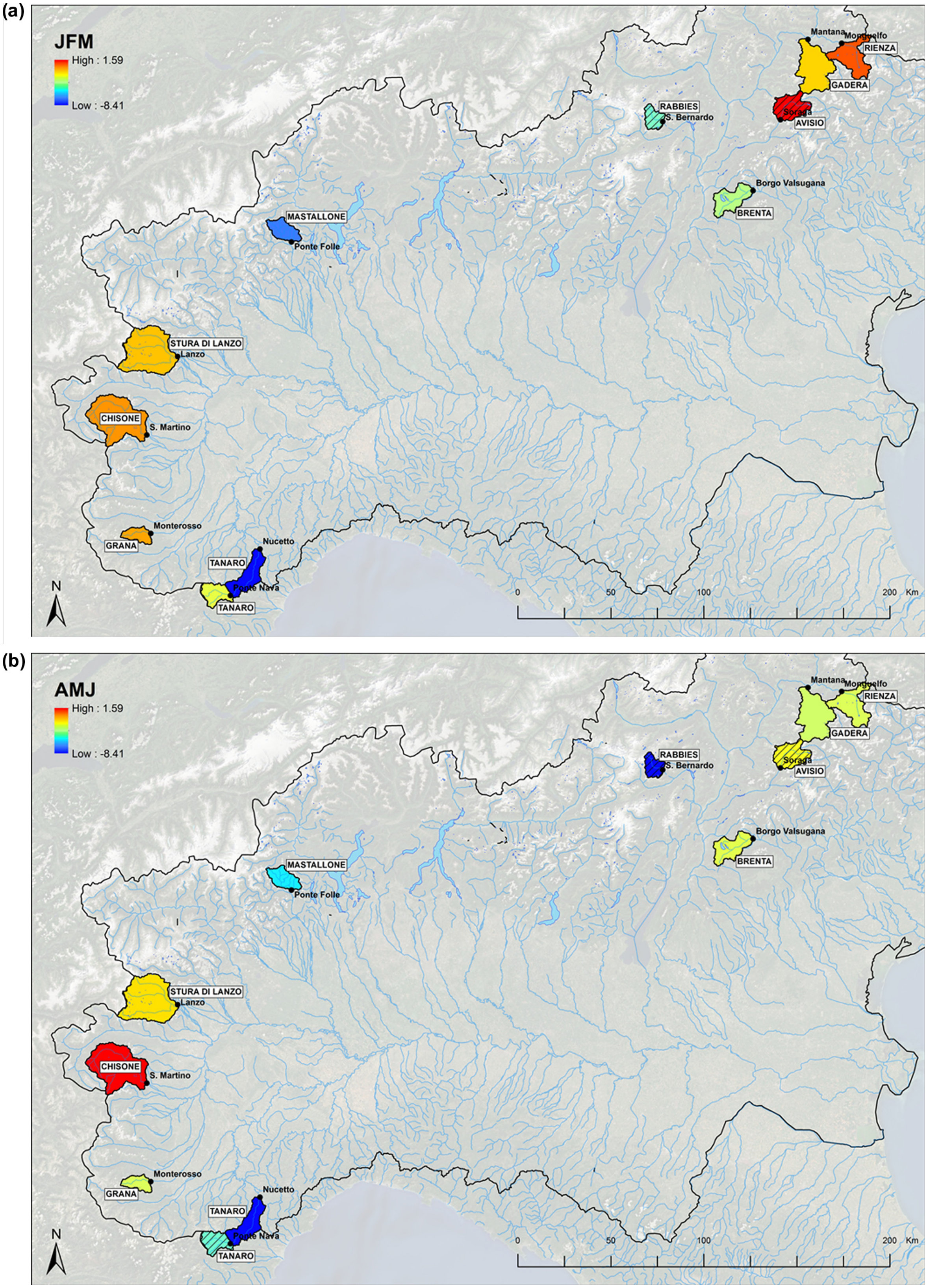

Fig. 3. Spatial distribution of trends of stream flows against years, highlighted by linear regression LR [$m^3\ s^{-1}\ km^{-2}\ y^{-1}\ E^4$]. Diagonal lines indicate significant values ($\alpha = 5\%$). (a) JFM. (b) AMJ. (c) JAS. (d) OND. (e) Year.

significant. In Table 5, the results of the correlation analysis of slope LR, LR_{NAO} and LR_{DT} against physiographic attributes are reported, and in Fig. 4 the significant relationships therein displayed. Linear regression is somewhat correlated (albeit not significantly at 5%) against physiography. At Winter scale, LR-JFM, positive correlation is found against average altitude A_m

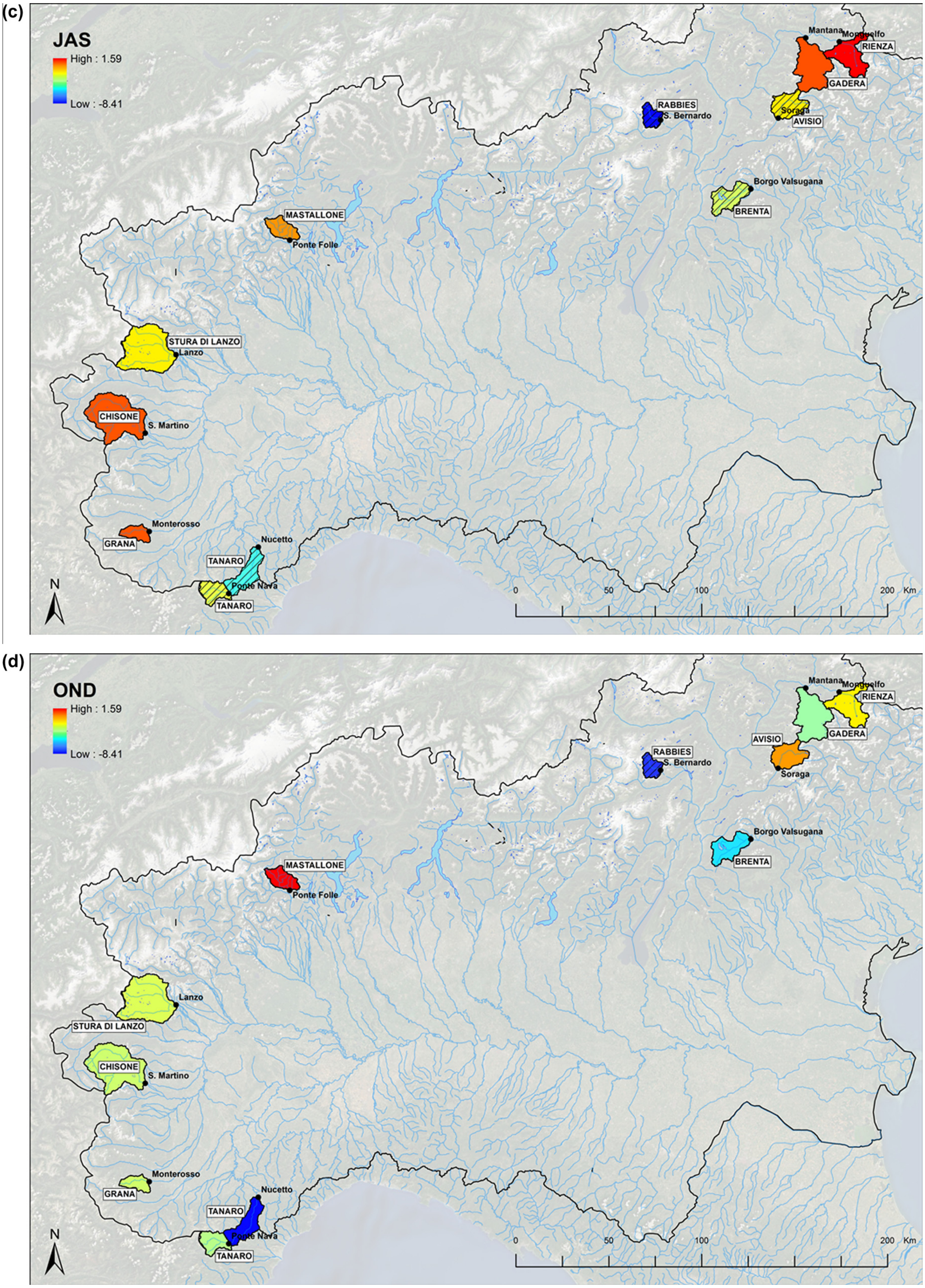

Fig. 3 (*continued*)

($\rho = 0.53$), i.e. the higher the mean catchment altitude, the larger the increase (or the smaller the decrease) in specific (to catchment area) stream flows. The trend of Spring discharges LR-AMJ displays positive correlation against S ($\rho = 0.50$), meaning that smaller catchments may lose more water proportionally. When NAO is considered, Winter hydrological patterns LR_{NAO}-JFM are notably

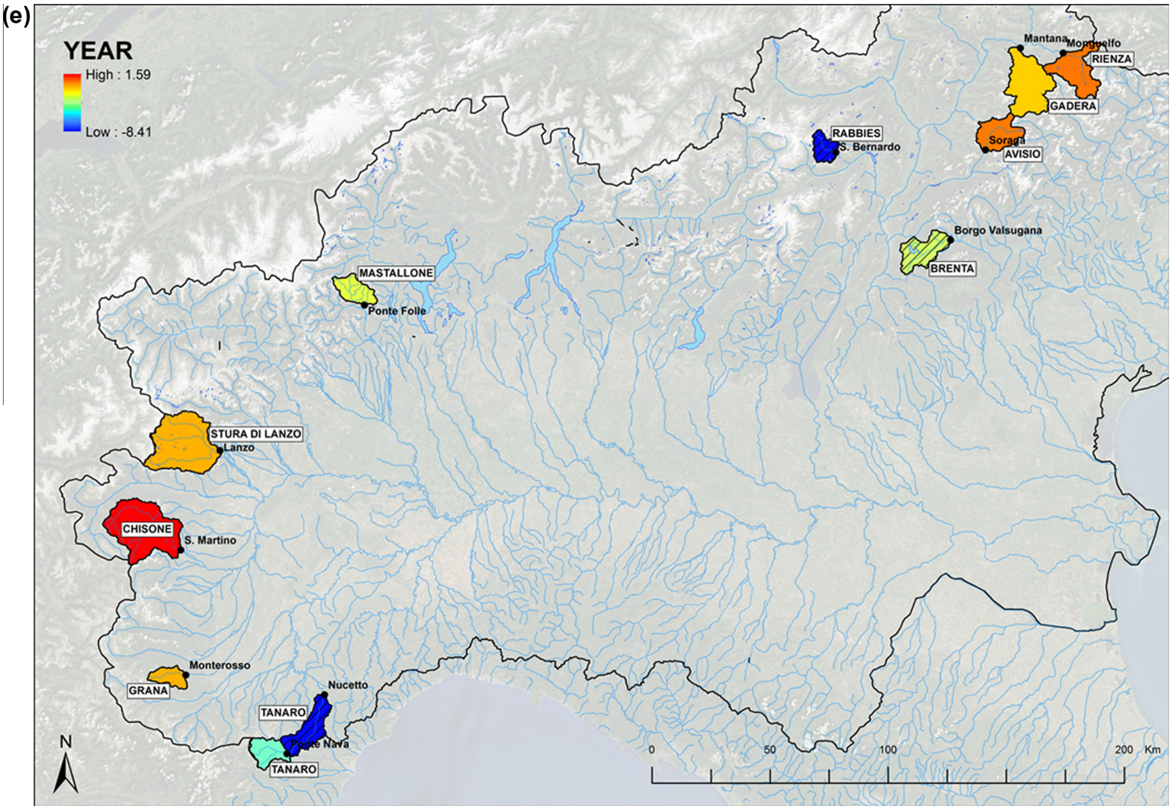

Fig. 3 (*continued*)

Table 3

Starting year of increasing trends according to progressive Mann Kendal test (MK), when detected. Year of slope break, and slope before and after [$m^3\ s^{-1}\ km^{-2}\ y^{-1}\ E^4$], when detected. In **bold** significant ($\alpha = 5\%$) slopes.

	AVISIO Soraga		RABBIES S. Bernardo
Break Y	1945	Break Y	1977
LR 1 Y	**−4.14**	LR 1 Y	**15.46**
LR 2 Y	0.29	LR 2 Y	**−7.28**
Start (MK) JFM	1992	Break AMJ	1977
Break JFM	1973	LR 1 AMJ	26.04
LR 1 JFM	−0.17	LR 2 AMJ	**−10.67**
LR 2 JFM	**1.45**	Break JAS	1977
	AVISIO Soraga	LR 1 JAS	**24.17**
Start (MK) AMJ	1942	LR 2 JAS	**−12.45**
Break OND	1949	Break OND	1976
LR 1 OND	**−6.14**	LR 1 OND	11.84
LR 2 OND	**1.86**	LR 2 OND	**−4.28**
	BRENTA B. Valsugana		TANARO P. Nava
Break Y	1979	Start (MK) AMJ	1951
LR 1 Y	1.27	Start (MK) JAS	1952
LR 2 Y	**−4.95**		TANARO Nucetto
Break AMJ	1985	Start (MK) JAS	1956
LR 1 AMJ	3.65	Break JAS	1966
LR 2 AMJ	**−16.19**	LR 1 JAS	**−4.63**
Break JAS	1976	LR 2 JAS	0.85
LR 1 JAS	0.66		STURA LANZO Lanzo
LR 2 JAS	**−3.97**	Start (MK) JAS	1941

(but not significantly) correlated to outlet altitude A_o ($\rho = 0.45$), i.e. for higher catchments NAO may be positively correlated with stream flows.

In Spring, LR_{NAO}-AMJ is significantly linked ($\rho = 0.57$, Fig. 4) to longitude, i.e. as one moves East ward NAO seems to affect less (i.e. with negative slopes, but closer to zero) stream flows. When Summer flows are considered, LR_{NAO}-JAS is negatively (not significantly) correlated against latitude, i.e. NAO impacts less the more Northern.

Concerning DT_G, significant dependence if found for LR_{DT}-JFM against A_m ($\rho = 0.64$, Fig. 4), with an inverse effects of increasing DT_G below and above a given altitude (ca. 1600 m a.s.l. with decrease of stream discharges below and increase above). LR_{DT}-AMJ in Spring is correlated against S ($\rho = 0.68$, Fig. 4), meaning again that smaller catchments lose proportionally more flow for increasing Global temperatures.

4.4. Correlation with climatic variables

In Table 6 the results of correlation analysis against climate are reported. Therein, seasonal discharges in the considered river station displaying a trend are labelled (see Table 2). When significant correlation values are seen, and a trend in discharge is also detected, in the parentheses it is reported the presence of a trend of the climatic variables, if present, together with its sign (+ for positive, − for negative). Also, it is reported a judgment of concordance between the trends with respect to the sign of correlation (e.g. if discharge has an increasing trend, and it is negatively correlated against temperature, a decreasing trend of temperature is labelled as concordant, while a negative trend of temperature is labelled as discordant). Also, they are labelled those catchments where it was possible to analyse correlation before, and after reservoirs' building (i.e. station labelled with *), and it was found that correlation intensity decreased after construction. It is seen from Table 6 that mostly seasonal discharge is correlated with precipitation, and in one case correlation decreases significantly after regulation (Soraga). Temperature is significantly correlated in few cases, and mostly negatively (i.e. higher temperatures lead to decreasing flows, possibly via increased evapotranspiration), unless for Winter JFM, when increasing temperature may lead to

Table 4
Results of the LR test vs. NAO [$m^3\ s^{-1}\ km^{-2}\ E^4$] and DT_G [$m^3\ s^{-1}\ km^{-2}\ °C^{-1}\ E^4$]. In **bold** significant ($\alpha = 5\%$) slope of linear regression.

River	Station	NAO Y	NAO JFM	NAO AMJ	NAO JAS	NAO OND	DT_G Y	DT_G JFM	DT_G AMJ	DT_G JAS	DT_G OND
AVISIO	Soraga	−10.7	**2.4**	−20.1	4.2	−18.5	−0.3	**58.0**	−57.1	−72.3	61.1
BRENTA	B. Valsugana	−22.1	−13.5	−15.5	−16.5	−13.4	**−167.8**	−88.1	**−215.9**	−148.9	−193.6
CHISONE	S. Martino	2.7	3.3	−65.7	22.5	−5.9	38.3	12.7	177.6	−10.4	18.6
GADERA	Mantana	−26.1	3.9	−20.1	10.3	−15.4	18.0	−9.7	−109.3	215.9	45.0
GRANA	Monterosso	12.7	2.3	−58.2	−2.5	−19.2	−36.3	−5.2	−150.5	−4.0	12.0
MASTALLONE	Ponte Folle	−100.7	−16.5	**−163.7**	−10.1	−19.5	120.5	**−292.6**	−39.3	−127.6	**1006.2**
RABBIES	S. Bernardo	−10.1	0.2	−32.8	−0.4	−22.5	**−254.6**	−35.9	**−348.9**	**−465.2**	**−150.1**
RIENZA	Monguelfo	−12.5	1.2	−19.5	−0.6	−19.1	24.6	−7.7	−77.5	190.5	52.2
STURA DI LANZO	Lanzo	1.2	−1.7	**−67.3**	−5.1	−24.6	−20.0	−39.1	57.8	−42.4	−3.4
TANARO	Ponte Nava	−35.2	−18.0	−44.3	38.2	−31.3	−162.3	−122.9	−214.0	−321.8	−40.2
TANARO	Nucetto	30.9	8.9	−35.9	14.4	6.5	−232.2	**−216.7**	−269.3	76.3	−26.8
	Mean	−15.4	−2.5	−49.4	4.9	−16.6	−61.1	−67.9	−113.3	−64.5	71.0

Table 5
Results of the correlation analysis of slope LR, LR_{NAO} and $LR_{DT,}$ against physiographic features. In **bold** significant ($\alpha = 5\%$) correlation coefficients.

Slope/Physiographic feature	Lat	Long	S	A_m	A_o
LR-Y	0.12	−0.01	0.35	0.01	−0.24
LR-JFM	0.31	0.27	0.12	0.53	0.19
LR-AMJ	0.03	−0.07	0.50	0.02	−0.37
LR-JAS	−0.11	−0.14	0.33	−0.32	−0.31
LR-OND	0.23	−0.01	−0.05	0.13	−0.10
LR_{NAO} Y	−0.31	−0.11	0.36	0.14	0.23
LR_{NAO} JFM	0.09	0.10	0.42	0.42	0.45
LR_{NAO} AMJ	0.23	**0.58**	0.03	0.25	0.50
LR_{NAO} JAS	−0.51	−0.32	0.18	0.19	0.11
LR_{NAO} OND	−0.16	−0.08	−0.38	−0.10	−0.10
LR_{DT} Y	0.27	−0.04	0.26	0.11	−0.18
LR_{DT} JFM	0.31	0.36	0.20	**0.64**	0.38
LR_{DT} AMJ	0.00	−0.29	**0.68**	0.11	−0.39
LR_{DT} JAS	0.16	0.15	0.49	−0.11	0.03
LR_{DT} OND	0.09	−0.21	−0.16	−0.18	−0.22

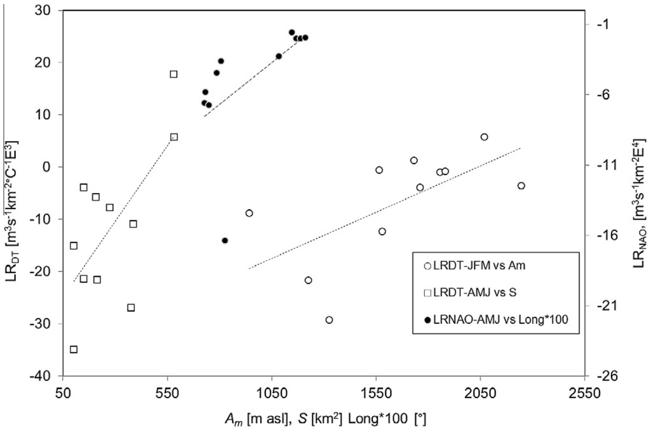

Fig. 4. Linear regression coefficients of stream flows against NAO, and DTG, plotted against physiographic features. Only cases displaying significant dependence again physiography are reported (Table 5), namely LR_{DT}-JFM vs. A_m, LR_{DT}-AMJ vs. S, LR_{NAO}-AMJ vs. *Long*. The variable in the x axis changes accordingly.

less snowfall, and more discharge. Small (not significant) correlation against precipitation (and temperature) in some or all seasons is found for some catchments (e.g. Rabbies at S. Bernardo, and Tanaro at Nucetto). This may occur because climate variables as measured by the available network here are less representative, and *in situ* stations would have been necessary. Again, this results from the lack of spatially dense, long term climate series that may be readily used for conjectures within this catchments.

5. Discussion

In Table 7, it is reported a final resume, based upon a joint analysis of the findings above. This table provides a judgment about the presence of an actual change in hydrological conditions, including the potential effect of regulation (for the three lightly regulated catchments), and climate therein. In case regulation is labelled as significantly impacting downstream flows, a reason for this choice is provided.

The results here provide some room for discussion. Most (all but one) of the investigated alpine rivers display decreased discharge yearly (variable as per data availability for different catchments), with an average of $-0.149\ ls^{-1}\ km^{-2}\ y^{-1}$. One may roughly estimate on average a loss of ca. $-13.4\ ls^{-1}\ km^{-2}$ during the 90 years window here, which given the mean value of 29 $ls^{-1}\ km^{-2}$, would imply on average a loss of ca. −46% of the long term mean. Such variation however is not evenly distributed seasonally. During Winter, 8 catchments display decreased discharge, and 3 the vice versa, and the average trend provides $-0.07\ ls^{-1}\ km^{-2}\ y^{-1}$. During Spring, all but 1 catchment display decreasing discharges, and average of $-0.22\ ls^{-1}\ km^{-2}\ y^{-1}$ is reached, witnessing noticeable loss of stream flows during this season. During Summer 10 out of 11 catchments display negative trends, on average $-0.17\ ls^{-1}\ km^{-2}\ y^{-1}$. In Fall, 9 catchments display flow decrease, reaching an average value of $-0.11\ ls^{-1}\ km^{-2}\ y^{-1}$. In few cases, slope break have been detected, especially concerning the Eastern most catchments, indicating onset of period with stronger trends. Spring flows decrease, in some cases with clear onset between the late sixties, and the early eighties (Rabbies at San Bernardo, Brenta at Borgo Valsugana). Summer flows start decreasing significantly in the late seventies (Rabbies at S. Bernardo, 1977, and Brenta at Borgo Valsugana, 1976). The analysis of correlation against physiographic features provides interesting hints. Smaller catchments lost proportionally more of their stream flows (specific to area) yearly, witnessing highest vulnerability water wise. When average catchment altitude A_m is high, i.e. when large parts of the catchment flows tend to rely upon cryospheric water (e.g. snow and possibly ice), increased discharge may be seen during Winter, thus likely implying increased runoff given by trading of snowfall for rainfall. Possibly as a result, discharge during Spring LR-AMJ decreases more as one moves upward the outlet section A_o. This may be explained by lack of snow cover as a consequence of decreased Winter snow fall at the highest altitudes, which contributes the main flows in thaw season for catchments dwelling at high altitudes. During Summer, discharges decrease everywhere in our batch of catchments, independently of physiography, and similarly during Fall.

Looking at the general drivers of circulation, NAO is possibly correlated to flow variation as modulated by geographic patterns.

Table 6

Correlation of seasonal discharge against seasonal precipitation *P*, and temperature *T* climatic variables. Station names in **Bold** indicate flow regulation. Correlation values in **Bold** indicate significant (linear) correlation. *Italic* values indicate that seasonal discharges in the considered river station display a trend (Table 2). When significant correlation values are seen, and a trend in discharge is detected, in the parentheses the presence of a trend of the climatic variables is reported, if present, together with its sign (+ for positive, − for negative). Also, in the parentheses it is reported a judgment of concordance between trends with respect to the sign of correlation (e.g. if discharge has an increasing trend, and it is negatively correlated against temperature, a decreasing trend of temperature is labelled as concordant, *C*, while a negative trend of temperature is labelled as discordant, *D*). Underlined values are reported for those catchments where it was possible to analyse correlation before, and after reservoirs' building (i.e. station labelled with *) and it was found that correlation intensity decreased after construction (i.e. significant correlation occurred before construction, and not significant correlation is found after construction).

Station	PY	PJFM	PAMJ	PJAS	POND	TY	TJFM	TAMJ	TJAS	TOND
Soraga*	**0.6**	*−0.01*	***0.45(−,C)***	***0.40(−,C)***	**0.38**	−0.18	*0.15*	*−0.08*	*−0.14*	−0.14
B. Valsug.	***0.70***	**0.44**	**0.42**	***0.57***	**0.77**	*−0.12*	0.01	−**0.32**	−***0.35 (−,D)***	0.12
S. Martino	**0.69**	**0.46**	**0.7**	0.3	**0.62**	−0.24	0.21	−**0.35**	−**0.43**	−0.1
Mantana	**0.60**	0.16	**0.47**	**0.44**	**0.5**	−0.33	0.26	−0.05	−**0.42**	−0.18
Monterosso	**0.74**	**0.49**	**0.63**	**0.45**	**0.57**	−0.01	0.29	−0.23	−0.21	−0.05
P. Folle	**0.71**	**0.73**	**0.58**	**0.72**	**0.62**	−**0.57**	0.18	−**0.58**	−**0.7**	0.01
S. Bern.	*−0.14*	*−0.06*	*0.23*	*−0.29*	*0.29*	−***0.65(+,C)***	*−0.2*	−***0.60(+,C)***	−***0.51(+,C)***	*−0.18*
Monguelfo	**0.54**	−0.04	0.26	**0.46**	**0.43**	−0.12	0.27	−0.06	−0.23	−0.27
Lanzo	**0.64**	**0.62**	**0.61**	**0.46**	**0.69**	−0.08	−0.18	−0.11	−0.09	−0.14
P. Nava	0.28	**0.57**	***0.39***	*0.32*	**0.5**	−**0.36**	0.21	*−0.1*	*−0.13*	0.02
Nucetto	*−0.17*	0.01	0.05	*0.13*	−0.07	*0.03*	0.21	−0.06	*0.13*	−0.13

Table 7

Final judgment about the presence of an actual change in hydrological conditions, including the potential effect of regulation (three catchments in **Bold**), and the potential effect of climate therein. The period P where visually a trend was detected is reported (compare with Tables 2 and 3). Then, the building period P_B of large reservoirs is given. J is a qualitative assessment of the influence of regulation and/or climate. U is unregulated. N indicates a likely little influence, C indicates substantially constant flow. W indicates that correlation patterns against weather variables has been changed by regulation. F indicates those cases when climate variation may explain flow variation (see Table 6). *Italic* symbols indicate the presence of trends labelled as significant with LR analysis (Table 2), and their sign ±. **Bold** indicates those streams and periods where observed significant trends may not be charged to regulation. Use of more indexes highlights presence of more than one item.

River station	P_{Y}	P_{JFM}	P_{AMJ}	P_{JAS}	P_{OND}	P_{B}	J_{Y}	J_{JFM}	J_{AMJ}	J_{JAS}	J_{OND}
Soraga	1926–1950	1973–2012	1926–1950	1926–2012	–	1955	N	***N+***	***NWF***–	***NF***–	WC
B. Valsugana	1956–1999	–	–	1956–1999	–	–	***U***–	U	U	*U*	U
S. Martino	–	–	–	–	–	?	N	N	N	N	N
Mantana	–	–	–	–	–	–	U	U	U	U	U
Monterosso	–	–	–	–	–	–	U	U	U	U	U
Ponte Folle	–	–	–	–	–	–	U	U	U	U	U
S. Bernardo	1977–2012	1968–2012	1977–2012	1977–2012	1976–2012	–	***UF***–	***U***–	***UF***–	***UF***–	***U***–
Monguelfo	–	–	–	–	–	–	U	U	U	U	U
Lanzo	–	–	–	–	–	1932–1933	N	N	N	N	N
Ponte Nava	–	–	1951–2011	1960–2012	–	–	U	U	***U***–	***U***–	U
Nucetto	1947–1979	–	–	1955–1979	–	–	***U***–	U	U	***U***–	U

At Winter scale, the investigated catchments display anti correlated stream flows against NAO, and the higher A_0 (and less A_m) the higher (in absolute value) LR_{NAO}-JFM. Therefore, NAO is less (negatively) affecting those catchments with higher A_m (and A_o), possibly implying that NAO driven climate variability in Winter does not yet reach the highest altitudes. During Spring, NAO affects negatively stream flows, more strongly in the Western Alps, possibly indicating limited Eastern wise intrusion of NAO effect within the Alps in that season.

During Summer LR_{NAO}-AMJ is mostly negative, and largest at the lowest latitudes (and longitudes), i.e. NAO effects are felt more strongly in the South-East areas.

Global temperature anomaly DT_G effect is visible and mostly negative (Table 4). During Winter, clearly highest catchment display largest increase of discharge (Fig. 4). Similarly to LR_{NAO}-JFM, LR_{DT}-JFM ranges from negative values for the lowest catchments to positive (albeit smaller in absolute values) values for the highest ones, implying that the main direct effect of global warming upon hydrology of the Alps would be a decrease of Winter stream fluxes at low altitudes, and an increase at the high ones, likely via trading of snowfall for rainfall.

During Spring LR_{DT}-AMJ is mostly negative, and larger for smaller catchments (Fig. 4), and similarly (albeit less significantly) during Summer (Table 4).

Analysis of the present literature concerning climate variability in the Alps, and potential effect upon the cryospheric dynamics may complement the hydrological analysis here, and aid drawing of conjectures concerning climate control upon hydrology. Among others, Brunetti et al. [17,18], also based upon Nanni et al. [43], and Lo Vecchio and Nanni [37] investigated trends of temperature and precipitation (1866–1995) for a number of stations in Italy (see Fig. 1 in [17]). For Northern Italy, they found a spatially averaged rate of increase in temperature of +0.4 °C/100y at yearly scale (+0.7 °C/100y Winter, +0.3 °C/100y Spring, +0.2 °C/100y Spring, and +0.5 °C/100y Fall). Precipitation was found to decrease yearly, in reason of -47 mm/100y, but unevenly spread seasonally (+8 mm/100y Winter, −20 mm/100y Spring, −7 mm/100y Summer, −28 mm/100y Fall).

Brunetti et al. [17] investigated precipitation variability (1800–2003) upon the greater Alpine region GAR using 192 measurement stations, split into four homogenous regions. Their South West region, roughly containing the portion of Italian Alps investigated here, displayed on average a significant, ca. −10% precipitation variation (reference, 1961–1990) at the yearly scale, and significant seasonal variation (−14%) only in Fall. A number of other studies highlighted locally increasing temperatures, substantially constant precipitation, and largely decreasing snow cover and ice cover for Northern Italy (e.g. [10,21,23] for Lombardy region, nesting Adda, Brembo, Oglio, Chiese, and part of Ticino here, all heavily regulated, [24] for Val d'Aosta region, laid between Mastallone, and Stura di Lanzo here). The climate trends highlighted within the Italian Alps recently seem consistent with our findings concerning hydrological trends. During Winter, the documented lack of snowfall may have resulted into increased flows at the highest altitudes (above

1600 m a.s.l. or so, Fig. 4), and possibly this effect is higher at more Northern latitudes, albeit not significantly (Table 5, $\rho = 0.31$). At lower (and more Southern) sites, decreased discharge is found instead. Even under substantially constant precipitation, this effect may be explained by increased temperature, with subsequent evapotranspiration, drawing moisture from soil, and possibly increasing hydrological losses. Among others, Groppelli et al. [30] investigated potential variation of hydrological cycle of Oglio river (therein closed at Sarnico, $A_o = 185$ m a.s.l. $A_m = 1417$ m a.s.l. nearby Capriolo here). Under a scenario of unchanged precipitation, an increase of +2 °C or so (LOC scenario in [30]) resulted into doubled evapotranspiration at 1200 m a.s.l. during Winter (from ca. 12 mm, to ca. 25 mm on average), and noticeably increased yearly (from ca. 300 mm, to ca. 380 mm on average), indicating credibility if such hypothesis. At the highest altitudes, this effect seems directly linked to worldwide temperature anomaly (Fig. 4), with discharges decreasing with DT_G below 1600 m a.s.l. or so, and increasing above, so possibly witnessing the effect of global warming upon Alpine hydrology. Also, NAO correlates to discharges during Winter in a way that the highest catchments (A_m, A_o) have increased discharge when NAO increases, and the lowest the vice versa (Table 4). D'Agata et al. [21] studied glacier changes and climate during 1951–2007 in the Ortles Cevedale group (nested within Adda river here), finding anti-correlation of total precipitation against NAO in all seasons, and especially in Winter and Summer ([21], Table 7). Thus, one may conjecture that periods of high NAO lead to decreased precipitation, in turn decreasing stream flows. However, high NAO also carries high temperature ([21], Table 7), especially in Winter and Summer, thus at the highest altitudes snowfall is traded for rainfall, and specific discharge may increase notwithstanding decreased rainfall. Spring flows decrease noticeably in most catchments, and the highest the outlet the larger the decrease (Table 4). The Western most catchments display largest anti-correlation against Spring NAO (Fig. 4). Spring flows within the Alpine catchments here are sustained by snow during thaw, and Western areas of the Alps display decreased snow cover when high values of NAO occur, as reported (e.g. [23]), so possibly affecting flows in thaw season. Summer flows were detected to decrease in all but two catchments, and the higher the larger decrease (Table 4). Again correlation against NAO shifts from negative to positive as one moves upward (A_m, Table 4), and the vice versa moving towards North (with latitude Table 4), so most Northern catchments suffer Summer flow decrease from NAO increase. Fall discharges display a less coherent pattern, with general decrease everywhere. Brunetti et al. [18] studied seasonal precipitation trends (1920–1998) for seven stations in North Eastern Italy, all embedded within the greater Adige catchment here (unless for Belluno, see Fig. 1 therein). On average they found slight (and not significant) decrease of total precipitation in all seasons, faster since the sixties onward, which may explain slightly decreasing Fall discharges in this area.

Only in very few cases here a direct link between climate variation, and flow variation could be flagged (see Table 6). These cases displayed change of discharge in response to precipitation decrease (flow decrease in Spring and Summer, at Soraga), and in response to changes in temperature (e.g. Summer temperature increase results into decreased discharges in S. Bernardo). Albeit the results here seem consistent qualitatively with the expected effect of climate variation upon stream flows, they indicate that investigation of the relationship between climate trends and hydrology may require more complicate techniques than the statistical approach here, including e.g. more sophisticated local hydrological modelling, and possibly use of meteorological information from stations closer to the catchments than here, whenever available. Such degree of complexity seems especially required for the investigation of the dynamics of snow (and ice, when present) cover, which depends in a complex manner upon both precipitation and temperature, and affects considerably the dynamics of stream flows in ways that cannot be captured by a large scale statistical analysis. Here, the lack of direct connection between climate and flow trends found here may still be given by flow regulation in three catchments. However, one has to notice that (i) low correlation between climate and hydrological fluxes was also found for unregulated rivers, and (ii) even in cases where flow trends were found, and correlation against climate was significant, climate trends were not necessarily present.

The present analysis covered a limited number (23) of catchments, eleven of which were taken as pristine enough to tentatively carry out an analysis of the hydrological changes therein. As expected the so chosen catchments were relatively small (contributing area 100–600 km^2), and high (average altitude 1000–2500 m a.s.l.).

Albeit such Alpine catchments represent a relevant test bed for investigation of climate change impact, larger, downslope catchments are of tremendous interest given large the water supply therein, necessary for civil, environmental, and agricultural purposes. Therefore, even in regulated rivers, clear assessment of climate to hydrology relationships need to be tackled.

Here, some changes have been highlighted also for such largest catchments (Fig. 2), and in the future, transient, and prospective climate change there will require investigation.

6. Conclusions

The results here provide a benchmark for hydrological changes within alpine rivers of Italy, yield evidence of the linkage between such changes and general climate drivers also depending upon geographic setting, and depict a preliminary framework for the physical interpretation of modified hydrological regimes in the Italian Alps during the last century. In this study relatively small unregulated, or little regulated rivers were studied, where the effect of climate can be reasonably well separated from anthropic activity, which limited the extent of the analysis.

Notwithstanding so, the evidences here suggest that hydrological changes are undergoing in Northern Italy, and that statistically visible linkage against physiography, local climatology, and general drivers of circulation is indeed present. The study demonstrates that further effort is worth being made towards the interpretation of the behaviour of Alpine catchments, those here and others, to unravel small scale meteo-hydrological mechanisms undergoing the observed patterns, and to further separate the effect of anthropic regulation when present. The proposed results may be useful to scientists willing to tackle such effort, and also to river managers and decision makers in the field of water resources and agriculture, willing to gather a quantitative assessment of the observed long term trends (and potential future evolution) of water resources in the area, for medium to long term planning purposes.

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