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Variation in discharge, precipitation and temperature in Po river and tributaries basins

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SUMMARY This report provides a preliminary analysis of discharges, precipitation and temperature data since 1923 for 18 closure sections of Po river and its tributaries. First we have investigated the consistency of the data, evaluating the inter-basin correlations, and the relationship between precipitation and discharge timeseries. This analysis provides a coherent picture, suggesting that the data used are reliable. Then we have explored the variation in temperature, precipitation and discharge in each sub-basin. While temperatures show a clear positive trend, precipitation and, generally discharge series did not show any trend at annual scale. Greater changes have been observed at monthly scale, with discharge increasing in May and October. However, the higher values of interannual variability (estimates with the standard deviation of the series), compared to these variations, suggest care in interpreting these results.

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INTRODUCTION

At global scale, the potential impact of warming on the hydrological cycle is an intensification of this cycle, associated to an increase in the frequency and severity of floods and droughts [2]. Moving from global to regional scales, there are larger uncertainties and more knowledge gaps on the expected hydrological changes linked to climate and environmental changes. This consideration is exacerbate considering mountain regions, defined as ”the blackest of black boxes in the hydrological cycle” [7]. In these regions, the knowledge of the hydrological cycle is mainly hampered by data limitation. Besides, compared to other areas, the water budget in mountain regions generally shows an higher spatial-temporal variability due to the heterogeneous terrain, with strong precipitation (liquid and solid) and temperature gradients in addition to other orographic effects, like slope and exposition. Thus, hydrology of mountain regions is highly sensitivity to climate and environmental change.

The Po river basin provides a relevant case to analyse climate and hydrological changes in a mountain region because is characterized by a complex orography, about 50% of its surface is covered by mountains (Alps in the north and Apennines in the south). In addition, it is the longest (652 km) river in Italy and it is one of the largest basins in Europe and the widest of Italy, with an area of about 71000 km^2 in Italy and about 3000 km^2 between France and Switzerland. The Po basin is one of the mostly populated areas in Italy, with about 16 million inhabitants, mainly concentrated in cities like Milan and Turin, and one of the most important Italian areas in terms of productive enterprises and water utilization. This basin is prone to hydrogeological disasters related to severe floods and droughts, mostly related to the high hydrogeological hazard and the strong human pressure [9]. The precipitation regime over the Po river basin shows a great spatial variability due to the influences of different climatological regimes, such as Mediterranean, Continental, Atlantic, and Polar [3]. Therefore, due to this climatic variability and the topographic complexity, this region is a challenging area to quantitatively assess its water cycle and related variations due to climate change.

Several studies analysed the river flow variability of the Po River discharge, focussing on the data at the closure of the entire basin (see e.g. [11, 8, 5]). On the other hand, it is still missing an extensive analysis of discharge changes using all the available observed values of Po river sub-basins, with a comparison with recent climate fluctuations. In this work, of preliminary nature, we summarize the results of a hydrological analysis of 18 gauging stations in the Po river basin and tributaries basins over the period 1923-2012. In addition, we investigate precipitation and temperature time series linked to each sub-basin considered. Specifically, the objectives of this study are twofold: (i) assessing the reliability of the data used, in particular comparing discharge and precipitation data and (ii) investigate the decadal variation in discharge, precipitation and temperature in each sub-basin.

The study is organized as follows. After this Introduction, section ”Data” describes the observed data. Then, section ”Results” presents the results obtained and section ”Discussion and Conclusions” describes and resumes the main findings of this report.

DATA

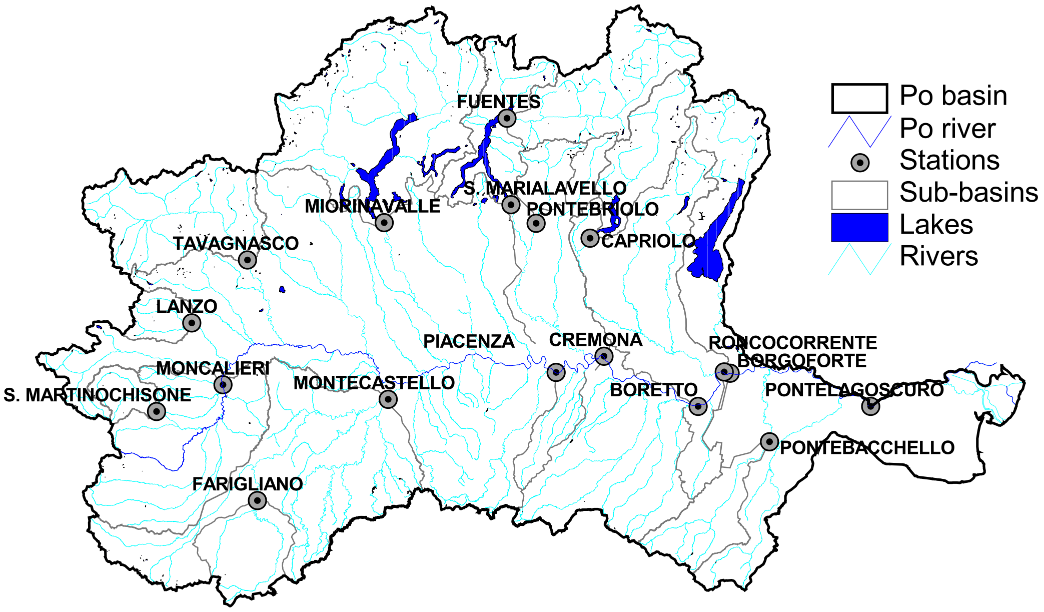

Figure 1:
Po river basin and location of the gauging stations and relative sub-domains.

We considered 18 timeseries of flow river observations recorded over the period 1923-2012. Data were extracted from Hydrological Annals Part II that are available from ISPRA (Institute for environmental Protection and Research) and ARPA Emilia-Romagna (Regional Agency for Environment and Protection of Emilia-Romagna region) websites.

Figure 1 shows that the gauging stations are quite uniformly distributed over the domain. Sub-basins at the closure of available stations have been identified in GIS environment from DEM (Digital Elevation Model) and aggregating or splitting Po sub-basins (shape files available at the following link: www.adbpo.it).

All the available time series were checked and incorrect or suspect data were excluded from further analysis. Table 1 summarizes the main characteristics of each sub-basin, including its mean elevation, the first and the last year in which there are data, and the number of years in which there are at least 90% of valid measurements. Figure 2 shows the availability of the measurements in each year for each station and basin. Few stations provided valid data for the entire period of interest while the majority of the stations do not provide data at the beginning of the period and in recent years. However they provide valid data from a minimum of 39 years to a maximum of 89 years. In the following we analyse only measured data without filling the gaps by means of interpolation techniques. Discharge at annual and monthly scales are converted into equivalent depth of water over the entire catchment (mm per year, or per month) dividing the volume of flow (m^3/s) by the area of the river basin to facilitate the comparison with precipitation data

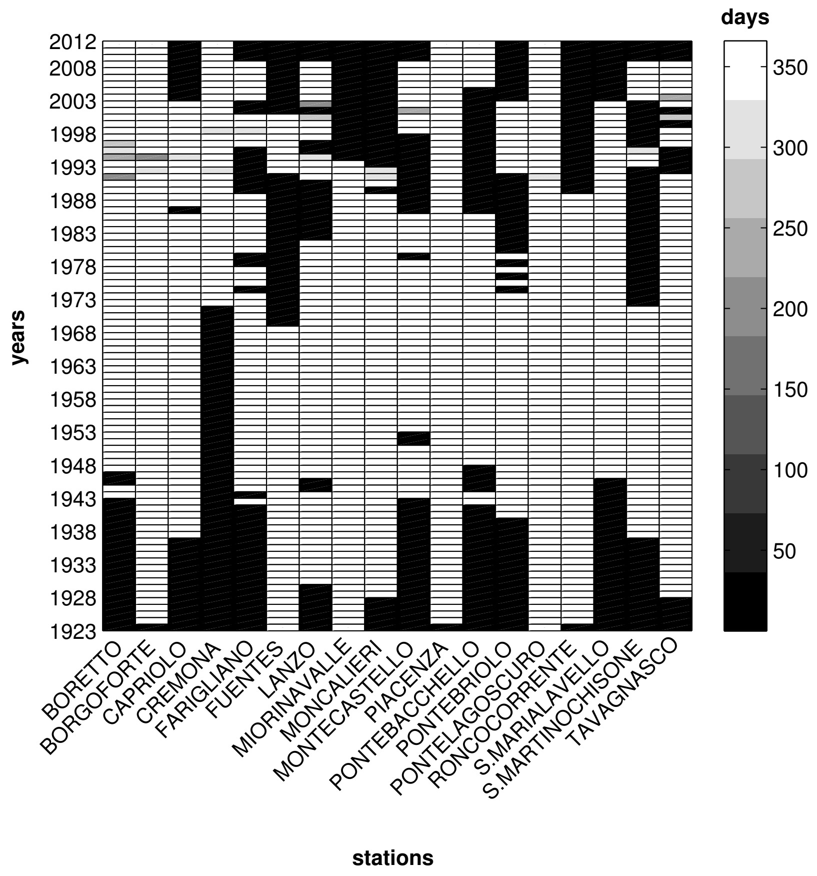

Figure 2:
Number of valid daily data in each year and for each station. The gray scale ranges from black (i.e. there is no data in that year) to white (the year is complete).

Sub-basin	Mean elev (m)	Surface (km^2)	First year	Last year	N° valid years
Boretto	831	56112	1943	2012	64
Borgoforte	808	63272	1924	2012	87
Capriolo	1364	1798	1937	2002	64
Cremona	872	51558	1972	2012	39
Farigliano	917	1559	1942	2008	53
Fuentes	1868	2859	1923	2000	55
Lanzo	1609	624	1930	2008	62
Miorinavalle	1261	6593	1923	1993	71
Moncalieri	855	5234	1928	1992	62
Montecastello	622	8143	1942	2008	50
Piacenza	828	42125	1924	2012	89
Pontebacchello	642	1438	1942	2012	48
Pontebriolo	1106	765	1940	2002	48
Pontelagoscuro	742	74281	1923	2012	89
Roncocorrente	807	63239	1924	1988	65
S.Marialavello	1606	4854	1946	2002	57
S.Martinochisone	1658	580	1937	2008	43
Tavagnasco	2081	3319	1928	2008	73

Table 1
Sub-basin characteristics.

A river basin is generally defined as the portion of the territory where runoff of surface water drain towards a fixed section of a watercourse (i.e. the closure section), and smaller basins can be identified by prescribing a closure section upstream [6]. The Po river basin, due to is size, includes a series of tributaries rivers each one characterised by its basin. That is, smaller sub-basins combine into larger basins in a hierarchical pattern. For example, the Po river basin closed at ”Pontelagoscuro” station (close to the river outlet) is wide, and integrated the contribution of the basin measured at the basin’s outlet ”Pontebacchello” and fully includes the Po river basin closed at ”Borgoforte”, which in turn integrates the measurements of the upstream sub-basins. Based on the available stations, in Figure 3 we summarize this hierarchical pattern.

Po river and tributaries are directly influenced by human activities: they are mostly regulated by to the presence of several dams as reservoirs for hydroelectricity productions, and also the lakes (Como, Garda, Iseo, Idro and Maggiore) are managed as reservoirs [11]. In interpreting the hydrological results, these influences need to be kept in mind.

The monthly precipitation and temperature data used in this study are provided by the HISTALP gridded dataset ([1]). These data are available on a regular grid of 10 min resolution ranging from 4° to 19°E and from 43° to 46°N, from 1801 to 2003 for precipitation and from 1870 to 2008 for temperature. The temporal evolution of precipitation and temperature has been analysed considering the regional average of the grid-points within each sub-basin. Since temperature and precipitation series display a dependence on elevation, we standardized the individual series in order to reduce the presence of possible biases in the regional average. The standardized series are dimensionless quantities obtained by (a) defining an anomaly by subtracting the long-term mean from the original series and (b) dividing the anomaly by its long-term standard deviation. Qualitatively similar results have been obtained with the original series (i.e. instead of the standardized ones).

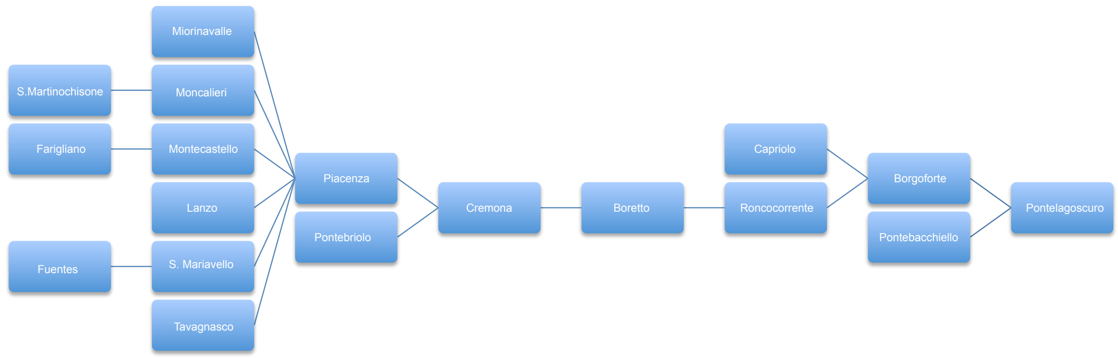

Figure 3:
Schematic view of the sub-basins under study.

Annual discharge (R), mean temperature (T) and precipitation (P) are calculated for the hydrological year, September to August.

RESULTS

SUB-BASIN CHARACTERISTICS

In this section we analyse the inter-basin correlations of the annual discharge timeseries, and the correlations between catchment annual discharge and precipitation time series, both to better understand these relationships, and to evaluate the consistency of the data used.

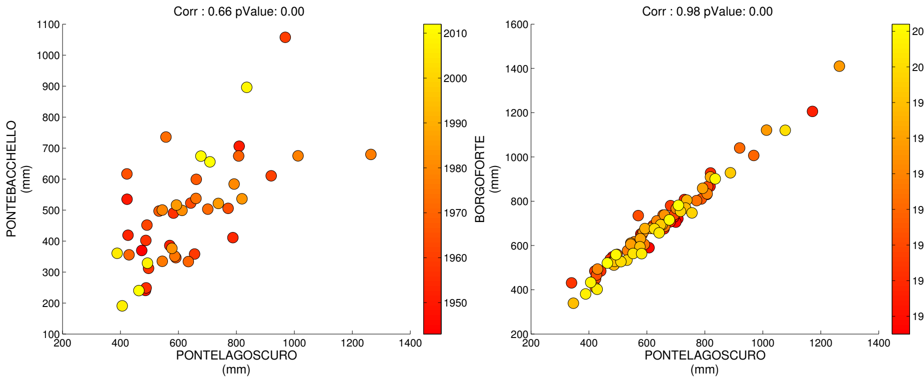

Figure 4:
Scatter plots of Pontebacchello vs Pontelagoscuro discharge series (left) and Borgoforte vs Pontelagoscuro discharge series (right).
The years are shown with different colours.

For each closure section pair, we compared the annual average discharges calculating the correlation between the series and plotting a scatter plot, Figure 4 provides an example of the results. Please notice that the years are shown with different colours. Thus, since the colours (i.e. years) are not clustered in a specified portion of the graph, we can consider that the relationship between R and P is substantially stable in time. Additional analyses will be performed to assess this issue. Figure 5 summarizes the inter-basin correlation in terms of annual discharge. The station order follows the one of the schematic view of the sub-basins under study depicted in Figure 3. First, these figures indicate that these sub-basins possess similar hydrological interannual variability. This is not surprising since the relative small area of the Po basin could be considered relatively homogeneous in term of atmospheric circulation anomalies that drive the precipitation temporal variability, which in turn drive the hydrological regime. Secondly, as expected, the correlations are stronger if direct nested sub-basins are considered. For example, ”Pontelagoscuro” is significantly correlated with the small tributary measured at ”Pontebacchello” and ”Borgoforte”. In the latter case, the correlation is larger, most likely because ”Borgoforte” is a larger contribution to "Pontelagoscuro" in respect to "Pontebacchello". Instead, the upstream sub-basins, in the top or in the right of the plot, show the smallest correlation values. In these cases, probably small local effects complicate the inter-basin relationships.

Table 2 shows the correlation between catchment annual discharge and precipitation time series. The correlations are quite high, generally with largest values for the biggest sub-basins. On the

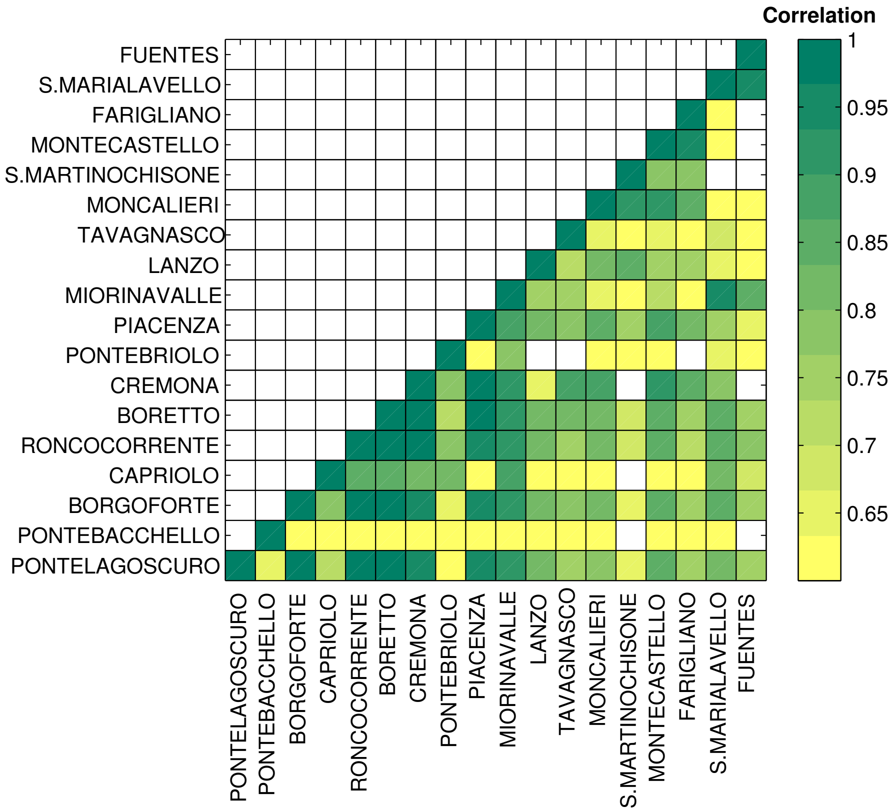

Figure 5:
Inter-basin correlation matrix of annual discharge. Only significant (P<0.05) values are shown.

other hand, the lower association between precipitation and discharge of the smaller sub-basins could be due to local physical effect that obscure this relationship, but also casts doubts about the representativeness of the basin precipitation estimates for small basins.

Overall, this analysis shows a coherent pattern of relations between inter-basins discharge, and between discharge and precipitation timeseries, suggesting consistency in data used.

Sub-basin	Correlation R vs P
Boretto	0.95
Borgoforte	0.94
Capriolo	0.78
Cremona	0.89
Farigliano	0.89
Fuentes	0.83
Lanzo	0.89
Miorinavalle	0.90
Moncalieri	0.90
Montecastello	0.92
Piacenza	0.93
Pontebacchello	0.81
Pontebriolo	0.69
Pontelagoscuro	0.93
Roncocorrente	0.94
S.Marialavello	0.91
S.Martinochisone	0.92
Tavagnasco	0.71

Table 2

Correlation between annual precipitation and discharge for each sub-basin. All the correlation are significant (P<0.01)

SUB-BASIN VARIATION

The trend significance is estimated with the bootstrap test discussed in Turco and Llasat (2011, [10]). Briefly, this method consists in: (i) decompose the time series into a linear trend line and a time series of residuals, (ii) resample the residuals 1000 times, (iii) added back the resampled residual to the best fit line obtaining 1000 new plausible trend estimations, and (iv), estimate the probability to have a significant trend if the zero-trend falls outside the distribution of these 1000 plausible trend values.

With 3 variables and 18 sub-basins seasons, the total number of analyses at annual scale is 54. A plot showing the trends was produced for each analysis and inspected visually, to get a comprehensive impression of the results and, possibly, to identify anomalous cases. Then the results are summarized in Tables 3, 4, and in the Figures 6 and 7.

Sub-basin	Trend R (mm/10y)	Trend P (mm/10y)	Trend T ($^{\circ}$C/10y)	Period
Boretto	13	6	0.2***	1944-2003
Borgoforte	3	6	0.2***	1925-2003
Capriolo	-34**	21	0.2***	1938-2002
Cremona	-89*	-56	0.6***	1973-2003
Farigliano	-17	24	0.1	1945-2000
Fuentes	-28*	-8	0.2***	1924-2000
Lanzo	-5	20	0.2**	1931-2003
Miorinavalle	-24	24	0.1**	1924-1993
Moncalieri	-5	14	0.1	1929-1992
Montecastello	18	20	0.1	1944-2003
Piacenza	5	6	0.2***	1925-2003
Pontebacchello	27	45	-0.1	1943-1985
Pontebriolo	-68	54	0.3***	1941-2002
Pontelagoscuro	6	7	0.2***	1924-2003
Roncocorrente	10	16	0.1	1925-1988
S.Marialavello	15	26	0.2***	1947-2002
S.Martinochisone	11	13	0.0	1938-1994
Tavagnasco	-25**	2	0.1**	1929-1997

Table 3

Trend in discharge, precipitation and temperature time-series over the common available period. * $P < 0.10$, ** $P < 0.05$, *** $P < 0.01$.

Similar results for the discharge series are obtained, considering the entire available periods (table 4).

At annual scale, a clear increasing in temperature appears, while no general trends are observed, considering discharge or precipitation data. These results agree with previous studies, analysing precipitation and temperature, [4] or discharge data [11, 8]. Contrasting the steady trend of the discharge data, we note few exceptions, 3 small alpine sub-basins: ”Capriolo”, ”Fuentes” and ”Tavagnasco”, and 1 large sub-basin, ”Cremona”. However, this latter station covers ”only” the period 1973-2012, thus it cannot capture changes at longer time scale. Instead, considering the former stations, these changes may be due to anthropogenic influences. Future analysis should be carried out to investigate this issue.

Sub-basin	Trend R (mm/10y)	Period
Boretto	-4	1944-2012
Borgoforte	-5	1925-2012
Capriolo	-34**	1938-2002
Cremona	-64*	1973-2012
Farigliano	-33	1945-2008
Fuentes	-28*	1924-2000
Lanzo	-21	1931-2008
Miorinavalle	-24	1924-1993
Moncalieri	-5	1929-1992
Montecastello	-9	1944-2008
Piacenza	-3	1925-2012
Pontebacchello	14	1943-2012
Pontebriolo	-68	1941-2002
Pontelagoscuro	-2	1924-2012
Roncocorrente	10	1925-1988
S.Marialavello	15	1947-2002
S.Martinochisone	-6	1938-2008
Tavagnasco	-26***	1929-2008

Table 4

Trend in discharge over the entire available period. * $P < 0.10$, ** $P < 0.05$, *** $P < 0.01$.

To assess whether discharge, precipitation and temperature have changed in other periods of the year, we have estimated the trends of these variables also on monthly scale. To this aims, we calculate the annual cycle of the three variables, averaged over three periods of 27 years: 1923-1949, 1950-1976 and 1977-2003. The averaged values are calculated only if, for each of period under consideration, there are at least 90 % of valid data. In addition to the mean values, for the last period 1977-2003, we also plot the monthly standard deviation as a proxy of the interannual variability of the data. In the following plots, we present the sub-basin analysis where a great amount of data is available, and most significant results emerge.

Most of the discharge series show two peaks: one in Spring, driven by precipitation and fed by snow melting from the Alps, and one in Autumn mostly driven by the precipitation. An exception is represented by the "Tavagnasco" station, that show a typical example of alpine regime, with prevailing flow season in summer. Finally, considering the variations, we observe some changes, but the interannual variability (represented by standard deviation, the error-bars) is very large, and substantially masks any trend.

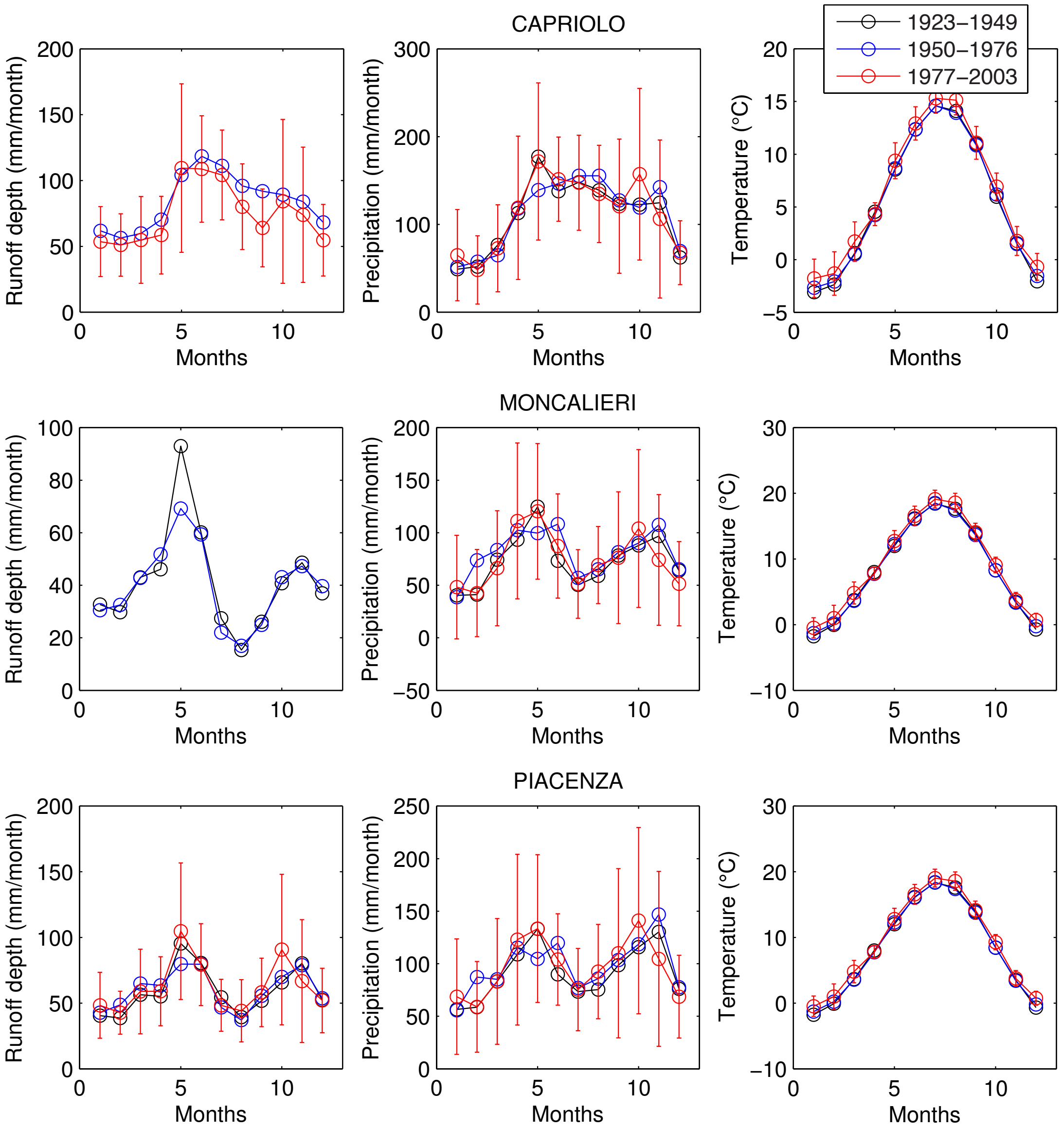

Figure 6:
Seasonal cycle (averaged monthly values over three periods) of discharge, precipitation and temperature for some representative sub-basin. The red bands span the standard deviation of the monthly values.

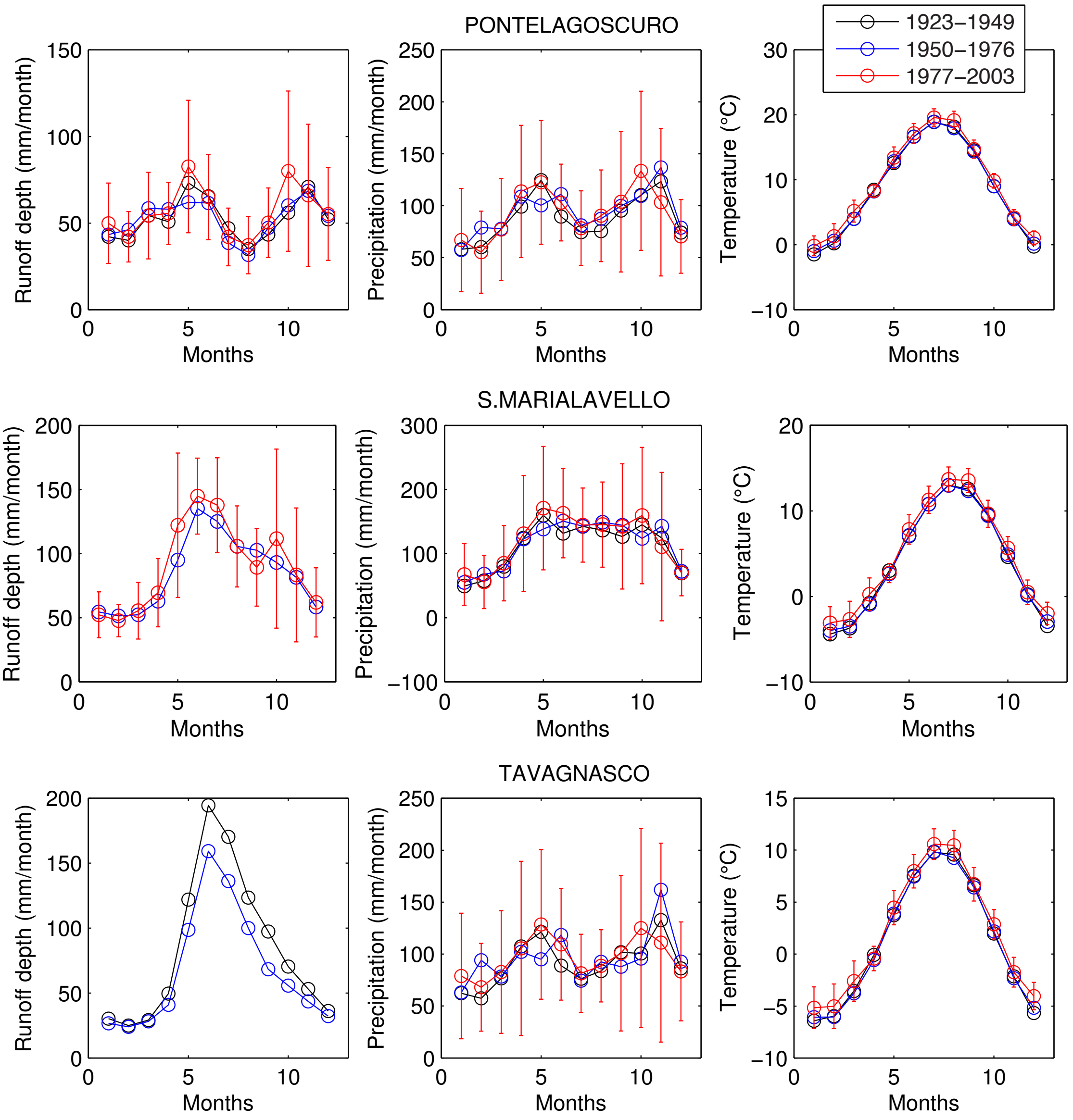

Figure 7:
Seasonal cycle (averaged monthly values over three periods) of discharge, precipitation and temperature for some representative sub-basin. The red bands span the standard deviation of the monthly values.

DISCUSSION AND CONCLUSIONS

The goals of this Research Paper were to (i) briefly report some preliminary assessment of the consistency of long-term discharge data over the Po basin, including upstream and downstream sub-basins, and (ii) to investigate potential decadal variations in discharge, precipitation, and temperature in each sub-basin. To address these issues, we analysed 18 gauging stations in the Po river basin over the period 1923-2012. Precipitation and temperature data are provided by the HISTALP gridded dataset. This work aims to better understand the past variability of discharge, precipitation and temperature series over the Po basin and set up a base to develop climate regional scenarios.

The analysis of the inter-basin correlations of the annual discharge timeseries, and the correlations between catchment annual discharge and precipitation time series, shows a coherent pattern of relationship between the series, suggesting consistency in data used. Indeed, high correlations were expected, as one can reasonably assume a cause and effect relationship between rainfall and discharges, at least when considering the average annual values. This consideration is more probable on large spatial scale, where local effect due to particular conditions will likely averaged out. On the other hand, it seems possible that any transfers of groundwater between sub-catchments may contribute to the lower correlation values between precipitation and discharges for the smallest sub-basins. Furthermore, the presence of artificial reservoirs and regulated lakes may contribute to lower correlations values for small sub-basins. These effects would be lost at the scale of the entire basin, which integrates all of incoming flows. For example, one of the lowest correlation values is obtained for the sub-catchment closed at the ”Capriolo” station. It may not be a coincidence that this gauging station is located downstream of the Iseo Lake, a regulated reservoir of great capacity. On this topic, it would be useful a retrospective analysis of the results, introducing specific information on the territory and on the use of water resources. However, it is not possible to detect a clear pattern between P-R correlations and the average altitudes of the sub-basins. Even for some snow-dominated sub-catchment the correlation is higher than 0.9; this may be justify by the fact that the effect of the temporary accumulation of precipitation as snow cover is lost if the data grouping period ends in the late summer.

Considering the climate variations, at annual scale, generally discharge and precipitation data are stationary, while the temperature increases. At monthly scale we observed important changes in all the three variables analysed. Investigating the trends in the sections of ”Piacenza” and ”Pontelagoscuro”, representative of the streamflows in the lowlands, we can see an increased spring peak even if the fluctuation bar is wide (similar results for the other downstream stations). Precipitation shows a similar trend, with higher values in April and May. Thus, despite an increase in winter and spring temperatures, it seems difficult to link the higher spring discharge to an early melting of the snowpack in the Alpine area. Further studies should be carried out to deeper investigate this important issues. At Pontelagoscuro and Piacenza, we can also observed an early autumn peak, even also in this case lower than the interannual variability. Also this peak seems to follow the precipitation shift. However this behaviour is not found at Capriolo, a station characterized by a relatively low correlation precipitation-discharge. As the discharge in this section may reflect the impact of the regulation of release from Iseo Lake, especially on the monthly mean values, this difference is not surprising. Thus it might be interesting to investigate whether this effect may be common to other sub-basins affected by regulated reservoirs when more data will be available.

Finally, in this work, of preliminary nature, we have provide evidences of the reliability of the long-term discharge series analysed, and presented an analysis of the observed changes in discharge, precipitation and temperature data. Several issues could be deeper investigated, leaving the door open for further research. For example could be interesting to add other stations if available, compare HISTALP data with other dataset, and confront the discharge evolution with hydrological model results. Thus, this report set the base to start with deeper future research in order to gain a better understanding helpful to establish a more rational water management.

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