ATTRIBUTION OF HYDROLOGICAL TRENDS IN THE ADIGE RIVER BASIN

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KEY POINTS

- *Data-driven approach for attributing hydrological trends in the Alpine region.*
- *Water uses for irrigation overwhelm the effects of climate change in the Alpine lowlands.*
- *Climate change is the main driver of water balance variations in headwater basins.*

1 INTRODUCTION

The importance of climate change on the observed alterations of the water cycle in snow-dominated regions is widely recognized, thought it varies across the globe and it has not been fully explored yet, particularly in the European Alps (see e.g., *Beniston, 2003*). A number of contributions suggest that recent changes in the precipitation patterns and the contemporaneous rise of temperatures have led to rapid glaciers melting and intensification of evaporation with a consequent alteration of the typical Alpine hydrological regime (see e.g., *Birsan et al., 2005*). Furthermore, other pressure factors such as land use changes, hydropower and agricultural developments, increasing population and other anthropogenic stress factors are shown to drive important streamflow alterations in some Alpine catchments (see e.g., *Chiogna et al., 2016*) and their influence should be carefully quantified and separated from the climatic one. Disentangling climatic and human impacts on hydrological fluxes is a difficult task since they combine in a complex nonlinear manner. Here we propose a rigorous data-driven multi-method approach with the aim to identify drivers of hydrological changes in a large Alpine catchment. Indeed, we analyzed changes of hydrological variables by considering nested catchments of size ranging from 207 km^2 to 9,852 km^2 within the Adige River Basin. Statistical methods (i.e. Mann-Kendall trend tests, Sen's slope estimates, multivariate data analyses and Kriging algorithms) have been applied to assess the variability of hydro-meteorological variables both in time and space, identifying the associated local drivers' effects. In addition, seasonal analysis was performed in order to detect intra-annual variations of the hydrological fluxes, and to attribute them to season specific drivers. Reliability of the results was assessed through a careful uncertainty analysis.

2 DATA AND METHODS

2.1 Data

In the present work we analyzed long-term time series of hydrological data in the Adige catchment, a large Alpine river basin located in the Southeastern Alps, North-East of Italy. The Adige River has a total length of its main stem of 420 km and a catchment area of about 12,100 km^2. Mean streamflow registered at the most downstream gauging station of Boara Pisani is about 202 m^3 s^{-1} (*Chiogna et al., 2016*). Meteorological data were obtained from the meteorological offices of the Provinces of Trento and Bolzano, and the Austrian weather service (ZAMG). Air temperature (daily average as well as maximum and minimum) and daily precipitation data were available from 350 and 244 stations, respectively, since 1920. Daily streamflow data at 4 selected gauging stations (i.e., Adige at Trento and Bronzolo, Avisio at Soraga and Gadera at Mantana) were provided by the Hydrological Offices of the Autonomous Provinces of Trento and Bolzano. Temporal changes in land use within the river basin were investigated using CORINE products available for the years 1990, 2000, 2006 and 2012.

2.2 Methods

Daily precipitation as well as daily minimum, maximum and mean temperatures were first interpolated over a regular grid with size of 1 km and then spatially averaged by computing the arithmetic mean of the values at the cells contained within the catchment. Interpolation at the level of the grid was performed by using both Ordinary Kriging (OK) and Kriging with the External drift (KED) (*Goovaerts, 1997*). This geostatistical interpolation provides both the conditional mean and the conditional variance, representing the most probable value and an estimate of uncertainty, respectively. Leave-one-out cross-validation was then applied to select the most suitable interpolation scheme and the optimal number of neighbouring stations, identifying KED with 16 stations as the most suitable interpolation scheme for all the four interpolated variables (precipitation, mean, maximum and minimum temperature). The obtained mean of the absolute error was 1.3 mm for daily precipitation and 0.02 °C for the daily average temperature. In this study we evaluated the uncertainty introduced by the spatialization of point measurements, performing 5,000 Monte Carlo simulations of the precipitation time series associated to each grid cell of the study domain. We also assumed that the precipitation at each grid point follows a Gamma distribution with mean and variance at each time step given by the conditional mean and variance provided by KED. Daily reference crop potential evapotranspiration (ET_0) was estimated by using the Hargreaves - Samani model (see e.g., *Hargreaves & Samani, 1985*). Potential evapotranspiration was then obtained by multiplying ET_0 by the crop coefficient K_c, depending on the site-specific vegetation and growth stage. In addition, following e.g., *Allen et al. (1998)*, a 30% reduction factor was applied in order to counterbalance the tendency of the Hargreaves - Samani model to overestimate ET_p under non-standard conditions. Therefore, climate-driven actual evapotranspiration AET_{clim} was computed by multiplying ET_p by a stress factor α (<1), reducing the potential evapotranspiration since it represents the upper limit of actual evapotranspiration.

At the sub-catchment scale the annual water budget assumes the following form:

$$P - Q - AET_{wb} = 0 \qquad (1)$$

where P [mm] is the precipitation total, Q [mm] is the streamflow volume, AET_{wb} [mm] is the "water balance constrained Actual Evapotranspiration" (*Destouni et al., 2013*) and accounts for the combined effect of water losses due to evapotranspiration and water uses. In the present work we separated these two components and rewrote Eq. (1) as follows:

$$P - Q - \alpha\, ET_p - W = 0 \qquad (2)$$

where, $\alpha\, ET_p$ is the climatic actual evapotranspiration and W is the water volume withdrawn from the catchment. We proposed to disentangle these two contributions by applying the water budget to the period 1920-1950, when water uses can be considered marginal such that $W \cong 0$ (*Zolezzi et al., 2009*). Consequently, α can be obtained by averaging Eq. (2) over the period 1920-1950:

$$\alpha = \frac{\bar{P} - \bar{Q}}{\overline{ET_p}} \qquad (3)$$

where $\bar{P}$, $\bar{Q}$, $\overline{ET_p}$ are average hydrological fluxes in this period. The resulting stress coefficient for the river basin closed at Trento is $\alpha = 0.699$.

The time series of P and ET_p were then aggregated over the drainage area of the 4 selected sub-catchments. Successively, trends of P, ET_p and Q were calculated by applying the Mann Kendall test (*Kendall, 1975*) with significance level of 0.05 and considering both annual and seasonal aggregations and a moving time window of 30 years. The width of the moving window was selected for mitigating the effects of small (temporal) scale fluctuations due to well know cyclic changes. Since a main objective of this research is to identify changes in streamflow due to changes in water uses, typically acting more quickly than climate change, the analysis of abrupt changes in the observed time series is of our interest. There are several methods for detecting change points in time series. In this study, we employed the Pettitt's test (*Pettitt, 1979*).

3 RESULTS

The investigation revealed that the uncertainty bounds in the annual estimates of precipitation were narrow for all the investigated sub-catchments, being lower than the 1.5% of the average annual rainfall total. Hence, we concluded that the uncertainty linked to the spatialization of the precipitation field was negligible.

Annual aggregation of the data (Figure 1) evidences relatively large trends for precipitation (P) and streamflow volume (Q), while climate-driven evapotranspiration shows a small positive trend (at most 2 mm year^{-1}) with statistical significance extending over longer periods. Precipitation trends are similar in all sub-catchments. Streamflow volume follows the observed trends in precipitation only partially. Adige at Trento experienced a significant reduction of the streamflow in the period 1975-2009 (about -9 mm year^{-1}), whereas at Bronzolo no trends are evidenced in the streamflow. However, in the nested small sub-catchment of Gadera at Mantana and Avisio at Soraga streamflow shows positive trends. When aggregated at the seasonal scale the variables show different behaviors (not illustrated here for the sake of brevity). Climate-driven evapotranspiration shows negligible trends in all seasons, except in summer when the trend is slightly positive, thereby showing that changes in evapotranspiration are small and limited to the summer season. Precipitation denotes similar patterns in all the nested sub-catchments, but with contrasting values between the different seasons. In fact, significant negative trends are observed in winter during the period 1970-2010, with maximum decrease of about -4 mm year^{-1}. Springs show positive significant trends in the first part of the study period, whereas from the '70$_s$ negative trends prevail. Summer precipitation reveals not significant trends in the whole study period. At all locations autumn precipitation trends are positive in the period 1970-2000. This is more evident in the Avisio catchment closed at Soraga, where positive trends of about 7 mm year^{-1} are observed. Similarly to what observed at the annual scale, streamflow volumes vary in space. In the past 30 years, winter trends are nearly absent at Trento gauging station and slighly positive at Bronzolo. Conversely, significant positive trends characterize streamflow in the other, smaller, nested sub-catchments since the '70$_s$. In spring, trends of precipitation and streamflow are more consistent. Significant negative trends are observed for summer streamflow starting from the '70$_s$, especially at Trento gauging station in which negative trends reach almost -6 mm year^{-1} in the period 1977-2007. As in winter, these patterns are not reflecting changes in precipitation. Finally, autumn trends in streamflow are higher in the small nested sub-catchments of Gadera at Mantana and Avisio at Soraga than in the Adige at Trento and Bronzolo located along the main stem of the Adige River and with a much larger contribution area. In this season, maximum increasing trends in the Avisio at Soraga amount to +5 mm year^{-1}. Patterns at all the investigate locations are similar to that of precipitation in the same season.

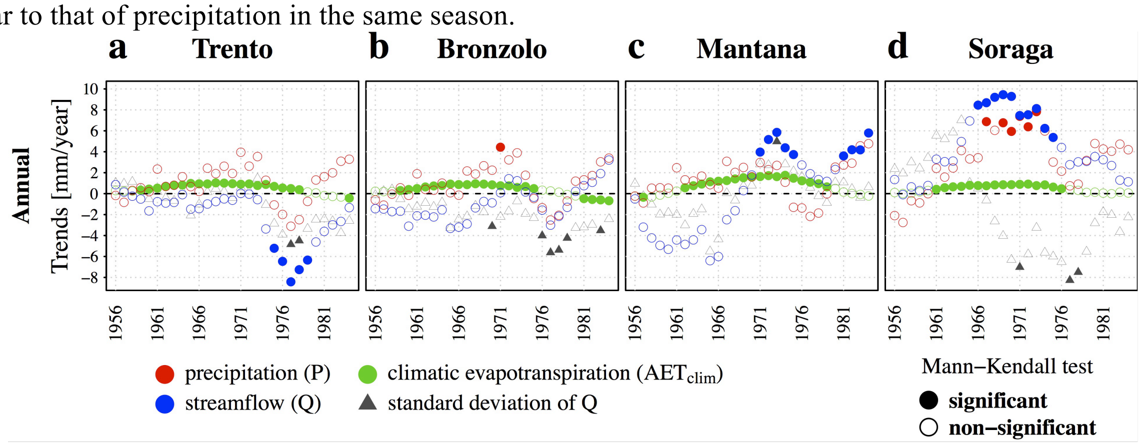

Figura 1. Trend analysis of the selected hydro-climatic variables in the Adige River Basin at Trento (A), Bronzolo (B), Mantana, on the Gadera tributary (C) and Soraga, on the Avisio tributary (D).

4 DISCUSSION AND CONCLUSIONS

The results of this study highlight non-stationary features of the hydrological dynamics in this large Alpine area. We observed the effects of climatic variations in the small sub-catchments of the Gadera and upper Avisio rivers. In these headwater basins, the increasing winter streamflow is caused by a larger groundwater contribution triggered by a proportional increase of groundwater recharge in autumn due to larger precipitations. Conversely, we did not recognize the same behavior at large scale, particularly at the southernmost part of the Adige River Basin, in which we appreciate a significant reduction in summer streamflow not attributable to climate changes. In this work, we applied a multiple-method framework in the attempt to attribute these changes to their controlling factors. Various techniques (i.e., Mann Kendall trend test, standard deviation analysis, Pettitt's test, freezing days analysis, Spearman's rank correlation and multiregressions and analysis of variance) were applied in order to provide proofs of consistency of the tested hypoteses and proofs of inconsistency of the possible alternatives. In Table 1 we report a summary of the analyses and the considerations made in order to perform a strong attribution of the observed hydrological alterations (for more details see *Mallucci et al., 2018*).

Hydrological alterations	*Possible causes*	*Yes/No*	*Reasons*
Decreasing summer streamflow at the outlet	§ precipitation reduction	No	inconsistent with trends of P
	§ raised evapotranspiration	No	inconsistent with trends of ET
	§ agriculture	Yes	change point detection
			data of apple production
			standard deviation analysis
Increased winter streamflow at the headwaters	§ snow and glacier melting	No	glacier waters diverted outside basin
			absence of correlation
			analysis of variance
	§ shift from solid to liquid precipitation	No	increasing freezing days
			absence of correlation
			analysis of variance
	§ autumn aquifer recharge	Yes	consistent with trends of autumn P
			high correlation
			analysis of variance

Table 1. Summary of the attribution exercise.

In the present work we analyzed long-term time series of daily climatic and hydrological variables in the Adige River Basin, an important Alpine river basin in the Northeast of Italy. Trends of climatic forcing, hydrological fluxes and storage term in the water budget were computed and compared in 4 nested sub-catchments of the Adige River Basin. The analyses evidenced temporal patterns differentiated within the river basin depending on the reciprocal strength of water uses and climate change. The attribution of the observed alterations to their main causes was made as rigorously as data availability allowed. At the headwaters positive trends in winter streamflow are detected at the gauging stations of Gadera at Mantana and Avisio at Soraga, despite an evident reduction of winter precipitation. Accurate trend analysis revealed that this change cannot be attributed to a shift of winter precipitation from solid to liquid, rather to a larger groundwater contribution triggered by a proportional increase of groundwater recharge in Autumn due to larger precipitations. This is the stigma of climate change, given that headwaters are only marginally impacted by agricultural activities and seasonal storage for hydropower is very limited. This effect vanishes as the drainage area increases moving downstream, with only a marginal increase of winter streamflow observed at the Bronzolo and Trento gauging stations. On the contrary, starting from the middle of the '70$_s$ a strong reduction of summer streamflow is observed at Trento gauging station, possibly due to the effect of withdrawals for irrigation. In fact, an intense development of irrigated agriculture in the drainage area of the Noce River, a tributary of the Adige, is recorded in the same period. In the southern part of the river basin, therefore, agricultural uses offset the impact of climate change.

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