65-year changes of annual streamflow volumes across Europe with a focus on the Mediterranean basin

Daniele Masseroni\textsuperscript{1}, Stefania Camici\textsuperscript{2}, Alessio Cislaghi\textsuperscript{1,3}, Giorgio Vacchiano\textsuperscript{1,3}, Christian Massari\textsuperscript{2}, Luca Brocca\textsuperscript{2}

\textsuperscript{1}Department of Agricultural and Environmental Sciences, University of Milan, Via Celoria 2, 20133 Milan, Italy
\textsuperscript{2}Research Institute for Geo-Hydrological Protection, National Research Council, Via Madonna Alta 126, 06128 Perugia, Italy
\textsuperscript{3}Centre of Applied Studies for the Sustainable Management and Protection of Mountain Areas (Ge.S.Di.Mont), University of Milan, Via Morino 8, Edolo, 25048 Brescia, Italy

Correspondence to: Daniele Masseroni (daniele.masseroni@unimi.it)

Abstract. Determining the spatio-temporal variability of annual streamflow volume plays a relevant role in hydrology for improving and implementing sustainable and resilient policies and practices of water resource management. This study investigates annual streamflow volume trends in a newly-assembled, consolidated and validated dataset of daily mean river flow records from more than 3,000 stations, which cover near-natural basins in more than 40 countries across Europe. Although the dataset contains streamflow time-series from 1850 to 2015 in some stations, the statistical analyses were carried out by including observations from 1950 to 2015 in order to have a consistent and reliable dataset over the continent. Trends were detected calculating the slope of Theil-Sen’s line over the annual anomalies of streamflow volume. The results show annual streamflow volume trends emerged at European scale, with a marked negative tendency in Mediterranean regions (about -$1 \times 10^{-3} \text{ m}^3/(\text{km}^2 \text{ year})$) and a generally positive trend in northern ones (about $0.5 \times 10^{-3} \text{ m}^3/(\text{km}^2 \text{ year})$). The annual streamflow volume trend patterns appear in agreement with the continental-scale climate change observations in response to climate change drivers. In the Mediterranean area, the declining of annual streamflow volumes started in 1965 and since early 80’ volumes are consistently lower than the average.

The spatio-temporal annual streamflow volume patterns observed in this work can help to contextualize short-term trends and regional studies already available in the scientific literature as well as to provide a valid benchmark for further accurate quantitative analysis on annual streamflow volumes.

1 Introduction

Elucidating continental patterns of annual streamflow volume changes in the Anthropocene epoch to confirm unequivocally the effects of climate change and human impact on water resources has become a challenge in contemporary hydrology (Bloschl et al. 2019). Although the hydrological scientific community undertook a great effort, almost no research robustly demonstrates an ubiquitous and uniform trend in European annual streamflow volumes, especially in Mediterranean areas where drought periods have been increased during the last fifty years (Caloiero et al. 2018). Few regional studies, mainly
located in northern Europe, detected potential trends in river flow, relying mainly on data from the beginning of the second middle of the twenty-first century (Piniewski et al. 2018, Renard et al. 2008, Birsan et al. 2005, KLIWA 2003, Schmocker-Fackel and Naef 2010, Demeterova and Skoda 2005, 2009, Fiale 2008, Fiala et al. 2010). These studies showed a clear seasonal change in streamflow without finding a solid correlation with the geographic position of the catchments (Bard et al. 2015, Bormann et al. 2017). In addition, such studies have faced the extreme sensitivity of the river streamflow on the data selection, the method used for the trend detection and the analyzed time window (Stahl et al. 2010). For these reasons, Kundzewicz et al. (2005) advocated particular caution in interpreting streamflow trend signals resulting from a restricted number of stations with a small recording period as the first consequence of potential gaps in the data time series or missing values which could alter the significance of the statistical tests.

Recent national studies aiming at identifying which could be the secondary drivers that cause alterations in regional river streamflow trends (apart from the dominant climate change drivers), demonstrated that factors such as the economic growth of large part European citizens and the migration of population from rural environments to urban centers have been increasing the pressure on rivers causing the diversion of their paths, the reduction of their cross-sections and the exploitation of their flows under different levels from production of energy to boat-tourism (Vag et al. 2007, Ceola et al. 2014). In this respect, Bormann and Pinter (2017) found that reservoir management, snow and ice melt processes, mining activities, land sealing are factors that overlapped to the direct climate-change effects (i.e., increase of temperatures and modifications in rainfall patterns) contributing to modify river regimes. Therefore, extracting large-scale considerations on patterns of annual streamflow volume change staring from single-catchment or regional studies is significantly complex because local drivers can cause anomalous hydrological behaviors in rivers. On this background, it appears more useful soliciting large-scale studies in order to investigate predominant annual streamflow volume continental trends, which can provide basis for understanding processes in regional hydrology. To achieve this aim, reliable networks of river streamflow measures in near-natural catchments are necessary. Several countries in the world have nowadays developed reference hydrometric networks composed by gauged stations with long and uninterrupted river flow records (Burn et al. 2012, Hannah et al. 2010). Such networks are generally managed and maintained by regional authorities or civil protection agencies, and are composed by gauging stations for measuring the river water level (stage) combined with updated stage-discharge relationships (Kundzewicz and Robson 2004). Datasets for large parts of Europe are nowadays available (e.g. for Alpine, Mediterranean, Continental, Baltic and Nordic regions) with thousands of stations and records which starting from the nineteenth century. This amount of data covers a wide variety of catchments, from the small-size (few hundreds of hectares) to large-size (thousands of square kilometers) (Steiru et al. 2017, Mediero et al. 2014). Nevertheless, the development of the hydraulic infrastructures in Europe associated with the increase of population density and a lack of undisturbed natural environments makes measurement less representative of the natural flow conditions (Bertola et al. 2019). Recording a high quality streamflow measurements unaffected by potential anthropogenic disturbances and suitable for large-scale trend analysis is a major challenge (Hisdal et al. 2001, 2007, Shorthouse and Arnell 1997). The request of reference river flow dataset of near-pristine catchments has been largely recognized worldwide and has been supported by some international programs. The most famous is the FRIEND program, an initiative supported by the UNESCO
International Hydrological Programme (IHO), the European Water Archive (EWA) and the European Environmental Agency (EPA) that allows to share scientific information to improve methods applicable in water resources planning and management (Arnell 1997). However, updating streamflow measures and installing new flow meters is not straightforward in Europe. In particular, the organization has become complicated by regional and local jurisdictions, including political, administrative and technical constraints, as well as economical barriers (Viglione et al. 2010). In the absence of national or regional datasets, the Global Runoff Data Center (GRDC) can represent a valid global database of large continental river flow measures in Europe (Haddeland et al. 2010, Stahl et al. 2010), despite most studies preferred to combine data with models predictions to fill gaps and reconstruct time series of comparable length (Dai et al. 2009). Hence, the challenge is combining the results of regional and national streamflow measures into a pan-European scale study of annual streamflow volume trends, which uses a consistent methodology on a consolidated and validated continental river flow dataset. In fact, detection and attribution of European trends in annual streamflow volumes can represent a strategic point in water management policies both in terms of flood security, drought and desertification control (Ban et al. 2015). National and basin authorities could plan tailored irrigation methods in targeted areas as well as encourage the use of non-conventional water for irrigation or funding modernization of irrigation systems where streamflow negative trends occur (Rogger et al. 2017). On the contrary, authorities could promote the use of natural water retention measures (http://nwrm.eu/) and best management practices (Urbonas and Stahre 1993) in territories affected by a positive trends (Brooks 2013).

The propose of the present study is, therefore, to provide an analysis of spatio-temporal variability of annual streamflow volumes in the European continent, starting from the analysis of consolidated observations over a long-time period with a particular emphasis on flow regimes relevant for water resource management especially in Mediterranean areas. Specifically, the added value of the present work is (i) to characterize annual streamflow volume trends over the entire European continent, using a long-time period of actual river flow observations, (ii) to deep the analysis on annual streamflow volume trends in the Mediterranean area which is under increasing pressures of climate change effects and (iii) to determine whether evidences of a marked inversion point in the annual streamflow volume availability can be found directly in the observations.

2 Material and methods

1.1 River flow data

A large dataset of daily river streamflow records measured by 3,913 gauged stations over the entire European continent was analyzed for characterizing the continental patterns of the river flow regime over time. The original dataset, compiled by the authors merges stations from 5 different databases, i.e., the Global Runoff Data Base (GRDC), the European Water Archive (EWA); the Italian ISPRA HIS national database (http://www.hiscentral.isprambiente.gov.it/hiscentral/default.aspx); the Portuguese national database (http://snirh.pt/) and the Spanish national database (http://ceh-flumen64.cedex.es/anuariosforos/default.asp), consists of observed streamflow, recorded between 1850 and 2015. Unfortunately, not all the gauged stations have been worked since the same time and with a consistent and reliable dataset.
Thus, 3,485 stations were selected to assemble a dataset that guarantees the best balance between the necessities to investigate a dataset as large as possible (which covers a large part of the continent), and to detect a historical variability. Location of the different gauged stations is reported in Fig. 1 on physical European map. The selected gauged stations belong to more than 40 European countries and provided time-series data from 1950 to 2015, characterized by about 1.200 points of measure per year, on average (Fig. 2a). Unlike previous studies, more attention was given to the analysis of river flow time-series over the Mediterranean basin for which a dedicated effort was carried out in this study to fill the gap existing in previous studies. About one-third of gauged stations falls in this area, especially in Spain, southern France and Italy. Gauged stations that enclose catchments with an area more than 100,000 km² were excluded by the analysis because human disturbance is unavoidable at this scale (Piniewski et al. 2018). Nevertheless, about 90% of stations belongs to catchments with size less than 1,000 km² as shown in Fig. 2b. Daily hydrographs for all gauges were inspected to identify dubious patterns, all records were screened visually and those with visible inhomogeneity, problems in low flow range, or missing values for a long period of time (> 2 year) were excluded (Kundzewicz et al. 2005). Despite potential levels of human-induced alterations of river flow regime could be still present in time-series data, a certain degree of disturbance can be tolerated (Murphy et al. 2013). For this reason, high flow conditions were not investigated and we focused the analysis on annual streamflow volumes.

Fig. 1. Map of European study area. Digital Elevation Model (DEM), main rivers and lakes as well as position of gauging stations are presented.
Fig. 2. (a) Number of stations included in the dataset for each year; (b) number of catchments belonging to each area class (from 0 to 1,000 km²).

1.2 Trend detection

Trend magnitude of a hydro-meteorological series of data is usually estimated using the Theil–Sen's estimator (Theil, 1950; Sen, 1968), a non-parametric test usually adopted for indicating monotonic trend and amplitude of change per unit time. It is a robust estimate of the magnitude of a trend in hydrological and climatic time-series as demonstrated in literature (e.g., Kundzewicz and Robson 2004, Stahl et al. 2010, Burn et al. 2012, Hammanfor et al. 2013). In the present study, the slope of Theil-Sen’s line, known as Theil-Sen’s slope or Sen’s slope, was calculated on the annual anomalies in streamflow volumes, an innovative modality with respect to the application on direct streamflow data. The annual anomalies in volumes were detected by comparing them with the baseline obtained by averaging annual streamflow volumes in the entire period of observation for each station. This strategy allows to emphasize trends, minimizing the random errors derived from uncorrected measures or unexpected signals, as already tested by Pandžić and Trninić (1992). A positive anomaly indicates that the observed annual streamflow volume is greater than the baseline, while a negative anomaly indicates the observed annual streamflow volume is lower than the baseline. To homogenize the annual streamflow volume time-series and further to compare the streamflow volume anomalies among all the gauged stations, the value of each anomaly was divided for the catchment area obtaining volume anomalies per unit of area. Moreover, significance of the annual streamflow volume trend was tested by adopting a non-parametric statistical approach based on Mann-Kendall (MK) (Mann, 1945; Kendall, 1975) test. Such test has already shown its robustness in trend detection, in particular in case of non-normally distributed data such as the meteorological and hydrological series (e.g., Yue and Wang 2002; Yue et al. 2003; Yue and Pilon 2004; Piniewski et al. 2018). In particular, if the result of the test is returned in $H = 1$, it indicates a rejection of the null hypothesis (i.e. presence of trend) at the alpha significance level (here assumed equal to 0.05). Conversely, if $H = 0$, it indicates a failure to reject the null hypothesis at the alpha significance level (i.e. no presence of trend).
3 Results and discussion

3.1 Annual streamflow volume trends in Europe

Anomalies in annual streamflow volumes for each gauged station was calculated, and in Fig. 3a and b an example of positive and negative trend evaluated through the slope of the Theil-Sen’s line and confirmed by MK test for two stations located in central Europe, is reported.

![Graphs showing streamflow volume anomalies for Neustadt and Goerlitz stations](image)

Fig. 3. Anomalies in annual streamflow volumes for the station of Neustadt (a) and Goerlitz (b). In the graphs, the slope of the Theil-Sen’s line, H and p-value of the Mann Kendall test are also reported.

Results found that in 95% of the European gauged stations the MK test confirmed the presence of a trend in annual streamflow volumes. In general, 70% of positive and 30% of negative trends in annual streamflow volume anomalies is recognized, with clear positive trend in northern regions and negative trend in southern ones, as shown in Fig. 4.

Adopting the subdivision of the European continent in the four macro-regions as provided by Gudmundsson et al. (2017) i.e. Boreal, Continental, Atlantic and Mediterranean areas, the results show a marked negative trend in annual streamflow volumes especially in Mediterranean region with about 90% of stations with negative trend. The percentages of positive and negative trends for each macro-region are summarized in Tab. 1. The results reveal that, on average, a decrease in annual streamflow volume of about -1 \(10^3\) m\(^3\)/(km\(^2\) year) in Mediterranean areas and an increase of about 0.5 \(10^3\) m\(^3\)/(km\(^2\) year) in northern regions occur.

The spatial pattern of the annual streamflow volume trend reported in Fig. 4, appear broadly consistent with the findings obtained in previous sub-regional studies of Piniewski et al. (2018), Ilnicki et al. (2014), Bormann and Pinter (2017), Bard et al. (2015), Milly et al. (2005), Milliman et al. (2008), Manabe et al. (2004) and Dai et al. (2009). Although based on observed streamflow time-series with many differences (i.e., time interval, time length, methodology of measurement, etc.), sometimes affected by local river regulation or hydraulic infrastructure, and often completed with model-derived data, these studies predominantly found positive trends in regions close to the Atlantic Ocean and North Sea and negative trends in areas close to the Mediterranean Sea.
Fig. 4. Annual trend of streamflow volume anomalies in European continent subdivided in Boreal, Continental, Atlantic and Mediterranean regions.

| Region       | Number of stations | Positive trend | Negative trend |
|--------------|---------------------|----------------|----------------|
| Boreal       | 358                 | 95             | 5              |
| Continental  | 704                 | 68             | 32             |
| Atlantic     | 1261                | 71             | 29             |
| Mediterranean| 1162                | 8              | 92             |

The European spatial pattern of the annual streamflow volume trend appears congruent also with the observed European temperature and rainfall long-period changes as shown in Fig. 5a and b, where the annual streamflow volume trends are overlapped to daily mean temperature and rainfall trend maps built starting from E-OBS gridded dataset 20.0e (https://www.ecad.eu/) (Morice et al. 2012).
Fig. 5. Comparison between annual streamflow volume trends and daily mean temperature (a) and rainfall (b) trends over the European continent.
Concerning air temperature changes, the works of Staggle et al. (2017), Vicente-Serrano et al. (2014), Spinoni et al. (2015), Zeng et al. (2012), Willems (2013) and Madsen et al. (2014) confirm a global increase of mean temperatures with a marked trend in Mediterranean areas, where air temperature is expected to increase up to 0.3 °C/decade. The increase of air temperature in northern regions more reasonably affect the positive trend in annual volume streamflows observed in those areas, as a consequence of a potential increase of snow-melt processes in glacier or in mountain high latitudes basins. On the contrary, in southern regions, the marked increase of temperatures produces an increase in evapotranspiration fluxes and, consequently, drought situations are amplified. This might in part explain the negative trend in annual streamflow volumes observed in Mediterranean areas which is amplified by the reduction of rainfall volumes. In fact, concerning rainfall changes, the southern regions are affected by a marked negative trend (even below -3 mm/decade), while the northern regions are characterized by a positive trend which can overcome 10 mm/decade. The spatial distribution over the continent of both patterns appears perfectly congruent with the findings in annual streamflow volumes, as shown in Fig.4.

Despite the spatial annual streamflow volume trend is very clear at a synoptic scale (i.e. increase of annual streamflow volumes in northern Europe and vice versa in southern Europe), in some local cases it can be opposite. In northern Germany, Scandinavian Peninsula and the east part of the Alps, positive and negative annual streamflow volume trends are mixed. This can be closely linked to complexity of snow-melt processes in glacier or mountain basins and the potential interactions between groundwater levels and river flows, as suggested by Renard et al. (2008), Birsan et al. (2005) and Pelliciotti et al. (2010). The authors found that in some regions such as southeast of England, northeast of France, as well as Danish the contribution of the aquifer to streamflow is high especially in summer periods (i.e. when irrigation occurs). Various studies, moreover, have demonstrated that the mechanisms of interactions between groundwater and river flow contribute to moderate the influence of climate change drivers on streamflow, conversely, basins with less productive aquifers show a more direct response to climate drivers (Fleig et al. 2010, Laize et al. 2010).

3.2 Annual streamflow volume trend in Mediterranean area

Focusing on the main Mediterranean river catchments (according with European Environmental Agency classification), the number of stations with positive and negative Theil-Sen’s slope for each catchment was computed, and the results are reported in Fig.6. In all main river basins in Spain, France and Italy prevails negative trends of annual streamflow volumes. In Garonne and Rhone river basins is found the larger magnitude of negative annual streamflow volume trends, respectively, of about \(-2.2 \times 10^3\) m³/(km² year) and \(-3 \times 10^3\) m³/(km² year). No basin with marked artefact trends is found as demonstrated by the very close distance of the 25th and 75th percentiles from the median slope value, confirming, thus, trend homogeneities inside each basin. Lack of information in the Padana Plain is still present today. This is due to the complexity of its river network and its peculiar ecosystem mainly based on a strong interaction between river discharge and groundwater, which makes difficult to carry out reliable flow measurements (Masseroni et al. 2017).
Negative trend over the entire Mediterranean basin is also confirmed by the analysis performed on the mean annual streamflow volume produced in this area. The annual streamflow volumes of each station were standardized by their mean value, and then the standardized annual streamflow volumes of all stations were averaged. The result is reported in Fig. 7, where the standardized annual streamflow volumes smoothed by a simple rolling average with a sliding window of 5 year length is shown along with the 25\(^{th}\) and 75\(^{th}\) percentile trends. When standardized annual streamflow volume is greater than 1 it means that the annual streamflow volume is greater than the average of annual streamflow volumes, vice versa if standardized annual streamflow volume is lower than 1. The former case can be considered as a positive signal of annual streamflow volume exceedance, whereas in the latter an annual streamflow volume deficit. Fig. 7 shows a change in the annual streamflow volume pattern between 1980 and 1985 moving from positive to negative availabilities with respect to the mean of annual streamflow volume observations. This finding is consistent with the results found by Hannaford et al. (2013) on the marked decreasing of low flow regimes in southern Europe in the last thirty years as well as with the conclusions of the International Panel of Climate Change (IPCC) work on climate change prospective (IPPC 2007) which highlighted how in the Northern Hemisphere climate change effects in reducing water resource availability have increased notably from the post-1980 period.

Fig. 6. Number of stations with positive and negative annual streamflow volume trends in the main Mediterranean river basins. Box plot of the Theil-Sen’s slope for each catchment is also reported.
Conclusions

This study closes the gap between regional researches on annual streamflow volume trend and a continental-scale pattern of its spatio-temporal variability. Starting from a dataset constituted by more than 3,000 gauge stations over more than 40 countries across Europe, anomalies in annual streamflow volume were computed and Theil-Sen’s line slope was evaluated for each catchment over a recorded period from 1950 to 2015. A clear and undisputed trend pattern in annual streamflow volumes is recognized by the statistical analysis, showing marked negative trends in Mediterranean areas and positive trends in northern regions of Europe. All main Mediterranean river basins reveal negative trends in annual streamflow volume with an expected decreasing in annual streamflow volume of about $-1 \times 10^3$ m$^3$/km$^2$ year. On the contrary, in northern regions of Europe, a positive increase of annual streamflow volume is expected to be on average about $0.5 \times 10^3$ m$^3$/km$^2$ year. This trend patterns agree with the increase of temperatures and the decreasing in rainfall volumes detected by long-period observations on European continent. Indeed, these observations confirm an increase in drought situations in the southern regions of Europe, whereas revel an increase of rainfall volumes and runoff production in the northern European countries. In the Mediterranean area, the effect of climate change caused an inversion of the annual streamflow volume availability with respect to the mean of observations, i.e. from positive to negative values, starting from about 1985. In the recent 30-year period (1985-2015), the streamflow volumes are consistently lower than the average availability of the period 1950-2015.

The results of this study, therefore, can pave the way for more detailed quantitative analysis of annual streamflow volume variability (especially during different seasons) in order to meet the needs of managing water resources in agricultural, industrial and civil sectors.
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