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

Daniele Masseroni[1], Stefania Camici[2], Alessio Cislaghi[1,3], Giorgio Vacchiano[1,3], Christian Massari[2], Luca Brocca[2]

[1] Department of Agricultural and Environmental Sciences, University of Milan, Via Celoria 2, 20133 Milan, Italy
[2] Research Institute for Geo-Hydrological Protection, National Research Council, Via Madonna Alta 126, 06128 Perugia, Italy
[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 1900 to 2013 in some stations, the statistical analyses were carried out by including observations from 1950 to 2013 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 10^3 m^3/(km² year)) and a generally positive trend in northern ones (about 0.5 10^3 m^3/(km² year)). The annual streamflow volume trend patterns appear in agreement with the continental-scale meteorological 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 1950-2013 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, Teuling et al. 2019). These studies showed a clear seasonal change in streamflow without finding a solid correlation with the geographic position of the

35   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.

40   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,

45   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

50   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

55   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

60   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

65 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

70 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

75 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

80 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,

85 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 selection and processes

90 A large dataset of daily river streamflow records measured by 3,913 gauged stations over the entire European continent was analysed 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-

95 flumen64.cedex.es/anuarioaforos/default.asp), consisted of observed streamflow, recorded between 1900 and 2013.

Unfortunately, not all the gauged stations have been worked since the same time (Fig. 1) and with a consistent and reliable dataset.

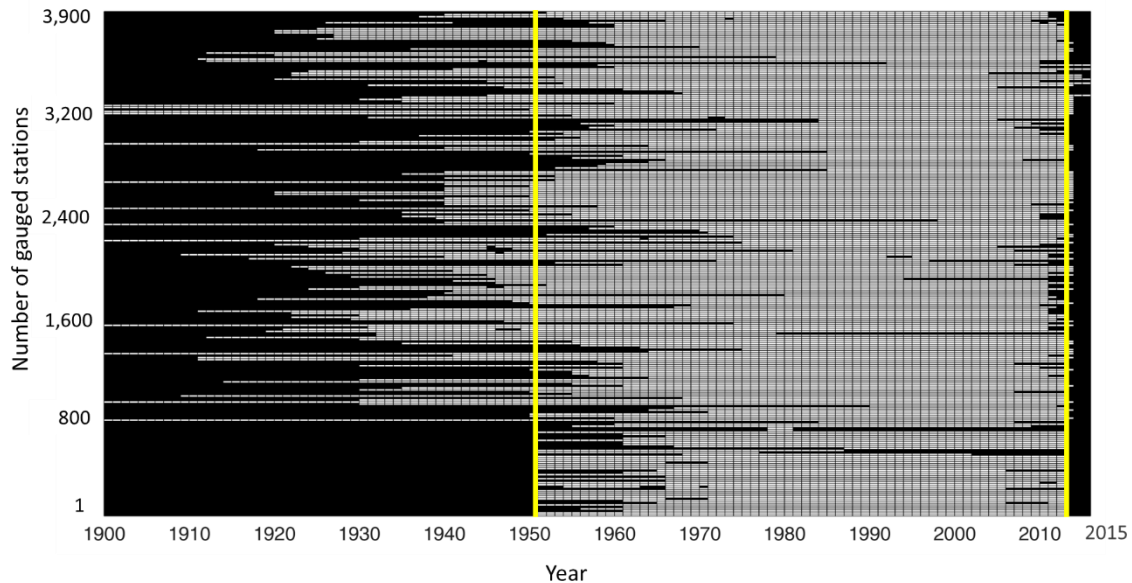



Fig. 1. Available years for the 3,913 gauged stations. Vertical lines in yellow indicate the selected common study period 1950–2013.

For assessing the reliability of streamflow daily values of each gauged station of the original dataset, a quality control and a homogeneity assessment were performed according the methodologies described in Buishand (1984), Chu et al. (2014), Ghiggi et al. (2019) and Kundzewicz (2015).

The quality control was conducted in succession on daily and aggregated time-series following the steps reported in Gudmundsson and Seneviratne (2016):

(i)   a visual hydrograph inspection to identify evident malfunction, consistent gaps (Fig. 2) and hydrograph disturbs such as presence of dams or reservoirs;

(ii)   excluding catchments with a drainage area larger than 100,000 km^2 to minimize the possibility that the human actives can significantly cause disturbances on the streamflow time-series (Piniewski et al. 2018);

(iii)   remove values with negative daily streamflow values;

(iv)   remove time-series with more than 2 years of missing data.

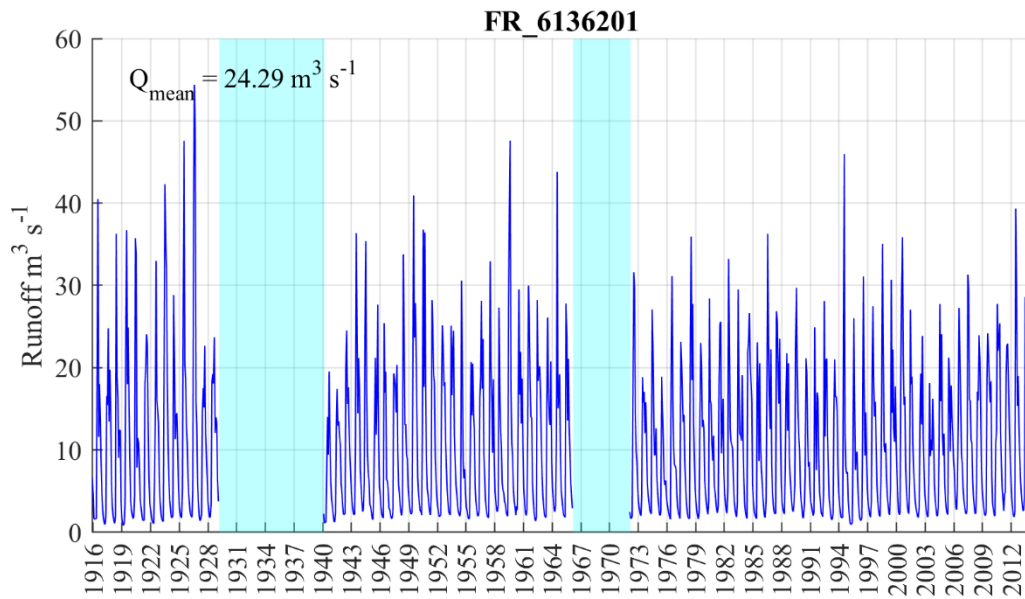



Fig. 2. Example of a series with gaps.

The homogeneity detection of data series (Fig. 3) was performed combining four different tests (Gudmundsson et al. 2018): (i) the standard normal homogeneity test of Alexandersson (1986); (ii) the Buishand range test (Buishand, 1982); (iii) the Pettitt test (Pettitt, 1979) and (iv) the Von Neumann ratio test (von Neumann, 1941). Homogeneity tests were carried out using the "iki.dataclim" statistical package for R (Orlowsky, 2014). The streamflow time series were considered as consistent when the null hypothesis at the 1% level was accepted at least in 3 of 4 tests (ECA&D) (Gudmundsson and Seneviratne, 2016; Merino et al., 2016).

Despite potential levels of human-induced alterations of river flow regime could be still present in time-series data after the application of the aforementioned controls, a certain degree of disturbance can be tolerated (Murphy et al. 2013). In order to further reduce the disturbance, high flow conditions were not investigated and we focused the analysis on annual streamflow volumes.

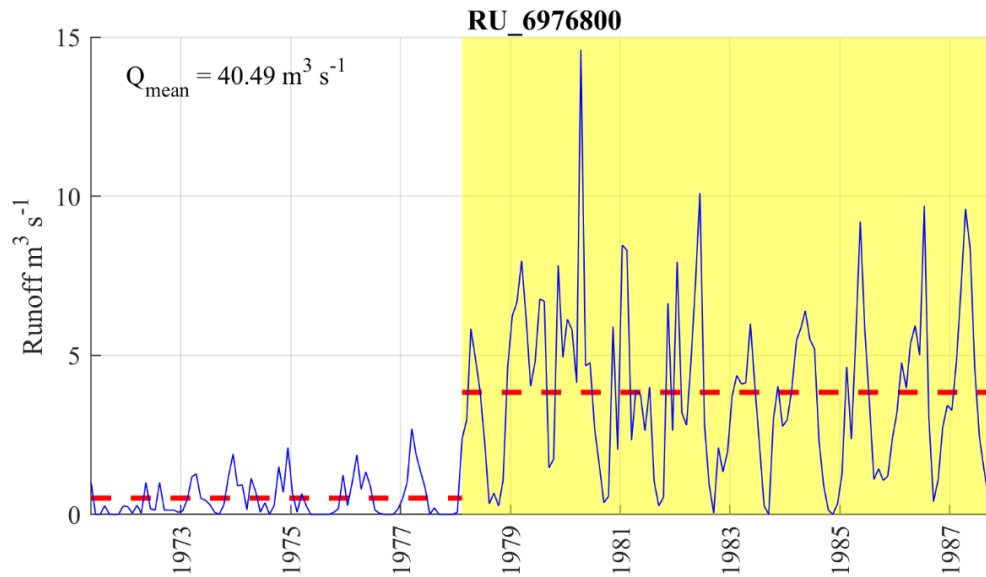



Fig. 3. Example of the results of the homogeneity test with a detection of a discontinuity point in a streamflow daily series of data.

130

The application of quality control and homogeneity tests led to discard 428 series of data. Thus, 3,485 stations were selected to assembly 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 a nearly complete period of analysis), and to detect a historical variability. Location of the different gauged stations is reported in Fig. 4 on physical European map, whereas some statistics are reported

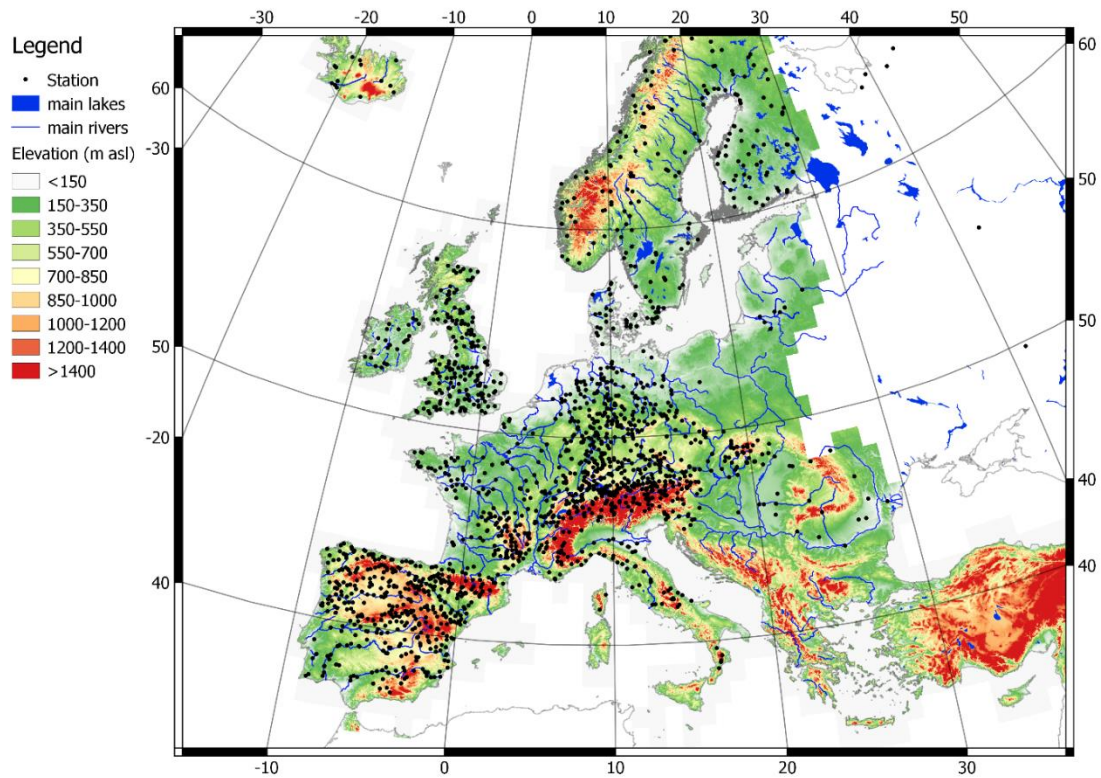
135 in Tab.1. The selected gauged stations belong to more than 40 European countries especially over the Mediterranean basin. In fact, about one third are located in Spain, French and Italy. The dataset provided time-series data from 1950 to 2013 (i.e. 63-year study period has been considered as the maximum record length enable to guarantee a uniformity of series of data among the stations as reported in Fig. 1).

140

Fig. 4. Map of European study area. Digital Elevation Model (DEM), main rivers and lakes as well as position of gauging stations are presented.

Tab. 1. Overall characteristics of examined basins.

Area range (km^2)	Percentage of basins (%)	Elevation of basin centroid (m asl) Maximum – Minimum (Mean)	Annual streamflow volume (Mln m^3) Maximum – Minimum (Mean)
0-100	30	2900 - 2 (677)	247.40 – 40.81 (112.78)
100-200	21	2700 - 19 (510)	241.85 – 44.15 (139.03)
200-300	13	2170 – 30 (320)	306.06 - 52.82 (154.01)
300-400	10	2200 – 11 (621)	338.43 – 68.38 (188.40)
400-500	7	1980 – 10 (321)	431.28 – 80.36 (246.83)
500-600	6	1970 – 21 (452)	526.43 – 106.32 (307.59)
700-800	5	1856 – 31 (322)	554.09 - 90.12 (312.32)
800-900	3	1879 – 12 (398)	671.32 - 98.89 (363.59)
900-1,000	3	1900 – 10 (532)	889.22 - 143.21 (488.03)

| >1,000 | 2 | 1970 – 8 (601) | 931.21 - 150.01 (498.98) |

145

About 90% of stations belongs to catchments with size less than 1,000 km^2 of which more than 50% ranging from 1 to 200 km^2. Temporal autocorrelation level of the selected near-natural daily streamflow series was verified calculating lag-1 serial autocorrelation coefficient with a 95% of confidence bounds as suggested by Khaliq et al. (2009), Kulkarni and von Storch (1995) and von Storch (1995). All autocorrelation coefficients were found included in the confidence bounds, as shown in Fig.

150 5, and, therefore, they can be considered ready for the trend identification.

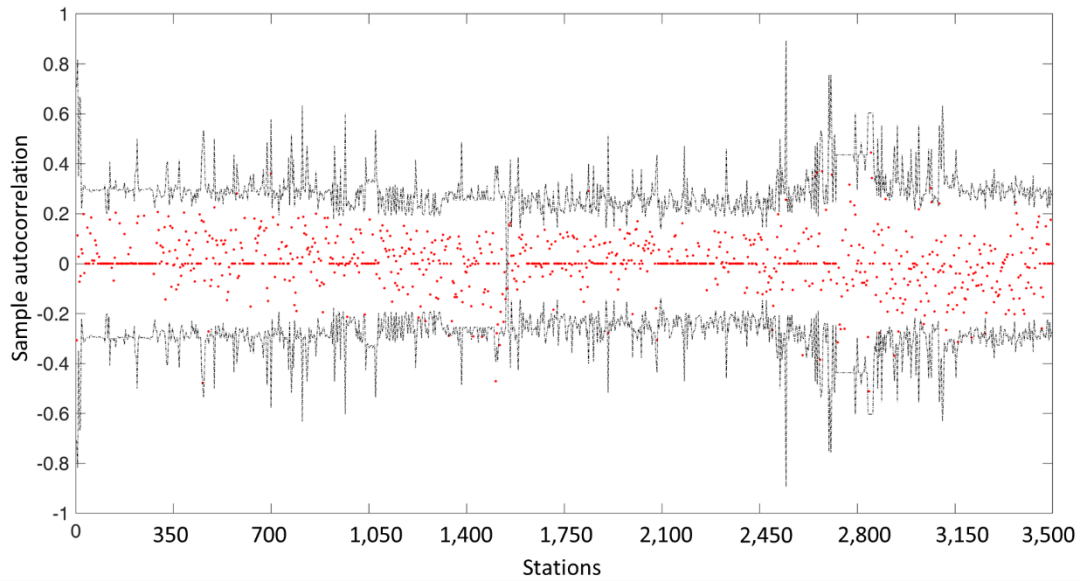



Fig.5. Samples autocorrelations. Red points are the value of lag-1 autocorrelation coefficient, whereas black dotted lines represent the 95% confidence bounds.

155

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.,

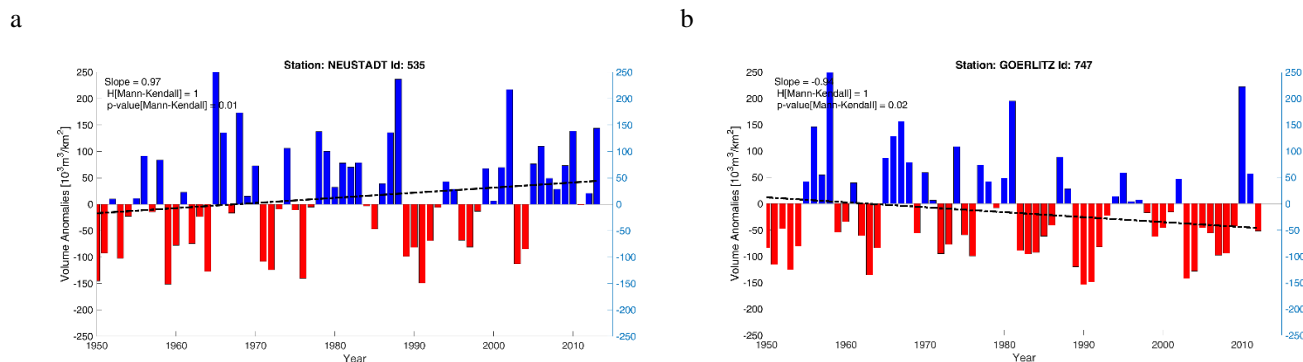
160 Kundzewicz and Robson 2004, Stahl et al. 2010, Burn et al. 2012, Hammanfor et al. 2013). In the present study, the slope of Theil-Sen's line, known as Theil-Sen's slope or Sen's slope, was calculated on the annual anomalies in streamflow volumes, an innovative modality with respect to the application on direct streamflow data (Birsan et al. 2005). 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

165 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. 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

170 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).

175 **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. 6a and b an example of positive and negative trend evaluated thought the slope of the Theil-Sen's line and confirmed by MK test for two stations located in central Europe, is reported.

180 **Fig. 6. Anomalies in annual streamflow volumes for the station of Neustadt (a) and Goerlitz (b). In the graphs, the slope of the Theil-Sens's line, H and p-value of the Mann Kendall test are also reported.**

Results found that in 95% of the European gauged stations (i.e. 3,310 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

185 is recognized, with clear positive trend in northern regions and negative trend in southern ones, as shown in Fig. 7.

Adopting the subdivision of the European continent in the four macro-regions as provided by Gudmundsson et al. (2017) and Fernandez-Carrillo et al. (2019) 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. 2. 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. 7, 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.

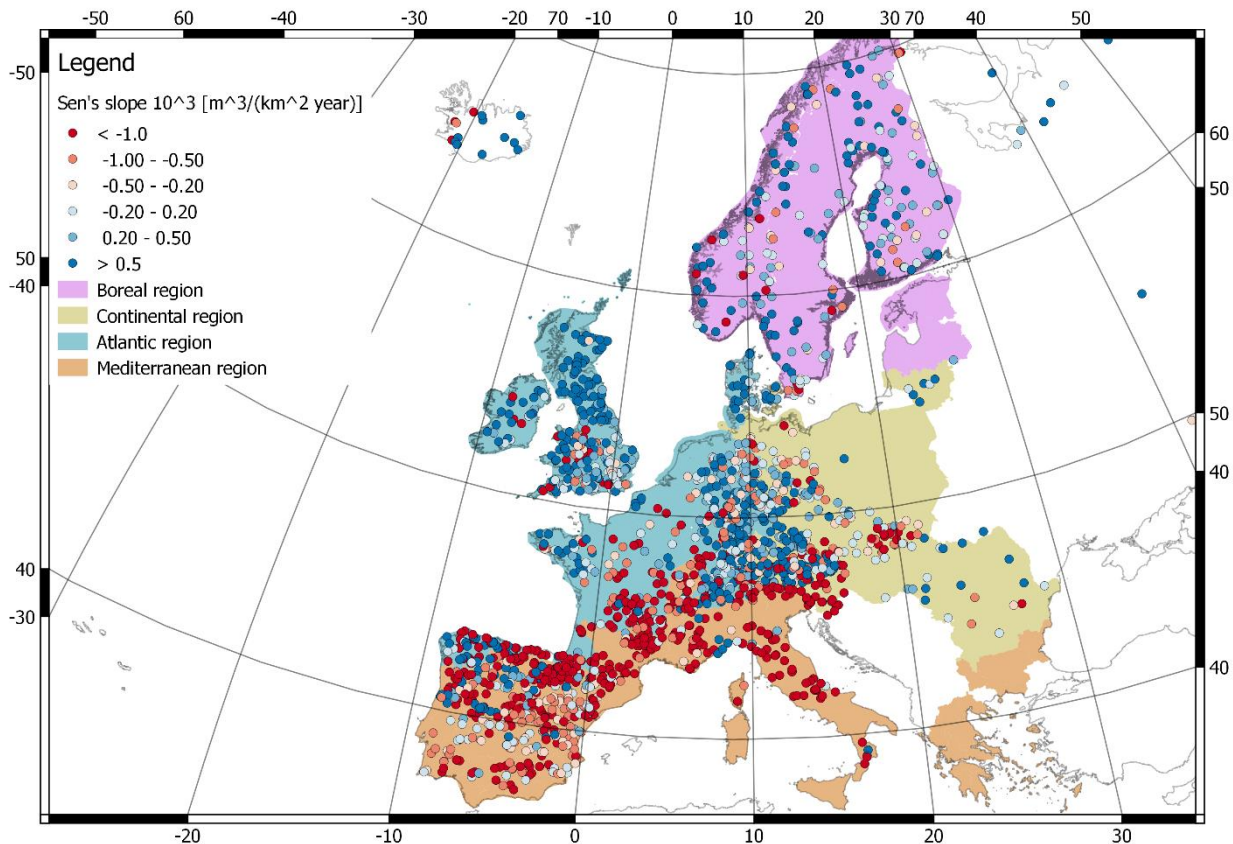
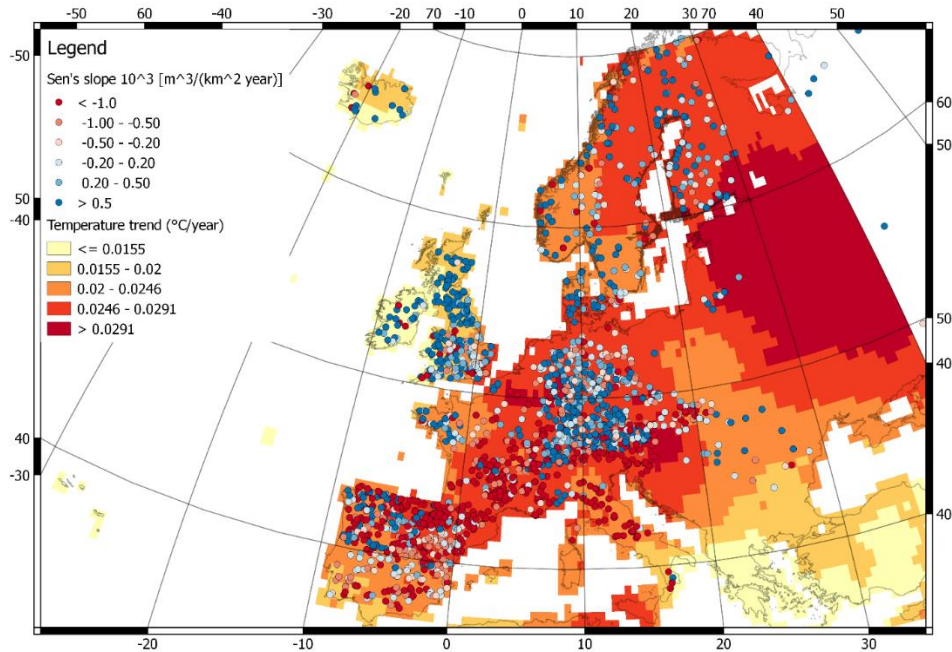



Fig. 7. Annual trend of streamflow volume anomalies in European continent subdivided in Boreal, Continental, Atlantic and Mediterranean regions. Only significant trend are shown.

Tab. 2. Percentage of significant (i.e. 3,310 stations) positive and negative trends in annual streamflow volumes in the European macro-regions.

Region	Number of stations	Positive trend	Negative trend
Boreal	323	95	5
Continental	694	68	32
Atlantic	1191	71	29
Mediterranean	1102	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. 8a and b, where the annual streamflow volume trends are overlapped to daily mean temperature and rainfall trend maps obtained by E-OBS gridded dataset 20.0e (https://www.ecad.eu/ - Morice et al. 2012) for the same selected period of daily streamflow series (i.e. 1950-2013).

a

b

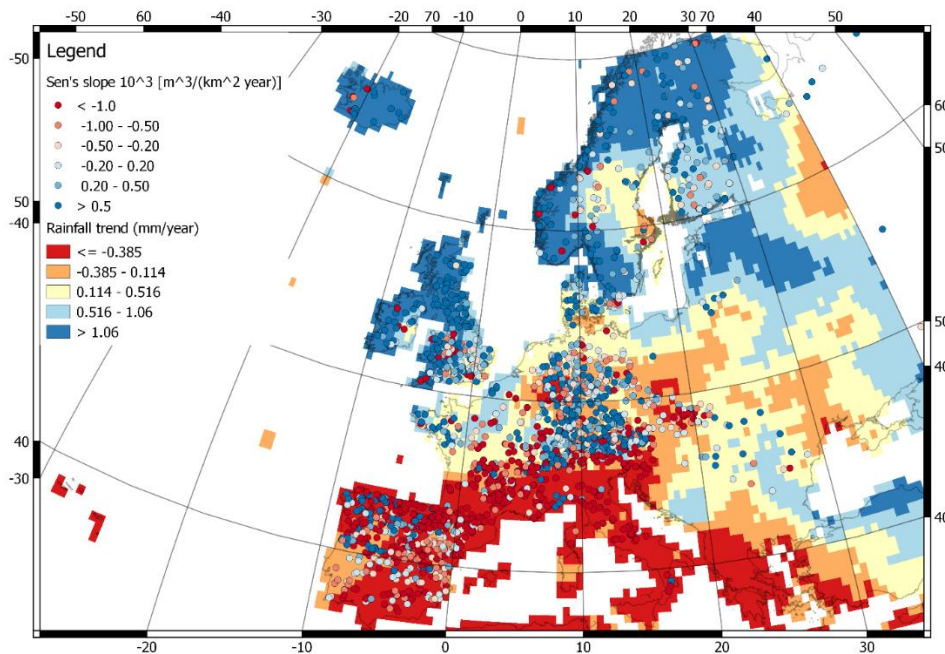



Fig. 8. Comparison between annual streamflow volume trends and daily mean temperature (a) and rainfall (b) trends over the European continent. Only significant trend are shown.

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.7.

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

230 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

235

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. 9. In all main river basins in Spain, France and Italy prevails negative trends of annual streamflow volumes. The larger magnitude of negative annual streamflow volume trends is found in Garonne and Rhone river basins, respectively, of about -

240 2.2 10^3 m^3/(km^2 year) and -3 10^3 m^3/(km^2 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.

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

245 the standardized annual streamflow volumes of all stations were averaged. The result is reported in Fig. 10, 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 25th and 75th 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

250 exceedance, whereas in the latter an annual streamflow volume deficit. Fig. 10 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

255 Hemisphere climate change effects in reducing water resource availability have increased notably from the post- 1980 period.

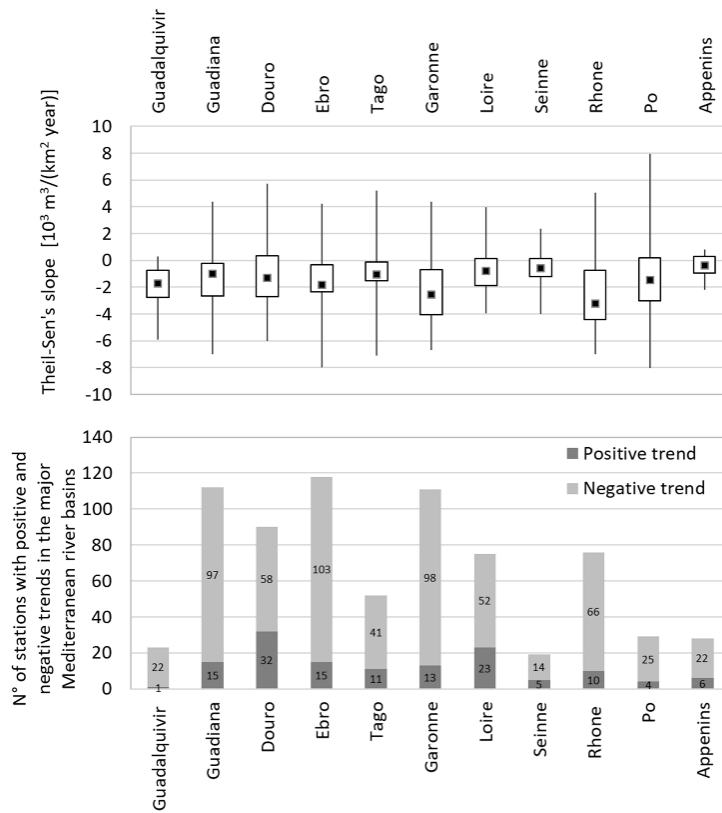



Fig.9. Number of stations with positive and negative annual streamflow volume trends in the main Mediterranean river basins. Box plot of the Theil-Sen's slope for each catchment is also reported.

260

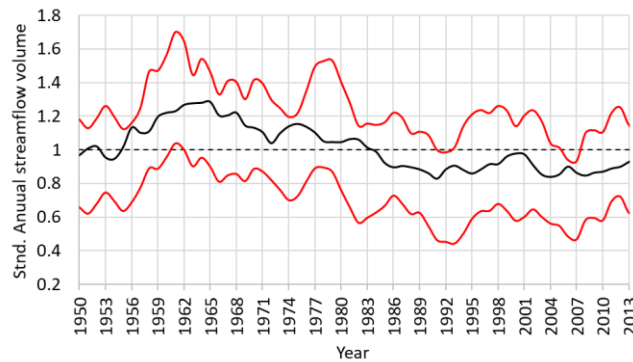



Fig. 10. Standardized annual streamflow volume pattern from 1950 to 2013. Black line shows the simple rolling average of the standardized annual streamflow volume behavior over the entire Mediterranean area. Red lines show the 25th and 75th percentiles of the standardized annual streamflow volume series.

4 Conclusions

265 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 2013. 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

270 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 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 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,

275 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 (1985-2013), the streamflow volumes are consistently lower than the average availability of the period 1950-2013.

The results of this study, therefore, can pave the way for more detailed quantitative analysis of annual streamflow volume

280 variability (especially during different seasons) in order to meet the needs of managing water resources in agricultural, industrial and civil sectors.

Acknowledgement

This study was developed in the context of IrriGate project "Toward a smart and flexible irrigation management in gravity-fed

285 irrigation contexts' funded by Regione Lombardia PSR 1.2.01 year 2019.

References

Ban, N., Schmidli, J. & Schär, C. Heavy precipitation in a changing climate: does short-term summer precipitation increase faster? Geophys. Res. Lett. 42, 1165–1172 (2015).

Bard A, Renard B, Lang M, Giuntoli I, Korck J, Kobolsching G, Janza M, d'Amico M, Volken D (2015) Trends in the

290 hydrologic regime of Alpine rivers. J Hydrol 529:1823–1837

Bertola, M., Viglione, A., Hall, J., and Blöschl, G.: Flood trends in Europe: are changes in small and big floods different?, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-523, in review, 2019.

Birsan, M.-V., Molnar, P., Burlando, P., and Pfaundler, M.: Streamflow trends in Switzerland, J. Hydrol., 314, 312–329, 2005.

Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A., Parajka, J., Merz, B., ... & Boháč, M. (2019). Changing climate both

295 increases and decreases European river floods. Nature, 573(7772), 108-111.

Bormann H, Pinter N (2017) Trends in low flows of German rivers since 1950: comparability of different low-flow indicators and their spatial patterns. River Res Appl 33:1191–1204

Brooks, H. E. Severe thunderstorms and climate change. Atmos. Res. 123, 129–138 (2013)

Burn DH, Hannaford J, Hodgkins GA, Whitfield PH, Thorne R, Marsh T (2012) Reference hydrologic networks II. Using reference hydrologic networks to assess climate-driven changes in streamflow. Hydrol Sci J 57(8):1580–1593

Caloiero, T., Veltri, S., Caloiero, P., & Frustaci, F. (2018). Drought Analysis in Europe and in the Mediterranean Basin Using the Standardized Precipitation Index. Water, 10(8), 1043.

Casanueva et al., "Variability of Extreme Precipitation over Europe and Its Relationships with Teleconnection Patterns"; A. K. Fleig et al., "Attribution of European Precipitation and Temperature Trends to Changes in Synoptic Circulation,"Hydrology and Earth System Sciences 19, no. 7 (July 13, 2015): 3093–3107, doi:10.5194/hess-19-3093-2015.

Ceola, S., A. Montanari, and D. Koutsoyiannis (2014), Towards a theoretical framework for integrated modelling of hydrological and societal change, WIREs Water, 1, 427–438, doi:10.1002/wat2.1038.

Cohn TA, Lins HF (2005) Nature's style: naturally trendy. Geophys Res Lett 32(23):L23402

Cox, D.R. and Stuart, A. (1955). Some quick sign tests for trend in location and dispersion. Biometrika 42, 80-95.

Dai, A., Qian, T., Trenberth, K. E., and Milliman, J. D.: Changes in continental freshwater discharge from 1948 to 2004, J. Climate, 22, 2773–2791, 2009.

Daniela Jacob et al., "EURO-CORDEX: New High-Resolution Climate Change Projections for European Impact Research,"Regional Environmental Change 14, no. 2 (2014): 563–78, doi:10.1007/s10113-013-0499-2.

Demeterova, B. and Skoda, P.: Low flows in selected streams of Slovakia, J. Hydrol. Hydromech., 57, 55–69, 2009.

Demeterova, B. and Skoda, P.: Minimal discharges at Slovak rivers in the period 1961–2000 at the stations of the National Climate Programme, Meteorol. J., 8, 155–163, 2005.

Fiala, T., Ouarda, T. B. M. J., and Hladn´y, J.: Evolution of low flows in the Czech Republic, J. Hydrol., 393, 206–218, 2010.

Fiala, T.: Statistical characteristics and trends of mean annual and monthly discharges of Czech rivers in the period 1961–2005, J. Hydrol. Hydromech., 56, 133–140, 2008.

Fleig, A. K., Tallaksen, L. M., Hisdal, H., and Hannah, D. M.: Regional hydrological drought in north-western Europe: linking a new Regional Drought Area Index with weather types, Hydrol. Process., in press, 24, doi:10.1002/hyp.7644, 2010.

Gudmundsson, L., Seneviratne, S. I., & Zhang, X. (2017). Anthropogenic climate change detected in European renewable freshwater resources. Nature Climate Change, 7(11), 813.

Haddeland, I., Clark, D. B., Franssen, W., Ludwig, F., Voß, F., Arnell, N. W., Bertrand, N., Best, M., Folwell, S., Gerten, D., Gomes, S., Gosling, S. N., Hagemann, S., Hanasaki, N., Harding, R., Heinke, J., Kabat, P., Koirala, S., Oki, T., Polcher, J., Stacke, T., Viterbo, P., Weedon, G. P., and Yeh, P.: Multi-model estimate of the global water balance: setup and first results, J. Hydrometeorol., submitted, 2010.

Hannaford, J., Buys, G., Stahl, K., & Tallaksen, L. M. (2013). The influence of decadal-scale variability on trends in long European streamflow records. Hydrology and Earth System Sciences, 17(7), 2717-2733.

330   Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S., and Prudhomme, C.: Examining the large-scale spatial coherence of European drought using regional indicators of rainfall and streamflow deficit, Hydrol. Process., in press, doi:10.1002/hyp.7725, 2010.

Hannah, D. M., Demuth, S., Lanen van, H. A. J., Looser, U., Prudhomme, C., Rees, G., Stahl, K., and Tallaksen, L. M.: Large-scale river flow archives: importance, current status and future needs, Invited Commentary, Hydrol. Process., in press,

335   doi:10.1002/hyp.7794, 2010.

Hisdal, H., Holmqvist, E., J´onsd´ottir, J. F., J´onsson, P., J¨arvet, A., Lindstr¨om, G., Kolcova, T., Kriauciuniene, J., Kuusisto, E., Lizuma, L., Meilutyte-Barauskiene, D., Reihan, A., and Roald, L. A.: Climate change signals in streamflow data in the Nordic and Baltic region, in: Proceedings of the Third International Conference on Climate and Water, edited by: Heinonen, M., 3– 6 September 2007, SYKE, Helsinki, Finland, 182–187, 2007.

340   Hisdal, H., Stahl, K., Tallaksen, L. M., and Demuth, S.: Have droughts in Europe become more severe or frequent?, Int. J. Climatol., 21, 317–333, 2001.

Ilnicki P, Farat R, Go´recki K, Lewandowski P (2014) Impact of climatic change on river discharge in the driest region of Poland. Hydrol Sci J 59(6):1117–1134

IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report

345   of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp., 2007.

Kendall, M.G., 1975. Multivariate analysis. London: Griffin.

KLIWA: Langzeitverhalten der mittleren Abfl¨usse in Baden- W¨urttemberg und Bayern, Karlsruhe, http://www.kliwa.de/

350   download/KLIWAHeft3.pdf, last access: 27 November 2010, 93 pp., 2003.

Koutsoyiannis D, Montanari A (2007) Statistical analysis of hydroclimatic time series: uncertainty and insights. Water Resour Manag 43:W05429. https://doi.org/10.1029/2006WR005592

Khaliq, M. N., Ouarda, T. B. M. J., Gachon, P., Sushama, L., & St-Hilaire, A. (2009). Identification of hydrological trends in the presence of serial and cross correlations: A review of selected methods and their application to annual flow regimes of

355   Canadian rivers. Journal of Hydrology, 368(1-4), 117-130.

Kulkarni, A., von Storch, H., 1995. Monte Carlo experiments on the effect of serial correlation on the Mann–Kendall test of trend. Meteorol. Z. 4 (2), 82–85.

Kundzewicz ZW, Robson AJ (2004) Change detection in river flow records—review of methodology. Hydrol Sci J 49(1):7– 19

360   Kundzewicz, Z. W., Graczyk, D., Maurer, T., Pińskwar, I., Radziejewski, M., Svensson, C., & Szwed, M. (2005). Trend detection in river flow series: 1. Annual maximum flow/Détection de tendance dans des séries de débit fluvial: 1. Débit maximum annuel. Hydrological Sciences Journal, 50(5).

La Jeunesse, I., Bressers, H., & Browne, A. (2019). What Could Change Drought Governance in Europe? A Comparative Analysis between Two Case Studies in France and the UK. Facing Hydrometeorological Extreme Events: A Governance Issue,

365   301-311.

Laiz´e, C. R. L. and Hannah, D. M.: Modification of climate-river flow associations by basin properties, J. Hydrol., 389, 186–204, 2010.

M R Haylock et al., "A European Daily High-Resolution Gridded Data Set of Surface Temperature and Precipitation for 1950–2006,"Journal of Geophysical Research 113, no. D20 (2008): D20119, doi:10.1029/2008JD010201.

370   Madsen, H., Lawrence, D., Lang, M., Martinkova, M., & Kjeldsen, T. R. (2014). Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. Journal of Hydrology, 519, 3634-3650.

Manabe, S., Wetherald, R. T., Milly, P. C. D., Delworth, T. L. & Stouffer, R. J. Century-scale change in water availability: CO2-quadrupling experiment. Clim. Change 64, 59--76 (2004).

Masseroni, D., Ricart, S., de Cartagena, F., Monserrat, J., Gonçalves, J., de Lima, I., ... & Gandolfi, C. (2017). Prospects for

375   improving gravity-fed surface irrigation systems in Mediterranean European contexts. Water, 9(1), 20.

Mediero, L., Santillán, D., Garrote, L. & Granados, A. Detection and attribution of trends in magnitude, frequency and timing of floods in Spain. J. Hydrol. 517, 1072–1088 (2014).

Milliman, J. D., Farnsworth, K. L., Jones, P. D., Xu, K. H., and Smith, L. C.: Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000, Global Planet. Change, 62, 187—194, 2008.

380   Milly, P. C. D., Dunne, K. A., and Vecchia, A. V.: Global pattern of trends in streamflow and water availability in a changing climate, Nature, 438, 347–350, 2005.

Morice, C.P., Kennedy, J.J., Rayner, N.A. and Jones, P.D., 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 dataset. Journal of Geophysical Research, 117, D08101,doi:10.1029/2011JD017187

385   Murphy C, Harrigan S, Hall J, Wilby RL (2013) Climate-driven trends in mean and high flows from a network of reference stations in Ireland. Hydrol Sci J 58(4):755–772

Pandžić, K., & Trninić, D. (1992). Principal component analysis of a river basin discharge and precipitation anomaly fields associated with the global circulation. Journal of Hydrology, 132(1-4), 343-360.

Pellicciotti, F., Bauder, A., and Parola, M.: Effect of glaciers on streamflow trends in the Swiss Alps, Water Resour Res., 46,

390   W10522, doi:10.1029/2009WR009039, 2010.

Piniewski, M., Marcinkowski, P., & Kundzewicz, Z. W. (2018). Trend detection in river flow indices in Poland. Acta Geophysica, 66(3), 347-360.

Renard, B., Lang, M., Bois, P., Dupeyrat, A., Mestre, O., Niel, H., Sauquet, E., Prudhomme, C., Parey, S., Paquet, E., Neppel, L., and Gailhard, J.: Regional methods for trend detection: assessing field significance and regional consistency, Water Resour.

395   Res., 44, W08419, doi:10.1029/2007WR006268, 2008.

Rogger, M. et al. Land use change impacts on floods at the catchment scale: challenges and opportunities for future research. Wat. Resour. Res. 53, 5209–5219 (2017).

Schmocker-Fackel, P. and Naef, F.: More frequent flooding? Changes in flood frequency in Switzerland since 1850, J. Hydrol., 381, 1–8, doi:10.1016/j.jhydrol.2009.09.022, 2010.

400 Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63(324):1379–1389. https://doi.org/10.2307/2285891

Shorthouse, C. A. and Arnell, N. W.: Spatial and temporal variability on European river flows and the North Atlantic Oscillation, FRIEND'97 – Regional Hydrology: Concepts and Models for Sustainable Water Resource Management, IAHS-AISH P., 246, 77–85, 1997.

405 Spinoni, J., Naumann, G., Vogt, J. & Barbosa, P. European drought climatologies and trends based on a multi-indicator approach. Global and Planetary Change 127, 50–57, https://doi.org/10.1016/j.gloplacha.2015.01.012 (2015).

Stagge, J. H., Kingston, D. G., Tallaksen, L. M., & Hannah, D. M. (2017). Observed drought indices show increasing divergence across Europe. Scientific reports, 7(1), 14045.

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L., Van Lanen, H., Sauquet, E., ... & Jordar, J. (2010). Streamflow trends in
410 Europe: evidence from a dataset of near-natural catchments. Hydrology and Earth System Sciences, 14, p-2367.

Steirou LG, Gerlitz L, Apel H, Merz B (2017) Links between largescale circulation patterns and streamflow in Central Europe: a review. J Hydrol 549:484–500

Theil, H.: A rank-invariant method of linear and polynomial regression analysis, Indagat. Math. New Ser., 12, 85–91, 1950.

Urbonas, B., & Stahre, P. (1993). Stormwater: best management practices and detention for water quality, drainage, and CSO
415 management.

Teuling, A. J., De Badts, E. A., Jansen, F. A., Fuchs, R., Buitink, J., Van Dijke, A. J. H., & Sterling, S. M. (2019). Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe. Hydrology and Earth System Sciences, 23(9), 3631-3652.

Vicente-Serrano, S. M. et al. Evidence of increasing drought severity caused by temperature rise in southern Europe.
420 Environmental Research Letters 9, 044001, https://doi.org/10.1088/1748-9326/9/4/044001 (2014).

Viglione, A., Borga, M., Balanbanis, P., and Bl¨oschl, G.: Barriers to the exchange of hydrometeorological data in Europe: Results from a survey and implications for data policy, J. Hydrol., 394, 63–77, 2010.

Vogt, J. et al. A pan-European River and Catchment Database. Report No. EUR 22920 (Office for Official Publications of the European Communities, 2007).

425 von Storch, H., 1995. Misuses of statistical analysis in climate research. In: von Storch, H., Navarra, A. (Eds.), Analysis of Climate Variability: Applications of Statistical Techniques. Springer-Verlag, Berlin, pp. 11–26.

Willems, P. (2013). Multidecadal oscillatory behaviour of rainfall extremes in Europe. Climatic Change, 120(4), 931-944.

Yue S, Wang C (2002) The Mann–Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resour Manag 18:201–218.

430   Yue, S., Pilon, P., 2004. Acomparison of the power of the t test, Mann–Kendall and bootstrap tests for trend detection. Hydrol. Sci. J. 49 (1), 21–37.

Yue, S., Pilon, P., Phinney, B., 2003. Canadian stream flow trend detection: impacts of serial and cross-correlation. Hydrol. Sci. J. 48 (1), 51–63.

Zeng, Z. et al. Global evapotranspiration over the past three decades: estimation based on the water balance equation combined

435   with empirical models. Environmental Research Letters 7, 014026, https://doi.org/10.1088/1748-9326/7/1/014026 (2012).

Fernandez-Carrillo, A., de la Fuente, D., Rivas-Gonzalez, F. W., & Franco-Nieto, A. (2019, October). A Sentinel-2 unsupervised forest mask for European sites. In Earth Resources and Environmental Remote Sensing/GIS Applications X (Vol. 11156, p. 111560Y). International Society for Optics and Photonics.

Alexandersson, H.: A homogeneity test applied to precipitation data, J. Climatol., 6(6), 661–675, doi:10.1002/joc.3370060607,

440   1986.

Buishand, T. A.: Some methods for testing the homogeneity of rainfall records, Journal of Hydrology, 58(1–2), 11–27, doi:10.1016/0022-1694(82)90066-X, 1982.

Buishand, T. A.: Tests for detecting a shift in the mean of hydrological time series, Journal of Hydrology, 73(1–2), 51–69, doi:10.1016/0022-1694(84)90032-5, 1984.

445   Chu, Ma. L., Ghulam, A., Knouft, J. H. and Pan, Z.: A hydrologic data screening procedure for exploring monotonic trends and shifts in rainfall and runoff patterns, J Am Water Resour Assoc, 50(4), 928–942, doi:10.1111/jawr.12149, 2014.

Ghiggi, G., Humphrey, V., Seneviratne, S. I. and Gudmundsson, L.: GRUN: an observation-based global gridded runoff dataset from 1902 to 2014, Earth Syst. Sci. Data, 11(4), 1655–1674, doi:10.5194/essd-11-1655-2019, 2019.

Gudmundsson, L. and Seneviratne, S. I.: Observation-based gridded runoff estimates for Europe (E-RUNversion 1.1), Earth

450   Syst. Sci. Data, 8(2), 279–295, doi:10.5194/essd-8-279-2016, 2016.

Gudmundsson, L., Do, H. X., Leonard, M. and Westra, S.: The Global Streamflow Indices and Metadata Archive (GSIM) – Part 2: Quality control, time-series indices and homogeneity assessment, Earth System Science Data, 10, 787–804, 2018.

Khaliq, M. N., Ouarda, T. B. M. J., Gachon, P., Sushama, L. and St-Hilaire, A.: Identification of hydrological trends in the presence of serial and cross correlations: A review of selected methods and their application to annual flow regimes of

455   Canadian rivers, Journal of Hydrology, 368(1–4), 117–130, doi:10.1016/j.jhydrol.2009.01.035, 2009.

Kundzewicz, Z. W.: Climate change track in river floods in Europe, Proceedings of the International Association of Hydrological Sciences, 369, 189–194, doi:10.5194/piahs-369-189-2015, 2015.

Merino, A., Fernández-Vaquero, M., López, L., Fernández-González, S., Hermida, L., Sánchez, J. L., García-Ortega, E. and Gascón, E.: Large-scale patterns of daily precipitation extremes on the Iberian Peninsula, Int. J. Climatol., 36(11), 3873–3891,

460   doi:10.1002/joc.4601, 2016.

Murphy, C., Harrigan, S., Hall, J. and Wilby, R. L.: Climate-driven trends in mean and high flows from a network of reference stations in Ireland, Hydrological Sciences Journal, 58(4), 755–772, doi:10.1080/02626667.2013.782407, 2013.

von Neumann, J.: Distribution of the ratio of the mean square successive difference to the variance, Ann. Math. Statist., 12(4), 367–395, doi:10.1214/aoms/1177731677, 1941.

465 Pettitt, A. N.: A non-parametric approach to the change-point problem, Applied Statistics, 28(2), 126, doi:10.2307/2346729, 1979.

Piniewski, M., Marcinkowski, P. and Kundzewicz, Z. W.: Trend detection in river flow indices in Poland, Acta Geophys., 66(3), 347–360, doi:10.1007/s11600-018-0116-3, 2018.

Stahl, K., Hisdal, H., Hannaford, J. and Tallaksen, L.: Streamflow trends in Europe: evidence from a dataset of near-natural

470 catchments, Hydrology and Earth System Sciences, 14, 2367–2382, doi:10.5194/hess-14-2367-2010, 2010.