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

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10   **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

15   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 10^3 m³/(km² year)) and a generally positive trend in northern ones (about 0.5 10^3 m³/(km² year)). The annual streamflow volume trend patterns appear in agreement with the continental-scale climate change

20   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

30   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,

35 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

90   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-

95   flumen64.cedex.es/anuarioaforos/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 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 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

100   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 km^2 were excluded by the analysis because human disturbance is unavoidable at

105   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,

110   high flow conditions were not investigated and we focused the analysis on annual streamflow volumes.

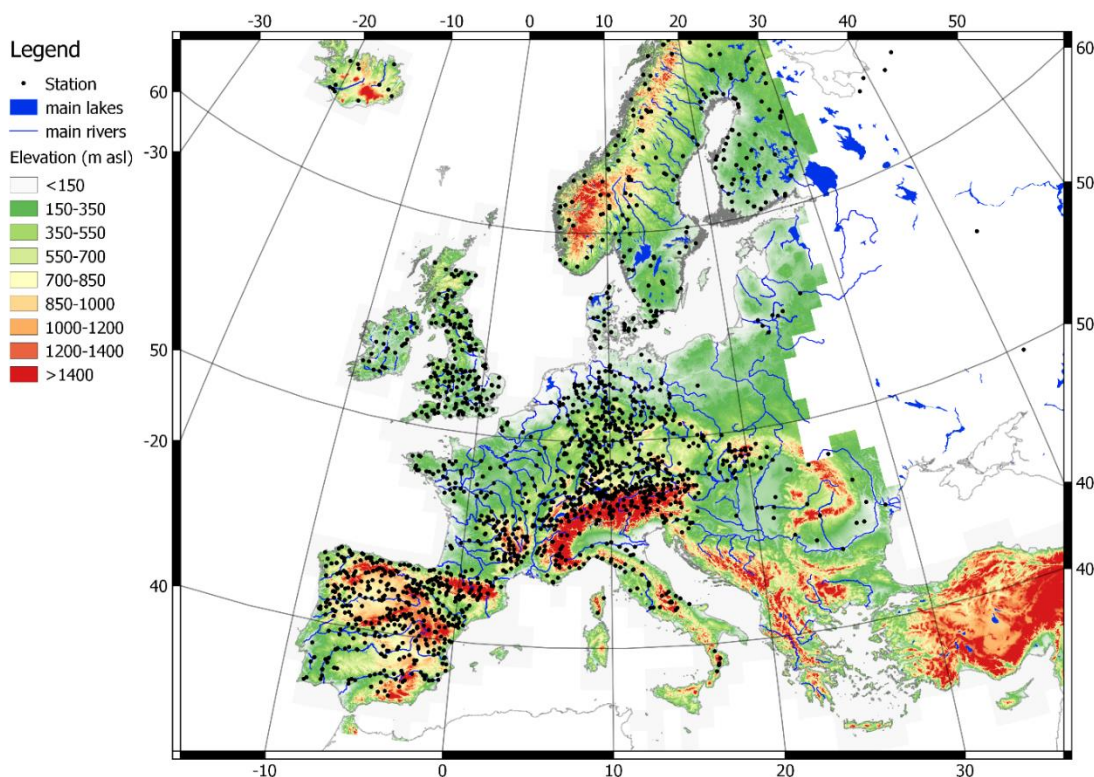
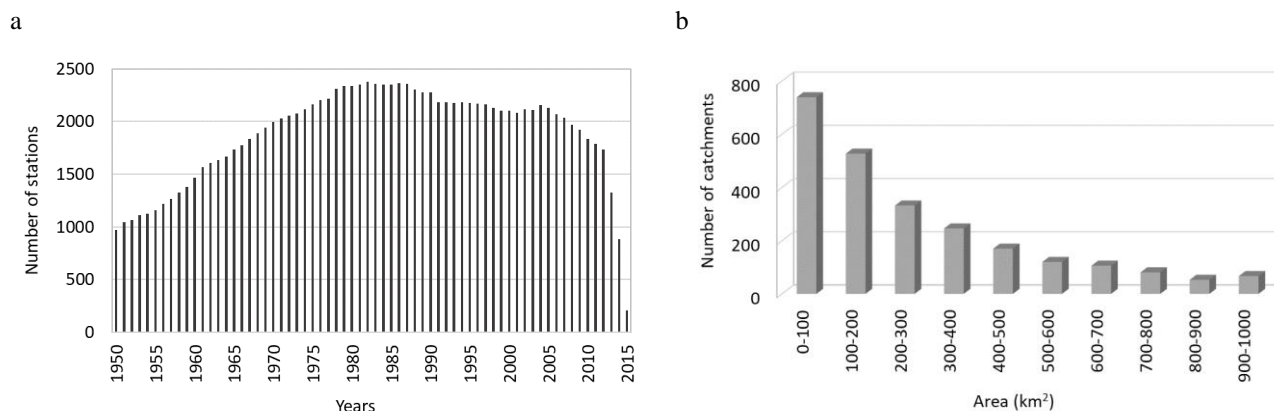



Fig. 1. Map of European study area. Digital Elevation Model (DEM), main rivers and lakes as well as position of gauging stations are presented.

a

b

115 **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 km^2).**

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

120 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

125 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

130 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)

135 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
140   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.

a   b

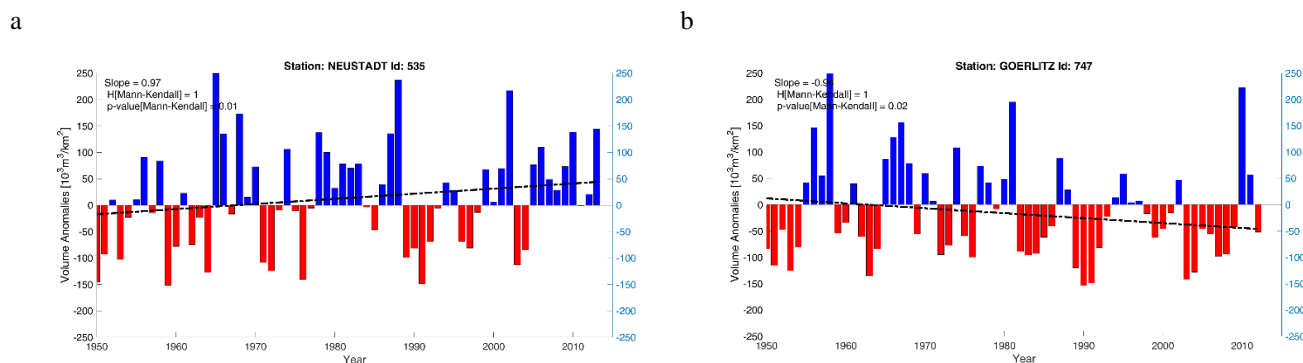



**Fig. 3. Anomalies in annual streamflow volumes for the station of Neustadt (a) and Goerlitz (b). In the graphs, the slope of the
Theil-Sens's line, H and p-value of the Mann Kendall test are also reported.**

145   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
150   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
155   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
160   the Mediterranean Sea.

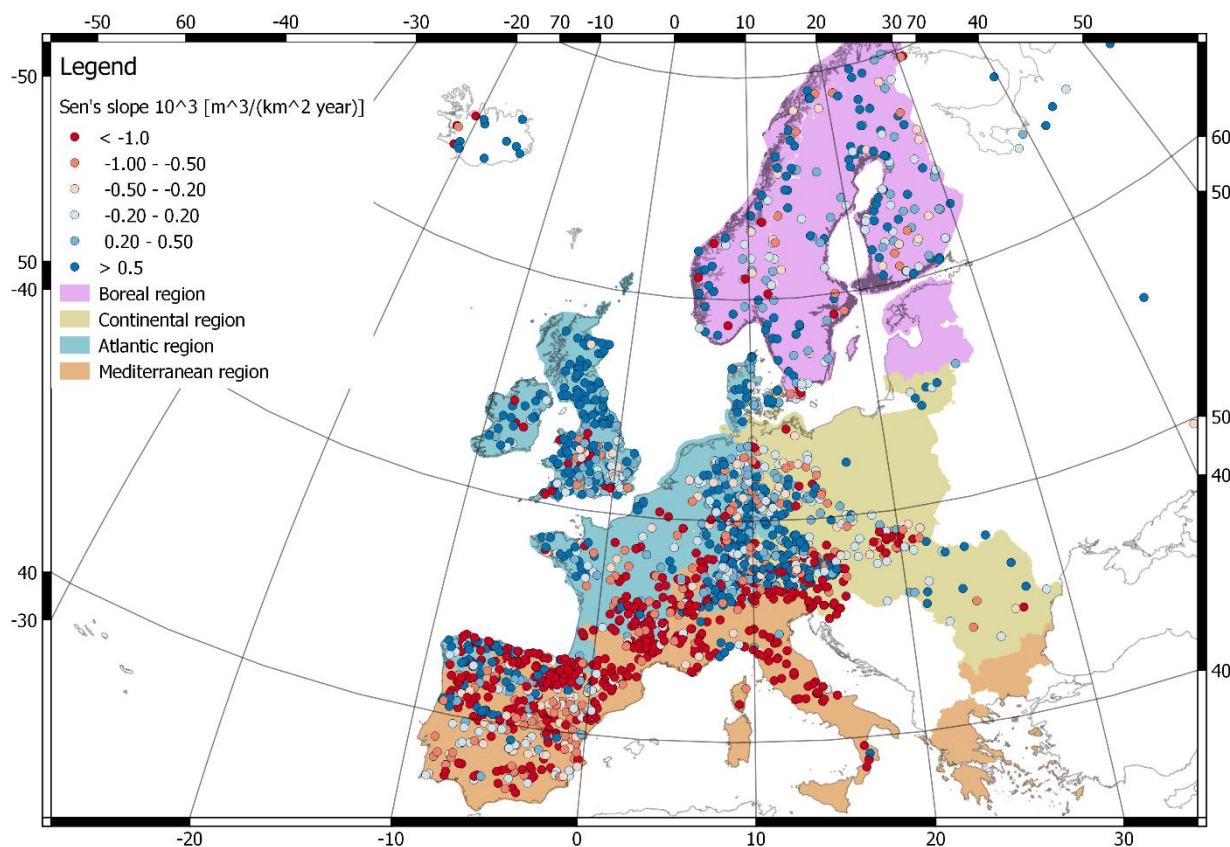



Fig. 4. Annual trend of streamflow volume anomalies in European continent subdivided in Boreal, Continental, Atlantic and Mediterranean regions.

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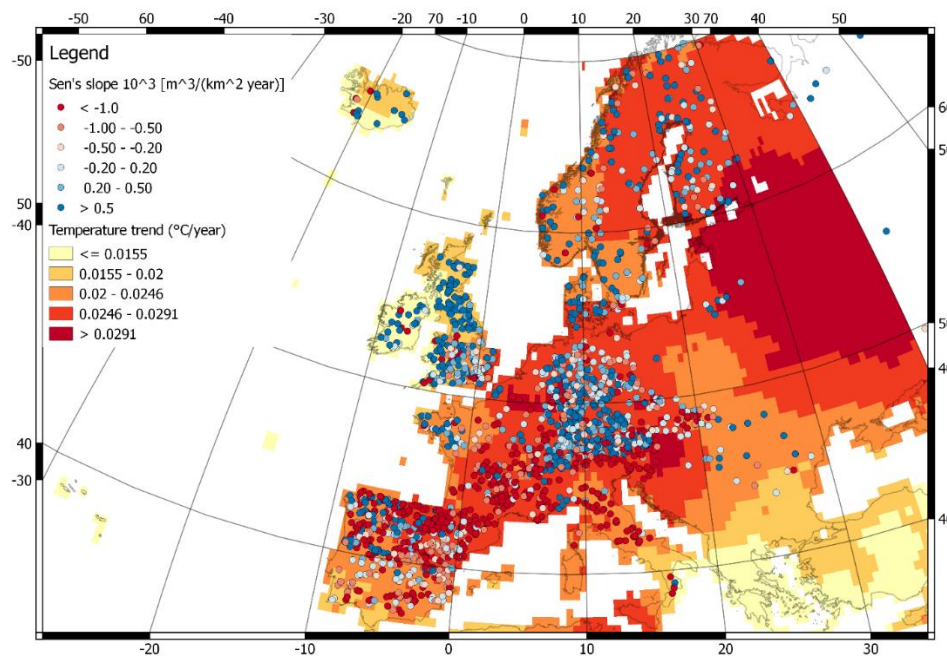
Tab. 1. Percentage of positive and negative trends in annual streamflow volumes in the European macro-regions.

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
170   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).

a

b

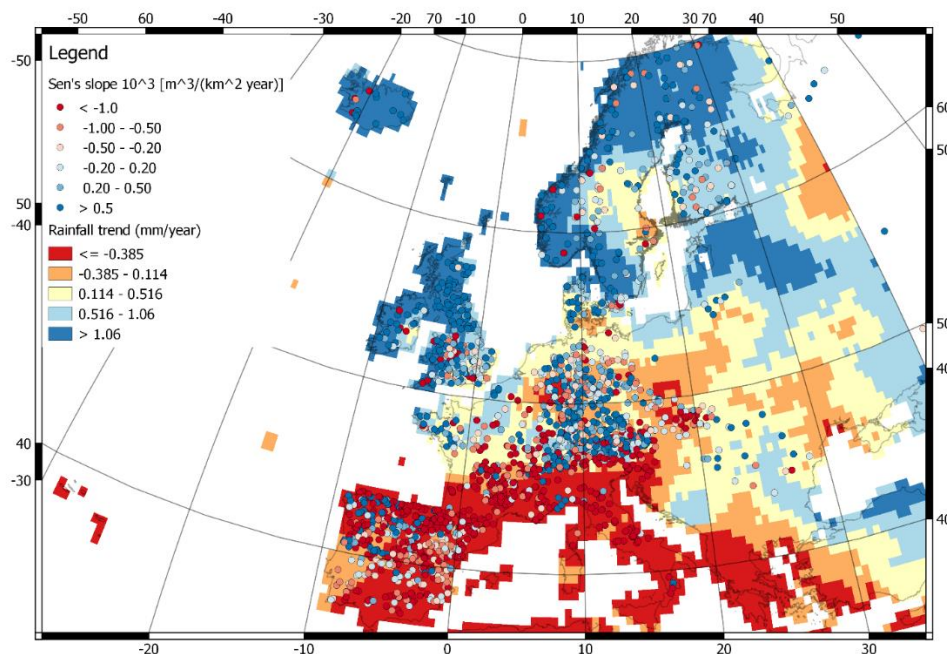



Fig. 5. Comparison between annual streamflow volume trends and daily mean temperature (a) and rainfall (b) trends over the European continent.

175 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

180 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

185 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

190 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

195 drivers (Fleig et al. 2010, Laize et al. 2010).

3.2 Annual streamflow volume trend in Mediterranean area

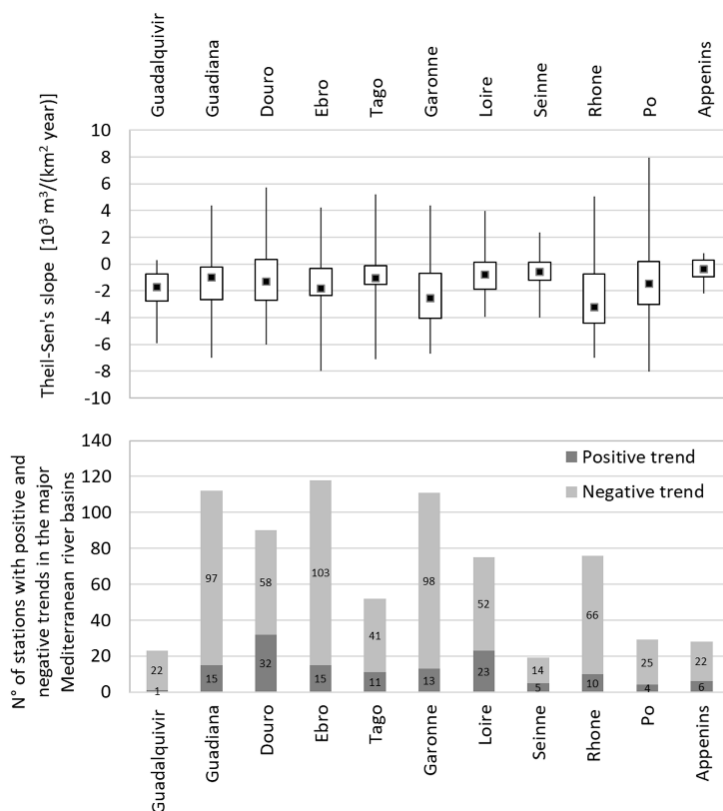
Focusing on the main Mediterranean river catchments (according with European Environmental Agency classification), the number of stations with positive and negative Theil-Sen's slope for each catchment was computed, and the results are reported in Fig. 6. In all main river basins in Spain, France and Italy prevails negative trends of annual streamflow volumes. In Garonne

200 and Rhone river basins is found the larger magnitude of negative annual streamflow volume trends, respectively, of about -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. 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

205 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 smoothened by a simple rolling average with a sliding window of 5 year length is

210   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 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

215   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.

220   **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.**

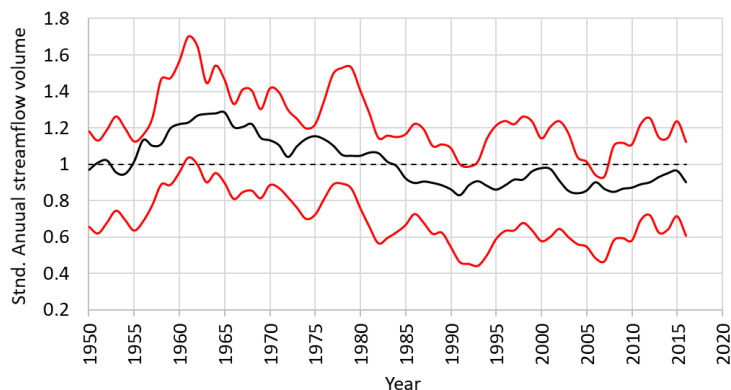



Fig. 7. Standardized annual streamflow volume pattern from 1950 to 2015. Black line shows the simple rolling average of the standardized annual streamflow volume behavior over the entire Mediterranean area. Red lines show the 25th and 75th
225 **percentiles of the standardized annual streamflow volume series.**

4 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
230 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 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
235 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
240 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.

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

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

255 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

260 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.

265 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.
270 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
275 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

280   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.,

285   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.

Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S., and Prudhomme, C.: Examining the large-scale spatial coherence of

290   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, doi:10.1002/hyp.7794, 2010.

295   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.

Hisdal, H., Stahl, K., Tallaksen, L. M., and Demuth, S.: Have droughts in Europe become more severe or frequent?, Int. J.

300   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 of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M.,

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

310   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

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

Kundzewicz, Z. W., Graczyk, D., Maurer, T., Pińskwar, I., Radziejewski, M., Svensson, C., & Szwed, M. (2005). Trend
315   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, 301-311.

320   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.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M., & Kjeldsen, T. R. (2014). Review of trend analysis and climate change
325   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: CO_2-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 improving gravity-fed surface irrigation systems in Mediterranean European contexts. Water, 9(1), 20.

330   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.

Milly, P. C. D., Dunne, K. A., and Vecchia, A. V.: Global pattern of trends in streamflow and water availability in a changing
335   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

Murphy C, Harrigan S, Hall J, Wilby RL (2013) Climate-driven trends in mean and high flows from a network of reference
340   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, W10522, doi:10.1029/2009WR009039, 2010.

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

350 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.

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63(324):1379–1389. https://doi.
355 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.

Spinoni, J., Naumann, G., Vogt, J. & Barbosa, P. European drought climatologies and trends based on a multi-indicator
360 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 Europe: evidence from a dataset of near-natural catchments. Hydrology and Earth System Sciences, 14, p-2367.

365 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 management.

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

Viglione, A., Borga, M., Balanbanis, P., and Blöschl, 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
375 European Communities, 2007).

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.

Yue, S., Pilon, P., 2004. Acomparison of the power of the t test, Mann–Kendall and bootstrap tests for trend detection. Hydrol.
380   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 with empirical models. Environmental Research Letters 7, 014026, https://doi.org/10.1088/1748-9326/7/1/014026 (2012).