Short Comment #1

Masseroni et al. provide an interesting analysis of streamflow trends at the European scale, with the aim to "... provide a valid benchmark for further accurate quantitative analysis on annual streamflow volumes". Such effort is much needed and appreciated. However the suggestion that accurate quantitative analyses of changes in the terrestrial hydrological cycle over Europe are missing is a bit misleading. Several studies have addressed attribution of streamflow changes. In a recent study (Teuling et al., Hydrol. Earth Syst. Sci., 23, 3631–3652, https://doi.org/10.5194/hess-23-3631-2019), we attributed patterns in streamflow and ET changes at the European scale to both changes in climate (temperature and precipitation) and land use (changes in forest age and cover and urbanisation) using a simplified Budyko framework. While more sophisticated studies will hopefully be undertaken in the future, we think that the current approaches and quantitative attribution to underlying causes (see also the extensive literature review in our paper) deserve discussion in this manuscript.

REPLY: *The reviewer is right; we miss to include some recent studies relevant to give to the readers a correct overview of the work done about quantitative analyses of changes in the terrestrial hydrological cycle over Europe. For that, in the revised manuscript the introduction will be revised in order to include the Teuling's and similar studies dealing the topic of analysis on annual streamflow volumes.*

Response to Reviewer #1

Concerning the comments provided by Rev#1, we improved substantially our manuscript especially in the material and method paragraph replying to all reviewer comments as follow. Specifically, the data selection and description was strongly improved including the criteria used for selecting river discharge time series and the procedures employed to mitigate errors and discontinuities in the whole dataset. Here in the follow the overall corrections are presented.

Comment 1: Line 100. "characterized by about 1.200 points of measure per year". This sentence is not clear. As a consequence it is not clear how the annual streamflow volumes are estimated.

Comment 2: Lines 107-110. The human activities in the river basin can significantly affect the trend, so it is not clear if a specific check on the time series was done. Specifically, a matching between analysed watersheds and dams could be helpful to understand if " the degree of disturbance can be tolerated". How many watersheds include a dam in it? When it was built? Etc. etc.

REPLY: *The size of original dataset was more clearly defined and it is of 3'913 stations. Of these, 3'485 were used for the analysis after filtering based on a quality control and a homogeneity assessment (as reported in the paragraph entitled 'river flow data selection and processes' of the new version of the manuscript). Specifically , 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 and hydrograph disturbs such as presence of dams or reservoirs;

(ii) excluding catchments with a drainage area larger than 100,000 km2 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.

The homogeneity detection of data series 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). We invite the Rev#1 to refer to the revised version of the manuscript for details on references.

Analysis on dams and their effect were included in the quality control, scrutinizing through a visual hydrograph inspection potential disturbed hydrographs. No substantial differences were found between the basins retained for the analysis and the basins for which a certain degree of disturbance can be tolerated.

Comment 3: Fig. 2 is not fully clear or better an additional figure could be added showing the distribution of the time series length. Indeed, it is not clear if all the analysed series have the same length (from figure 2a it does not seem). Fig. 2b could be enriched by some statistics like the min and max contributing areas.

REPLY: *A series of new figures were added in the revised version of the manuscript which show the available years for the 3,913 gauged stations and the selected common study period i.e. 1950–2013 (Fig.1). We clarified the length of the analyzed series and we enriched the description of basin characteristics with area range, elevation and annual streamflow (see Tab. 1). Moreover, example of series with gaps (Fig. 3) and results of the homogeneity test with a detection of a discontinuity point in a streamflow daily series of data (Fig. 4) were included in the revised text.*

Comment 4: Are the times series autocorrelated? And how much? This could affect the trend results and tests.

REPLY: *Temporal autocorrelation was verified calculating lag-1 autocorrelation coefficient for each time series as proposed by Khaliq et al. (2009). Autocorrelation coefficients for each series are shown in the Fig. 5 plot, together with their upper and lower 95% confidence bounds (y-axis: lag-1 autocorrelation coefficient; x-axis: series ID). All series of data are not significantly autocorrelated, therefore they were considered suitable for trend identification.*

Comment 5: The definition of Mediterranean is confusing, for sure it is an "official" characterization, however looking the figure 1 I see around 300-400 points that can be considered as affected by Mediterranean climate. For instance, all the basins located in the Alps at high altitude can be considered as Mediterranean? As well as all the basin around Portugal?

REPLY: *Concerning the subdivision of the European continent in Mediterranean, Boreal, Continental and Atlantic macro-areas, we used the classification provided by Gudmundsson et al. (2017) which is the same reported by official data of the EU Environmental Agency, such as Natura 2000 biogeographical regions (https://ec.europa.eu/environment/nature/natura2000/platform/knowledge_base/103_browse_categories_en.htm). This classification consistent with the map of biogeographical regions of Europe reported also in Fernandez-Carrillo, A. et al. (2019). In this classification, the Alps and large parts of Portugal and Spain are included in the Mediterranean region. In the revised version of the manuscript we included additional references concerning our geographical subdivision of the European territory.*

Comment 6: The comparison with Rainfall and Temperature should be better described. Which is the time series length used in the rainfall and temperature analysis? Is it correct to compare trends of data set with different length?

REPLY: *In the revised version of the manuscript, we preferred to refer the reader to E-Obs website to have more information about rainfall and temperature series. Nevertheless, we added specific sentences that clarify that rainfall and temperature data are consistent (i.e., for the same period) with our streamflow series and they can be compared (see par. 3.1).*

Reviewer #2

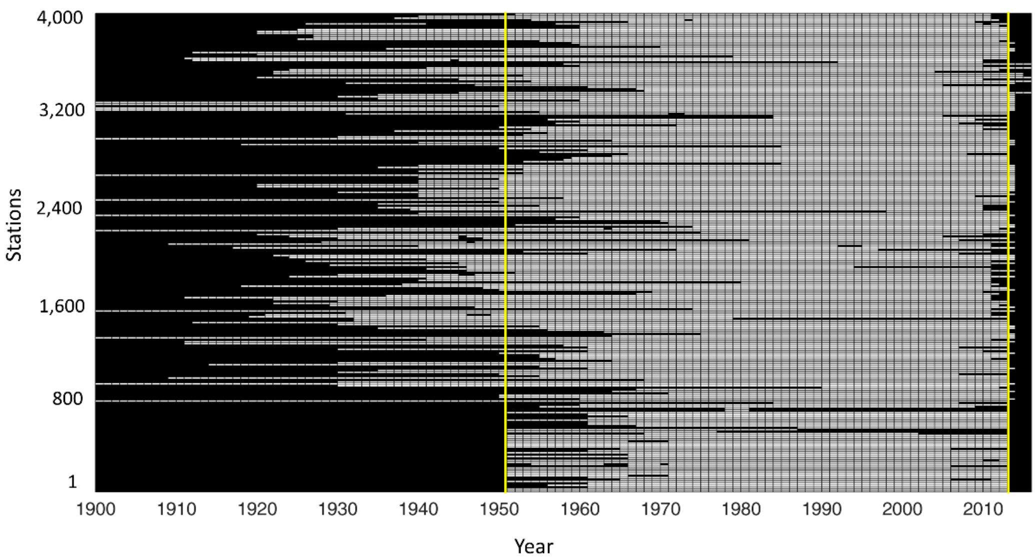
The study analyses trends in annual streamflow over the period 1950-2015 in Europe. This is a relevant topic certainly within the scope of HESS. The study generally applies standard methods for trend analysis (Theil-Sen slope, Mann-Kendall test). The spatial patterns of the trends are compared to spatial patterns of air temperature and precipitation. The study extends previous work on observed streamflow trends in Europe by including a higher number of catchments, particularly in Portugal, Spain, France and Italy. This was possible through assembling the database of streamflow records from various sources. The results largely confirm previous studies with dominant positive trends in northern Europe and dominant negative trends in the Mediterranean region.

REPLY: *We thank Rev#2 for her/his comments and suggestions which allowed to improve the quality of the manuscript in this revised version.*

Main comments:

1) Since the study states that records with missing data for more than two years were excluded from the database (L 107), I initially assumed that the calculated trends all relate to the period 1950-2015, which, looking at Fig. 2a, is apparently not the case.

REPLY: *Fig.2a was deleted because it created misunderstanding both in Rev#1 and #2. The original dataset included 3913 stations and after the checks on reliability, consistency and uniformity of series of data, 428 stations were discarded. The 63-year study period (from 1950 to 2013) has been chosen as the optimal threshold between maximizing series length and avoiding missing data, as shown in the following plot.*



This has of course a strong influence on the results and needs to be clarified. If the series length vary between catchments it will probably be more useful to analyze trends for different periods with nearly complete records, as the trends of course depend on the period analyzed (as discussed in the introduction).

REPLY: *We agree with the Rev#2 about the influence of length of series of data on trend identification. Dixon et al. 2006 coped with this problem by splitting the dataset in time frames of different length, with a different number of stations for each period (see also Birsan et al. 2005). Nevertheless, one of the added values of our work was to consider a continuous dataset as large as possible over the entire study domain in order to evaluate spatial trends over European basins with a consistent sample size. It was the same approach proposed in the recent work by Durocher et al. (2019) where stations with missing data were discarded and a single time frame for all study domain was considered.*

2) The criteria for inclusion/exclusion from the database should be described very clearly. It is not so clear whether the study aimed at only including near natural catchments. How were gaps smaller than 2 years treated? The steps that were undertaken to exclude inhomogeneous series, or series strongly affected by human interventions need to be mentioned clearly. For example, did the authors try to get information from the data providers on human interventions such as changes in flow abstractions etc.
It should be described clearly how the database was 'consolidated and validated'. Did you apply any automatic screening tests to systematically check the series for possible inhomogeneities?

REPLY: *We thank the reviewer for raising this issue. In the revised manuscript we have added details about the pre-processing activity done to select the discharge time series used for the analysis. In particular, to ensure quality of discharge observations, the following steps were followed: 1) check on data availability; 2) check for outliers (i.e. five st.dev. higher or lower than the means; 3) check on the presence of inhomogeneities through automatic screening tests.*
In order to filter out catchments affected by human disturbance, each discharge time series was accurately scrutinized through visual hydrograph inspection to identify disturbed hydrographs due to e.g. the presence of dams/reservoirs. Discharge time series characterized by disturbed hydrographs were discarded from the analysis. It should be noted that most of the basins considered in the analysis are taken from the EWA database, i.e. a discharge data collection of near-natural streamflow records from small catchments (Stahl et al, 2010).
Moreover, the Global Reservoir and Dam (GRanD, https://sedac.ciesin.columbia.edu/data/set/grand-v1-dams-rev01) has been used to identify if (how many) dams/reservoirs are actually present in the selected basins. At the end of this analysis we expect that no substantial differences will be found between the basins retained for the analysis and the basins for which a certain degree of disturbance can be tolerated.
Only stations with low human impact (no presence of dams/reservoir in the analysis period or no appreciable dam impact in the hydrograph); with less than 20% of missing data, showing no inhomogeneities in the time series were retained in the compiled dataset. Gaps smaller than two years were retained as missing data; during trend calculations, missing data were discarded on a case-by-case basis.

3) Some results are not very clear. The results section reports significant trends in 95% of the stations, which disagrees with results reported in Table 1. In the results section, it is not always clear whether results on trends also include non-significant trends.

REPLY: *The number of basins reported in tab 1 (tab. 2 in the revised version of the manuscript) were incorrectly transcribed by the authors. They referred to the total number of stations in each macro-region (i.e. 3,485). In the table only significant positive or negative trends are shown. These were 95% of total gauged stations (i.e. 3310 stations). In the revised manuscript, the number of stations in each macro-region has been corrected. The manuscript will also clearly state whether any summary result includes non-significant trends.*

4) I disagree with the finding of an inversion point in 1985 for the average series in the Mediterranean region. I do not see a change in the trend direction or trend slope in 1985. The fact that streamflow is above average before and below average after 1985 is a rather arbitrary result that depends on the selected study period. Streamflow has been decreasing since about 1965, and if anything, the rate of decrease has rather slowed down since the late 1980s.

REPLY: *The reviewer is right. Figure 7 in the manuscript highlights that streamflow has been decreasing since about 1965 and the rate of decrease has rather slowed down since the late 1980s. In the revised manuscript the sentences related to Figure 7 has been modified accordingly and supported by new statistical trend analyses on the entire time period.*
"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."

5) The calculation of the Sen's slope from annual streamflow anomalies is described as innovative, but if I do not overlook something this should not affect trends (and has probably been done in many studies).

REPLY: *By using anomalies to detect trends the absolute random error is minimized (Pandžić and Trninić, 1992), but the reviewer is right in that it does not affect the trend (i.e., regression slope against time). Also, it is routinely carried out in both hydrologic and climatologic research. The methods section has been amended accordingly.*

6) The introduction should be improved. The introduction should clearly convey what has been found previously on annual streamflow trends in Europe? What is the gap in the current literature? How is this approached by this study? Please also check the logic of individual sentences and the subdivision of the introduction into paragraphs.

REPLY: *We thank the reviewer for this suggestion also underlined in the short comment by Adriaan Teuling. In the revised version of the manuscript, the introduction includes a more complete summary of what has been found by recent studies on annual streamflow trends in Europe, what is missing in the current literature and in which way this study will fill the gap. The revised introduction also relies on a more logical paragraphing.*

6) The explanation of streamflow trends by trends in air temperature and precipitation remains a bit vague and overlooks areas where it is probably not possible to explain streamflow trends with trends in air temperature or precipitation (such as positive streamflow trends in northern Spain). Some arguments need to be clarified e.g. it is not clear to me how groundwater or snowmelt effects would affect annual (and not only seasonal or monthly) streamflow.

REPLY: *The discussion on groundwater and snowmelt roles has been improved, also specifying that it will rely on speculation and literature and not direct measure or testing of such variables. The cases in which the observed discrepancies between river discharge and weather series could be explained by based on logical and science-supported hypotheses using likely drivers, will be highlighted with their most relevant examples (eg Northern Spain).*

Detailed comments

P1, L28-30: The logic of the sentence is not clear. There is no contrast between a lot of research and not finding uniform streamflow trends in Europe. When mentioning a lot of research that aimed at investigating streamflow trends in Europe, this should be backed up by some references and their main findings (e.g. Stahl et al., 2010, Stahl et al., 2012).

REPLY: *The introduction, and in particular the review of past studies and their findings, has been deeply improved in the revised version of the manuscript. References has been added, including those suggested by the reviewer.*

P2, L33-34: Did these studies also analyze changes in annual streamflow volume? What were the main findings? How did seasonal streamflow change?

REPLY: *As for the previous comment, the review of past studies and their findings has been deeply improved in the revised version of the manuscript.*

P2 L40-47: The section on potential drivers of the streamflow trends remains a bit vague. Are changes in river cross-sections or boat tourism relevant for annual streamflow volumes?

REPLY: *Yes, if the shape of the river section is altered, or if flow itself is altered with recreational basin or locks for navigation. These sentences will be however moved to the Discussions to streamline the logical flow of the introduction. A missing refence to Vag et al. will be added in the Bibliography.*

P4, L97: I would suggest to first clearly list the criteria for selecting catchments and then mention the final number of selected catchments at the end.

REPLY: *The methods has bene amended accordingly – filtering criteria has been described in the methods, while the resulting number of catchments retained for analysis are reported in the Results.*

P4, L101-102: You may use this in the introduction in order to emphasize your contribution in comparison to previous studies.

REPLY: *Suggestion accepted, the sentence will be integrated in the introduction*

P4, L103-109: The description of the criteria for inclusion/exclusion from the database should be very clear. It is not very clear whether you aimed at including only near natural catchments. Did you check information from the data providers on human interventions such as changes in flow abstractions etc. (that would directly influence the trends)? Your database contains _3900 series of 65-years data. It is a lot of work to visually scan daily data of all these series. Could you provide some detail on how this was achieved? Did you apply any automatic screening tests? How were inhomogeneities identified?

REPLY: *Accepted - see reply to R2 comment 2 above.*

P5, L123ff: Why would it make any difference in terms of trend slope whether you calculate it on the original data or on the anomalies?

REPLY: *Accepted - see reply to R2 comment 5 above.*

P5, L128: Delete "To homogenize the annual streamflow series", since dividing by catchment area cannot homogenize a time series.

REPLY: *Deleted*

P5, L132ff: Have you checked the streamflow series for autocorrelation? How did you deal with series that contain significant autocorrelation?

REPLY: *The streamflow series of data were checked with lag-1 autocorrelation coefficient as proposed by Khaliq et al. (2009). The autocorrelation levels are reported in the picture in response to comment 4 of Rev#1. No series was significantly autocorrelated.*

P6, L138: Since the streamflow volumes were divided by area, runoff depths would be more appropriate (instead of streamflow volume), no? (adjust throughout the paper)

REPLY: *Suggestion rejected – the reviewer is right, but streamflow volume is a widespread measure which is readily understandable by managers and citizens. We decided to keep it that way.*

P6, L145 and 146: This seems not correct, Table 1 shows positive trends in 7% and negative trends in 5% of the catchments?

REPLY: *The overall figures were corrected – 52% of positive trends and 48%, consistent with Table 2.*

P6 Fig. 3: These figures are not necessary in my opinion.

REPLY: *The figure has been left in the revised manuscript just as an example of trend calculation.*

P6, L151: The unit of annual streamflow per area is length/time (e.g. $m^3/(km^2$ year), or mm y^{-1}). Therefore the change in runoff over a certain period is length/$time^2$ (e.g. $m^3/(km^2$ $year^2)$).

REPLY: *Accepted – the values and units will be updated to reflect yearly change expressed in m3/(km2 year2).*

P7, L170; legend and caption of Fig. 5: replace rainfall by precipitation (assuming that snow is included).

REPLY: *Snow is included. Suggestion accepted.*

P7, Fig. 4: Please add trend significance to the figure, e.g. different symbols for significant/insignificant trends.

REPLY: *Accepted – the figure will be amended using two set of symbols for significant/insignificant trends (p <0.05).*

P7, Fig. 4: I assume that the former Yugoslavian countries should also be part of the Mediterranean region?

REPLY: *There was a mistake in the background graphics – the figure will be amended by adding former Yugoslavian countries*

P9, L175-177: Please add time periods, are you discussing observed or future projected air temperature changes ("expected to increase" points to future changes)?

REPLY: *We are discussing future climate scenarios. The sentence has been clarified by adding time periods (e.g. "in 2020-2050")*

P9, L177ff.: Please explain why earlier snowmelt would result in increased annual streamflow. This is not so straightforward and there are studies pointing to the opposite (e.g. Berghuijs et al., 2014).

REPLY: *The study cited by the reviewer states that "A precipitation shift from snow towards rain leads to a decrease in streamflow", which is not the point being made here. The role of snowmelt in altering streamflow has been better explained and supported by additional references*

P9, L182: Replace rainfall by precipitation.

REPLY: *Accepted and edited throughout the manuscript.*

P9, L184/185: There are large agreements between the changes in runoff and precipitation/ air temperature. However, I do not agree that streamflow changes are "perfectly congruent" with the patterns of changes in air temperature and precipitation. For example, despite increases in air temperature and decreases in precipitation, streamflow has increased in northern Spain.

REPLY: *See reply to R2 comment 7 above. The tone of this conclusion has been de-emphasized.*

P9, L186-195: The discussion is not very clear. Please explain how groundwater or snowmelt effects would affect annual (and not only seasonal or monthly) streamflow. Furthermore, I would suggest keeping the different factors that may explain mixed positive and negative trends apart. For example, glacier melt processes are unlikely to be relevant in Northern Germany.

REPLY: *See reply to R2 comment 7 above. Positive and negative effects has been better distinguished.*

P10, Fig. 6, lower panel: Better only show significant trends. Also, better show percentage of positive/negative trends and add the number of stations, e.g. to the labels for each bar.

REPLY: *Accepted – the figure will be amended accordingly.*

P10, L213: Looking at the 1950-2015 series, streamflow is above average 1955-1985 and below average 1985-2015. However, I do not see any particular change point in 1985. Streamflow has been decreasing since about 1965, and if anything, the rate of decrease has rather slowed down since the late 1980s.

REPLY: *See reply to R2 comment 4 above.*

Additional references

Berghuijs, W. R., R. A. Woods, and M. Hrachowitz. "A precipitation shift from snow towards rain leads to a decrease in streamflow." Nature Climate Change 4.7 (2014): 583-586.

Birsan, M. V., Molnar, P., Burlando, P., & Pfaundler, M. (2005). Streamflow trends in Switzerland. Journal of hydrology, 314(1-4), 312-329.

Dixon, H., Lawler, D. M., Shamseldin, A. Y., & Webster, P. (2006). The effect of record length on the analysis of river flow trends in Wales and central England. IAHS-AISH publication, 490-495.

Durocher, M., Requena, A. I., Burn, D. H., & Pellerin, J. (2019). Analysis of trends in annual streamflow to the Arctic Ocean. Hydrological processes, 33(7), 1143-1151.

Stahl, Kerstin, et al. (2012). Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. Hydrology and Earth System Sciences 16.7: 2035-2047.

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. Hydrol. Earth Syst. Sci., 14, 2367–2382

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

ha eliminato: 65

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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 $m^3/(km^2$ year)) and a generally positive trend in northern ones (about 0.5 10^3 $m^3/(km^2$ 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.

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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 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 selection and processes

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

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

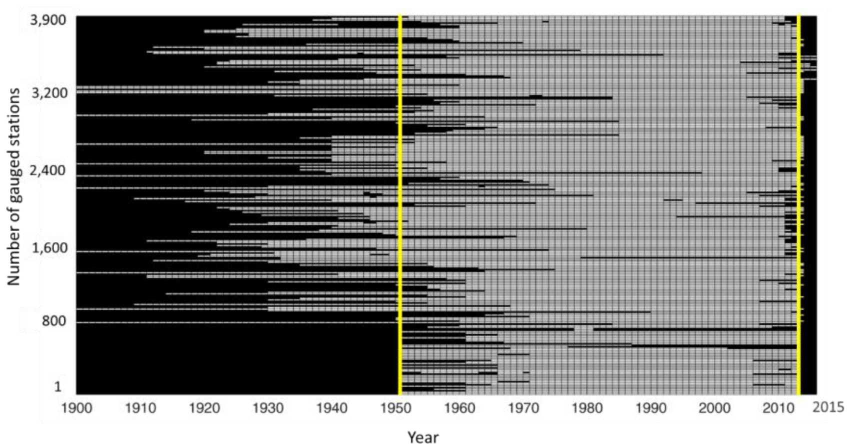

Fig. 1. Available years for the 3,913 gauged stations. Vertical lines in yellow indicate the selected common study period 1950–2013.

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.

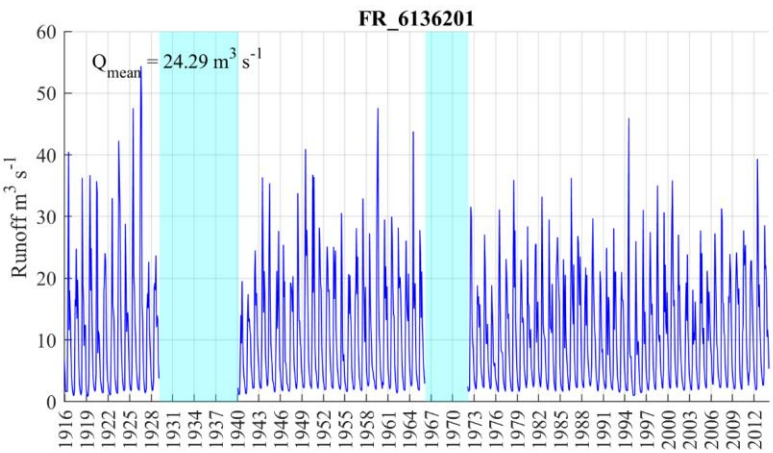

Fig. 2. Example of a series with gaps.

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.

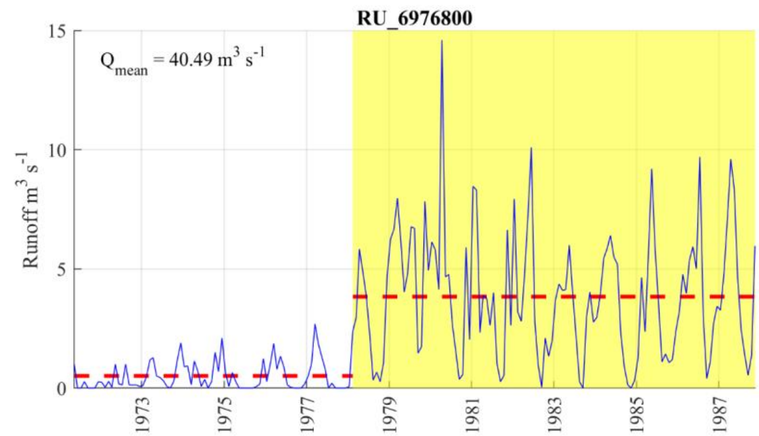

Fig. 3. Example of the results of the homogeneity test with a detection of a discontinuity point in a streamflow daily series of data.

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 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).

ha eliminato: 1 on physical European map. The selected gaug 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 tim series over the Mediterranean basin for which a dedicated effort carried out in this study to fill the gap existing in previous studie 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 b the analysis because human disturbance is unavoidable at this sca (Piniewski et al. 2018). Nevertheless, about 90% of stations belon to catchments with size less than 1,000 km2 as shown in Fig. 2b. Daily hydrographs for all gauges were inspected to identify dubio patterns, all records were screened visually and those with visible inhomogeneity, problems in low flow range, or missing values fo long period of time (> 2 year) were excluded (Kundzewicz et al. 2005). Despite potential levels of human-induced alterations of ri flow regime could be still present in time-series data, a certain de of disturbance can be tolerated (Murphy et al. 2013). For this reas high flow conditions were not investigated and we focused the analysis on annual streamflow volumes.

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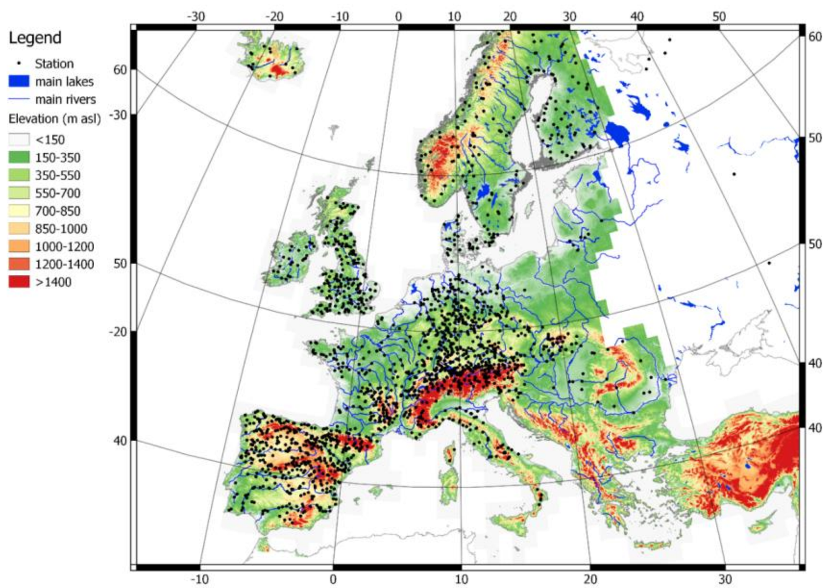

Fig. 4. Map of European study area. Digital Elevation Model (DEM), main rivers and lakes as well as position of gauging stations are presented.

Tab. 1. Overall characteristics of examined basins.

Area range (km^2)	Percentage of basins (%)	Elevation of basin centroid (m asl)	Annual streamflow volume (Mln m^3)
		Maximum – Minimum (Mean)	Maximum – Minimum (Mean)

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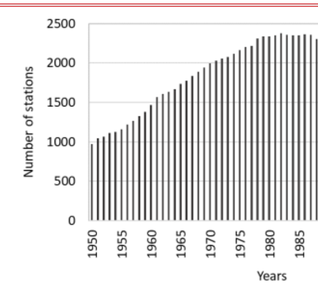

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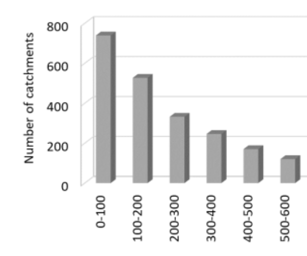

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0-100	30	2900 - 2 (677)	247.40 – 40.81 (112.78)
100-200	21	2700 - 19 (510)	241.85 – 44.15 (139.03)
200-300	13	2170 – 30 (320)	306.06 - 52.82 (154.01)
300-400	10	2200 – 11 (621)	338.43 – 68.38 (188.40)
400-500	7	1980 – 10 (321)	431.28 – 80.36 (246.83)
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)

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

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(1995) and von Storch (1995). All autocorrelation coefficients were found included in the confidence bounds, as shown in Fig. 5, and, therefore, they can be considered ready for the trend identification.

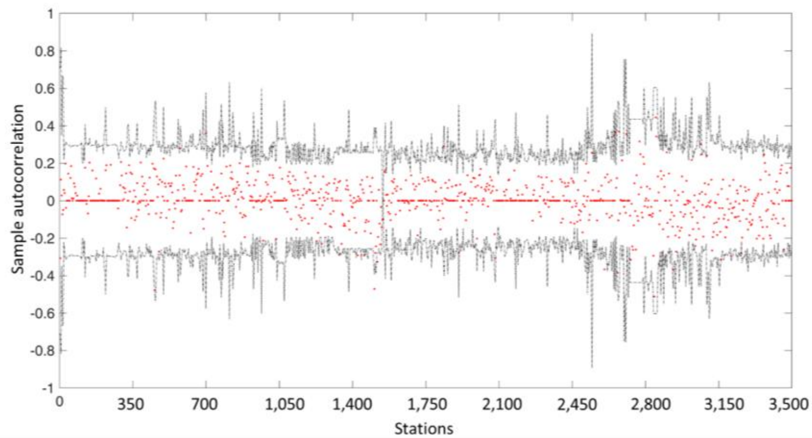

Fig.5. Samples autocorrelations. Red points are the value of lag-1 autocorrelation coefficient, whereas black dotted lines represent the 95% confidence bounds.

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 (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 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

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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.

a b

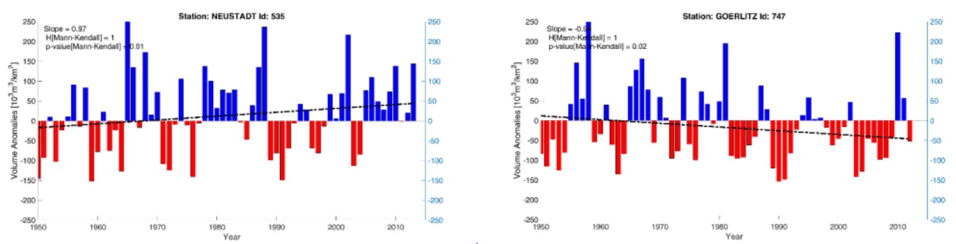

Fig. 6. Anomalies in annual streamflow volumes for the station of Neustadt (a) and Goerlitz (b). In the graphs, the slope of the Theil-Sens's line, H and p-value of the Mann Kendall test are also reported.

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 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.

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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.

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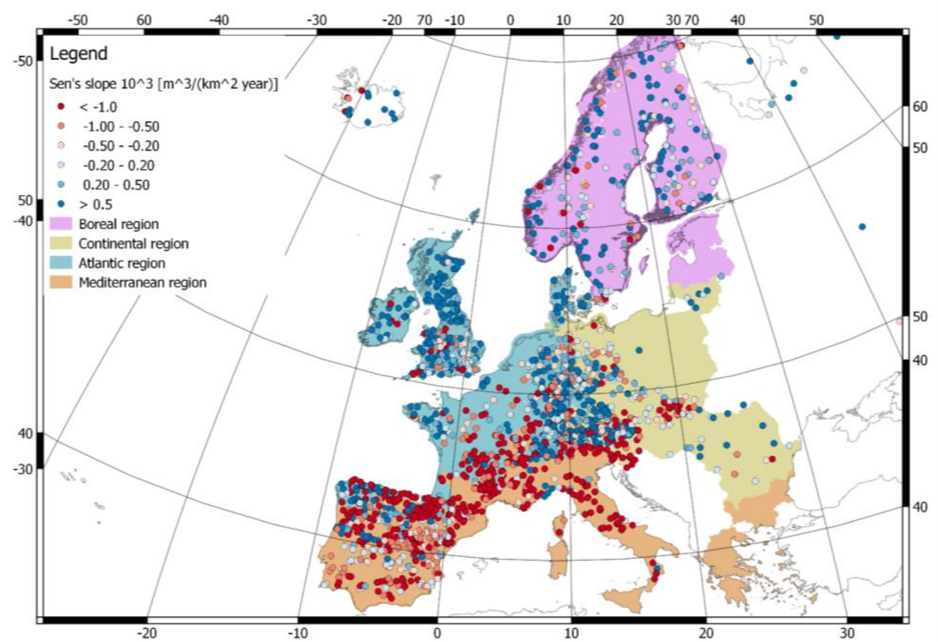

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Fig. 7. Annual trend of streamflow volume anomalies in European continent subdivided in Boreal, Continental, Atlantic and Mediterranean regions. Only significant trend are shown.

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

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Region	Number of stations	Positive trend	Negative trend
Boreal	323	95	5

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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).

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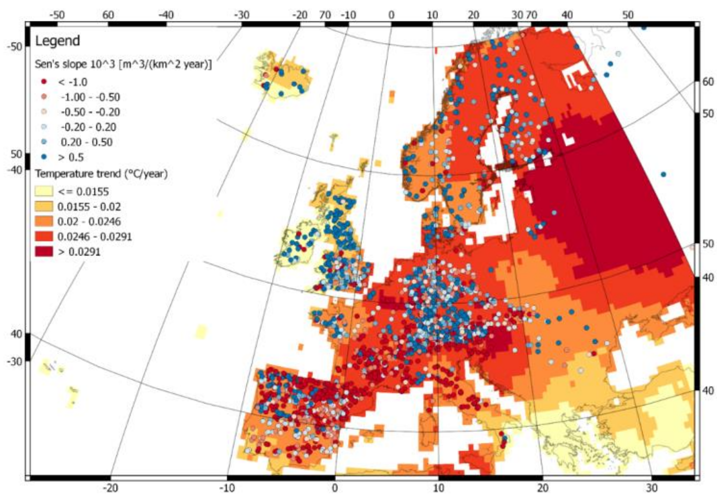

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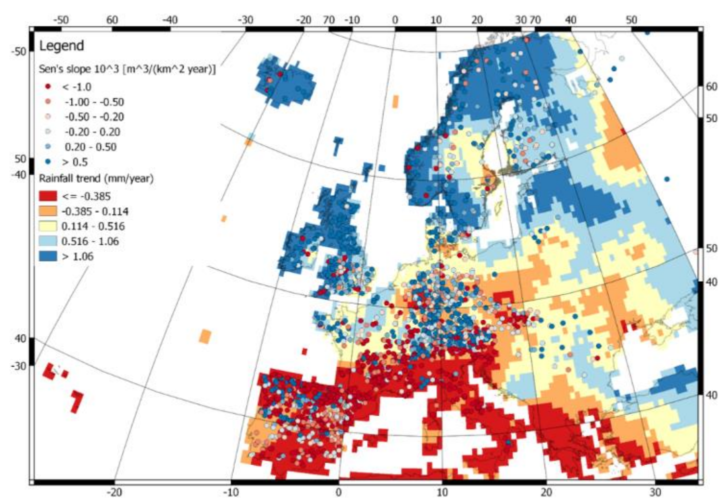

Fig. 8. Comparison between annual streamflow volume trends and daily mean temperature (a) and rainfall (b) trends over the European continent. Only significant trend are shown.

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

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

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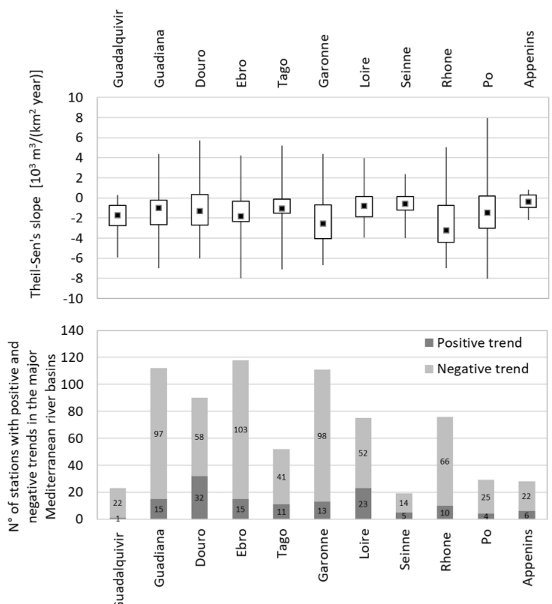

Fig. 9. Number of stations with positive and negative annual streamflow volume trends in the main Mediterranean river basins. Box plot of the Theil-Sen's slope for each catchment is also reported.

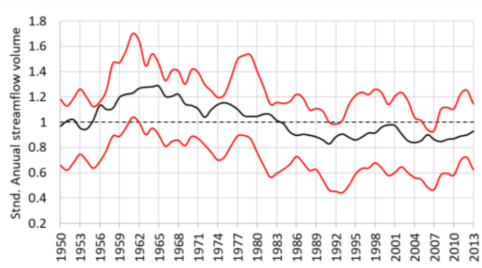

Fig. 10. Standardized annual streamflow volume pattern from 1950 to 2013. Black line shows the simple rolling average of the standardized annual streamflow volume behavior over the entire Mediterranean area. Red lines show the 25th and 75th percentiles of the standardized annual streamflow volume series.

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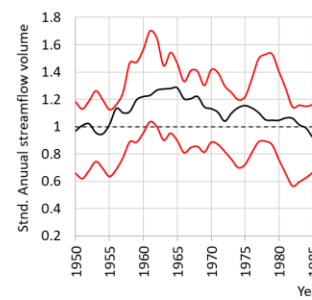

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4 Conclusions

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 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 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, 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.

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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.

Acknowledgement

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