Dear Prof. Laurent Pfister,

We thank the editor and two referees for their assessment of our manuscript. Please find our detailed responses below. We performed textual edits to the entire paper to increase readability and sharpen the text. We believe we have addressed all points raised by the reviewers carefully and modified the manuscript accordingly.

Kind regards,
Gregor Laaha

Response to the comment of Anonymous Referee # 1

We would like to thank the reviewer for his kind assessment of the manuscript. Below is our response to the issues raised in the review. The original comment is printed in plain font, our response is printed in italics.

General:
The paper is well written; it is highly descriptive and provides relevant facts on impacts of droughts in different countries for the year 2015. However for the reader it would have been easier to if the different aspects of droughts would have been summarized in a table for the different countries. One aspect however is missing when talking about droughts for a year. It is very important to provide information about the meteorological conditions of the previous year, especially if you look at the status of the aquifers.

We thank the referee for this excellent evaluation.
We added an Appendix where we provide tables summarizing the different aspects of drought by country, for all stations (Table A1) and stratified into stations with predominant summer low flow regime (Table A2) and stations with a predominant winter low flow regime. We further agree that it is relevant to provide information about the meteorological conditions preceding the event. Preconditions were summarized by SPI indices of various aggregation scales (6, 9 and 12 month), and these characteristics were integrated in the analyses. We further assessed to what degree these indices are correlated with low flow magnitude, and how these correlations compare to the correlations of the relative onset index.

Conclusions:
A European network experts on water scarcity and droughts produced a report in 2007 on drought management plans as part of the Common Implementation Strategy of the Water Framework Directive, which was endorsed by the member States in November 2007. The report sets out recommendations in preparing drought management plans. Examples are shown for some Member States. The authors could have explored in the first place the status of the implementation in the Member States instead of referring to the example given by GWP and WMO.

We appreciate the reminder and refer to the report and the need for a range of hydrological flow indices in introduction and discussion. The status of RBMP implementation appears not directly relevant to this study's objective of understanding the physical hydrological aspects of extent and propagation of the hydrological drought, but we agree that the report helps to highlight the need and potential benefits of common indices.

Reference:
Water Scarcity and Droughts Expert Network: Drought Management Plan Report - Including Agricultural, Drought Indicators and Climate Change Aspects. [online] Available from: http://ec.europa.eu/environment/water/quantity/pdf/dmp_report.pdf (Accessed 30 November 2016), 2007.

Response to the comment of Anonymous Referee # 2

We would like to thank the reviewer for his detailed assessment of the manuscript. Below is our response to the issues raised in the review. The original comment is printed in plain font, our response is printed in italics.

The manuscript describes the 2015 streamflow drought event relative to the 2003 event based on observed low flow conditions derived over a set of stations. Results are compared also with the corresponding 2015 meteorological drought event analysed in detail in a companion work. I find that the analysis presented provides limited advances for a better understanding of hydrological drought processes and many parts of the manuscript are too qualitative and descriptive.

The question of advanced understanding based on descriptive statistics and analysis is certainly an important one to assess the significance and potential impact of a study such as ours. We would like to argue that the analysis presented does indeed add to a better understanding of the characteristics of hydrological drought at the large cross-country scale in Europe. The scope of the work was to study a major hydrological event on the European scale soon after its occurrence. Unlike climatological information, the timely observational-based analysis of a hydrological event at a pan-European scale (across country boundaries) has not previously been undertaken due to the lack of hydrological data. Streamflow data are commonly only available in national databases in near-real time and updated large-scale databases would have a significant lag in the order of years between each update. The study thus presents a unique community effort and opportunity to capitalize on our common knowledge and enhanced local detailed information. We have explicitly chosen an approach based on extreme value statistics and seasonality indices, which allows us to interpret processes from spatio-temporal patterns directly, with a minimum number of modeling steps and assumptions. Interpreting patterns of indices and process indicators is often regarded to be superior to classification techniques and modeling because of the minimum number of assumptions made (Grayson and Blöschl, 2001; Laaha and Bloschl, 2006). In the revision, we further highlighted the added value of our work using additional quantitative analysis (specified in our detailed responses below).

My major concerns are:

– The influence of antecedent moisture conditions on drought developments is interesting and novel aspect, maybe the most relevant in the work. However it is analysed only on two stations. I suggest the authors to extent this investigation on the whole set of data to derive their conclusions in a more robust manner and spatially over the domain. The use of cluster analysis (or similar more objective techniques) to group stations with similar hydro-meteorological response may be an option. More details on the characteristics of antecedent moisture conditions, for instance timing and magnitude of antecedent precipitation that may reduce the probability of subsequent extreme drought events, would be relevant as well in view of an enhanced predictability and monitoring of low flow conditions.

The regional perspective is indeed important, hence it was also analyzed and discussed in our paper. An inductive approach has been chosen which infers the significance of the timing of low flow events from antecedent catchment conditions from single example catchments. Seasonality maps (Figure 6) of the relative timing of events were employed to analyze the regional perspective and to generalize the finding to the Pan-European scale. From pattern similarity between onset and severity of the low flow event, we deduced that the seasonality of the onset, being an indicator of antecedent conditions, is clearly related to drought severity at the regional scale.

To underpin the general relevance of our finding, and in accordance with the referee comment, we conducted an additional functional cluster analysis to generalize the local fingerprints provided by the hydrographs of two catchments at the European scale. The results are presented in new Section 4.5 which includes two new figures (Fig. 6 and 7).

We agree that more details on the characteristics of antecedent moisture conditions, for instance timing and magnitude of antecedent precipitation that may reduce the probability of subsequent extreme drought events, would be relevant and provide a view of an enhanced predictability and monitoring of low flow conditions. We therefore extended the analysis by including standardized precipitation indices (different aggregation intervals were tested) that summarize antecedent conditions based on meteorological measurements (ref. reply to Reviewer#1). The analyses include maps of January-SPI6, which we consider notably relevant for characterizing preconditions of the studied events (new Fig. 8). Hereby, the scope of former Section 4.5 on the "Effect of seasonality" was extended, and the title was changed to "Effect of preconditions" (now section 4.6). We also conducted a correlation analysis to assess the relative information content of the various indices of antecedent conditions (SPIs and relative onset of hydrological drought) for predicting summer low flow conditions. Note that soil moisture measurements were not available to undertake similar analysis.

– Section 5.2 is too descriptive and qualitative, and it does not add relevant new knowledge. Furthermore, it suffers of a poor methodological approach. There have been developed automated research algorithms to collect events and information from web and media in a systematic manner. I suggest the authors to implement such methods or to remove completely this section.

We wish there were automated methods, but they do not exist. The US Drought impact reporter and the European drought impact report inventory (EDII) differ in the way they collect data, but each entry is moderated, i.e. manually checked and coded into the system and manually transcribed as it is not legally possible otherwise to store the data. The JRC media monitor is only a real-time tool, which provides many false hits and so far has not been used in any quantitative analyses due to these difficulties. In reality, this process is not at all automated and data for 2015 does not yet exist as a consolidated dataset.
We agree that the section content deviates much from the main approach of our study, hence we removed Section 5.2, considerably shortened the discussion of impacts and integrated some of the text with Section 5.4 (now reordered to 5.3).

– Description of methods needs to be improved. In particular it is not specified what time series is used to derive fitting functions and return periods. I suppose the reference period, but this should be better clarified.

We clarified the issues raised and carefully reviewed and improved the method section.

In the comparison with meteorological droughts the following references may be relevant.
Bachmair et al., 2016 (http://onlinelibrary.wiley.com/doi/10.1002/wat2.1154/full)
Van Loon and Laaha, 2015
(http://www.sciencedirect.com/science/article/pii/S0022169414008543).
Barker et al., 2016 (http://www.hydrol-earth-syst-sci.net/20/2483/2016/),

These recently published studies were considered in the revision

Minor comments:

Page 1, line 29: please, consider to remove “in this second paper”
Sentence was rephrased.

Page 1, line 30: stream gauge stations instead of records?
We prefer to keep the term streamflow records as the second part of the sentence refers to records and not to stations.

Page 2, line 11: please, add the relevant references to support this sentence
Reference was added.

Page 2, line 16: “Droughts… to analyse”, too vague, consider to rephrase or remove.
Sentence was removed.

Page 2, line 19-20: This concept needs to be better expressed.
Sentence was rephrased to better express the concept.

Page 3, line 1: move the reference to the end of the sentence.
The sentence was rephrased and the reference moved.

Page 3, line 8: please do not abbreviate South, North, East and West throughout the manuscript. Such abbreviation is not a standard.
They are indeed contained in the list of common abbreviations in Oxford English Dictionary. We find the abbreviations useful to increase readability.

Page 5 lines 9-13: this information is not relevant for this work, consider removing it.
We shortened the description of the software packages.

Page 5, line 15: the 2013 is also compared to the 2003 event, this should be clarified.
Done.

Page 5 lines 20-25: I would suggest to synthesize this content and move to the next sections for a better organization of the text and to avoid redundancy. Are the low-flow indices calculated for the 2015, 2003 and reference period? Please, clarify.
We have clarified in Line 20: “A comprehensive characterisation of hydrological drought events, such as those of 2015 and 2003, requires a number of different indices ...

Page 6, line 18: how do you define “totally recovered”, please clarify.
We changed the sentence accordingly: “..., and two droughts are pooled if the catchment store has not totally recovered from the first drought when the second drought episode begins.”

Page 6, Section 3.2. Please clarify on what time series you estimate the fitting functions to derive return periods for reference period, 2015 and 2003. Why did you use such fitting functions instead of generalized extreme value or pareto distribution?
We have described the standard approach of low flow and drought frequency analysis. As this is standard in low flow hydrology, we don’t believe it necessary to elaborate. However, we have clarified the data used by extending the text of step (1): “Sample the annual extremes series AES” with “from daily discharge records of the reference period”. We also made minor changes to the remaining steps of the approach.

Page 7 line 21: contrasting response instead of dipole?

We changed the text accordingly.

Page 7, line 23: the patter discussed seems not including North-Austria. Maybe, because the graphical representation is not very clear in colours and symbols. I strongly suggest improving figures with maps by showing more contrasted colours.
The figure was carefully designed for the Pan-European scale, and hence can be difficult to read at a local scale. We did our best to increase the contrasts in the maps.

Page 7, line 26: the 2015 drought-affected area? Clarify
We clarified: "the area affected by the hydrological drought".

Page 8, line 10: Please, clarify.
We changed the wording: "…with the largest deficits occurring in S-Germany, west of the area with lowest flows…"

Page 9, line 3-4: Consider to remove winter plots from the graph, they do not add relevant information.
Although this group of stations is not of prime relevance for the paper we prefer to keep the winter boxplots, for the sake of completeness of the analysis.

Page 9, line 13: low flow threshold? I understood that you were looking at the minimum flows here. Please clarify.
Thanks, this is a typo and was corrected to "average annual low flow discharge".

Page 10 Section 4.5 please, rephrase without using bullet points.
Done.

Page 14 line 7: the extreme is most extreme… please rephrase.
The paragraph was entirely rephrased.

Page 14 line 25: add "streamflow" to drought.
Done (this is p14 line 31 in our original document).

Page 15, line 10-11. Is there any additional drought self-propagation mechanism linked to land atmosphere interactions that could contribute in explaining these processes? Dry soils may lead to lower probability of precipitation and thus cause intensified droughts. See for instance Senevitarne et al. 2010 (Earth-Science Reviews 99 (2010) 125–161).
This aspect was considered and a remark added to the paper.

Page 15 lines 20-33. This text is very speculative and not related to the work presented, please consider removing it.
Despite that the entire section was deleted, we carefully evaluated the paragraph and its relevance for the paper. Whilst perhaps not directly related to the specific analysis, the text is not speculative, and parts of the text were kept and integrated in the subsequent section.

References:

Grayson, R. and Blöschl, G., Eds.: Spatial patterns in catchment hydrology: observations and modelling, Cambridge University Press, Cambridge, U.K. ; New York., 2001.

Laaha, G. and Bloschl, G.: A comparison of low flow regionalisation methods–catchment grouping, J. Hydrol., 323(1–4), 193–214, 2006.

The European 2015 drought from a hydrological perspective

Gregor Laaha[1], Tobias Gauster[1], Lena M. Tallaksen[2], Jean-Philippe Vidal[3], Kerstin Stahl[4], Christel Prudhomme[5,6], Benedikt Heudorfer[4], Radek Vlnas[7,8], Monica Ionita[9], Henny A. J. Van Lanen[10]
Mary-Jeanne Adler[11], Laurie Caillouet[3], Claire Delus[12], Miriam Fendekova[13], Sebastien Gailliez[14], Jamie Hannaford[5], Daniel Kingston[15], Anne F. Van Loon[16], Luis Mediero[17], Marzena Osuch[18], Renata Romanowicz[18], Eric Sauquet[3], James H. Stagge[2], Wai K. Wong[19]

[1]Institute of Applied Statistics and Computing, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria
[2]Department of Geosciences, University of Oslo, Oslo, Norway
[3]Irstea, UR HHLY, Hydrology-Hydraulics Research Unit, Villeurbanne, 69100, France
[4]Hydrology, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany
[5]Centre for Ecology and Hydrology, Wallingford, UK
[6]Loughborough University, UK
[7]Czech University of Life Sciences Prague, Czech Republic
[8]T.G. Masaryk Water Research Institute, Prague, Czech Republic
[9]Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven Germany
[10]Hydrology and Quantitative Water Management Group, Wageningen University, Wageningen, the Netherlands
[11]National Institute of Hydrology and Water Management, Bucharest, Romania
[12]Université de Lorraine, Nancy, France
[13]Comenius University, Bratislava, Slovakia
[14]Service Public de Wallonie, Jambes, Belgium
[15]University of Otago, Dunedin, New Zealand
[16]University of Birmingham, UK
[17]Universidad Politécnica de Madrid, Spain
[18]Institute of Geophysics Polish Academy of Sciences, Warsaw, Poland
[19]Norwegian Water Resources and Energy Directorate, Oslo, Norway

Correspondence to: G. Laaha (gregor.laaha@boku.ac.at)

Abstract. In 2015 large parts of Europe were affected by ~~a~~ drought. ~~In two companion papers we summarize a collaborative initiative of members of UNESCO's EURO FRIEND-Water program to perform a timely pan-European assessment of the event.~~ In this ~~second~~ paper, we analyse the ~~event~~ hydrological footprint of the drought of 2015 ~~relative~~in terms of both severity (magnitude) and spatial extent and compare it to the ~~event~~extreme drought of 2003~~ based on streamflow observations.~~. Analyses are based on a range of low flow and hydrological drought indices derived for about 800 streamflow records across Europe~~ that were~~, collected in a community effort based on a common protocol. We compare the hydrological footprints of both events with the meteorological footprints~~ presented by Ionita et al. (2016),~~, in order to learn from similarities and differences of both perspectives and to draw conclusions for drought management. ~~Overall, the~~ The region affected by hydrological drought ~~of~~in 2015 ~~is characterised by a different spatial extent than~~differed somewhat from the drought of 2003~~.~~, with its centre located more towards eastern part of Europe. In terms of low flow magnitude, a region ~~around~~surrounding the Czech Republic was the most affected, with ~~annual~~summer low flows that exhibited return intervals of 100 years and more. In terms of deficit volumes, the geographical centre of the event was in ~~the area of Southern~~southern Germany, where the drought lasted particularly long. A detailed ~~assessment at various~~ spatial and temporal ~~scales~~assessment of the 2015 event showed that the ~~different~~particular behaviour in these regions was ~~also~~partly a result of diverging wetness preconditions in the studied catchments. Extreme droughts emerged where ~~antecedent conditions~~preconditions were particularly dry. In regions with wet preconditions, low flow events developed later, and were mostly less severe. ~~The space-time patterns~~For both the 2003 and 2015 events, the onset of the hydrological drought was well correlated with the lowest flow recorded during the event (low flow magnitude), pointing towards a potential for early-warning of the severity of streamflow drought. Time series of monthly ~~low flow characteristics show~~drought indices (both streamflow and climate based indices) showed that meteorological and hydrological events ~~spread differently across Europe, and they evolved~~developed differently in ~~regard to~~space and time, both in terms of extent and severity~~. The~~ (magnitude). These results underline that drought is a hazard that leaves different footprints on the various components of the water cycle, on different spatial and temporal scales. The ~~different~~ difference in the dynamic development of ~~major hydrometeorological characteristics, temperature~~ meteorological and ~~precipitation anomalies versus the streamflow magnitude, duration and deficit volume also determine differences in the impacts of~~ hydrological drought also implies that impacts on various water use sectors and ~~on~~ river ecology~~. For~~ cannot be informed by climate indices alone. Thus, an assessment of drought impacts on water resources~~, therefore,~~ requires hydrological data ~~is required~~ in addition to ~~the hydro-meteorological~~ drought indices~~. Additional~~ based solely on climate data. The transboundary scale of the event also suggests that additional efforts ~~with a pan-European dimension~~ need to be undertaken to make timely pan-European hydrological assessments more operational in the future.

1 Introduction

The summer of 2015 was hot and dry in many European countries~~: a meteorological situation similar to that of summer 2003 occurred.~~ when a meteorological situation similar to that of summer 2003 occurred (Van Lanen et al., 2016). The combined heatwave and drought of 2003 is now known as one of the most costly natural hazard events to ~~impact~~have impacted Europe (EurAqua, 2004; EC, 2007; EEA, 2010; EC, 2012; García-Herrera et al., 2010). A timely analysis of the ~~new~~recent event of 2015 ~~may add~~adds to the understanding of how summer droughts can develop in Europe, a prerequisite for improved drought management and policy making.

~~Droughts are complex phenomena and therefore difficult to analyse.~~ Droughts are rare events of temporary water deficit that propagate through the hydrological cycle (Tallaksen and Van Lanen, 2004; Van Loon, 2015) and affect its components on various spatial and temporal scales. Drought is also a natural hazard that affects a range of different water use sectors (Wilhite and Glantz, 1985; Gustard and Demuth, 2008; Stahl et al., 2016; Spinoni et al., 2016). ~~As such, every event is unique and needs a thorough analysis~~Because of the complex interaction of a range of atmospheric and terrestrial processes, detailed analyses of every event are crucial to improve the understanding of the phenomenon and ultimately, the predictability of future events.

For the event of 2015, some reviews of national and regional hydrometeorological agencies already exist~~,~~; these hint at its notable severity and transboundary occurrence. For example, the Swiss BAFU published a special report reviewing the drought conditions in Switzerland, and stated particularly severe low flow conditions in October 2015 in the Swiss Plateau and Jura regions (BAFU, 2015). Similar reports were released for two administrative regions of western France where the drought conditions were ~~mentioned~~characterised as generally moderate, even though at single locations warning levels were reached and water use restrictions came into force (l'ORE, 2015a, 2015b). ~~Severe low flow affected navigation on major European rivers, including the Rhine at the Dutch-German boundary (BfG, 2015, report of 11.11.2015)~~Severe low flow affected navigation on major European rivers, including the Rhine at the Dutch-German border (BfG, 2015) and parts of the Danube (Radio Romania International, 2015), but we could not find any official reports quantifying the severity of the low flow event ~~yet~~at the time. Because of a lack of observed pan-European near real-time hydrological data, a thorough analysis of the hydrological dimension of ~~the event~~events is

~~hardly possible today. As a consequence, often meteorological (and not hydrological) indices are used preferentially to describe the spatial-temporal characteristic of drought.~~generally challenging.

~~It is indeed~~As a consequence, only meteorological (and not hydrological) indices have so far been used to describe the spatial-temporal characteristic of the drought of 2015, providing important ~~to analyse~~knowledge about the droughts from a climactic perspective. In a companion paper to this study, the meteorological drought of 2015 was identified as one of the most severe droughts since the summer event of 2003, affecting a large portion of continental Europe (Ionita et al., 2016)~~ we show that the meteorological drought of 2015 affected a large portion of continental Europe and was one of the most severe droughts since the summer event of 2003. From a climatological perspective,~~. As reported by Ionita et al. (2016), the summer of 2003 was characterized by exceptionally high temperatures in many parts of central and eastern Europe, with daily maximum temperatures 2 – 3 °C warmer than the seasonal mean (1971 – 2000). ~~Atmospheric~~Meteorological indices such as the ~~standardized precipitation evaporation index~~Standardized Precipitation Evaporation Index (SPEI) ~~show~~showed a dipole-like structure with rainfall deficit and extreme droughts in the central and southern part of Europe and comparatively high amounts of rainfall over parts of the Scandinavian Peninsula and the British Isles. The event of 2015, on the other hand, first appeared in the early spring in S-France and the Iberian Peninsula~~ and shifted to~~, shifting toward central and eastern Europe~~.~~ as it developed. In August 2015, precipitation ~~events occurred~~lessened the drought over SW-Europe while meteorological drought conditions persisted in eastern Europe and, notably, in central Europe where the drought lasted the longest. ~~SPEI values as low as -4 were recorded, and the~~ The most extreme ~~values~~climatic water deficits (precipitation less potential evaporation) were found in southern Spain, parts of France and Germany, Belarus and western Ukraine. From a climatological point of view, the main factors controlling the occurrence and persistence of the 2015 drought event ~~are~~were extreme temperatures and lack of precipitation, in turn driven by blocking episodes influenced by anomalously cold (warm) sea surface temperatures in the central North Atlantic Ocean (Mediterranean Sea). ~~From the extremeness of atmospheric conditions, one would expect severe hydrological impacts as well.~~

Although hydrological drought is driven by anomalous atmospheric conditions, ~~many~~catchment hydrological processes may dampen or amplify the drought signal and thus, any negative drought-related impacts (e.g. restrictions to water-borne transport, degradation of aquatic ecosystems, water supply shortages, and energy production losses~~) are associated with hydrological processes that may dampen or amplify the effect of the dry weather.~~). Hydrologically-oriented drought studies have shown that drought in groundwater or streamflow can deviate considerably from meteorological drought ~~(Changnon, 1987; Peters et al., 2003; Vidal et al., 2010; Hannaford et al., 2011; Van Loon and Van Lanen, 2012; van Dijk et al., 2013).~~in terms of lagged occurrence (Changnon, 1987; Barker et al., 2016) and statistical characteristics (Peters et al., 2003; Vidal et al., 2010; Hannaford et al., 2011; Van Loon and Van Lanen, 2012; van Dijk et al., 2013; Tallaksen et al., 2009). These differences can be ascribed to regional and local factors such as the catchments' ability to store and release water during dry weather, reflected in the amount of water stored in the soil, groundwater, lakes and snow pack, and are therefore spatially variable as well (Haslinger et al., 2014). Moreover, water managers take actions in response to the predicted impacts (e.g. on abstractions and effluent discharges, water transfers and water storage) in which hydrology plays a key role (Van Lanen et al., 2016). As such, additional analyses are warranted to better characterise the hydrological dimension of the event and mitigate its impacts.

In this study, we analyse the European drought of 2015 from a hydrological perspective based on streamflow observations. Such an analysis is challenging for several reasons. First, and foremost, the analyses require up-to-date streamflow records across Europe. The pan-European perspective is crucial to study droughts as a number of processes are acting on a continental scale and require large-scale data sets. However, to date, no publicly available pan-European databases that include near real-time records exist. Secondly, drought is a spatio-temporal phenomenon. Hence, its dynamic development over space and time, which we herein refer to as the “footprint” of a drought (e.g. Herring et al., 2015; Heim, 2015), needs to be considered. Thirdly,~~ streamflow~~ drought needs to be analysed by a range of indices that characterise different aspects such as magnitude or duration of the event~~. These indices need to be made comparable across European regimes.~~, indices which need to be made comparable across European flow regimes (Water Scarcity and Droughts Expert Network, 2007). All these challenges need to be tackled in order to characterize the drought event in a manner that is relevant for a range of management purposes.

The paper stems from a collaborative ~~initiative~~effort of members of UNESCO’s EURO FRIEND-Water program (IHP-VIII, UNESCO, 2012). Our study focuses on low flow events, characterised by ~~recognised~~standard methods including annual minimum discharges and drought duration and deficit below ~~a constant~~an annual threshold (Gustard and Demuth, 2008). We analyse the dynamic development of the severity of the hydrological drought at different spatial and temporal scales and use seasonality indices to characterise the timing of key hydrological characteristics. The following research questions are addressed: (i) What is the hydrological footprint of the drought of 2015? (ii) How is it compared to the drought of 2003, ~~which is~~ often ~~perceived as~~considered a worst-case benchmark? (iii) How similar, or different, are the hydrological footprints of these events contrasted to the meteorological footprints? (iv)~~-~~ What ~~are~~may be the implications of ~~possible differences~~differing footprints for ~~drought impacts on environment, society~~environmental, societal and ~~economy~~economical drought management?

The paper is organised as follows. Section 2 describes the data collation strategy. In Section 3 we define the low flow and drought indices used in ~~this~~the study and present the assessment method. Section 4 presents results that characterise the event of 2015 ~~relative~~and compare it to the drought event of 2003 at different spatial and temporal scales, based on a range of discharge and seasonality indices. We first analyse the continental scale footprint of drought events from maps of annual low flow and drought indices, and then move to a regional scale in order to elaborate specifics of drought events in more detail. The spatio-temporal development is assessed from monthly maps of indices ~~on a monthly~~at the pan-European scale, before analysing the “local fingerprints” of the drought from daily hydrographs at the catchment scale. Functional clustering of hydrographs was employed to put these local regimes in the pan-European context. We finally ~~seek to~~ generalize our local process understanding using seasonality as an indicator of governing processes. Section 5 presents an in-depth discussion of the results~~. This includes~~, including a comparison of the hydrological footprint ~~sketched~~ from all analyses with the ~~atmospheric~~ meteorological footprint from the study~~ of the meteorological drought of 2015~~ by Ionita et al. (2016).

2 Data collation strategy

Severe droughts are characterised by a large spatial ~~scale~~extent and may cover larger parts of the European continent (EEA, 2010). Assessing the hydrological characteristics of droughts therefore requires streamflow data across Europe. ~~However, hydrological data are not freely available or can be hard to access in a number of European countries. There~~However, there are still major barriers in data exchange, which have hindered initiatives to build up international data archives and to perform urgently needed transboundary intercomparison studies (Hannah et al., 2011; Viglione et al., 2010). Existing data archives such as the FRIEND-Water European Water Archive (EWA, http://undine.bafg.de/servlet/is/7413) and the Global Runoff Dataset (http://www.bafg.de/GRDC) at the Global Runoff Data Centre (GRDC) are precious initiatives to make data accessible across Europe. But their content is still limited with respect to spatial coverage. Moreover, they are designed as data archives of the past rather than for monitoring ~~the~~in near real~~-~~-time~~ situation~~. Keeping the data up-to-date is challenging, and the fact that flow records are often officially released ~~not earlier than~~only 2 – 3 years after recording make these archives inappropriate for a timely assessment of extreme events.

For collecting ~~near-time data as they are required in this study a different strategy needs to be pursued. We have chosen a bottom-up data access strategy to collect ~~hydrological information from different European countries in near real-time a bottom-up strategy was pursued in this study. Instead of collecting streamflow records, we collect low flow indices for about 800 gauges across Europe, which were calculated by partners in the individual countries. It appears ~~to be ~~easier to do the data processing in the home country and to exchange only derived data (indices~~)~~), rather than the raw flow data. To ensure consistent derivation of the low flow and drought indices, we have compiled and distributed low flow software~~, which allows uniform calculation of indices across countries.~~. Our software is open-source and consists of two packages based on the widely~~-~~ used statistical software R.

The first package, termed lfstat (Koffler et al., 2016), provides a collection of state-of-the-art functions to compute a range of low flow characteristics ~~which~~that are fully described in the WMO manual on low flow estimation and prediction (Gustard and Demuth, 2008). The package has been recently extended to perform extreme value statistics of both~~,~~ low flow discharges and drought characteristics such as duration and deficit volume. The package uses a robust approach based on L-moments to fit extreme value distributions (Hosking and Wallis, 2005). It contains ~~methods~~approaches for pooling interrupted events (Hisdal et al., 2004) and for series containing zero values (Stedinger et al., 1993).

The second package, termed drought2015 (Gauster and Laaha, 2016), builds on lfstat and extends it to perform consistent multi-station analysis. ~~It is used to compute detailed low flow and drought reports on a country basis and at a pan-European scale. The package employs literate programing provided by the package knitr (http://cran.r-project.org), allowing us to execute and embed the results of R computations and graphics within a document. This enables the creation of~~The package employs literate programing enabling all partners to generate dynamic reports that are updated automatically if data or analyses change.

We use a common reference period 01 January 1976 – 31 December 2010 to calculate indices and statistics representing long-term average conditions. The year 2015 is then compared to the characteristics of the reference period~~.~~ and the year 2003. As the end of available records for the year 2015 differs across countries, a common termination date (31 October 2015) was chosen.

3 Methods

3.1 Low flow characteristics

A comprehensive characterisation of hydrological drought events~~ requires a number of different indices (Tallaksen and Van Lanen, 2004; Laaha et al., 2013; Smakhtin, 2001). First, the magnitude of low flow discharges~~, such as those of 2015 and 2003, requires a number of different indices (Tallaksen and Van Lanen, 2004; Laaha et al., 2013; Smakhtin, 2001; Salinas et al., 2013). First, the magnitude of the low flow discharge is important, which may be characterised by annual minimum flows or flow quantiles with high exceedance probability. Second, the timing of low ~~flows~~flow is important. It may be characterised by a monthly low flow index, such as the monthly 7-day minimum flow MM(7), or by a seasonality ~~indices~~index such as the day of occurrence of the annual minimum. Third, a characterisation of drought events when the flow is below a given threshold is important. These drought events may be characterised by their duration, deficit volume, or similar indices (Yevjevich, 1967; Hisdal et al., 2004). Each aspect may be seen as a temporal fingerprint or “signature” of the drought event (cf. Blöschl et al., 2013). From a water management perspective, these ~~aspects can~~characteristics may be associated with impacts on different water-related sectors. In this study, we ~~therefore~~ calculate ~~a~~the following range of different streamflow indices to characterise the various aspects of hydrological drought~~. The indices are defined as follows~~.

3.1.1 Annual minimum discharge AM(7)

The annual minimum n-day index, AM(n-day) represents the magnitude of the low flow event of a year. It is the annual minimum n-day average discharge, obtained by using a central n-day moving average. The moving average filter is applied to reduce short-term disturbances of the discharge record. Here we use a seven day moving average filtering, i.e. AM(7).

3.1.2 Drought duration (D) and deficit volume (V)

A streamflow drought event is defined as a dry-spell in the flow record when discharge is below some given threshold (Yevjevich, 1967). Depending on the purpose of the study different threshold concepts have been proposed. While seasonally varying thresholds (e.g. Hisdal et al., 2004; Van Loon and Laaha, 2015) enable a view on seasonal anomalies (we use them later to investigate the genesis of the low flow event and details are given in Section 4.4), our study focuses on low flow events to identify the largest absolute dry ~~states~~state of the system. Hence, we use a constant threshold, given by the Q_{80} low flow quantile [P($Q \geq Q_{80}$) = 0.8] computed for the entire reference period. The Q_{80} is used in many drought studies (e.g. Andreadis et al., 2005; Corzo Perez et al., 2011; Sheffield et al., 2009; Van Huijgevoort et al., 2014; Van Loon and Van Lanen, 2012).

During a drought event, minor precipitation events or disturbances may separate the drought event into several smaller events. As a remedy, pooling procedures have been recommended (Tallaksen and Van Lanen, 2004). In this study, the SPA (Sequent Peak Algorithm, e.g. Vogel and Stedinger, 1987; Tallaksen et al., 1997) is used. The SPA concept is based on depletion and recovery of the storage required to sustain the threshold discharge. An uninterrupted sequence of positive values of required storage defines a period with catchment storage depletion and a subsequent filling up~~.~~ ~~Based on this method~~, and two droughts are pooled if the catchment store has not totally recovered from the first drought when the second drought episode begins.

After the drought event series have been identified, the event with the ~~maximum~~largest volume per year is selected. This annual event is described by two characteristics: drought duration (D in days) and deficit volume (V in m^3). As these indices refer to the most severe event per year, they ~~present~~represent annual maximum series.

3.1.3 Seasonality

The timing or “seasonality” of the low flow event may be characterised by various indices, such as onset and termination of drought (Parry et al., 2016), date of annual ~~low flows (Laaha and Blöschl, 2006), and others. We use here the start date (τ) of the pooled~~minimum low flow (Laaha and Blöschl, 2006a, 2006b), and others. We use here the start date (τ) of the event as the most informative of the conditions leading up to the low flow event. The start date is expressed as day-of-year. To characterise the relative timing of ~~events~~an event, we compute the difference between the start date of ~~an~~the event relative to ~~the other, and~~another event, or relative to the average start date in the reference period. The relative timing (Δ_τ) is expressed in days.

3.2 Extreme value analysis

~~In this study we use~~The return ~~periods~~period of the low flow and drought characteristics ~~to analyse~~is used as a measure of their severity for a given event (here the 2003 and 2015 drought in Europe). The return periods are obtained by frequency analysis of extreme event series.

For each gauging station, the estimation of return periods is performed in the following steps:

(1) Sample the annual ~~extremes~~ extreme value series ~~AES.~~(AMS) from daily discharge records of the reference period. Note that low flow discharges, AM(7~~) present~~), represent annual minima series, whereas drought characteristics, *D*~~,~~ and *V* ~~present~~, represent annual maxima series.

(2) Fit the theoretical extreme value distribution ~~on AES~~to the AMS based on L-moments. For annual minima AM(7) we use the 3-parameter Weibull distribution~~;~~ and for annual maxima we use the General Extreme Value Distribution~~.~~ as recommended in Tallaksen and van Lanen (2004). Both series might contain zero values. In case of AM(7) series, zero flows may arise due to drying up of rivers; in case of drought characteristics (*D*,*V*~~,~~), zero values arise due to “no-drought” years, ~~when discharges were always above~~i.e. the discharge never goes below the threshold level. In both cases a conditional probability model (e.g. Stedinger et al., 1993) is employed that takes the proportion of zero values into account.

(3) Check model fit by visual inspection of extreme value plots.

(4) Calculate the ~~annual series of~~ return periods ~~representing~~of the ~~severity of~~ events.

The 2003 and 2015 events are compared using spatial plots of return periods for each low flow characteristic, and numerical and graphical summaries. The main focus is on the return period of ~~the annual 7-day minimum~~ AM(7), a measure of low flow magnitude ~~reflecting the peak of the drought~~, but duration and deficit volumes are also investigated.

3.2 Functional clustering

Hydrographs permit the analysis of the catchments’ response to the atmospheric drought signal and express “local fingerprints” of events (Section 4.4). To identify groups of catchments that show a similar hydrograph response to the drought signal, we apply a specific form of cluster analysis known as functional clustering, which is appropriate for time graphs (James and Sugar, 2003). Instead of considering measurements as multivariate observations, functional clustering accounts for their autocorrelation structure by considering the temporal dependency of observations. This is achieved by projecting hydrographs on a p-dimensional spline basis, equivalent to finding an adequate set of basis coefficients such that the shape of hydrographs is well represented. In our case, a four-dimensional B-spline basis was used for the approximation. Clustering is then performed on the basis coefficients rather than on multivariate observations, which has the benefit that temporal structures are conserved. Analyses are performed using the method fscm of R-package funcy (Yassouridis et al., 2016), which applies the functional mixed mixture model of Jiang and Serban (2012) to perform the clustering. The method returns a classification of hydrographs into groups of similar shape, together with an estimation of the mean hydrograph of each cluster centre.

4 Results

4.1 Continental scale footprint

Pan-European spatial patterns of low flow magnitude, AM(7~~)~~), characterised by return periods $T_{AM(7)}$ are presented for 2015 and 2003 (Fig. 1, left panels), showing different extent and severity. ~~While the~~The low flows in 2003 covered most of Europe, from central France to N-Poland and continuing towards southeast of the Alps, with the lowest flows ~~were~~ observed in central and eastern France, SE-Germany and E-Austria. South-eastern Europe was also affected (e.g. EEA, 2012, p.120–121), but is excluded from our quantitative assessments because ~~our database contained no~~of lack of data. The drought of 2015 was, within the study area, less spatially extensive and showed a ~~dipole effect~~contrasting response: wetter conditions in the north and south, and drier conditions in a band north of the Alps. The drought was rather moderate in most parts of this band. However, drought ~~was~~conditions were more severe than in 2003 in some areas around the Czech Republic, SE-Germany and N-Austria~~ while drought~~, whereas the conditions were less extreme from E-France to S-Poland, including S-Germany and N-Romania. The lack of available hydrological data precluded any assessment of the conditions further east, but the severity of ~~August atmospheric~~meteorological drought indices ~~such as SPI3 and SPEI3~~at the drought peak in August 2015 (Ionita et al., 2016) ~~suggest~~suggests that the ~~drought~~ area affected ~~area~~ by the hydrological drought may have extended further to the east, to Ukraine and Belarus, and maybe Russia (flow in the River Don was exceptionally low, pers. communication of Drs. E. Rets and M. Kireeva).

Durations of the two drought events are presented in the central panels of Fig. 1. For both events, the spatial patterns of drought durations correspond well with the low flow discharge, AM(7~~)~~), patterns (left panels), but there is a clear difference in the spatial variability. Drought ~~durations exhibit~~duration exhibits more homogeneous patterns than the magnitude of low flows in drought-affected regions. The return periods of ~~durations~~duration are overall more moderate than for ~~the~~ AM(7). For the 2015 event, the longest durations are observed in NE-France and SW-Germany, whereas the region around the Czech Republic is characterised by shorter durations. Note, however, that the results are only preliminary as drought may not have concluded everywhere by the end of the records ~~used~~ (October 2015), as we further discuss in Section 5.1. For the 2003 event, the longest durations are observed for S-Germany and NE-Austria, ~~while~~whereas central and eastern France exhibit shorter durations. Again, the 2015 event appears to cover a smaller part of the study area than the 2003 event, but in the affected regions, the return periods of ~~durations~~duration are comparable to those of 2003.

The deficit volume is a cumulative measure of drought that integrates information on both flow magnitude and duration. In 2015 deficit volumes with return periods of 50 years and more occurred~~,~~ (Fig. 1, right panel), with the largest deficits ~~(~~occurring in S-Germany~~)~~, west of the area with lowest flows (Fig. ~~1, compare right and~~1, left panels). In regions where the drought event was short, such as central France and NE-Austria, deficit volumes are ~~low~~small regardless of AM(7). For drought-affected areas, ~~the~~deficit volume exhibits a rather patchy pattern ~~that arises from the~~ similar to pattern of low flow discharge AM(7~~)~~), and thus reflects local hydrological conditions. Compared to 2003, the 2015 event covered a smaller part of the study area in terms of deficit volume, but with high severity within the drought-affected region.

4.2 Comparison by regions

The severity of the events of 2015 and 2003 ~~are~~is compared for three contrasting regions: the Czech Republic, which was the most affected region in 2015; E-France (Rhine and Saône hydrographic regions), which was one of the most affected regions in 2003; and S-Germany (Baden-Württemberg and Bavaria south of river Maine), which was ~~quite~~ strongly affected in both years. Figure 2 shows the distribution of annual minima low flow, AM(7~~) (magnitude)~~), and drought deficit ~~volumes~~volume for each ~~of the regions.~~event and region. Catchments with a winter low flow regime are presented in separate box-plots, as ~~extreme~~ low flows ~~generally do not~~that occur in ~~summer.~~winter may be triggered by different processes (Van Loon et al., 2015). Overall, the regional distribution of return periods are broader for AM(7) than for deficit volume~~.~~, and AM(7) ~~generally~~ shows higher return periods~~.~~ in the most affected catchments.

There is a major difference in the severity of the events of 2003 and 2015 in the Czech Republic (left panels of Fig. 2) with moderate return periods in 2003 for both low flow discharge AM(7) (median T_{med} = 10~~.3~~ yr) and drought deficit volume (T_{med} = ~~20.6~~21 yr). In 2015, volumes have a slightly higher severity (T_{med} = ~~31.4~~32 yr~~) and~~), whereas record low values of AM(7) were ~~often significantly below the recorded minima in the reference period and associated~~ observed leading to return intervals of more than 100 years~~.~~ in more than half of all catchments (i.e., $T_{med} > 100$ yr). Note however, that due to the limited record length ~~of record to estimate the~~(around 35 yr), estimated return periods ~~(around 35 yr) frequencies~~ are only indicative and must be interpreted as such.

In E-France the 2003 event was characterised by ~~extreme~~high return periods ~~in~~for AM(7) (often ≥ 100 yr) and ~~more) and quite~~moderately high severity in deficit volume (T_{med} = 27~~.4~~ yr). In the pan-European context, it was one of the most severely affected regions in 2003. In 2015, however, the drought was relatively mild in terms of AM(7) (only slightly below the average summer conditions), but slightly more severe in terms of volume.

S-Germany, ~~geographically~~located between the Czech Republic and E-France, experienced similar severity for both events~~: AM(7) were~~ (summer catchments), with slightly ~~lower~~ higher return periods in 2003 than in 2015. Both events were more severe in terms of deficit volumes (T_{med} = 26 yr in 2003, and T_{med} = 19 yr in 2015) than in terms of AM(7) (T_{med} = 13~~.4 yr) than in 2015 (T_{med} = 11.9 yr) but the volumes were similar on average. Return periods of low flow magnitude associated with both events range between the values of E-France and Czech Republic, suggesting a gradual decline of low flow magnitude from west to east in 2003 and from east to west in 2015. The volumes, however, do not follow the same pattern. With values of T_{med} = 24.5~~ yr ~~for~~in 2003, and ~~25.4~~T_{med} = 9 yr ~~for~~in 2015~~the return periods correspond always to those of the more affected neighbour, E-France in 2003 and Czech Republic in 2015. Obviously, the~~). The S-Germany region ~~is~~appears to be prone to relatively long drought periods that let deficits accumulate over a long time. Note that analysis of catchments with winter regimes does not show exceptional conditions in the winter prior to the 2015 summer low flow event.

When finally comparing across regions, it can be seen that return periods of low flow magnitude associated with both events range between the values of E-France and Czech Republic, suggesting a gradient of low flow magnitude increasing from east to west in 2003, but increasing from west to east in 2015. The deficit volumes show a similar, but less pronounced gradient in 2015, and there is almost no gradient for the volumes in 2003. Again, the lower gradients in deficit volumes are due to the long durations of drought events that make deficit volumes less dependent on peak magnitude.

Summary statistics of streamflow drought characteristics for individual countries in Europe are provided in Appendix A.

4.3 Spatio-temporal development

Figure 3 and Table 1 show the spatio-temporal development of the drought of 2015 and 2003 ~~drought~~ based on each flow record's low flow discharge, MM(7) (monthly magnitude) ~~during each month~~from February to November. For comparison, the low flow values are expressed as the corresponding return period in the annual extreme-value distribution of the entire record. Hence, the maps show in which month low flows with at least a severity of an annual low flow event occurred, and Table 1 provides a statistical summary of the affected stations. Similar methods of display are used by ~~some~~various national ~~or~~and regional real-time flood and low flow information systems that label ‘hazard levels’ by return periods or flow quantiles (e.g. LfU Bayern, 2016). ~~Here~~In our results, the maps for both drought events show that an exceptional situation started to develop in June (with first indications already in May) when discharges began to fall under the average annual low flow ~~threshold Q_{80}.~~discharge. However, onset was more dramatic in 2003, ~~covering~~affecting more quickly and more homogeneously, a larger region. Interestingly, the regions that were first affected during an event are consistent with the regions that were later also affected most severely, i.e., central France and E-Austria in 2003, and Czech Republic and central Germany in 2015. By the end of July~~,~~ (2015) - beginning of August (2003), the full spatial extent of both droughts was ~~already~~ reached. This is also reflected in the monthly number of stations under drought ~~presented in~~(ref. Table~~-~~ 1~~, which shows a strong increase until July and almost no increase afterwards.~~). During this “peak” of the drought, differences emerged with respect to the drought characteristics and recovery periods. In 2003, the peak of the drought was reached in August, with a clear ~~relaxation visible in September when the most affected regions returned to more moderate conditions.~~recovery visible in September when the most affected regions returned to more moderate conditions. The spatio-temporal development seen from MM(7) is consistent with the findings of Stahl and Tallaksen (2010) where the drought event was assessed from daily discharge snapshots based on EWA stations. The recovery started in western Europe, reached the region north of the Alps in October, and finally eastern Europe in November. At this time, most parts of Europe had returned to ~~at least~~ above-average low flow conditions, except for a band north of the Alps (UK to Poland) ~~which~~that remained under mild drought conditions. In 2015, the timing of the peak ~~occurred~~differed across regions from August to October (some regions around S-Germany remained under moderate drought conditions by end of October 2015), with recovery starting later, ~~from west to east and~~first seen in western parts, being overall slower than in 2003.

4.4 Local fingerprint

The analyses so far have shown that a band north of Alps was most affected by the 2015 drought, but the severity of the event ~~differs~~differed between regions. Overall, the band corresponds well with the region affected by meteorological drought ~~indices~~ at the peak of the event. However, ~~they cannot explain the regional~~ there are important differences ~~in~~between hydrological and meteorological drought patterns on a smaller, regional scale. For instance, at the eastern end of the Alps, N- and E-Austria exhibit similar precipitation anomalies, temperature anomalies and ~~SPI3~~SPEI3 values for the summer drought season (JJA) (Ionita et al., 2016). Nevertheless, there are striking differences in low flow discharges and volumes. ~~A~~ In the following, we look closer ~~look is needed to determine~~into why some catchments saw very low flows in 2003, but not in 2015.

To gain insight in these differences we selected hydrographs of both events for two contrasting ~~exemplary~~ catchments (Fig. 4 and 5). The first example is the gauge Altschlaining at river Tauchenbach in E-Austria (~~Figure~~Fig. 4). The catchment has an area of 89.2 km² and the altitude of the gauge is 316 m.a.s.l. Its geology consists of phyllite and schist in one part, and clay marl and ~~sand~~sandstone formations in the other part of the catchment. The gauge represents a region that fell extremely dry in 2003, but exhibited no severe low flows in 2015. Figure 4 shows that the reason for the contrasting behaviour can be found in the conditions ~~before~~prevailing the summer event. ~~For the~~In 2003~~ event~~, discharge ~~anomalies~~was already ~~occurred~~lower than normal during winter and spring season. This is clearly indicated by the hydrograph, which ~~followed~~started to decrease below the seasonal Q_{80s} threshold in winter~~ and started to decrease much steeper in February~~. The seasonal deficits steadily increased during spring, leading to an early onset of the low flow event ~~at~~in the beginning of May. The ~~atmospheric~~meteorological summer drought exacerbated the hydrological situation and yielded ~~to~~the lowest discharges since beginning of records. ~~For~~In 2015, the ~~atmospheric~~meteorological situation in summer was comparable to 2003 in this region, ~~as it is visible from~~with small inter-annual differences of ~~August-SPEI3 in~~ accumulated summer (JJA) precipitation (Fig. 11e of Ionita et al~~. (~~., 2016). However, the hydrographs ~~start~~started at a much higher level in 2015, pointing to very wet preconditions. ~~Until June streamflow~~This is also reflected by the higher January-SPI6 value of 1.5 in 2015 as compared to 1.1 in 2003 in this region, with January-SPI6 accumulating August to January precipitation, and values above / below zero indicating wet / dry anomalies (Ionita et al., 2016; McKee et al., 1993). Streamflow remained above the average seasonal regime until June (indicated by the Q_{50s} line), leading to a late onset of the low flow event in August. It appears that surplus water from the winter and spring seasons fed discharge during the summer drought ~~season~~ and thereby prevented ~~the genesis of a~~an even more extreme low flow event to develop in 2015.

A different situation occurred in N-Austria at gauge Imbach at river Krems. The catchment has an area of 305.9 km², the altitude of the gauge is 231 m.a.s.l. and its geology consists of granite and gneiss. This ~~catchment~~river fell only moderately dry in terms of magnitude in both ~~years,~~ 2015 and 2003. However, Fig. 5 shows contrasting recession behaviour in the hydrographs due to different preconditions~~. This~~: The 2003 low flow event is characterised by an almost uniform streamflow recession. The catchment is situated in a region that was heavily affected by the flood event in August 2002 ~~(caused by massive precipitation).~~, reflected in an extremely high January-SPI6 value of about 4.0. Streamflow started to reduce in winter, but remained above seasonal average conditions (Q_{50s}~~) until April.~~). In spring, discharge was ~~only at the limit~~close to seasonal drought conditions, ~~and~~but there ~~were still~~was enough stored water ~~resources~~in the catchment to sustain streamflow in summer 2003. The 2015 low flow event, on the other hand, ~~is~~was characterised by ~~dry~~much drier preconditions in winter. However, there were several rainfall events in spring, which ~~are reflected by a~~can be seen in the number of pronounced streamflow peaks. ~~The~~These precipitation events delayed streamflow recessions and prevented more severe low flows to develop in summer.

4.5 Spatial clustering of hydrographs

To generalise the findings obtained from interpreting seasonal anomalies of the two hydrographs to the European scale, we performed functional clustering of hydrographs across Europe. For each event, we used monthly mean discharges of the Jan – Oct period, which were converted into a standardized streamflow index for each month (SSI, e.g. Staudinger et al., 2015; Barker et al., 2016) to make low flow hydrographs comparable across European regimes. Results for 2003 are shown in Fig. 6. Altschlaining, east of the Alps, is one of the driest regions in a band between central France and eastern Austria (belonging to Cluster 3). The cluster is characterised by an early onset and large dry anomalies. Imbach, north of the Alps, belongs to a broad cluster of stations with much smaller anomalies (Cluster 4). The distribution of both clusters corresponds well to the patterns of most affected and moderately affected regions across Europe. The region around southern Germany forms a distinct cluster (Cluster 5) with wet anomalies in spring leading to later recessions than in the surrounding area. The late onset of the drought in 2003 can be well explained by high precipitation amounts in the summer preceding the event, causing major floods in this area in 2002. The anomalously wet area is clearly visible in the January-SPI6 map in Fig. 8 (left panel) that shows standardized precipitation anomalies of the August – January period. These wet preconditions explain why the region is behaving differently to the surrounding regions despite that experiencing similar meteorological drought conditions in summer.

The clustering of 2015 is shown in Fig. 7. Imbach belongs to the cluster that contains the most affected catchments, situated in the band ranging from central France to Czech Republic (Cluster 1). Altschlaining belongs to a cluster that exhibits a similar, but somewhat shifted signal, showing a tendency towards less severe conditions (Cluster 6). Catchments in this cluster are characterised by a later onset, lower magnitude and earlier termination of the drought. Southern Germany deviates from these general patterns and forms a distinct group (Cluster 2). The cluster shows striking similarities with Cluster 5 of the event of 2003. The region is characterised by a later onset, moderate low flow magnitude and a later termination of the streamflow drought.

4.6 Effect of ~~seasonality~~preconditions

~~The section before has demonstrated how preconditions in spring, winter, and even before determine in the genesis of a drought event. In two exemplar gauges we found evidence that (i) extreme droughts developed as a consequence of dry preconditions, and (ii) that after wet preconditions low flow events developed later, and the event was often less severe. Here we investigate how much antecedent conditions influence drought development at a pan-European scale, looking at the relative seasonality (day of occurrenceΔ_τ) of the onset of both events (Fig. 6). We make the following observations:~~

~~(1)~~The previous section has shown that meteorological drought indices such as the January-SPI6 (ref. Fig. 8) contain relevant information about the preconditions of a hydrological drought event. While the some regional features of the hydrological drought of 2003 can be well explained by a superposition of January-SPI6 (Fig. 8, left panel) with August-SPEI3 from Ionita et al. (2016), this appears not to be the case for the event of 2015 (Fig. 8, right panel). The region around the Czech Republic was most affected in 2015. However, most parts of the area exhibited only moderate meteorological drought conditions in summer (August-SPEI3 = about -0.5 – -2.0) and above-average (i.e. wet) preconditions (January-SPI6 = about 0.2 – 1.2). Accordingly, the antecedent half-year precipitation (as represented by the SPI6) may not be considered a skilful indicator of antecedent catchment wetness in all cases.

Preconditions are also reflected by the timing (seasonality) of the onset of the drought event (Section 4.4). Figure 9 shows the relative seasonality (day of occurrence Δ_τ) of the onset of events across Europe. The maps exhibit some interesting features. Overall, the spatial ~~pattern~~patterns of the 2003 event (Fig. 9, left panel) and the 2015 ~~events~~event (Fig. 9, right panel) show ~~that both have a~~ much earlier ~~onset~~onsets than the long-term average ~~onset of low flow events. It is the~~onsets. The early onset ~~of drought conditions that~~ increases the risk of ~~running into~~ a severe low flow event ~~when the catchment is exposed to~~to develop during an extreme meteorological drought. In 2003~~ these preconditions were present on a much~~, the widespread early onset explains the larger scale ~~than in 2015. Given~~of the ~~similar~~drought event in 2003. Secondly, the spatial ~~extent of meteorological drought in summer in both years, it is obviously the preconditions that explain the larger scale of the drought event.~~

~~(2) In 2015~~distribution of catchments experiencing early, respectively late onset, corresponds well with most, respective least affected regions across Europe. In 2015, the hydrological drought was most severe in a band north of the Alps, ~~with a main focus around Czech Republic. This area is marked in the seasonality map by a~~ an area that had a notably early onset~~ of the event of more than 50 days before the long-term average.~~. In 2003, the same region ~~had~~encountered a later onset and ~~presented~~accordingly, more moderate low flow conditions. ~~In~~ The most affected area in 2003, ~~the focus was in~~ central France and E-Austria~~ and, again, the area is marked by~~, similarly experienced a very early onset. ~~We observe that the focal region~~Thirdly, it is interesting to analyse spatial patterns of the ~~drought event is always the one with the earliest onset.~~

~~(3) The regional differences in~~relative seasonality of the onsets ~~between~~of both ~~years (~~events (Fig. 9, central panel~~) are~~). The patterns appear closely related to the relative severity of events in terms of ~~annual minimum flows (~~magnitude~~)~~ (Fig. 1). The affected band ~~crossing~~across central Germany is marked by reddish colours, indicating a somewhat earlier onset ~~of the 2015 event, where low flows were mostly~~and more severe low flows in 2015 than in 2003. Central France and the band along the pre-Alps crossing S-Germany is marked by bluish colours and ~~associated with a drought event~~ a less severe drought event in 2015. The same indication ~~is~~were given for the part of southern Europe covered by the study, which shows blue colouring in 2015 and, thus, suggesting less severe low flow conditions.

We finally quantify the predictive skills of standardized precipitation indices of different accumulation periods (6, 9 and 12 month) and hydrological onset index by correlating their spatial patterns with those of low flow discharge AM(7) for stations with a summer low flow regime. For the two events 2003 and 2015, the relative onset Δ_τ exhibits a negative Spearman correlation coefficient, of -0.55 and -0.52 (earlier onset implies more severe low flows). These correlations are much higher than for the January-SPI6 (0.25 and -0.03), where a positive correlation indicates that a high SPI6 (representing wet preconditions) would lead to more severe low flows. Weak correlations are also observed for SPIs with longer aggregation scales. For instance, April-SPI9 correlations are 0.19 and -0.10 (with similar correlation coefficients of SPI9s and SPI12s for January to May). Only SPI6-values of April and May, reflecting winter and spring precipitation, are somewhat better correlated with the low flow magnitude (values of -0.03 and -0.34 for 2003, and -0.28 and -0.17 for 2015), but overall, the correlations are much lower than those of the relative onset Δ_τ.

5 Discussion

5.1 Merits and limitations of the study

This study presents a first timely analysis of the hydrological drought of 2015 at a nearly pan-European scale. Drought is one of the most costly hazards as it affects a number of water-related sectors. The potential for damage is high~~, particularly because of~~ as the ~~large spatial and temporal scale of~~ drought events ~~causes~~typically affect large areas ~~to be affected and this over~~last for a ~~long~~considerable time. ~~All~~Although mitigation measures ~~taken~~ on a European or regional level ~~to reduce risks~~ require timely and accurate information about the physical system~~. Despite that~~, a timely analysis of the hydrological situation is ~~difficult to make on a~~challenging at the continental scale. As described in Section 2, there are major barriers of data access, especially for eastern European countries. Wherever data are available, compatibility poses a challenge. All these obstacles were overcome in this study by capitalizing on the ~~full~~ potential of a well-established international network, provided by UNESCOs EURO FRIEND-Water program. Without this network, a timely analysis of the event would not have been possible. The collated data set ~~is of high value as it~~ offers ~~the~~a unique opportunity to analyse the 2015 drought from a hydrological perspective~~. The pan-European perspective is crucial to study droughts as a number of processes are acting on a continental scale and require large-scale data sets~~ across most of Europe.

Despite these merits, the study has ~~clearly a number of~~several limitations. For various reasons, we could not cover the European continent as a whole. Hence, there are white spots in the south, east and south-eastern Europe ~~which~~that could not be filled~~,~~ (data were not available), or where it may not be meaningful to use streamflow data as a drought indicator (e.g. for intermittent rivers in semi-arid regions and in highly regulated river systems). For these areas, meteorological data ~~may still be~~are currently the more useful and readily available information. ~~In the case of the drought of 2015, climate~~Climate indices, such as SPEI3 for August, suggest that the south and south-east

~~had~~experienced relatively wet conditions in 2015, so the lack of information in those regions ~~may not have large~~likely had only small consequences ~~in~~for the ~~interpretation~~results of the hydrological drought analysis~~ results~~. For 2003, however, it was the south-~~east~~eastern parts of Europe ~~which was~~that were particularly affected, and ~~analysis~~to gain full insight into the footprint of the hydrological ~~data~~drought would require ~~further collaboration and~~a larger effort in obtaining data exchange across the whole of Europe.

A second limitation arising from the need for a timely assessment is that discharge records until end of October 2015 might not have captured the true end of the drought for some sites: for example in the major rivers Rhine and Danube and some gauges in SW-Germany, the northern pre-Alps in Bavaria and Upper Austria, ~~where~~ additional analysis (not shown~~ in this paper~~) suggested that discharge was still decreasing after 31 October. Large catchments are known to respond slowly to atmospheric signals due to large storages and delay processes in the river network (Gustard and Demuth, 2008; Laaha et al., 2013; Salinas et al., 2013), explaining the later termination date of the 2015 drought for these gauges. ~~The catchments~~Catchments in the northern pre-Alps are much smaller and ~~therefore react~~typically fast responding, reacting much quickly to autumn precipitation~~, but here~~. Further, summer low flows are often followed by frost ~~what leads to a late seasonality of~~ in these regions, which imply that the low flow ~~events. Here the~~ situation continues in to the snow season. The lowest flows ~~generally~~typically occur in October and November ~~(Laaha and Blöschl, 2006). Hence~~in these regions (Laaha and Blöschl, 2006b) and thus, it ~~is likely~~may happen that the low flow situation was even more severe than reflected by the drought characteristics calculated in this study. ~~Our estimates of the monthly development of the 2015 low flow magnitude, however, are unlikely to be strongly affected by this limitation, while the estimates of drought duration may be underestimated for those catchments where the flows had not yet recovered fully by the end of the study period. Figure 7~~Figure 10 shows the stations that are ~~potentially~~ still under drought, ~~since~~according to the SPA method (i.e. the store has not totally recovered from the summer drought) at the end of the study period (31 October 2015). For these stations, the analysis of low flow magnitude and deficit characteristics (duration and volume) for 2015 may be incomplete. ~~Durations are~~Duration is notably sensitive to the further development of the drought situation, as they will grow linearly over time until the termination of the event. Volumes are more robust since their accumulation over time also depends on the magnitude of streamflow, and it was shown above that for most gauges streamflow was already increasing at the end of end of records. As a consequence, we consider the results on ~~deficit volumes~~low flow magnitude in this study to be ~~more~~quite representative for the full 2015 event~~.~~, and the results on deficit volume to be more representative than drought ~~durations~~duration, which ~~may mainly be~~still are useful for relative comparisons between gauges. ~~For obtaining definite drought characteristics the study would need to be updated after complete termination of the event.~~

~~5.2 Impacts of the hydrological drought~~

~~The drought of 2015 had many negative consequences, i.e. impacts on environments, society and economy.~~5.2 ~~Besides the widespread agricultural losses due to the meteorological and soil moisture drought, Van Lanen et al. (2016) also described a range of impacts that were directly related to streamflow drought. They include deterioration of water quality and instream habitats for fish, violation of legal minimum flow requirements, impairments of river navigation, reduced energy production from hydropower and thermal power plants, and water supply restrictions related to lack of inflows to reservoirs or to bank infiltration into aquifers. Compared to agricultural losses for rainfed crops, however, such impacts are documented less systematically and there is no real-time monitoring of drought impact information that can be used quantitatively. Previous studies have used collections of reports that were coded into occurrence of impacts in particular categories. An~~

~~example is the European Drought Impact Inventory (EDII, http://geo.uio.no/edc/droughtdb/) (Stahl et al., 2016), which has been used to describe the impacts of previous droughts, including the event of 2003 in detail (e.g. Stagge et al., 2013). A similar impact report collection for the 2015 event is currently in progress, but the database has only sufficiently populated so far for the two southern German States of Baden-Württemberg (BW) and Bavaria (BY) to allow a more formal analysis. Bachmair et al. (2016) summarized the numbers of impact reports for 2015, which can be accessed through the database: impacts related to hydrological drought occurred from June to November. The reported number of impacts on freshwater ecosystems peaked in July in BW and in August in BY but continued until November. Impacts on water supply and fisheries were also reported throughout the entire period. Impacts on energy production occurred in BY throughout the drought, but were reported in BW only in November. We call on the community to enter more impact reports from other countries into the EDII database (http://geo.uio.no/edc/droughtdb/), to allow a wider European analysis of the event.~~

~~Despite the limited data availability, selected impact reports from authorities and the media can serve to reflect the drought propagation through the hydrological cycle and the spatial footprint in the hydrological signal found in streamflow drought analysis of this study. For example, the French waterway network authority (vnf) reported on restrictions on navigation in some canals in north-eastern France from mid-June onwards (vnf, 2015a) and had to close some canals in mid-July (vnf, 2015b). As early as the beginning of June, a deterioration of surface water quality was reported in the Netherlands and one month later in Germany. The frequent situation reports of the "Low flow Information Service" of the German Federal State of Bavaria reported violations of the oxygen concentration threshold in rivers in northern Bavaria for the first time on July 9th and consistently in the following weeks, but without major consequences for the river ecology (LfU Bayern, 2015). Although streamflow records from the gauges used in this analysis did not show any zero flows, throughout August and September smaller headwaters were reported to have dried up fully or partially and fish had to be rescued locally in Switzerland and Germany (EDII, http://geo.uio.no/edc/droughtdb/). These extreme low flows prompted authorities in Switzerland and Southern Germany to issue restrictions to a common law that normally allows citizens to extract small amounts of water from rivers to water their gardens (BAFU, 2015) and in Southern Germany (exemplary: Stadt Waldkirch, 2015). The Drought Management Centre of South Eastern Europe (DMCSEE) reported mainly agricultural drought impacts in its monthly monitoring summaries for the region during early summer, but from July onward hydrological drought impacts are mentioned (DMCSEE, 2015).~~

~~Previous studies that have linked impacts to drought indicators have found longer lag times between meteorological drought indices and water supply impacts (e.g. Stagge et al., 2015; Bachmair et al., 2016) and these could also be observed in the event of 2015 when impacts on water supply followed with some delay in those regions where the streamflow drought continued into the autumn (Fig. 3). Reports indicate that from September onwards, springs dried up in the mountain regions of S-Germany affecting local water supplies fed from springs or fast reacting aquifers (EDII, http://geo.uio.no/edc/droughtdb/). Within the propagation scheme, these types of impacts, which are related to the depletion of natural storage in aquifers as well as storage in reservoirs, continued to occur throughout the autumn. Consistently with the identified spatial pattern of antecedent conditions and low flows in the study area, impacts on the navigability of larger rivers and thus on waterborne transport were first reported for the Elbe, Weser, and Odra Rivers in late May and from mid-late July onwards for the River Danube and then from early August onwards, for the River Rhine onwards (BfG, 2015). These examples illustrate the many interesting layers of impacts caused with various delays due to drought propagation through the water cycle and along a river network. All of the impacts are directly related to flowing or stored water resources, so for a meaningful~~

~~characterisation of water resources the hydrological perspective is needed. The number of reports that can be found certainly speak for the severity of the 2015 event in those places identified in this study.~~

~~5.3 Hydrological vs. climatic footprint~~

~~Drought events are often described either from a climatic or from a hydrological perspective. It is now interesting to analyse how these perspectives match. For both perspectives, it is very common to describe the drought at the peak of the event, when the extreme is most extreme. This phase of the drought is important because it is the time when we expect most impacts. From the atmospheric perspective, the peak of the event can be gleaned from a meteorological index such as the SPEI3 at the end of the summer heat period, using an aggregation time-scale that matches the usual aggregation time scales of catchments (Haslinger et al., 2014; Stagge et al., 2015; Ionita et al., 2016). From a hydrological perspective, the peak of the low flow event is well denoted by the minimum flow as they are occurring when the catchment water balance is at its minimum. Comparing both indices for the 2015 event, AM(7) from Fig. 1 and SPEI3 from Fig. 3 of Ionita et al. (2016), the differences are small. Climate and hydrological footprints are of similar size and at similar locations, but there are some regional differences where the severity of low flows deviates from the patterns of climate forcing, for example in Czech Republic where low flows were most severe but SPEI3 was only moderate.~~

5.2 Hydrological vs. climatic footprint

Drought events are often described either from a climatic or from a hydrological perspective. It is interesting to analyse how well these perspectives agree in terms of key drought characteristics. It both cases, it is common to describe the drought (location, extent and severity) at the peak of the event when the extreme event is most extreme. This phase of the drought is important because it is the time when we expect most impacts. From the atmospheric perspective, the peak of the event can be gleaned from a meteorological index such as a (daily or monthly) running SPEI3, using an accumulation period that matches the usual lagged response time of catchments (Haslinger et al., 2014; Stagge et al., 2015; Ionita et al., 2016). From a hydrological perspective, the flow is at its minimum when the catchment water balance is also at its minimum. Comparing AM(7) (ref. Fig. 1) and SPEI3 (ref. Fig. 3 of Ionita et al. (2016)) for the 2015 event, we see that differences are small. Thus, the climate and hydrological footprints are similar (in size and location), but there are some regional deviations in the two patterns, for example in Czech Republic where low flows were most severe but SPEI3 was only moderate.

Analysing the dynamic development of the drought reveals much greater differences. Ionita et al. (2016) showed that from a climatic perspective the 2015 event first appeared in S-France and the Iberian Peninsula where dry anomalies started in spring (May and earlier), and then slowly shifted to western Europe and along the northern Alps to the east. Although no streamflow data from the southern Iberian Peninsula ~~could be included in the~~were available for our analysis, it appears that the hydrological event had a somewhat different dynamic~~ with respect to the area covered by data~~, with first appearance of low flows in the Czech Republic and central Germany, followed by an extension to the south, west and east. This difference in the spatial development of hydrological and climatic ~~droughts~~drought is mainly due to the role of the catchment in transforming the climatic signal over different time scales. The analysis of streamflow dynamics at the catchment scale showed that preconditions in spring, winter, and even ~~before, and the~~ earlier, in combination with storage and release properties of the catchment, are critical in ~~influencing~~controlling the temporal and spatial development of summer streamflow droughts. This is in line with Van Loon and Laaha (2015) who emphasized that the spatial variation of hydrological drought severity is highly dependent on terrestrial hydrological processes, among which preconditions and storage play an important role. The magnitude of discharge in winter and spring reflects the initial condition of the catchment ~~water balance~~ before the ~~catchment is exposed to an atmospheric water deficit. Storage and release properties~~start of the ~~catchment determine the reaction time of discharges to the atmospheric water deficit.~~dry period. It is the combined effect of initial ~~conditions~~condition and catchment functioning, superimposed with the atmospheric signal that explains the development of a hydrological drought.

5.~~4~~3 Implications for water management

Our study presents drought as a complex phenomenon that leaves different footprints on land and atmosphere. Because of the complex interaction of atmospheric and land processes, each event is unique~~, therefore offering a fresh look into~~ and adds to current knowledge on drought generating processes~~ and critical conditions~~. We performed a comparative assessment of the event of 2015 relative to the benchmark event of 2003 to gain new ~~knowledge~~insight from ~~similarity~~their similarities and differences~~ of both events~~. Our findings may contribute to drought-related water management in several ways.

~~Firstly~~First, the ~~finding to what extent extreme droughts are conditional to~~ importance of winter and spring (pre-)conditions is ~~important~~crucial for early warning and risk assessment.~~ Hydrological events differ from atmospheric events because catchments collect and retain precipitation water, which exerts a modulating and delaying effect on meteorological water deficits. Hence, in addition to timing and severity of atmospheric events, the initial wetness conditions of the catchment are important.~~ Wet preconditions caused by precipitation in spring, winter and even in earlier periods (such as the extreme rainfall event of August 2002 for the 2003 event in some regions) can substantially ~~mitigate~~modify the ~~genesis of a~~ climatological drought~~.~~ signal and thus, the development of a hydrological drought. This was ~~born out~~clearly demonstrated by the example of the Imbach catchment (for both events) and the Altschlaining catchment (for 2015), where water from stored sources sustained streamflow and prevented more severe streamflow droughts. ~~Only following dry preconditions can an extreme streamflow drought could develop, such as the case for the Altschlaining catchment in 2003. For early warning and prediction~~Wet (or dry) precondition can also lead to positive land-atmosphere feedbacks, e.g. increased (decreased) soil moisture leading to a higher (lower) probability of precipitation that can relief or amplify a severe drought (c.f. Seneviratne et al., 2010). For catchments with substantial storage, only following dry preconditions an extreme streamflow drought could develop, such as the case for the Altschlaining catchment in 2003. For early warning and prediction, an early detection of drought-fostering conditions is therefore crucial. Our study suggests that a regional mapping of spring discharges in “hazard maps” (in the spirit of Fig. 3), and the relative seasonality of the beginning of an event with respect to average and benchmark conditions (such as in Fig. ~~6~~9), can offer ~~relevant tools~~ valuable information for early warning and detection of potential drought-affected regions. ~~At least for~~Based on the events analysed in this study, the regions that were later most affected by the drought ~~were always marked~~could be identified by unusually low spring discharges and an early onset of the low flow event. One may expect that ~~these indications are significant~~similar results would be valid for other extreme events as well, but this requires ~~testing in~~ additional studies. ~~The dynamics~~Further detailed studies of the link between climatological drought ~~events in atmosphere and land seem to contain a wealth of information whose better exploitation~~and hydrological drought characteristics, including their dynamic behaviour, may contribute to~~ both~~ improved models and better-informed decisions in water management.

Secondly, most drought impacts are ~~in majority~~ not simply caused by a lack of rainfall, but ~~also~~more so by a lack of ~~the relevant~~available water ~~resource, timing of rainfall, streamflow and~~resources at the right time, it being soil moisture, groundwater ~~deficits~~or streamflow, and sometimes by a direct effect of heat exposure as well.

During the drought of 2015, many impacts were noted. Besides the widespread agricultural losses due to the meteorological and soil moisture drought, Van Lanen et al. (2016) also described a range of impacts that were directly related to streamflow drought. They include deterioration of water quality and instream habitats for fish, violation of legal minimum flow requirements, impairments of river navigation, reduced energy production from hydropower and thermal power plants, and water supply restrictions related to lack of inflows to reservoirs or to bank infiltration into aquifers. For example, the French waterway network authority (vnf) reported on restrictions on navigation in some canals in north-eastern France from mid-June onwards (vnf, 2015a) and had to close some canals in mid-July (vnf, 2015b). As early as the beginning of June, a deterioration of surface water quality was reported in the Netherlands and one month later in Germany. The Drought Management Centre of South Eastern Europe (DMCSEE) reported mainly agricultural drought impacts in its monthly monitoring summaries for the region during early summer, but from July onward hydrological drought impacts were mentioned (DMCSEE, 2015). To study the link between drought magnitude and impacts, some studies have used retrospective collections of reports that were coded into occurrence of impacts in particular sectors and categories. An example is the European Drought Impact Inventory (EDII, http://geo.uio.no/edc/droughtdb/) (Stahl et al., 2016), which has been used to describe the impacts of previous droughts, including the event of 2003 in detail ~~In~~(e.g. Stagge et al., 2013). A similar impact report collection for the 2015 event is currently in progress, but not yet available as the EDII is only a research project and no operational effort exists, and each report must be carefully handled and the coding cross-checked manually.

Thirdly, in drought management, different ~~kind~~kinds of indices at various temporal scales have been considered~~.~~ (Bachmair et al., 2016). Crops in different growth periods differ in sensitivity to heat stress and lack of rainfall. Hence, accurate predictions of the timing and magnitude of meteorological drought and heat waves ~~will be most relevant~~are key when one aims to optimize irrigation water. Hydrological indices, on the other hand, are ~~more~~ relevant for a number of other water management tasks, such as those related to hydropower and navigation, but also for water quality, aquaculture and in-stream ecology~~ and aquaculture.~~. For the latter, low flow discharge during summer heat periods ~~will be~~is critical, as high solute concentrations at higher temperature ~~will~~may yield a cascade of hydrochemical processes with adverse effects on water quality. For navigation, the duration of critical water levels ~~will matter, while~~is important, whereas for hydropower ~~production~~ the total deficit over the event ~~will determine~~determines the economic losses. In absence of groundwater data, deficit volumes~~,~~ (in addition to base flow and recession analysis), representing the reduced outflow of stored sources in the catchment, may also be indicative for groundwater resources in a way that is relevant for water supply and irrigation planning. ~~Our study clearly shows that the various hydrological and meteorological indices differ for both events in timing and severity, so one cannot be substituted by the other. This implies that using a single meteorological drought index will not suffice.~~ All these types of drought impacts mentioned above occurred in 2015. The German Federal State of Bavaria reported violations of the oxygen concentration threshold in rivers (LfU Bayern, 2015). Switzerland and southern Germany issued restrictions to a common law that normally allows citizens to extract small amounts of water from rivers to water their gardens (BAFU, 2015 and exemplary: Stadt Waldkirch, 2015). Impacts on the navigability of larger rivers and thus on waterborne transport were first reported for the Elbe, Weser, and Odra Rivers in late May and from mid-late July onwards for the River Danube and then from early August onwards, for the River Rhine

(BfG, 2015). From September onwards, springs dried up in the mountain regions of S-Germany affecting local water supplies (personal communications).

Characterising events in a way that is relevant for drought management requires timely pan-European data to be made publically available. Such data ~~sets~~platforms exist for meteorological variables, but similar structures for the exchange of hydrological data are missing and need to be established. A lesson learned from this study is that droughts need to be characterised, monitored, and also ~~need to be~~ understood from both a hydrological and climatic perspective implying that it is not sufficient to analyse only meteorological or climatological drought indices to learn the full range of impacts on the natural, social and economic system. Current research is fragmented in different disciplines with partly different perceptions, with studies either focusing on the atmospheric side or on the hydrological side. In our collaborative ~~paper project~~effort within the EURO FRIEND-Water network, we aimed at an integral view from climatologists and hydrologists ~~from various~~across several countries~~.~~ (pan-European scale). This ~~setting is rewarding as it~~approach fostered the exchange of ideas, and ~~thereby enables~~enabled additional insights in the interaction of atmospheric drivers and catchment processes across regions that would not have been ~~gathered~~studied unitedly otherwise. This is especially important when investigating ~~drought because of its~~a large ~~spatial and temporal -~~scale ~~that crosses borders and disciplines~~phenomenon such as drought having adverse effects on several components of the hydrological cycle. There are indeed a vast number of open questions related to drought that require interdisciplinary research. For instance, a better understanding of how drought propagates through the water cycle would profit from exchanging specific knowledge and data about drought processes, and about how to best characterise them by indices. The dialogue between disciplines may yield ~~to the design of~~improved indices that are ~~different to the ones used today; which may be~~ better suited for understanding drought dynamics across scales. ~~Also, to the design of~~ In addition, there is a need for indices that ~~are more~~address operational needs and ~~more~~that are relevant for predicting drought impacts. Another gap in our knowledge that requires interdisciplinary research is the role of land-atmosphere feedbacks in drought generation. ~~They~~Such feedbacks may be important to understand the persistency of events and contribute to the ~~new knowledge may feed into~~development of both climate models and hydrological models.

All these examples demonstrate that a more complete understanding of droughts would be beneficial for a range of water management tasks, which also applies to drought policy making. Yet, a holistic view of drought is hampered by fragmentation into several disciplines. Communities need to ~~move~~collaborate closer ~~together~~ to further enhance our understanding of ~~hydrometeorological~~hydrometerological drought.

6 Conclusions

In this study we analysed the European drought of 2015 from a hydrological perspective. In a unique community effort of data collection and processing according to a common protocol, ~~this~~the analysis was based on a range of low flow indices calculated from observed streamflow records of about 800 gauges across Europe. Thus, it provided the first insight into the spatial and temporal characteristics of the hydrological drought of 2015. With a ~~dipole~~contrasting response of wet conditions in the north and south, and dryer conditions in a band north of the Alps, spanning from E-France to S-Poland and N-Romania ~~this~~, the hydrological drought had a different spatial extent than the benchmark drought of 2003. In terms of low flow magnitude, the drought was rather moderate in most parts, but severe with return periods of more than 100 years in a focal area from Czech Republic, SE-Germany and N-Austria. Here, the event was even more severe than the event of 2003. In terms of deficit volumes, the drought was particularly severe in a region around S-Germany where the duration of the event was notably long.

The data also revealed an interesting dynamic development of the hydrological drought ~~in space and time~~ with a southward spread and expansion from spring to summer and autumn. This development differs from the clear west-to-east spread of ~~climatic~~the climatological drought~~ indices~~ (Ionita et al., 2016). The difference in spatio-temporal characteristics of the climatic and hydrological drought can best be explained by diverging ~~conditions~~preconditions in the catchments. ~~Selected hydrographs~~Hydrographs provided~~ exemplar~~ local fingerprints of drought processes in which we found evidence that extreme droughts emerged as a consequence of dry preconditions in the preceding winter and spring months. Where wet preconditions occurred, low flow events and thus the onset of drought developed later, and the event was ~~mostly~~overall less severe. The preconditions can be well described by the onset of the hydrological event, which is notably higher correlated with the severity of the two events than with a long-term meteorological drought index such as SPI6 and SPI12. Overall, preconditions ~~are therefore a most likely explanation for~~seem to control the geographical ~~pattern~~patterns of onset, scale, and severity of the drought within the different regions studied. Moreover, the focal region of the drought event coincides with the region with the earliest onset.

The results of this study ~~therefore show~~demonstrate that drought leaves different footprints on the various components of the water cycle, on different spatial and temporal scales; with hydrological drought as a superposition of preconditions and the atmospheric water deficit in summer ~~having generated extreme streamflow drought in 2015.~~leading to the extreme streamflow drought in 2015. Hence, there is need for developing effective indicators and indices to detect and assess drought situations throughout Europe, as indicated by Water Scarcity and Droughts Expert Network (2007). Hydrological events differ from meteorological events because catchments collect and retain precipitation water, which exerts a modulating and delaying effect on meteorological water deficits. This finding has implications for the prediction and management of the impacts of hydrological drought, which the event of 2015 ~~illustrated~~illustrates in a manifold ~~way~~of ways. Using a single meteorological drought index such as SPEI may not suffice as a drought indicator in this respect. For many sectors suffering from long-term accumulated deficits, streamflow and groundwater hydrological indices ~~will be~~are likely more relevant. A more targeted large-scale drought monitoring ~~in that sense~~, however, requires hydrological data on a pan-European scale. Such data is available to some extent ~~to the models used by the~~(ref. European Drought Observatory (http://edo.jrc.ec.europa.eu~~),~~)), but largely unavailable for free ~~for timely science~~in near real-time. Providing the necessary data for managing drought in a pro-active way requires a concerted action of the hydrological and climatic communities. Such action should include pan-European provision of monitored streamflow and groundwater data in real~~-~~-time or near real~~-~~-time and of hydro-meteorological variables and multi-monthly and seasonal forecasting of both climatic and hydrological variables (Van Lanen et al., 2016). The results also highlight the need to implement national and European water policy where additional efforts need to be undertaken to make near real-time hydrological data available across borders in order to make drought management more operational in the future.

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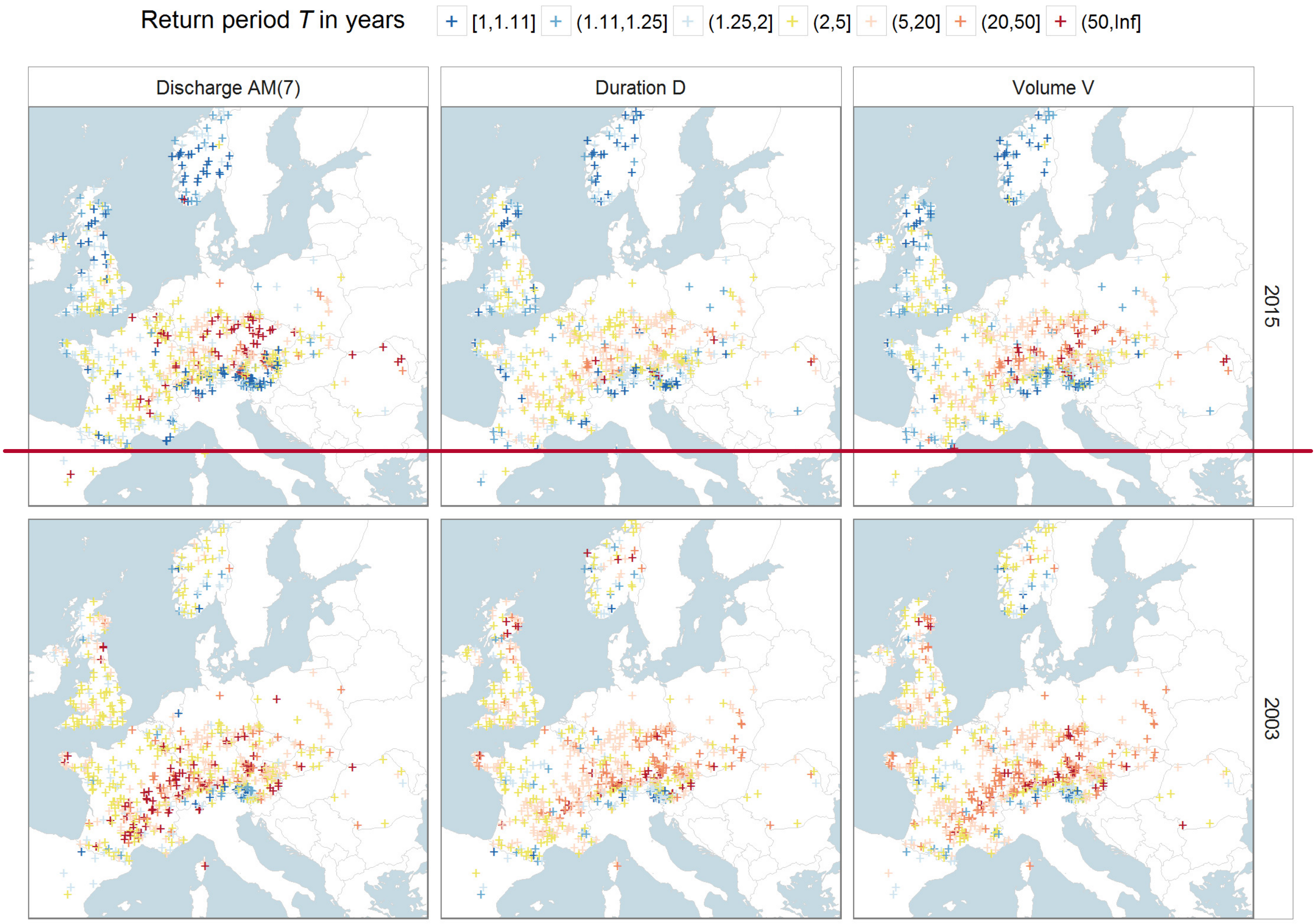
Table 1. Statistical summary of stations under drought for the individual month of 2015 (top) and 2003 (bottom). n_d is the number of stations under drought (i.e. with a severity of an annual low flow event and more). Median and quartiles summarize the return periods of low flow discharge MM(7) (monthly magnitude) of these stations (expressed as the corresponding return period in the annual extreme-value distribution of the entire record).

	Jun	Jul	Aug	Sep	Oct
2015					
n_d	78	261	332	293	227
Lower quartile	2.42	2.58	2.67	2.83	2.66
Median	2.86	3.38	4.13	4.51	3.87
Upper quartile	8.56	6.49	11.86	12.45	8.75
2003					
n_d	169	353	527	486	318
Lower quartile	2.32	2.45	3.37	2.98	2.62
Median	3.00	3.43	6.46	4.93	3.52
Upper quartile	4.26	6.31	17.00	9.99	6.26


Return period T in years
[1,1.11]
(1.11,1.25]
(1.25,2]
(2,5]
(5,20]
(20,50]
(50,Inf]
Discharge AM(7)
Duration D
Volume V
2015
2003

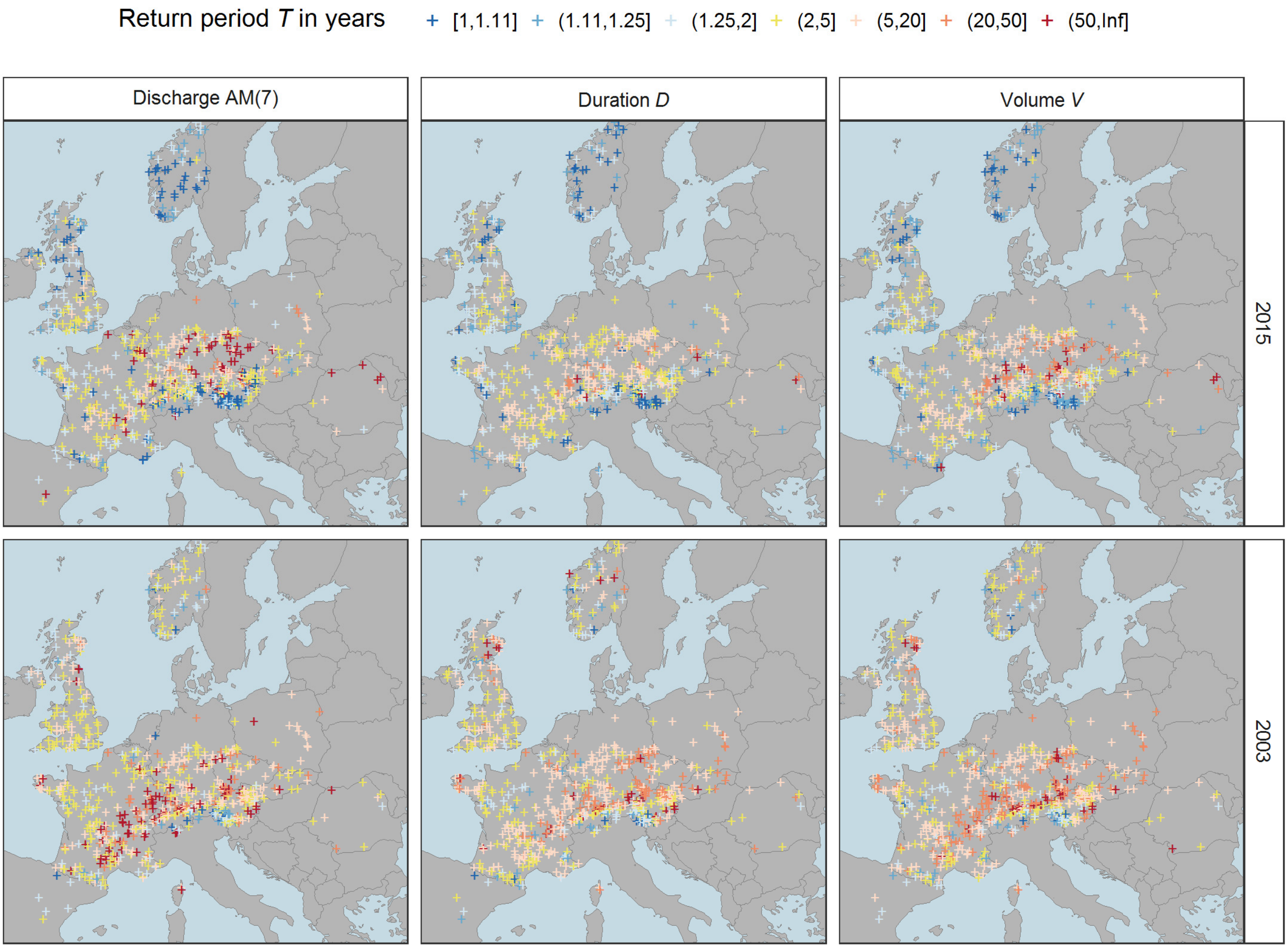
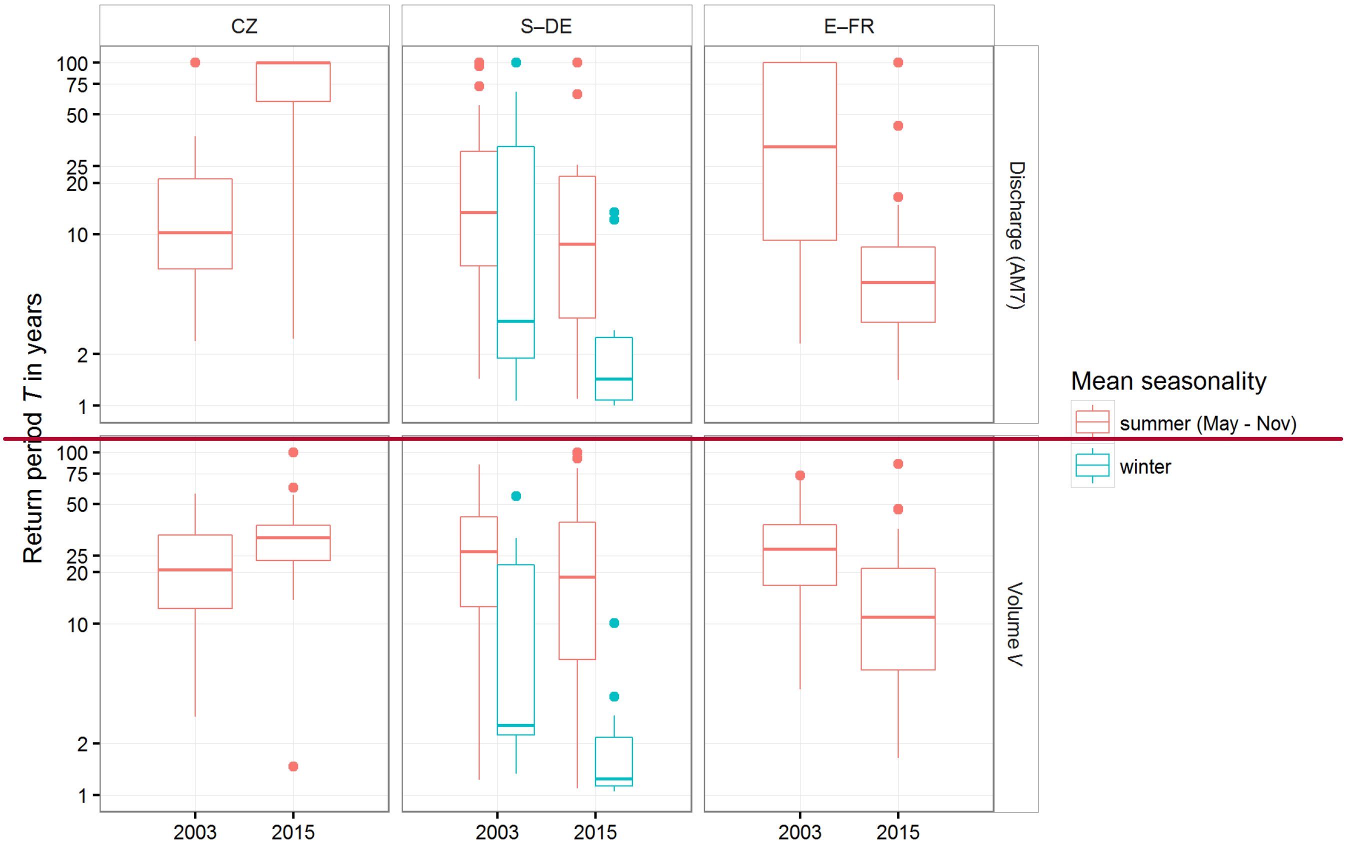


Figure 1. Return periods *T* (in ~~yrs.)~~yr) of annual low flow discharge AM(7) (left), duration *D* (centre) and deficit volume *V* (right panels) for the drought events of 2015 and 2003. Low flows and drought conditions below average conditions (return period > 2 years) are indicated by yellow to reddish colours. Severe events (return periods (20,50] and ~~(~~> 50~~,Inf] yrs.)~~ years) are indicated by orange and red colours.


CZ
S–DE
E–FR
Return period T in years
100
75
50
25
20
10
2
1
Discharge (AM7)
Volume V
2003
2015
Mean seasonality
summer (May - Nov)
winter

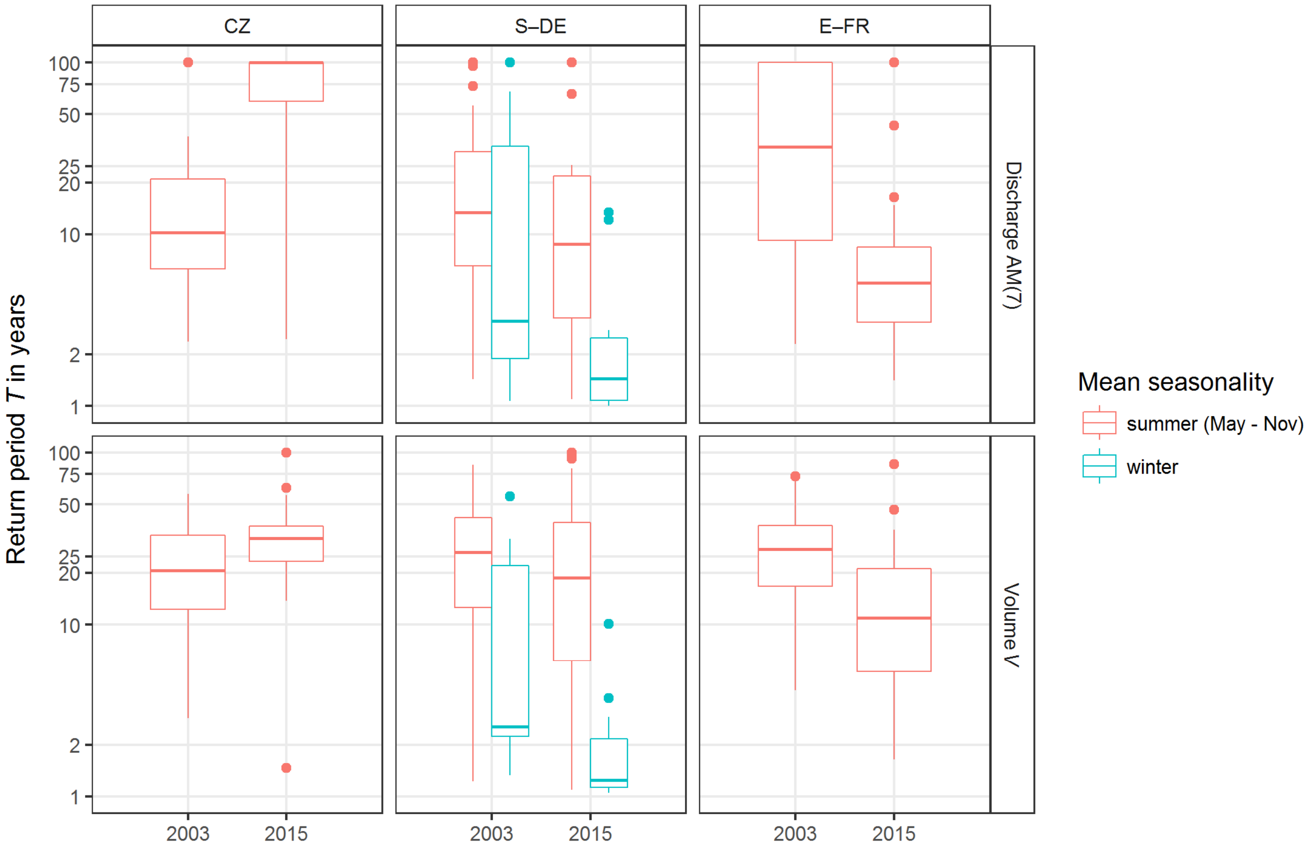
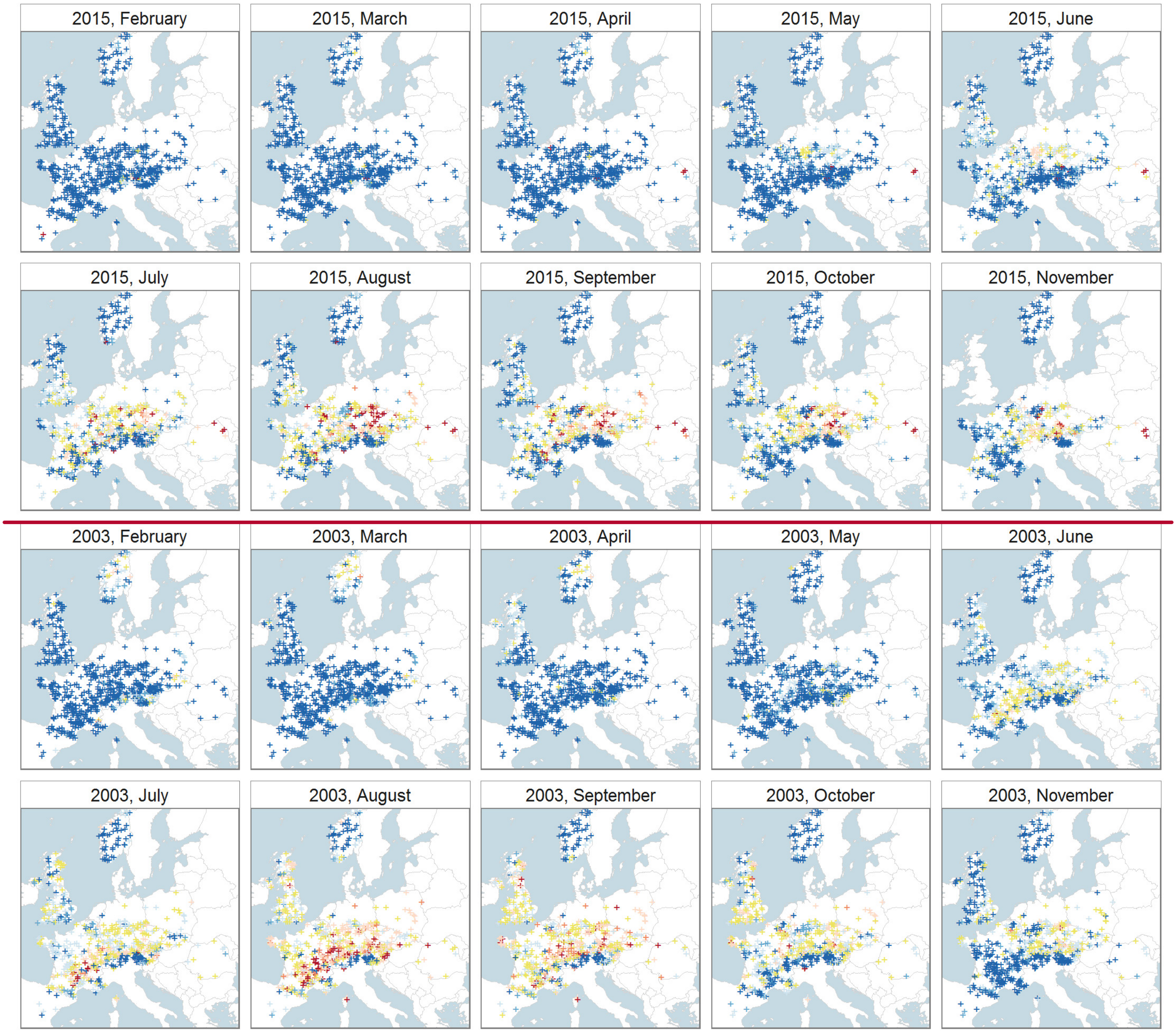

CZ
S–DE
E–FR
Return period T in years
100
75
50
25
20
10
2
1
Discharge AM(7)
Volume V
2003
2015
Mean seasonality
summer (May - Nov)
winter

Figure 2. Regional distribution of return ~~periods~~period *T* (in ~~yrs.)~~yr) of low flow discharge AM(7) (upper panels) and deficit volume *V* (lower panels) for the Czech Republic (left), S-Germany (centre) and E-France (right) (return periods > 100 ~~yrs.~~yr not shown). For S-Germany, the blue boxplots represent alpine catchments with a winter low flow regime (mean day of occurrence of AM(7) between December and March). Boxes refer to upper quartile (T_{75}), median (T_{med}) and lower quartile (T_{25}) of the return ~~periods.~~period, dots represent the maximum range of outliers. Return ~~periods~~period of about 2–10 years ~~represent~~represents mild drought conditions, 10-50 years moderate conditions, 50-100 years severe conditions, and >100 years extreme conditions.


2015, February
2015, March
2015, April
2015, May
2015, June
2015, July
2015, August
2015, September
2015, October
2015, November
2003, February
2003, March
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2003, September
2003, October
2003, November

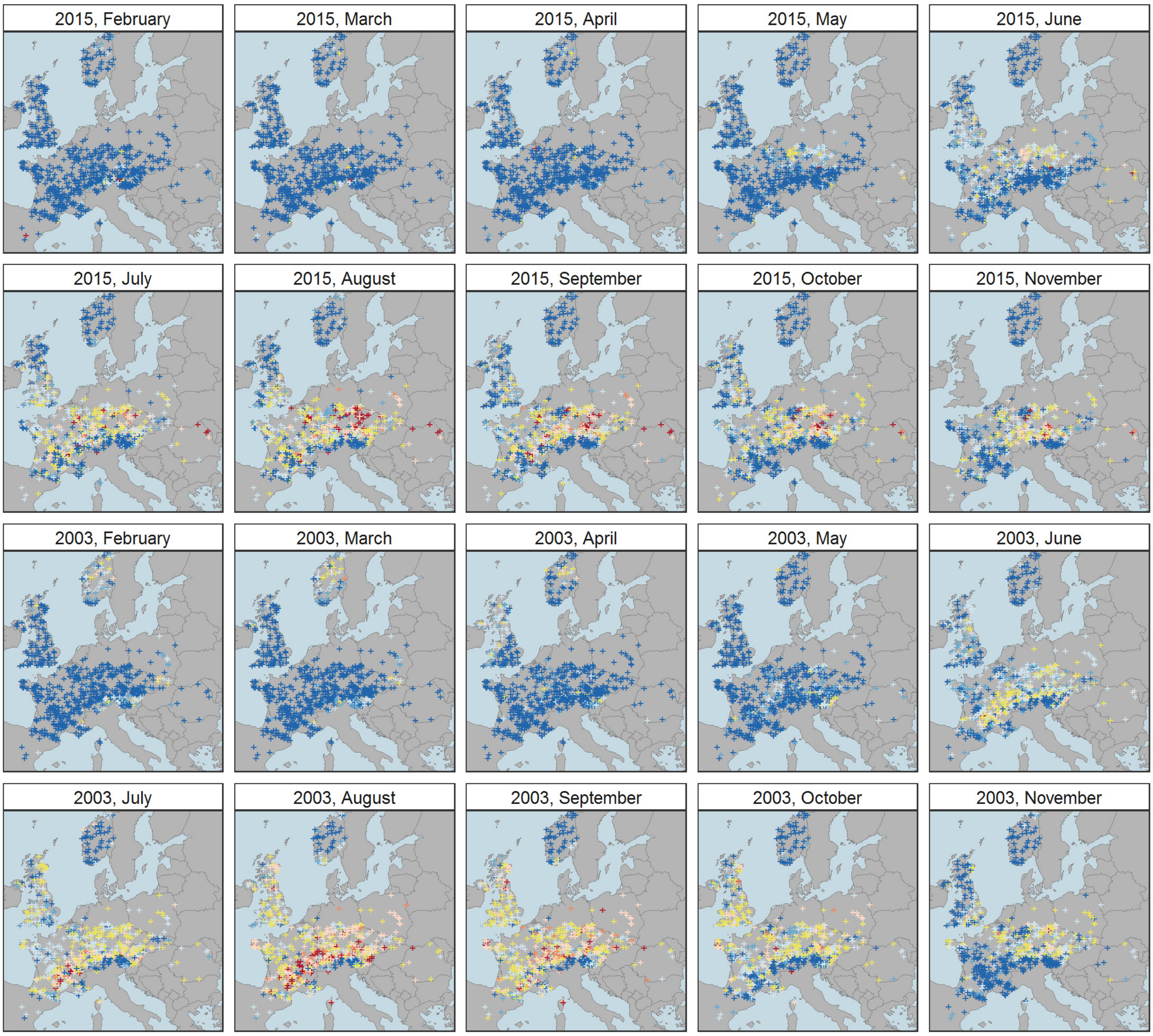


Figure 3. Return period T (in ~~yrs.)~~yr) of monthly 7-day minimum flows MM7. Colour codes are those of Fig. 1.

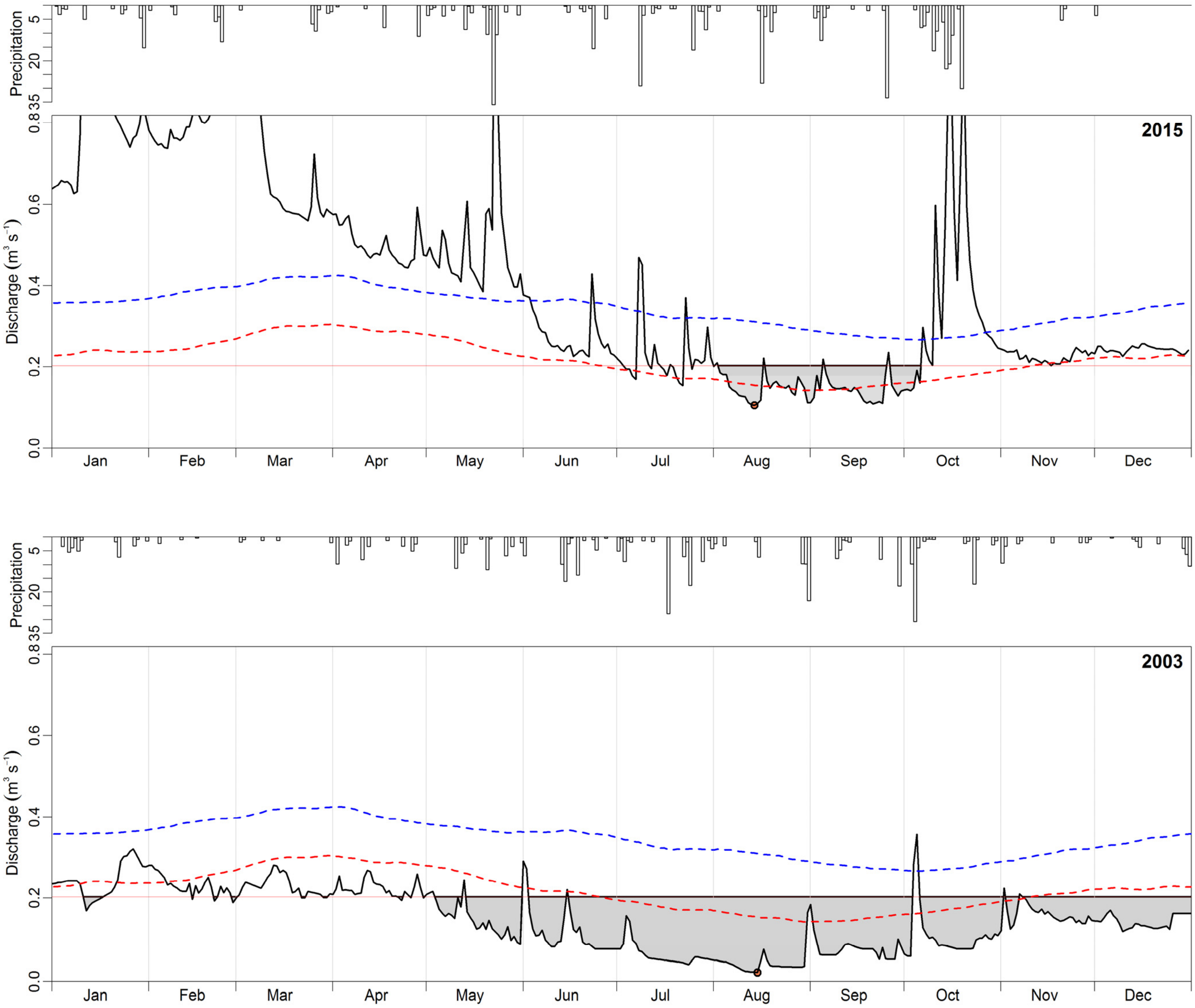


Figure 4. Hydrograph of gauge Altschlaining at river Tauchenbach in Austria (black line, large panels). Preconditions in 2015 (upper panel) were much wetter than in 2003~~.~~ (lower panel). The grey polygon indicates the maximum annual low flow event below the annual threshold Q_{80}. The area of the polygon corresponds to the deficit volume, and its length (between onset and termination date) is the duration of the event. Dashed lines show seasonal varying thresholds Q_{80s} (red) and Q_{50s} (blue), corresponding to smoothed (30-day moving average) daily flow quantiles with exceedance probability 0.8 and 0.5. These lines are used to benchmark long-term average and dry seasonal conditions, respectively. Precipitation (daily sums in mm) shown in the smaller panels above the hydrographs.

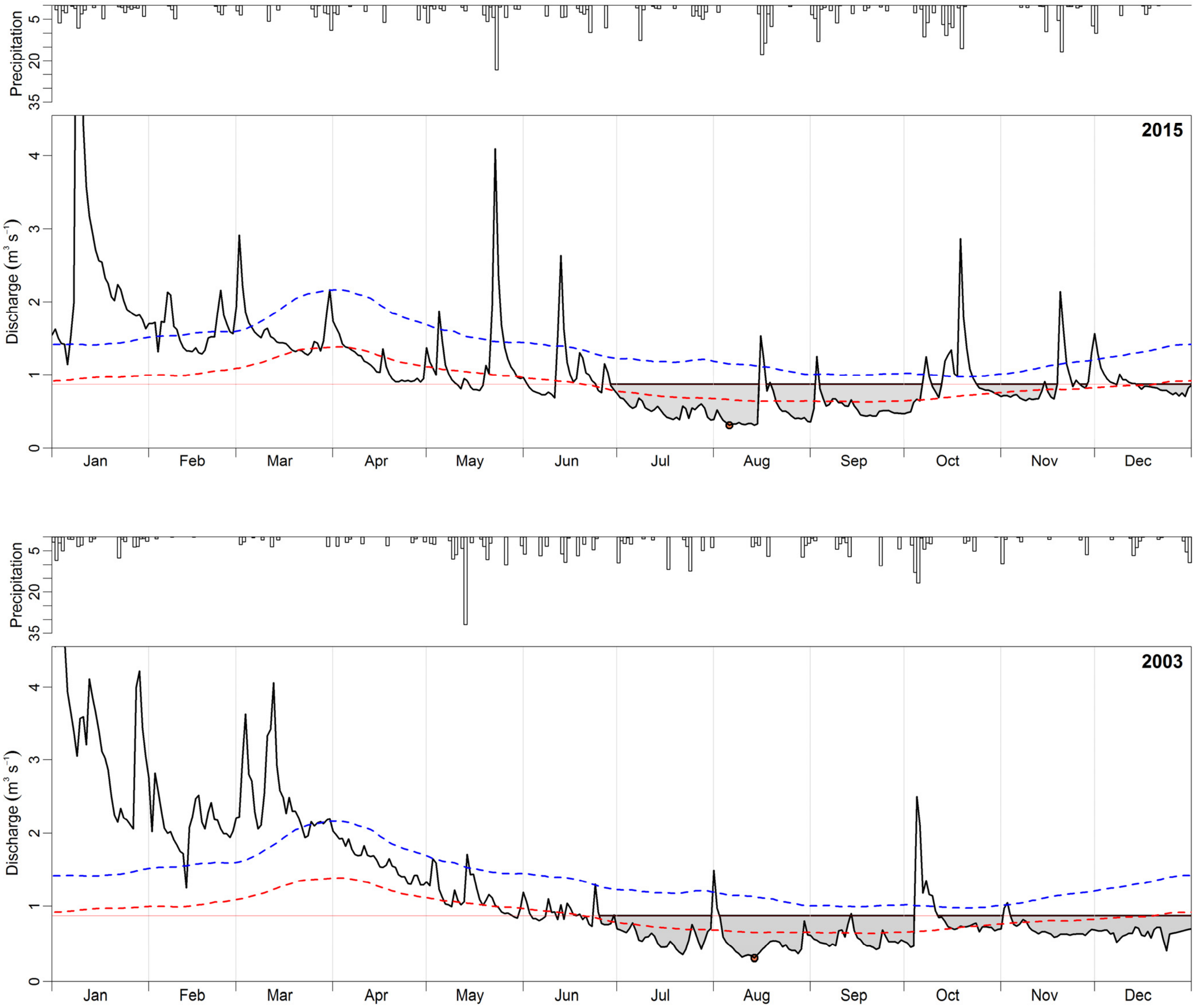
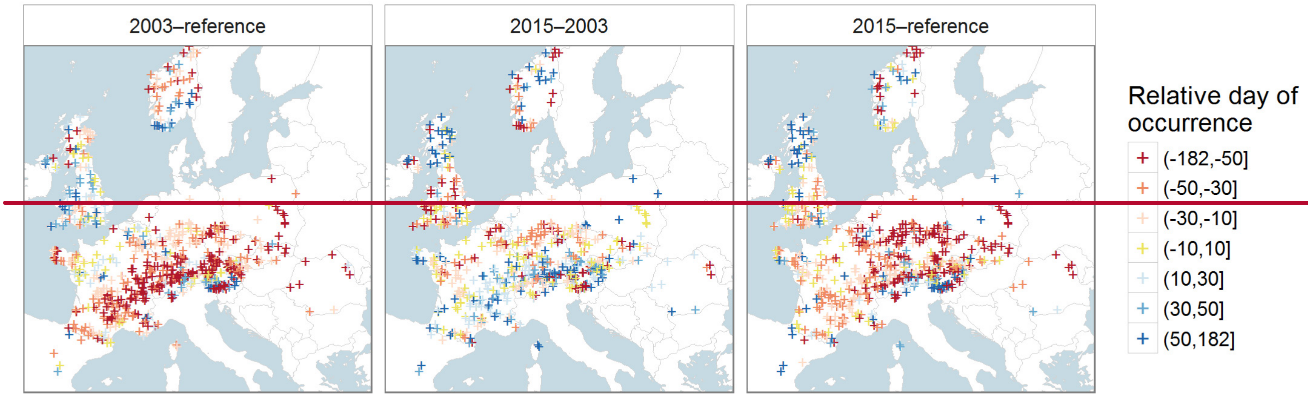


Figure 5. Hydrograph of gauge Imbach at river Krems, N-Austria (black line, large panels) together with weekly precipitation sums (mm, smaller panels above the hydrograph). Preconditions were much drier in 2015 than in 2003. Same signatures as Fig. 4.



~~Figure 6.~~

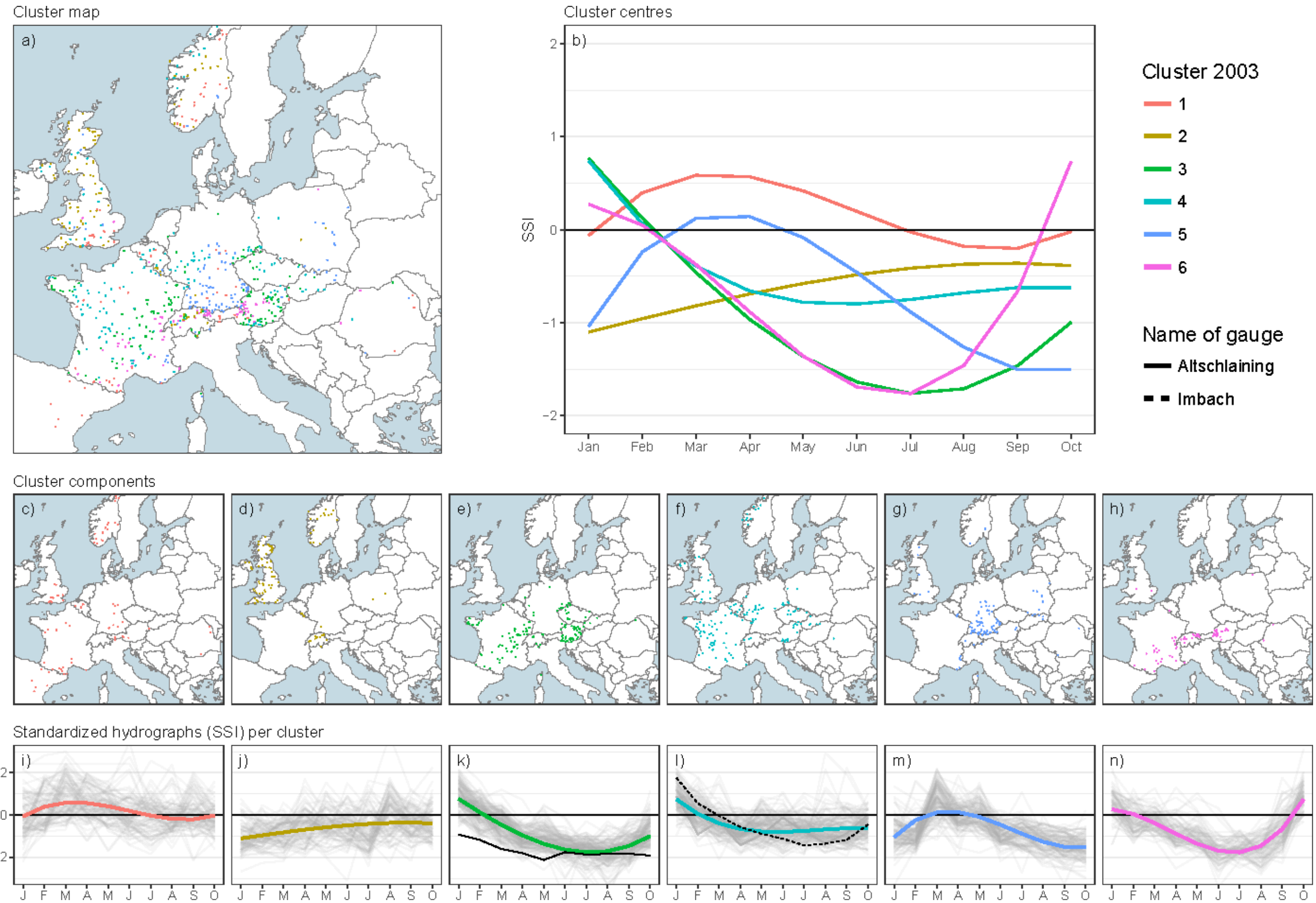


Figure 6. Clustering of the low flow event of 2003 based on monthly standardized streamflow index values SSI of the Jan – Oct period. a) combined cluster map showing allocation of catchments to the clusters, b) combined map of functional models of each cluster, c – h) cluster component maps, i – n) synoptic plots of standardized monthly hydrographs of Cluster 1 – 6 (thin black lines) together with the functional model of each cluster center (bold colored line). Altschlaining is marked by a bold black line, Imbach is marked by a dashed black line.

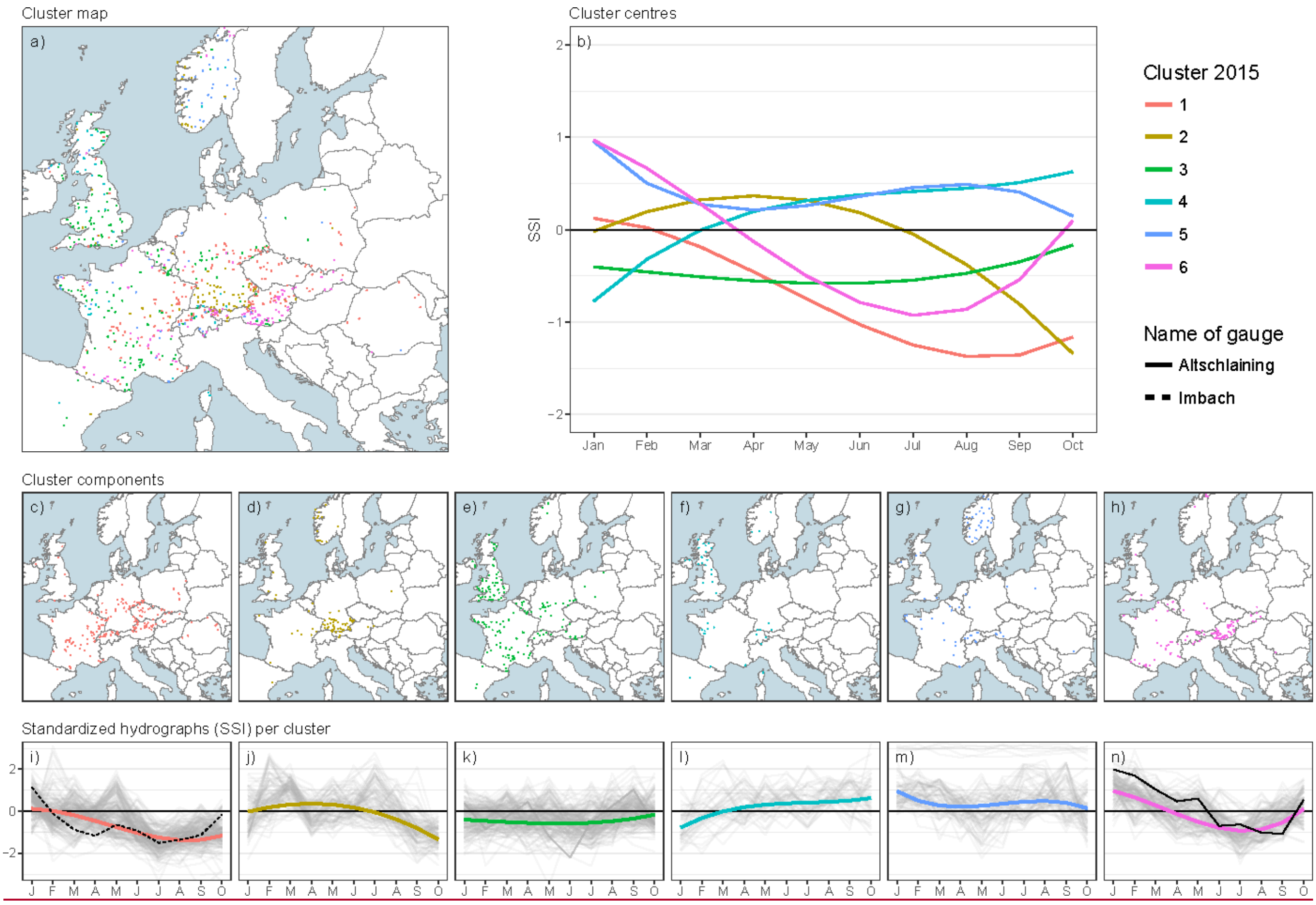


Figure 7. Clustering of the low flow event of 2015 based on monthly standardized streamflow index values SSI of the Jan – Oct period. a) combined cluster map showing allocation of catchments to the clusters, b) combined map of functional models of each cluster, c – h) cluster component maps, i – n) synoptic plots of standardized monthly hydrographs of Cluster 1 – 6 (thin black lines) together with the functional model of each cluster center (bold colored line). Altschlaining is marked by a bold black line, Imbach is marked by a dashed black line.

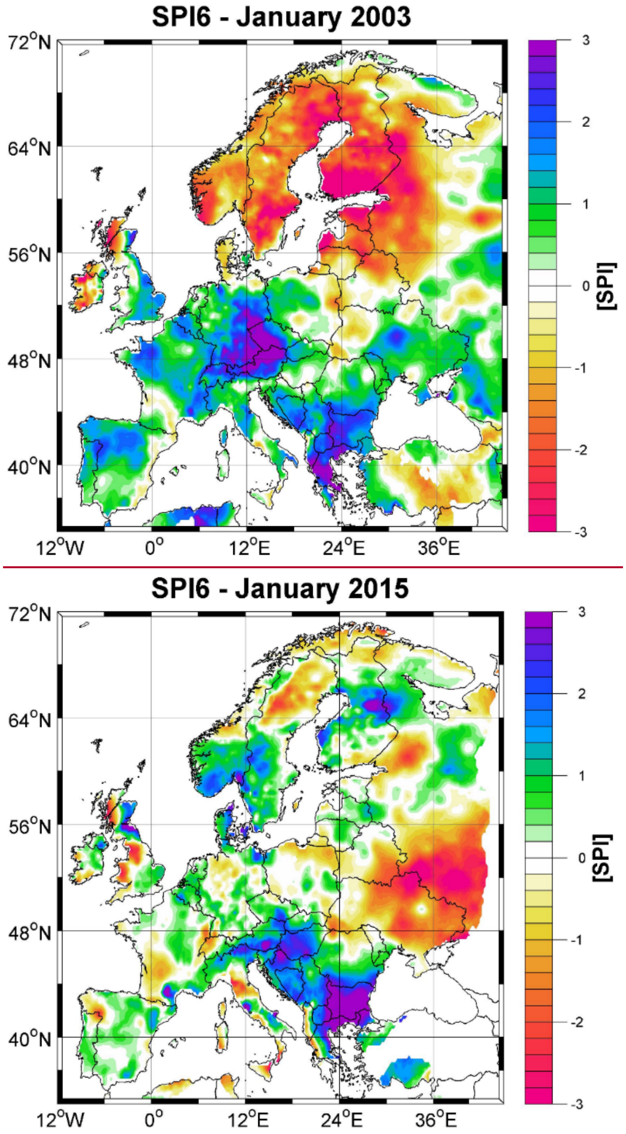


Figure 8. SPI6 for January 2003 (left) and January 2015 (right). Reference period 1971 – 2000.

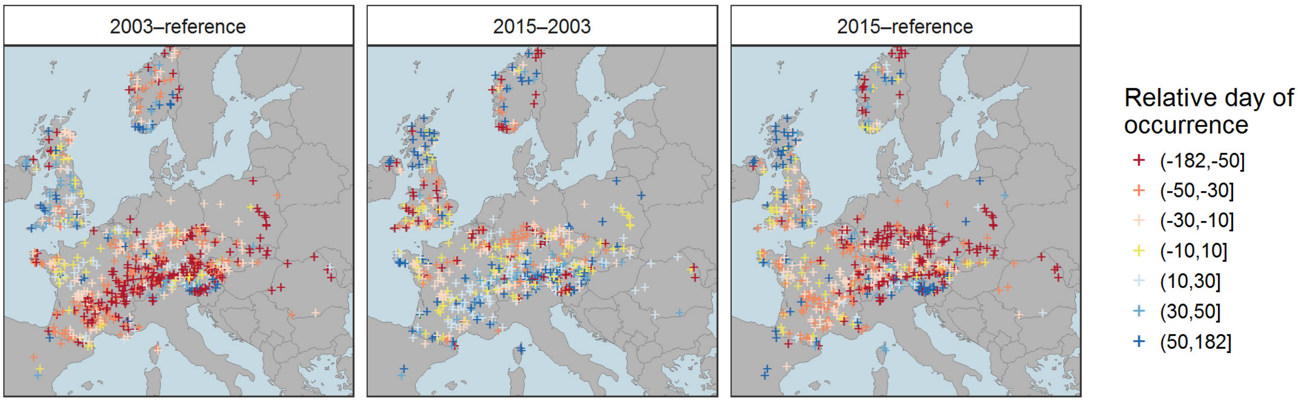


Figure 9. Relative day of occurrence Δ_τ of the onset of the events. Left panels, of 2003 with respect to the reference period, central panels, of 2015 with respect to 2003, and right panels, of 2015 with respect to the reference period. Earlier occurrence (red) relate to relatively drier preconditions in winter or spring. Later occurrence (blue) relate to relatively wetter preconditions.

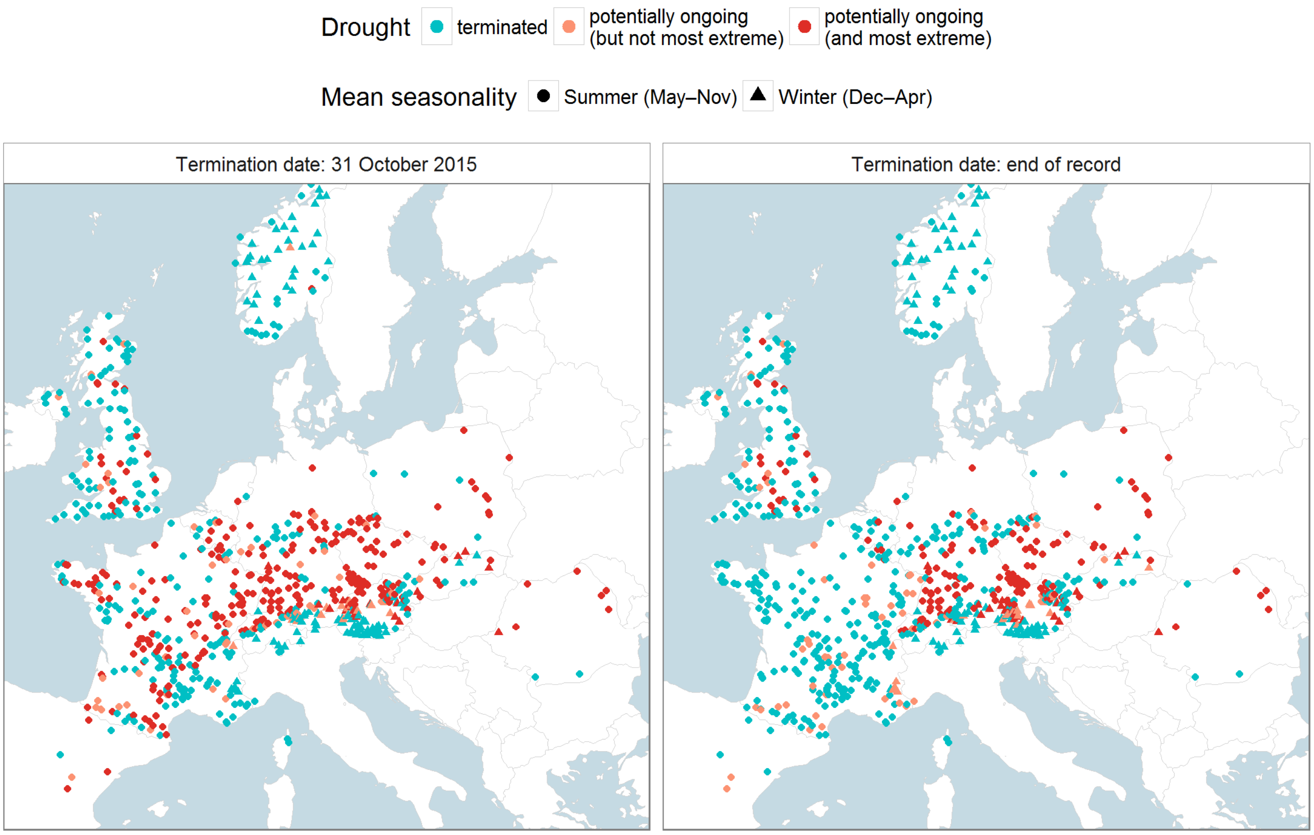


Figure ~~7~~10. Stations potentially under drought at common termination date 31 October 2015 (left) and at end of record (10 November 2015 – 6 February 2016, variable between gauges). Red points indicate that the catchment has not totally recovered from the summer drought so that an event just after the end of record would be pooled by the SPA pooling.

Appendix A

Table A1: Statistical summary of low flow and streamflow drought characteristics of the event of 2015 (top) and 2003 (bottom) by country. min, q25, q50, q75, and max refer to sample quartiles (with non-exceedance probabilities of 0, 0.25, 0.50, 0.75 and 1). These statistics are also displayed in the boxplots (right panels, where red color refers to low flow discharge AM(7), green: duration *D*, blue: deficit volume *V*, and grey lines mark return periods T = 1, 25, 50, 75 and 100 yr). Countries abbreviated by ISO2 codes.

	Discharge AM(7)					Duration D					Volume V				
	min	q25	q50	q75	max	min	q25	q50	q75	max	min	q25	q50	q75	max
2015															
AT	1.0	1.1	1.9	4.4	100.0	1.0	1.2	2.1	3.9	100.0	1.0	1.2	1.9	5.6	100.0
BE	1.4	2.6	3.2	73.2	100.0	1.2	2.8	3.6	6.0	17.9	1.2	3.0	4.9	11.5	22.6
CZ	2.5	59.3	100.0	100.0	100.0	1.3	10.0	12.6	16.2	24.2	1.5	23.3	31.9	37.5	100.0
FR	1.0	1.6	2.7	4.6	100.0	1.1	1.7	3.1	7.8	56.2	1.1	1.6	3.2	8.1	85.6
DE	1.0	2.8	7.9	18.0	100.0	1.0	3.0	6.1	10.9	29.3	1.1	4.2	7.8	21.7	100.0
NL	2.3	2.3	2.3	2.6	2.8	3.4	3.4	3.4	5.4	7.4	1.6	2.1	2.7	5.1	7.6
NO	1.0	1.0	1.1	1.4	27.8	1.0	1.1	1.1	1.5	6.0	1.0	1.1	1.1	1.3	8.3
PL	1.2	1.6	4.2	11.7	39.1	1.2	2.9	4.7	7.5	36.3	1.1	3.4	10.5	14.9	22.1
RO	1.7	7.0	9.6	100.0	100.0	1.2	2.4	6.8	12.1	100.0	1.2	4.7	18.3	26.3	100.0
SK	1.1	2.0	2.7	5.1	22.0	1.1	1.5	1.9	4.8	82.2	1.1	1.9	2.3	4.2	47.5
ES	1.3	1.4	1.9	2.4	100.0	1.2	1.2	1.2	1.4	3.5	1.2	1.2	1.3	1.8	4.5
CH	1.0	1.1	2.3	4.7	100.0	1.1	1.5	4.0	8.2	65.2	1.0	1.3	2.5	9.3	100.0
GB	1.0	1.2	1.6	2.3	9.7	1.0	1.2	1.6	2.5	17.1	1.0	1.2	1.5	2.2	8.7
2003															
AT	1.0	1.9	4.1	13.5	100.0	1.1	1.8	3.5	17.5	100.0	1.1	1.9	4.0	14.9	100.0
BE	1.2	2.0	2.9	5.3	100.0	1.1	2.5	6.4	13.4	30.4	1.2	2.1	5.2	16.9	46.0
CZ	2.4	6.3	10.2	21.0	100.0	4.7	8.8	14.4	29.5	34.2	2.9	12.3	20.6	33.0	57.4
FR	1.2	2.7	5.7	22.6	100.0	1.1	3.5	6.9	12.1	68.7	1.1	3.5	9.1	20.2	87.5
DE	1.1	3.9	8.4	26.7	100.0	1.2	6.6	13.3	24.1	69.3	1.2	7.7	15.6	33.5	85.4
NL	1.0	8.6	16.2	17.2	18.3	4.2	7.8	11.3	14.9	18.4	7.2	10.4	13.5	16.7	19.8
NO	1.0	1.4	2.1	3.4	100.0	1.0	1.4	2.2	4.4	97.7	1.1	1.7	2.3	4.0	41.9
PL	3.3	7.0	10.2	14.0	100.0	3.4	6.0	13.3	21.5	39.8	3.1	7.0	16.9	35.5	46.2
RO	1.7	2.9	4.1	15.3	100.0	1.5	3.5	5.0	13.4	31.5	1.4	3.3	4.8	16.1	62.1
SK	2.0	4.1	7.4	20.0	100.0	3.4	15.6	21.8	29.0	60.4	4.5	9.6	18.6	40.3	54.9
ES	1.0	1.6	1.8	1.9	2.6	1.1	1.2	1.6	1.7	3.9	1.1	1.4	1.4	1.5	6.4
CH	1.0	2.8	9.2	49.9	100.0	1.0	2.3	5.2	14.1	100.0	1.1	3.0	10.3	23.4	100.0
GB	1.2	2.2	3.1	5.9	100.0	1.2	2.6	4.6	11.6	79.8	1.2	2.7	5.2	11.5	85.1

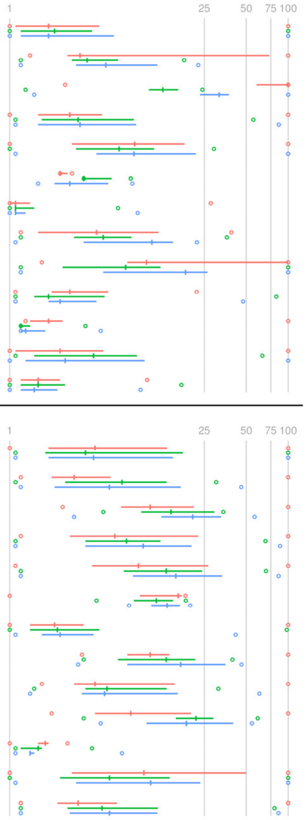


Table A2: Statistical summary of low flow and streamflow drought characteristics of stations with predominant summer seasonality: 2015 (top) and 2003 (bottom). Symbols and legend are those of Table A1.

	Discharge AM(7)					Duration *D*					Volume *V*				
	min	q25	q50	q75	max	min	q25	q50	q75	max	min	q25	q50	q75	max
2015															
AT	1.0	2.2	3.5	11.1	100.0	1.1	2.4	3.8	6.3	12.6	1.1	2.1	4.7	10.0	51.8
BE	1.4	2.6	3.2	73.2	100.0	1.2	2.8	3.6	6.0	17.9	1.2	3.0	4.9	11.5	22.6
CZ	2.5	59.3	100.0	100.0	100.0	1.3	10.0	12.6	16.2	24.2	1.5	23.3	31.9	37.5	100.0
FR	1.0	1.7	2.7	4.8	100.0	1.1	1.8	3.3	7.9	56.2	1.1	1.6	3.2	8.3	85.6
DE	1.1	3.5	8.7	21.2	100.0	1.1	3.6	6.7	11.2	29.3	1.1	5.4	8.3	23.8	100.0
NL	2.3	2.3	2.3	2.6	2.8	3.4	3.4	3.4	5.4	7.4	1.6	2.1	2.7	5.1	7.6
NO	1.0	1.1	1.1	1.3	3.1	1.1	1.1	1.1	1.6	2.3	1.0	1.1	1.1	1.4	3.2
PL	1.2	1.7	4.4	12.6	39.1	1.2	2.5	4.6	6.6	36.3	1.1	3.8	10.7	15.2	22.1
RO	1.7	8.5	39.3	100.0	100.0	1.2	3.9	8.8	14.4	100.0	1.2	8.1	21.3	36.9	100.0
SK	1.2	2.4	3.6	5.1	22.0	1.1	1.5	1.9	6.5	82.2	1.1	2.0	2.4	5.0	47.5
ES	1.3	1.4	1.9	2.4	100.0	1.2	1.2	1.2	1.4	3.5	1.2	1.2	1.3	1.8	4.5
CH	1.0	1.6	3.3	5.6	100.0	1.3	1.9	5.2	11.5	65.2	1.3	2.1	4.2	11.4	100.0
GB	1.0	1.2	1.6	2.3	9.7	1.0	1.2	1.6	2.5	17.1	1.0	1.2	1.5	2.2	8.7
2003															
AT	1.2	4.8	12.3	26.6	100.0	1.1	6.7	15.2	29.0	92.7	1.1	6.3	15.7	23.8	100.0
BE	1.2	2.0	2.9	5.3	100.0	1.1	2.5	6.4	13.4	30.4	1.2	2.1	5.2	16.9	46.0
CZ	2.4	6.3	10.2	21.0	100.0	4.7	8.8	14.4	29.5	34.2	2.9	12.3	20.6	33.0	57.4
FR	1.2	2.9	5.7	22.8	100.0	1.1	3.6	7.2	12.2	68.7	1.1	3.8	9.4	20.3	87.5
DE	1.2	4.3	9.1	26.5	100.0	1.2	7.1	15.2	24.9	69.3	1.2	7.8	17.3	34.4	85.4
NL	1.0	8.6	16.2	17.2	18.3	4.2	7.8	11.3	14.9	18.4	7.2	10.4	13.5	16.7	19.8
NO	1.1	1.3	1.7	2.5	8.1	1.1	1.4	1.9	2.7	67.8	1.1	1.3	1.8	2.3	6.3
PL	3.4	7.2	10.4	16.1	100.0	3.4	7.0	17.7	23.0	39.8	3.1	8.6	18.0	36.1	46.2
RO	1.7	2.7	5.1	16.9	100.0	1.5	3.5	7.7	16.5	31.5	1.4	4.0	10.4	16.1	62.1
SK	2.0	4.6	9.2	27.7	100.0	3.4	12.6	22.3	29.0	60.4	4.5	9.0	22.7	40.3	54.9
ES	1.0	1.6	1.8	1.9	2.6	1.1	1.2	1.6	1.7	3.9	1.1	1.4	1.4	1.5	6.4
CH	1.3	5.0	12.9	56.6	100.0	1.9	2.6	8.9	16.0	100.0	1.4	4.0	12.4	26.8	100.0
GB	1.2	2.2	3.1	5.9	100.0	1.2	2.6	4.6	11.6	79.8	1.2	2.7	5.2	11.5	85.1

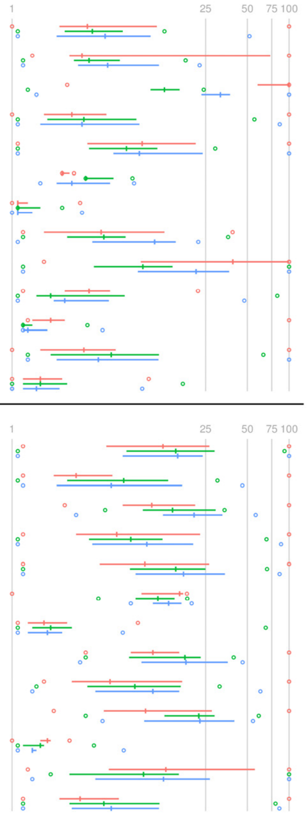


Table A3: Statistical summary of low flow and streamflow drought characteristics of stations with predominant winter seasonality: 2015 (top) and 2003 (bottom). Symbols and legend are those of Table A1.

	Discharge AM(7)					Duration *D*					Volume *V*				
	min	q25	q50	q75	max	min	q25	q50	q75	max	min	q25	q50	q75	max
2015															
AT	1.0	1.0	1.2	2.1	100.0	1.0	1.1	1.3	2.2	100.0	1.0	1.1	1.2	1.9	100.0
FR	1.1	1.1	1.5	1.9	2.0	1.1	1.3	1.5	2.2	2.9	1.1	1.3	1.4	1.8	2.2
DE	1.0	1.1	1.4	2.5	13.5	1.0	1.1	1.5	1.6	3.9	1.1	1.1	1.2	2.2	10.1
NO	1.0	1.0	1.1	1.4	27.8	1.0	1.1	1.1	1.5	6.0	1.0	1.1	1.1	1.2	8.3
PL	1.4	1.4	1.4	1.4	1.4	11.1	11.1	11.1	11.1	11.1	3.1	3.1	3.1	3.1	3.1
RO	2.1	2.1	2.1	2.1	2.1	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
SK	1.1	1.8	2.2	5.5	14.5	1.1	1.6	2.0	2.8	4.2	1.1	1.8	2.1	3.5	7.4
CH	1.0	1.0	1.1	1.1	3.2	1.1	1.1	1.1	1.2	6.4	1.0	1.1	1.1	1.1	2.2
2003															
AT	1.0	1.4	2.3	4.4	100.0	1.1	1.4	2.0	3.6	100.0	1.1	1.5	2.1	3.8	100.0
FR	1.3	1.5	2.2	7.5	28.3	1.2	1.2	1.5	1.6	3.0	1.2	1.3	1.8	2.2	3.0
DE	1.1	1.9	3.1	32.5	100.0	1.6	1.9	3.2	11.8	47.0	1.3	2.2	2.5	22.1	55.6
NO	1.0	1.6	2.2	3.6	100.0	1.0	1.6	2.6	5.7	97.7	1.1	1.8	2.8	4.5	41.9
PL	3.3	3.3	3.3	3.3	3.3	3.5	3.5	3.5	3.5	3.5	5.8	5.8	5.8	5.8	5.8
RO	4.1	4.1	4.1	4.1	4.1	4.3	4.3	4.3	4.3	4.3	3.3	3.3	3.3	3.3	3.3
SK	2.8	3.6	4.9	8.9	18.0	15.7	16.0	19.5	27.4	40.6	8.6	10.8	16.1	27.2	46.9
CH	1.0	1.2	1.4	1.8	4.9	1.0	1.1	1.2	2.9	4.6	1.1	1.1	1.3	2.6	23.4