The European 2015 drought from a hydrological perspective

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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 of 2015 relative to the event of 2003 based on streamflow observations. Analyses are based on range of low flow and hydrological drought indices for about 800 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 hydrological drought of 2015 is characterised by a different spatial extent than the drought of 2003. In terms of low flow magnitude, a region around the Czech Republic was most affected with annual 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 Germany where the drought lasted particularly long. A detailed assessment at various spatial and temporal scales showed that the different behaviour in these regions was also a result of diverging wetness preconditions in the catchments. Extreme droughts emerged where antecedent conditions were particularly

dry. In regions with wet preconditions, low flow events developed later, and were mostly less severe. The space-time patterns of monthly low flow characteristics show that meteorological and hydrological events spread differently across Europe, and they evolved differently in regard to extent and severity. The 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 dynamic

5 development of major hydrometeorological characteristics, temperature and precipitation anomalies versus the streamflow magnitude, duration and deficit volume also determine differences in the impacts of hydrological drought on various water use sectors and on river ecology. For an assessment of drought impacts on water resources, therefore, hydrological data is required in addition to the hydro-meteorological drought indices. Additional efforts with a pan-European dimension need to be undertaken to make timely hydrological assessments more operational in the future.

10 **1 Introduction**

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

15 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

20 needs a thorough analysis.

For the event of 2015, some reviews of 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

25 mentioned 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) 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. Because of a lack of observed pan-European near-time hydrological data, a thorough analysis of the hydrological dimension of the event is hardly possible today.

30 As a consequence, often meteorological (and not hydrological) indices are used preferentially to describe the spatial-temporal characteristic of drought.

It is indeed important to analyse droughts from a climactic perspective. In a companion paper to this study (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, 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

5   warmer than the seasonal mean (1971 – 2000). Atmospheric indices such as the standardized precipitation evaporation index (SPEI) show 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 central and eastern Europe. In August 2015, precipitation events occurred over SW-Europe while meteorological drought conditions persisted in eastern

10 Europe and, notably, in central Europe where the drought lasted longest. SPEI values as low as -4 were recorded, and the most extreme values 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 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

15 would expect severe hydrological impacts as well.

Although hydrological drought is driven by anomalous atmospheric conditions, many 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

20 (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). 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.

In this study, we analyse the European drought of 2015 from a hydrological perspective based on streamflow observations.

25 Such an analysis is challenging for several reasons. First, and foremost, the analyses require up-to-date streamflow records across Europe. However, to date, no publicly available pan-European databases that include near-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

30 need to be made comparable across European regimes. 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 of members of UNESCO's EURO FRIEND-Water program (IHP-VIII, UNESCO, 2012). Our study focuses on low flow events, characterised by recognised methods including annual minimum discharges and drought duration and deficit below a constant 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 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 2003, which is often perceived as a worst-case benchmark? (iii) How similar or different are the hydrological footprints of these events to the meteorological footprints? (iv)

5   What are the implications of possible differences for drought impacts on environment, society and economy?

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 study and present the assessment method. Section 4 presents results that characterise the event of 2015 relative to the 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

10   move to a regional scale in order to elaborate specifics of drought events in more detail. The spatio-temporal development is assessed from maps of indices on a monthly scale, before analysing the "local fingerprints" of the drought from daily hydrographs at the catchment scale. We finally seek to generalize local process understanding using seasonality as an indicator of processes. Section 5 presents an in-depth discussion of the results. This includes a comparison of the hydrological footprint sketched from all analyses with the atmospheric footprint from the study of the meteorological drought of 2015 by Ionita et al.

15   (2016).

2 Data collation strategy

Severe droughts are characterised by a large spatial scale 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 are still major

20   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

25   past rather than for monitoring the 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 2 – 3 years after recording make these archives inappropriate for a timely assessment of 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. Instead of collecting streamflow records, we collect low

30   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 are fully described in the WMO manual on low flow estimation and prediction (Gustard and

5 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 volume. The package uses a robust approach based on L-moments to fit extreme value distributions (Hosking and Wallis, 2005). It contains methods 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

10 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 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-

15 term average conditions. The year 2015 is then compared to the characteristics of the reference period. 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

20 Lanen, 2004; Laaha et al., 2013; Smakhtin, 2001). First, the magnitude of low flow discharges is important, which may be characterised by annual minimum flows or flow quantiles with high exceedance probability. Second, the timing of low flows is important. It may be characterised by a monthly low flow index, such as the monthly 7-day minimum flow MM(7), or seasonality indices 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

25 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 be associated with impacts on different water-related sectors. In this study, we therefore calculate a 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).

5   ### 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

10   to identify the largest absolute dry states 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

15   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 two droughts are pooled if the catchment 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 volume per year is selected. This annual event

20   is described by two characteristics: drought duration (D in days) and deficit volume (V in m³). As these indices refer to the most severe event per year, they present 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

25   the pooled 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, we compute the difference between start date of an event relative to the other, and 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 return periods of the low flow and drought characteristics to analyse their severity for a given event (here

30   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 series AES. Note that low flow discharges AM(7) present annual minima series, whereas drought characteristics D,V present annual maxima series.

(2) Fit the theoretical extreme value distribution on AES based on L-moments. For annual minima AM(7) we use the 3-parameter Weibull distribution; for annual maxima we use the General Extreme Value Distribution. 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 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 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.

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 low flows in 2003 covered most of Europe, from central France to N-Poland and continuing towards southeast of the Alps, 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 data. The drought of 2015 was, within the study area, less spatially extensive and showed a dipole effect: 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 more severe than in 2003 in some areas around the Czech Republic, SE-Germany and N-Austria while drought 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 indices such as SPI3 and SPEI3 (Ionita et al., 2016) suggest that the drought-affected area 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 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 more homogeneous patterns than the magnitude of low flows in drought-affected regions. The return periods of durations 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, 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 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 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, with the largest deficits (S-Germany) west of the area with lowest flows (Fig. 1, compare right and left panels). In regions where the drought event was short, such as central France and NE-Austria, deficit volumes are low regardless of AM(7). For drought-affected areas, the volume exhibits a rather patchy pattern that arises from the similar 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 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 AM(7) (magnitude) and drought deficit volumes for each of the regions. Catchments with a winter low flow regime are presented in separate box-plots, as extreme low flows generally do not occur in summer. Overall, the regional distribution of return periods are broader for AM(7) than for deficit volume. AM(7) generally shows higher return periods.

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 yr). In 2015, volumes have a higher severity (T_{med} = 31.4 yr) and AM(7) were often significantly below the recorded minima in the reference period and associated return intervals of more than 100 years. Note however that due to the length of record to estimate the 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 return periods in AM(7) (often 100 yr and more) and quite 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 more severe in terms of volume.

S-Germany, geographically between the Czech Republic and E-France, experienced similar severity for both events: AM(7) were slightly lower in 2003 (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 2003, and 25.4 yr for 2015 the return periods correspond always to those of the more affected neighbour, E-France in 2003 and Czech Republic in 2015. Obviously, the region is 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.

5 **4.3 Spatio-temporal development**

Figure 3 and Table 1 show the spatio-temporal development of 2015 and 2003 drought based on each flow record's low flow discharge MM(7) (monthly magnitude) during each month. 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

10 the affected stations. Similar methods of display are used by some national or 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, 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}. However, onset was more dramatic in 2003, covering more quickly and more homogeneously a larger region. Interestingly, the regions that were first affected are consistent with the

15 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, the full spatial extent of both droughts was already reached. This is also reflected in the monthly number of stations under drought presented in 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

20 affected regions returned to more moderate conditions. 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 remained under mild drought conditions. In 2015, the peak occurred 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 slower than 2003.

25 **4.4 Local fingerprint**

The analyses so far have shown that a band north of Alps was affected by the 2015 drought, but the severity of the event differs between regions. Overall, the band corresponds well with meteorological drought indices at the peak of the event. However, they cannot explain the regional differences in hydrological drought. For instance, at the eastern end of the Alps, N- and E-Austria exhibit similar precipitation anomalies, temperature anomalies and SPI3 values for the summer drought season (JJA)

30 (Ionita et al., 2016). Nevertheless, there are striking differences in low flow discharges and volumes. A closer look is needed to determine 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 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 formations in the other part of the catchment. The gauge represents a region that fell extremely dry in 2003 but

5 exhibited no severe low flows in 2015. Figure 4 shows that the reason for the contrasting behaviour can be found in the conditions before the summer event. For the 2003 event discharge anomalies already occurred during winter and spring season. This is clearly indicated by the hydrograph which followed 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 the beginning of May. The atmospheric summer drought exacerbated the hydrological situation and yielded to lowest

10 discharges since beginning of records. For 2015, the atmospheric situation in summer was comparable to 2003 in this region, as it is visible from small inter-annual differences of August-SPEI3 in Fig. 11e of Ionita et al. (2016). However, the hydrographs start at a much higher level, pointing to very wet preconditions. Until June streamflow remained above the average seasonal regime (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

15 of a more extreme low flow event.

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 fell only moderately dry in terms of magnitude in both years, 2015 and 2003. However, Fig. 5 shows contrasting recession behaviour due to different preconditions. This region was heavily affected by the flood event in August 2002 (caused by massive precipitation).

20 Streamflow started to reduce in winter, but remained above seasonal average conditions (Q_{50s}) until April. In spring, discharge was only at the limit to seasonal drought conditions, and there were still enough stored water resources to sustain streamflow in summer 2003. The 2015 low flow event, on the other hand, is characterised by dry preconditions in winter. However, there were several rainfall events in spring, which are reflected by a number of pronounced streamflow peaks. The precipitation events delayed streamflow recessions and prevented more severe low flows in summer.

25 **4.5 Effect of seasonality**

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

30 (day of occurrence Δ_τ) of the onset of both events (Fig. 6). We make the following observations:

(1) Overall, the spatial pattern of the 2003 and 2015 events show that both have a much earlier onset than the long-term average onset of low flow events. It is the early onset of drought conditions that increases the risk of running into a severe low flow event when the catchment is exposed to an extreme meteorological drought. In 2003 these preconditions were present on a

much larger scale than in 2015. Given the similar 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 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 notably early onset of the event of more than 50 days before the long-term

5   average. In 2003, the same region had a later onset and presented more moderate low flow conditions. In 2003, the focus was in central France and E-Austria and, again, the area is marked by a very early onset. We observe that the focal region of the drought event is always the one with the earliest onset.

(3) The regional differences in the onsets between both years (central panel) are closely related to the relative severity of events in terms of annual minimum flows (magnitude) (Fig. 1). The band crossing central Germany is marked by reddish colours,

10   indicating a somewhat earlier onset of the 2015 event, where low flows were mostly more severe 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 less severe in 2015. The same indication is given for the part of southern Europe covered by the study, which shows blue colouring in 2015.

5 Discussion

15   ### 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 the large spatial and temporal scale of drought events causes large areas to be affected and this over a long time. All mitigation measures taken on a European or regional level to reduce risks require timely and accurate information about the

20   physical system. Despite that, a timely analysis of the hydrological situation is difficult to make on a 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 unique

25   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.

Despite these merits, the study has clearly a number of 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 could not be filled, or where it may not be meaningful to use streamflow data as a drought indicator (e.g. for intermittent rivers in semi-arid regions

30   and in highly regulated river systems). For these areas meteorological data may still be the more useful readily available information. In the case of the drought of 2015, climate indices such as SPEI3 for August suggest that the south and south-east had relatively wet conditions so the lack of information in those regions may not have large consequences in the interpretation

of the hydrological drought analysis results. For 2003, however, it was the south-east of Europe which was particularly affected, and analysis of hydrological data would require further collaboration and 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 end of the drought for some sites: for example in the major rivers Rhine and Danube and some gauges

5   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 (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 in the northern pre-Alps are much smaller and therefore react quickly to autumn precipitation, but here summer low flows are often followed by frost what leads to a late seasonality of low flow events. Here

10   the lowest flows generally occur in October and November (Laaha and Blöschl, 2006). Hence it is likely that the situation was 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 shows the stations that are potentially still under drought, since the SPA method store has not totally recovered

15   from the summer drought at the end of the study period (31 October 2015). For these stations, the analysis of deficit characteristics for 2015 may be incomplete. Durations are 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 in this study to be more

20   representative for the full 2015 event than drought durations, which may mainly be 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. Besides the

25   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

30   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

5   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

10   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

15   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

20   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

25   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

30   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

5   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

10   (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

15   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 analysis, it appears that the hydrological event had a

20   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 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 storage and release properties of the catchment are critical in influencing the temporal development of summer

25   droughts. 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 of the catchment determine the reaction time of discharges to the atmospheric water deficit. It is the effect of initial conditions and catchment functioning, superimposed with the atmospheric signal that explains hydrological drought.

5.4 Implications for water management

30   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 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 from similarity and differences of both events. Our findings may contribute to drought-related water management in several ways.

Firstly, the finding to what extent extreme droughts are conditional to winter and spring conditions is important for early warning and risk assessment. Hydrological events differ from atmospheric events because catchments collect and retain

5   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 the genesis of a drought. This was born out by the example of the Imbach catchment (for both events) and the Altschlaining catchment (for 2015), where water from stored sources sustained

10   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 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), can offer relevant tools for early detection of potential drought-affected regions. At

15   least for the events analysed in this study, the regions that were later most affected by the drought were always marked by unusually low spring discharges and an early onset of the low flow event. One may expect that these indications are significant for other extreme events as well, but this requires testing in additional studies. The dynamics of drought events in atmosphere and land seem to contain a wealth of information whose better exploitation may contribute to both improved models and better-informed decisions in water management.

20   Secondly, drought impacts are in majority not simply caused by a lack of rainfall, but also by a lack of the relevant water resource, timing of rainfall, streamflow and groundwater deficits, and sometimes by a direct effect of heat exposure as well. In drought management, different kind of indices at various temporal scales have been considered. 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 when one aims to optimize irrigation water. Hydrological indices,

25   on the other hand, are more relevant for a number of other water management tasks, such as related to hydropower and navigation, but also for water quality, in-stream ecology and aquaculture. For the latter, low flow discharge during summer heat periods will be critical, as high solute concentrations at higher temperature will yield a cascade of hydrochemical processes with adverse effects on water quality. For navigation, the duration of critical levels will matter, while for hydropower production the total deficit over the event will determine the economic losses. In absence of groundwater data, deficit volumes,

30   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.

Characterising events in a way that is relevant for drought management requires timely pan-European data to be made publically available. Such data sets 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 monitored and also need to be understood from both a hydrological and climatic perspective. Current research is fragmented in different disciplines

5 with partly different perceptions, with studies either focusing on the atmospheric side or on the hydrological side. In our collaborative paper project within the EURO FRIEND-Water network we aimed at an integral view from climatologists and hydrologists from various countries. This setting is rewarding as it fostered the exchange of ideas, and thereby enables additional insights in the interaction of atmospheric drivers and catchment processes across regions that would not have been gathered otherwise. This is especially important when investigating drought because of its large spatial and temporal scale that

10 crosses borders and disciplines. 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 about drought processes and how to best characterise them by indices. The dialogue between disciplines may yield to the design of 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 indices that are more operational and more relevant for

15 drought impacts. Another gap in our knowledge that requires interdisciplinary research is the role of land-atmosphere feedbacks in drought generation. They may be important to understand persistency of events and the new knowledge may feed into 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

20 into disciplines. Communities need to move closer together to further enhance our understanding of hydrometeorological 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 analysis was based on a range of low flow indices calculated

25 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 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 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 100 years in a focal area from Czech Republic, SE-Germany and N-Austria.

30 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 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 in the catchments. Selected hydrographs provided exemplar local

5   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 less severe. Overall, preconditions are therefore a most likely explanation for the geographical pattern of onset, scale, and severity of the drought within regions. Moreover, the focal region of the drought event coincides with the region with the earliest onset.

10   The results of this study therefore show 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.This finding has implications for the prediction and management of the impacts of hydrological drought, which the event of 2015 illustrated in a manifold way. Using a single meteorological drought index such as SPEI may not suffice as a drought indicator in this respect. For many sectors suffering

15   from long-term accumulated deficits streamflow and groundwater hydrological indices will be more relevant. A more targeted 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 European Drought Observatory (http://edo.jrc.ec.europa.eu), but largely unavailable for free for timely science. 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

20   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-time hydrological data available across borders in order to make drought management more operational in the future.

Acknowledgements

25   This study was conceived by a team of European drought experts from the UNESCO EURO FRIEND-Water Low Flow and Drought network, which enabled collection of near-real time hydrological data and impact reports across Europe that otherwise, would have been impossible. This research supports the work of the UNESCO-IHP VIII FRIEND-Water programme. Data provision by national hydro-meteorological services was highly appreciated. Funding from ACRP project DALF-Pro (GZ B464822) is gratefully acknowledged. The paper is dedicated to Dr. Alan Gustard (Institute of Hydrology /

30   Centre for Hydrology and Ecology, Wallingford, UK), one pioneer of transboundary low flow research who inspired this community effort to overcome data barriers across Europe and beyond.

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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
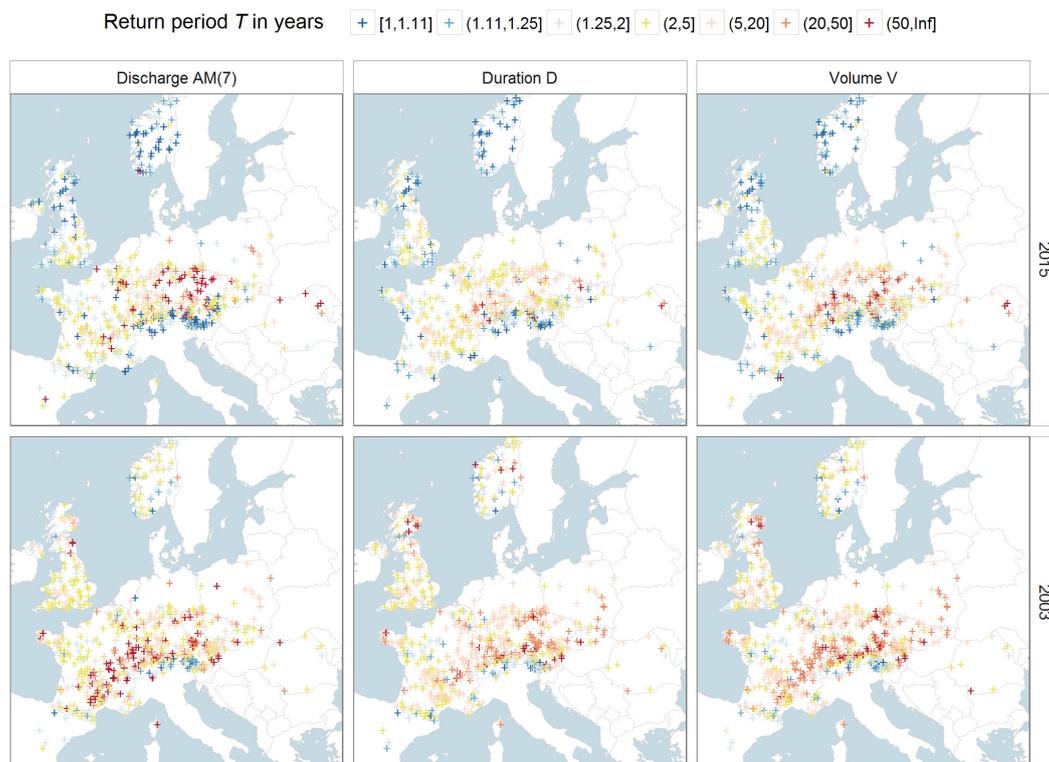
Figure 1. Return periods T (in yrs.) of annual low flow discharge AM(7) (left), duration D (centre) and deficit volume V (right panels) for the events of 2015 and 2003. Low flows and drought conditions below average conditions (return period > 2 years) are indicated by yellow to reddish colours. Severe events (return periods (20,50] and (50,Inf] yrs.) are indicated by orange and red colours.
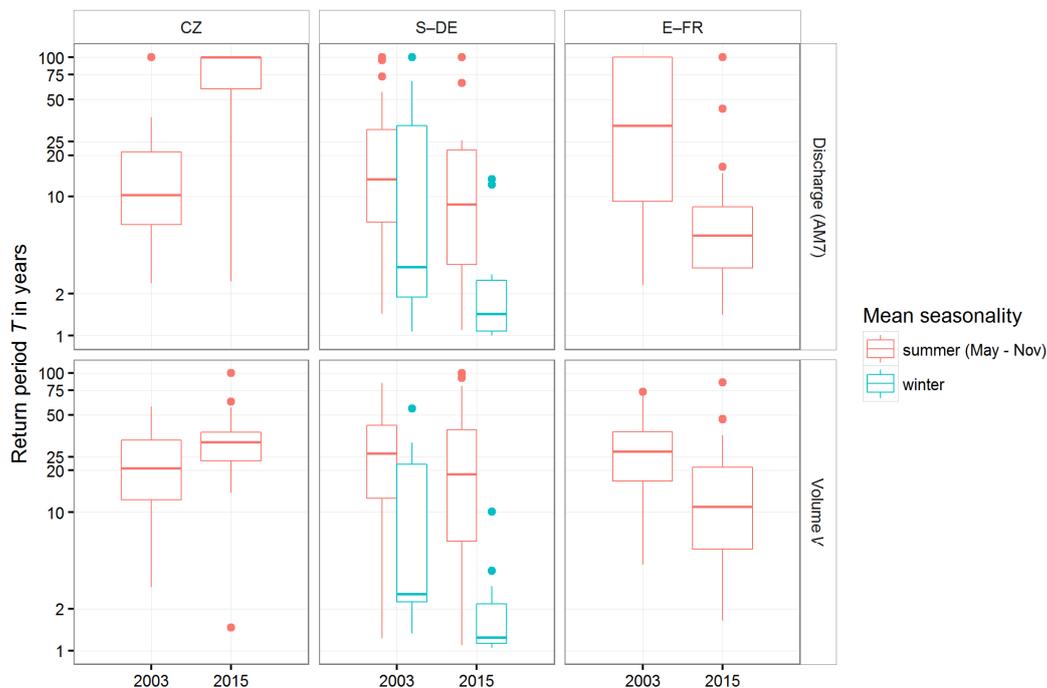
Figure 2. Regional distribution of return periods T (in yrs.) of low flow discharge AM(7) (upper panels) and deficit volume V (lower panels) for the Czech Republic (left), S-Germany (centre) and E-France (right) (return periods > 100 yrs. not shown).

5   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 return periods. Return periods of about 2–10 years represent mild drought conditions, 10-50 years moderate conditions, 50-100 years severe conditions, and >100 years extreme conditions.
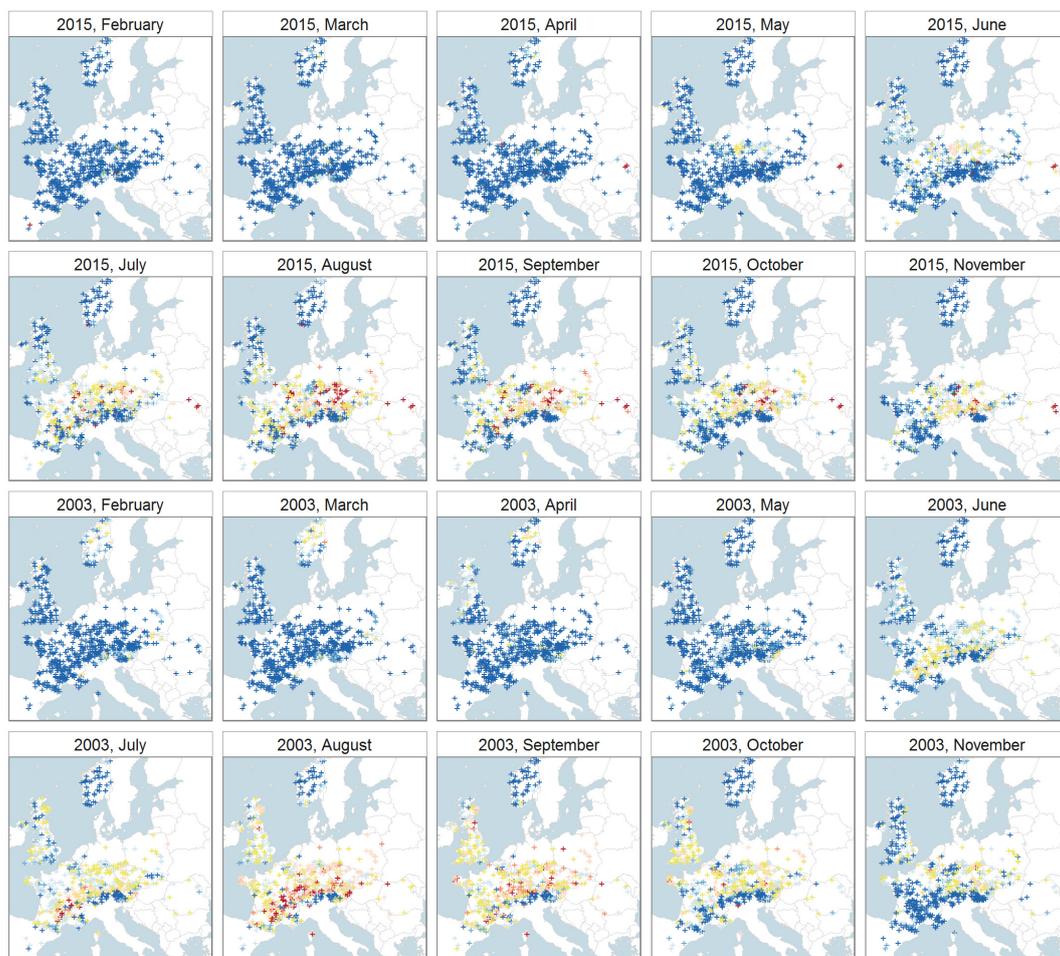
Figure 3. Return period T (in yrs.) of monthly 7-day minimum flows MM7. Colour codes are those of Fig. 1.
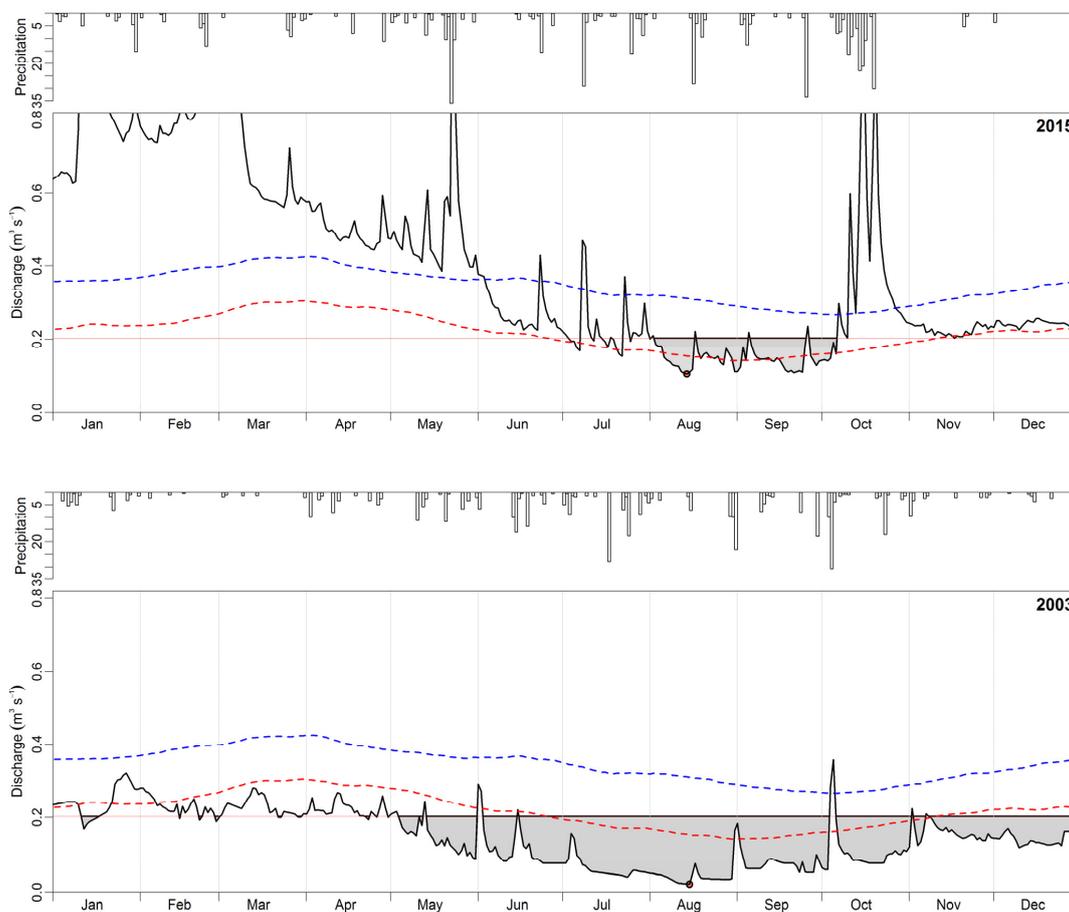
Figure 4. Hydrograph of gauge Altschlaining at river Tauchenbach in Austria (black line, large panels). Preconditions in 2015 were much wetter than in 2003. The grey polygon indicates the maximum annual low flow event below the annual threshold

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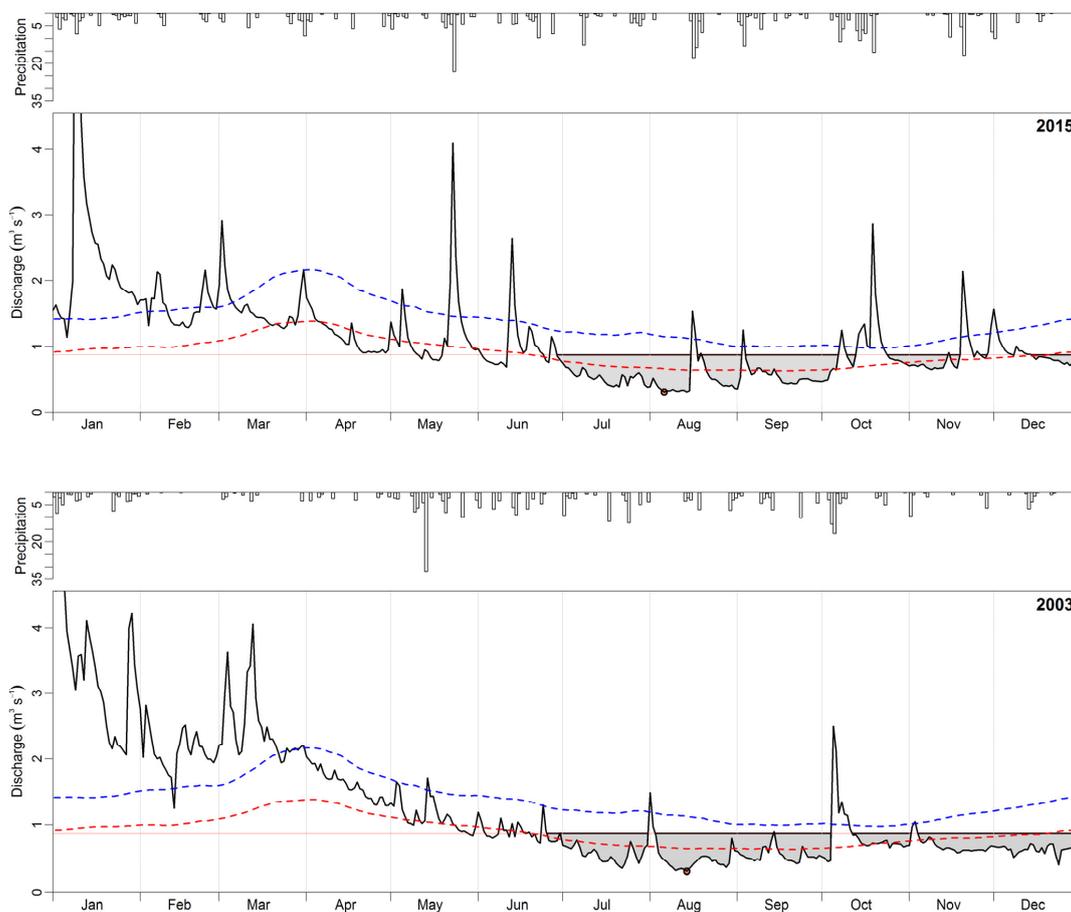
Figure 5. Hydrograph of gauge Imbach at river Krems, N-Austria (black line, large panels) together with weekly precipitation sums (mm, smaller panels above the hydrograph). Preconditions were much drier in 2015 than in 2003. Same signatures as

5   Fig. 4.
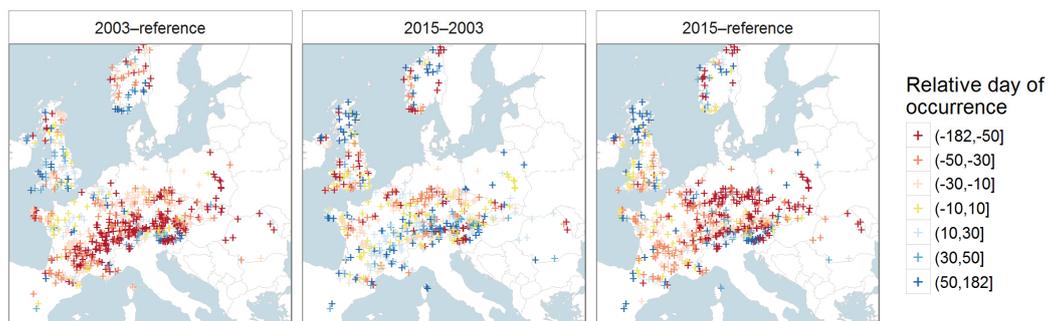
Figure 6. Relative day of occurrence $\varDelta_\tau$ of the onset of the events. Left panels, of 2003 with respect to the reference period, central panels, of 2015 with respect to 2003, and right panels, of 2015 with respect to the reference period. Earlier occurrence (red) relate to relatively drier preconditions in winter or spring. Later occurrence (blue) relate to relatively wetter preconditions.
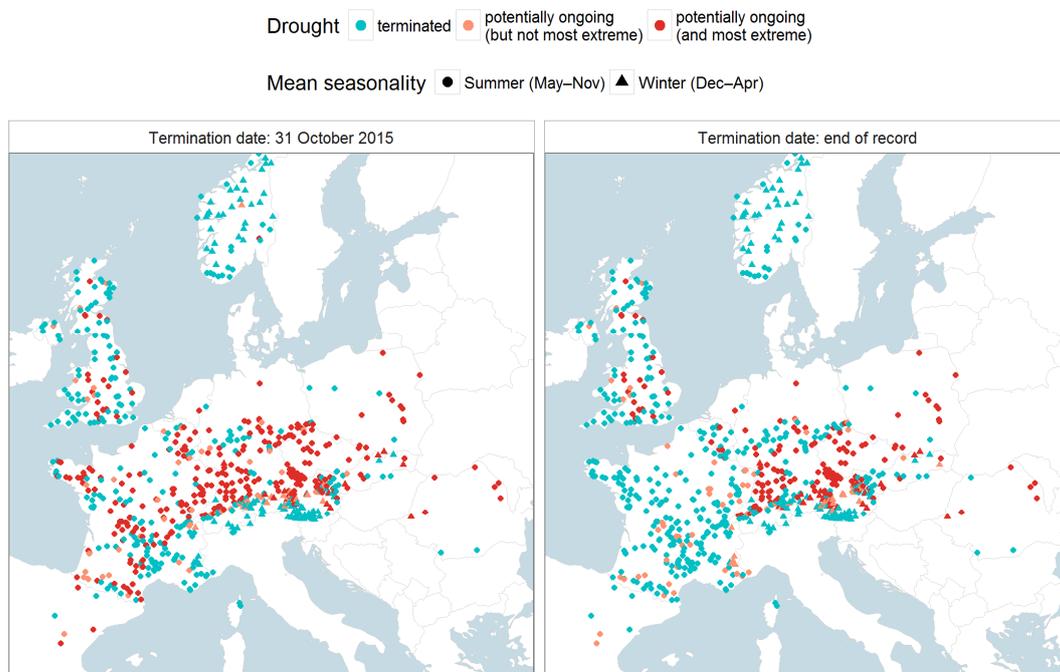
Figure 7. Stations potentially under drought at common termination date 31 October 2015 (left) and at end of record (10 November 2015 – 6 February 2016, variable between gauges). Red points indicate that the catchment has not totally recovered from the summer drought so that an event just after the end of record would be pooled by the SPA pooling.