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# Exploring the added value of a long-term multidisciplinary dataset in drought research - a drought catalogue for southwestern Germany dating back to 1801

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**Abstract.** Droughts are multidimensional hazards that can lead to substantial environmental and societal impacts. To understand causes and impacts, multiple variables need to be considered. Many studies identified past drought events and investigated drought propagation from meteorological droughts via soil moisture to hydrological droughts and some studies have included the impacts of these different types of drought. Here, we analyse different droughts and their impacts in a regional context using a multidisciplinary approach and compiled a comprehensive and long-term data set to place recent drought events into a historical context. We assembled a dataset of drought indices and recorded impacts over the last 218 years in southwestern Germany. Meteorological and river-flow indices were used to assess the natural drought dynamics. In addition, tree-ring data and recorded impacts were utilized to investigate drought events from an ecological and social perspective. Since 1801, 20 extreme droughts were identified as common extreme events when applying the different indicators. All events were associated with societal impacts. Our multi-dataset approach provides insights into similarities but also the unique aspects of different drought indices and highlights the unprecedented frequency and severity of droughts in the 21st century.

## 1 Introduction

Droughts are natural hazards with widespread negative consequences for environment and society. These consequences are the result of the physical drought hazard and of the underlying socio-economic and ecological vulnerabilities. Hence the impacts depend on the resilience of natural and man-made systems to drought. While the hazard aspect of drought events is

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generally well understood, our understanding of vulnerability to drought is still limited. Also, comprehensive information on past drought impacts is still missing (van Lanen et al., 2016, Kreibich et al., 2019). To fully understand past drought events, a multi-perspectives approach is essential. In particular the development of plans to manage future droughts will benefit from synthesis and understanding of the complex patterns of past droughts across different sectors that may be impacted.

As droughts are rare and irregular extremes, it is essential to analyze drought from a long-term perspective**.** Due to the high natural variability in precipitation patterns, the influence of climate change on future drought is still difficult to detect (Seneviratne et al., 2012). Knowledge of historical droughts is needed to assess the severity of current and future drought events. For such comparisons, catalogues of drought events have been developed in many countries. For example, European summer droughts during the last two millennia were identified and catalogued based on tree-ring reconstructions by Cook et al. (2015). A global database of meteorological drought events from 1951 to 2016 has been provided by Spinoni et al. (2019). For Ireland, a meteorological drought catalogue exists for the last 250 years using reconstructed precipitation series as well as documentary sources from newspaper archives (Noone et al., 2017) and for the Czech Republic drought events were catalogued using documentary evidence and meteorological records (Brazdil et al., 2013). A systematic characterisation of historical hydrological droughts (1891 to 2015) for a diverse set of catchments exists for the UK (Barker et al., 2019). All these catalogues depict mainly one or two types of drought based on individual (e.g., tree-ring based) indicators.

As droughts are multifaceted hazards which affect all components of the water cycle, multidisciplinary approaches to assess droughts are needed. Different drought types using a variety of drought indices provide an understanding of drought severities and intensities (van Loon et al., 2016). Different types of drought may be linked as droughts propagate, for example from meteorological to agricultural and/or hydrological droughts (Haslinger et al., 2014; Bachmair et al., 2018, 2015; Blauhut et al., 2015; Stagge et al., 2015). Different types of drought do not necessarily occur simultaneously. For example, the propagation from meteorological anomalies to streamflow anomalies is affected by climate and catchment characteristics as well as by anthropogenic influences. Catchments with high natural or artificial water storage might be able to sustain flow through short-term dry conditions, whereas catchments without significant water storage are likely more susceptible to short term water deficits (e.g., Barker et al., 2016). Negative anomalies in precipitation or streamflow do not necessarily lead to drought impacts on society and economy as impact occurrence and severity also depends on the vulnerability of a given system (Erfurt et al., 2019, Blauhut et al., 2016). Therefore, when human-environment systems are the subject of interest, a characterization of drought hazards represents an incomplete description of drought events and a comprehensive analysis of past drought impacts is key to understand the chain of processes during a drought event.

The purpose of this article is to catalogue and analyse historical drought events of the last 218 years at a regional scale, i.e. for the state of Baden-Wuerttemberg in southwestern Germany. Furthermore, this study explores different perspectives on drought and determines the added value of multi-dimensional datasets for a comprehensive understanding of drought events from the year 1800 onward. For this purpose, we:

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a) combine information from four different sources: meteorological and hydrological observations, dendrochronological analysis of tree growth, and written evidence on past climate and drought impacts into a full catalogue of droughts, b) compare the occurrence and assessment of major extreme drought events from these different perspectives, c) identify strengths and weaknesses of the datasets and indices, and d) build a drought catalogue of "consensus-events" for the state of Baden-Wuerttemberg from the multi-disciplinary perspective.

## 2 Data and Methods

### 2.1 Multi-variable Dataset

The drought catalogue is based on datasets that represent the major drought types and multiple levels of classification of individual and combined drought indices. Figure 1 gives an overview of the data, the derived indices and time series of drought events used (details in Section 2.2) and the overall analysis for the drought catalogue (Section 2.3).

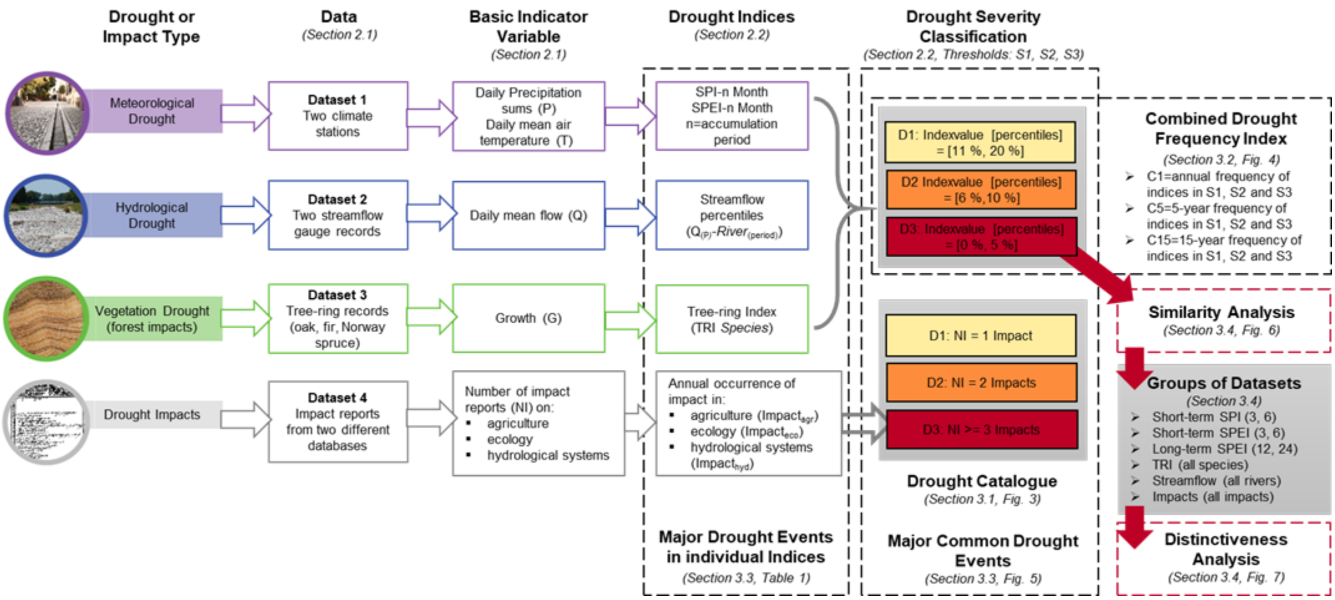


**Figure 1: Conceptual overview of the multi-variable dataset, variables and terminology used in this study.**

The study employs an assembly of several drought-related variables, herein defined as datasets 1 to 4 (Fig. 1 and Fig. 2). Dataset 1 comprises **meteorological records** from 1801 to 2018 of monthly temperature means (T) and monthly precipitation sums (P) for two stations in Baden-Wuerttemberg, which provided the longest continuous time-series of the required variables, Rheinstetten-Karlsruhe and Stuttgart (Fig. 2). Precipitation and temperature data were homogenized and retrieved from the project "Historical Instrumental Climatological Surface Time Series Of The Greater Alpine Region"

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(HISTALP, Auer et al., 2007). The time series of the HISTALP dataset cover the period 1801-2015 and were updated until the year 2018 using data from the German Weather Service (DWD, ftp://opendata.dwd.de/).

Dataset 2 consists of hydrometric records, namely daily **streamflow** records (Q) of the river Rhine (at Basel) and the river Danube (at Kelheim) (Fig. 2). Data for the period of 1900-2018 were retrieved from the Bundesanstalt für Gewässerkunde (BfG, www.bafg.de). The selection of these two stations was based on the availability of long continuous datasets. The streamflow at Basel reflects mainly the alpine flow component into the study region and only to a lesser degree the runoff produced within the study region. Nevertheless, the Rhine is an important river for the region of Baden-Wuerttemberg and its streamflow hence reflects whether social and economic impacts of drought are likely. The Danube River originates in the study region itself, i.e. its headwaters are in the Black Forest Mountains of southwest Germany, from where it flows eastwards cutting through limestone escarpment areas, and it also receives water from Germany's pre-alpine and alpine Region by way of its southern tributaries. Both rivers are among Europe's longest. They support critical ecosystems and have played an important role for the transport of goods, energy production, water supply and tourism for a long time.

Dataset 3 consists of annually resolved **tree-ring** data from oak (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.), fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* (L.) H. Karst.) trees from different sites in Baden-Wuerttemberg. Tree ring series of pine (*Pinus sylvestris* L.) were also tested but not included in the final dataset owing to their weak climate signal. These tree-ring series span the past ~200 years. The combined tree-ring data stem from multiple sources. One dataset contains oak tree-ring chronologies from the Rhine-valley which are described in more detail by Skiadaresis et al. (2019). Further, oak and fir tree-ring series were provided by Büntgen et al. (2011) and Büntgen et al. (2014). Spruce and fir tree-ring chronologies for the region were obtained from the international tree-ring database ITRDB (www.ncdc.noaa.gov) (appx. Table S1). Finally, more recent fir and spruce chronologies from the western part of the Black Forest were obtained from Schwarz and Bauhus (2019), and from Sohn et al. (2013). We included only tree-ring series with a length of more than 40 years. To ensure a common signal in each chronology, we restricted any further analyses to trees with high and significant inter-series correlation (IC) (IC > 0.3, $p < 0.05$) with the respective mean chronology of each species or the regional mean chronology. The final dataset consisted of 2089 individual tree-ring series (1632 oak, 241 fir and 216 Norway spruce).

Dataset 4 is based on reported textual information on the **impacts** of drought events from a variety of information sources: Two existing databases, the collaborative research environment tambora.org (Glaser et al., 2015, 2013) and the European Drought Impact Report Inventory EDII (www.geo.uio.no/edc/droughtdb/edr/impactdatabase.php, Stahl et al., 2016) provided the starting point, but were amended to create the specific dataset used in this study. Historical information from tambora.org comprises written documents from manifold sources and chronicles, flood marks and hunger stones, as well as pictures and official records, newspapers and early numerical statistical records on harvest yields, food prices, ecological impacts and societal information. The European Drought Impact Report Inventory (EDII) archives coded summaries of more recent reports on negative environmental, economic or social drought effects. Historical information (prior to 1900) stems from tambora.org, more recent drought impact reports from the EDII. Impact reports from questionnaires and interviews in the EDII were excluded because they merely focus on drought impacts on public water supply and hydropower production from

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the year 2000 onwards. All available **information on reported impacts** for southwestern Germany - from these databases and additional reports recently collected - were spatially referenced and time stamped. For the purpose of this study all drought impact reports were assigned to three impact categories (1) agriculture, (2) ecology (incl. forests) and (3) hydrological systems (incl. e.g. water use for drinking water and water-borne transportation).

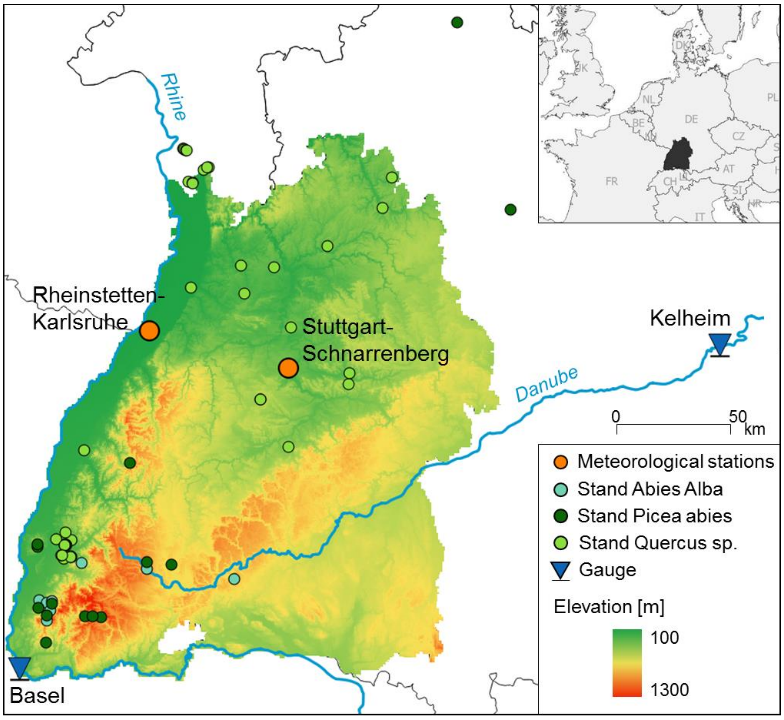


**Figure 2: Baden-Wuerttemberg and location of various data sources considered in the study.**

## 2.2 Drought indices and drought event severity classification

The four datasets were transformed into continuous time series of anomalies (Datasets 1-3) or impact occurrences (Dataset 4) in order to obtain drought indices that could be directly compared to each other (Fig. 1). The choice of variables and their transformations broadly followed common drought monitoring approaches such as the US Drought Monitor and Impact reporter, for example (https://droughtmonitor.unl.edu/). The anomalies and indices were then used to explore the different characteristics and severity of past drought events for the different types of drought.

**Meteorological Drought**, i.e. a lack of precipitation, was captured by the commonly used **Standardised Precipitation Index** (SPI, Mc Kee et al., 1993) and was calculated for Dataset 1. Given that summer droughts are often characterized by increased temperatures leading to higher evapotranspiration (e.g., Teuling, 2018), we also used the Standardised Precipitation Evapotranspiration Index (SPEI), which is based on the difference between precipitation and potential evapotranspiration. Potential evapotranspiration was estimated with the Thornthwaite equation(which only requires

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temperature and latitude as input), given that data to make more accurate PET estimations (e.g., solar radiation or wind speed) were not available for the entire period of record. In this study we were interested in both short-term droughts during the summer and vegetation season as well as long-term droughts. Hence, the following accumulation periods (n) were chosen: SPI/SPEI-3 ending in June (early vegetation period) and August (summer period important for impacts), SPI/SPEI-6 ending in June and September (for tree growth), SPI/SPEI-12 ending in December (annual) and SPI/SPEI-24 (biannual) for December. Computation of SPI and SPEI was performed using the R Package "SPEI" (Version 1.7) from Beguería and Vicente-Serrano (2017). For the SPI calculation, the precipitation series were fitted to a gamma distribution to define the relationship between precipitation amounts and probability for given accumulation periods. Parameter estimation of the probability distributions was based on unbiased probability weighted moments. The time from 1810 to 2018 (total period of record) served as the reference period. The SPEI was calculated in the same way, but based on the climatic water balance (difference between potential precipitation and evapotranspiration). For the SPEI, standardization was based on the generalized logistic distribution.

**Hydrological Drought** was calculated from daily streamflow observations (Dataset 2). The daily streamflow *(Q)* data for the period between 1901-2018 was aggregated to annual as well as seasonal averages for both the non-winter (March-November) and the summer and autumn (June-November) seasons. The aggregated streamflow data were then transferred to streamflow percentiles ($Q_P$), using Weibull plotting positions ($Q_P$ = rank(Q) / (n+1); where n in this case equals the amount of years).

**Vegetation Drought** indexing followed standard dendrochronological methods in order to derive a Tree Ring Index (TRI) from Dataset 3. The 2089 different tree-ring series originated from 70 locations in Baden-Wuerttemberg (Fig. 2 and Table S1). To remove age-related growth trends from individual tree-ring series while maintaining their inter-annual variability, we detrended raw ring-width series using a 30 year spline with 50 % frequency cutoff. This commonly used detrending approach removes the biological trends present in growth series (low frequency) while simultaneously preserving annual to decadal variability in growth (high frequency) (Cook and Peters, 1981, Speer, 2010). A bi-weight robust mean was then calculated to generate four residual chronologies: oak, fir, spruce and a combined chronology including trees from all three species (see Fig. S1, Fig. S2, Fig. S3 and Fig. S4). The quality of the developed chronologies was assessed using several descriptive statistics (EPS: expressed population signal, SNR: signal to noise ratio, and rbar: mean interseries correlation) commonly used in dendrochronology (Speer, 2010; Table S1). Quality control, detrending and chronology development were performed using the 'dplR' package in R (Bunn, 2008).

**Socio-economic Drought** was represented based on the reported drought impact information of Dataset 4. From this information on time, location, and impact category, an Impact Drought Index (IDI) time series was derived that contains an annual value indicating 'impact' (IDI=1) or 'no impact' (IDI=0) occurrence in each category. As the number of impact reports change over time with more digitized source material being available in the 20th and 21st century, we corrected for this trend in the data by converting every year before 1947 with one or more indicated impact into an impact year with

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IDI=1. In the period 1947-1999, years with more than two reported impacts were characterized as impact years. After 2000, years with more than three reported impacts were considered as impact years.

A **drought severity classification scheme** was then applied to the different individual drought indices to facilitate characterization and comparison of drought events across the continuous indices of datasets 1-3 (Fig. 1). A percentile approach was used to determine thresholds for three drought severity levels (D): D1 = moderate (11th to 20th percentile), D2 = severe (6th to 10th percentile) and D3 = extreme (below the 5th percentile). For each individual index, SPIn, SPEIn, QP, TRIspecies, drought events were classified accordingly. For IDI from dataset 4 D1 was assigned to years with one affected impact category, D2 for years with two categories and D3 for years with all three categories with IDI=1. Events identified with their severities comprise our drought catalogue: all drought events identified in the individual variables. Based on these severity classes, a combined drought index time series (C) was derived based on the **frequencies** of indices, with C1 reflecting an annual frequency, C5 a frequency of 5-years long periods, and C15 a frequency of 15-years long periods (Fig. 1).

To identify the major common drought events, the 20 drought years in which the most indices (from different groups) point to a drought, were selected (Fig. 1). To compare and select the major drought years individually, we ranked the ten most extreme years from 1900 onward for all indicators, and from 1801 onward for the meteorological and the tree-ring dataset.

### 2.3 Analysis of similarities and differences in drought variables

To assess similarities and uniqueness in drought events, we used three metrics to quantify relationships among the multiple drought indices. The first metric assesses the full range of anomalies (dry and wet). These were quantified by Pearson's correlation coefficient (*r*) between all pairs of drought indices. Additionally, we developed a similarity index (*s*) as a metric for only the extreme events (D3). This index was also calculated for each pair of drought indices. It relates the average number of extreme droughts in an index-pair to the number of common (simultaneous) droughts in the pair.

Both similarity measures, r and s, were calculated for all drought indices for the whole period of record (1901 to 2011). In a second step, they were calculated for an earlier 40-year period (1901 to 1940) and for a later 40-year period (1972 to 2011) to assess possible changes in the relationships between drought patterns in the different datasets over approximately the past 110 years. These periods of time were chosen for several reasons: first, we wanted to identify changes in extreme drought occurrence over time, and secondly, we wanted to include all groups of indices for this analysis. A reason to assess *s* for extreme drought events only was the hypothesis that global change may have intensified in particular the extremes in the more recent period.

To assess the distinctiveness of the extreme droughts identified by the different datasets contained in the drought catalogue, we first grouped datasets into different categories: (a) **Short-term SPI** (SPI-3 of June and August, and SPI-6 of June and September), (b) **Short-term SPEI** (SPEI-3 of June and August, and SPEI-6 of June and September), (c) **Long-term SPEI** (SPEI-12 and 24 of December), (d) **Tree-rings** (all 4 tree-ring chronologies), (e) **Low-flow** (Q-Rhine$_{(Mar\text{-}Nov)}$, Q-Danube$_{(Mar\text{-}Nov)}$, Q-Rhine$_{(Jun\text{-}Nov)}$ and Q-Danube$_{(Jun\text{-}Nov)}$) and (f) **Impacts** (agriculture, ecology and hydrology). Then, we investigated

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which extreme drought events would not be identified if excluding a single dataset. The number of extreme droughts, that our final catalogue would have failed to identify had we not included a specific dataset, was defined as the distinctiveness value.

## 3 Results

### 3.1 Drought catalogue: drought events in individual variables

Figure 3 presents the temporal distribution of drought occurrence for the different variables and drought severities. Drought events of all severities (D1 to D3) occurred throughout the last 218 years (Fig. 3a and b). However, several years are visible in all datasets; these include 1842, 1865, 1993, 1921, 1963, 2003, and 2018. No temporal trends of drought occurrences in general could be detected, but extreme droughts became more frequent over the last decade (Fig. 3a and b). Further, the occurrence of a drought event in a certain year often is indicated by multiple variables. Especially the occurrence of extreme drought events is visible in most indices, whereas moderate droughts often only appeared in one (or few) of the considered variables.

The drought impact time series provided insights into the actual occurrence of socioeconomic consequences of drought (Fig. 3a). In general, the drought events identified by impacts are in line with drought events which were identified by meteorological indices. Remarkably, the years of 1853 and 1854 were not identified as drought events by the meteorological drought indices but were identified by impact reports. In 1853 reports focused on hydrological impacts such as extreme low flow in the Rhine and problems with public water supply (low groundwater levels). In 1854, Rhine streamflow was extremely low again, impacts on hydropower production were reported, and water levels of Lake Constance were reported to be the lowest on record.

The meteorological indicators used in the catalogue identify the degree of dryness at different time scales (Fig. 3b). They are fairly distributed over the study period, although especially the last decade shows a higher severity of drought events. In particular when taking the potential evapotranspiration into account (SPEI for all different accumulation periods) extreme droughts became more frequent (e.g., 2011, 2015, 2018). For the year 1991 all meteorological indicators denoted severe to extreme precipitation shortfall yet this translates only into a moderate drought intensity based on indices of tree-rings and streamflow.

In many cases dendrochronological records show that years of extremely low tree growth coincided with drought events identified by other indices (Fig. 3b). For example, the years 1893 and 1976 are listed in the catalogue as extreme drought events based on all tree-ring chronologies and as extreme, severe or moderate droughts based on meteorological indices. On the other hand, in some cases tree-rings showed a delayed response to drought. For example in 1921, radial growth of fir and spruce appeared to be not affected by drought as indicated by meteorological indices, but tree-ring indices of both species indicated a drought in the year afterwards (1922). All other indices marked 1921 as an extreme drought year. Meteorological indicators revealed that the lack of precipitation occurred mostly before the summer season. SPI/SPEI-6 of September and

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SPI/SPEI-3 of August only show a moderate drought, whereas the lack of precipitation for the period March to June (SPI/SPEI-3 of June) of 1921 were classified as severe and for the half year January to June (SPI/SPEI-6 of June) as extreme droughts.

The hydrological view reflects the effects of precipitation shortfalls on streamflow (Fig. 3b). Streamflow data revealed that between 1976 and 2003, no severe or extreme drought was observed in the streamflow dataset. In both, Rhine and Danube, mainly the streamflow of the years 2003 and 2018 were marked as extremely low. For the same years, all other variables apart from SPI-6 of June indicated a moderate to extreme drought year.

**Annual frequencies** were analysed in order to **explore the drought events from all perspectives** except the impacts (Fig. 3c). Years with more than 25% of the indices pointing to an extreme drought event are 1842, 1865, 1893, 1921, 1949, 1964, 2003, 2015 and 2018. From the late 1850s to the early 1870s clusters of extreme droughts occurred (Fig. 3c). Another cluster was found at the end of the 1940s. Also the 1960s are marked by several consecutive drought years. Also the cluster of droughts between 2010 to 2018 stands out (because of SPEI but also streamflow).

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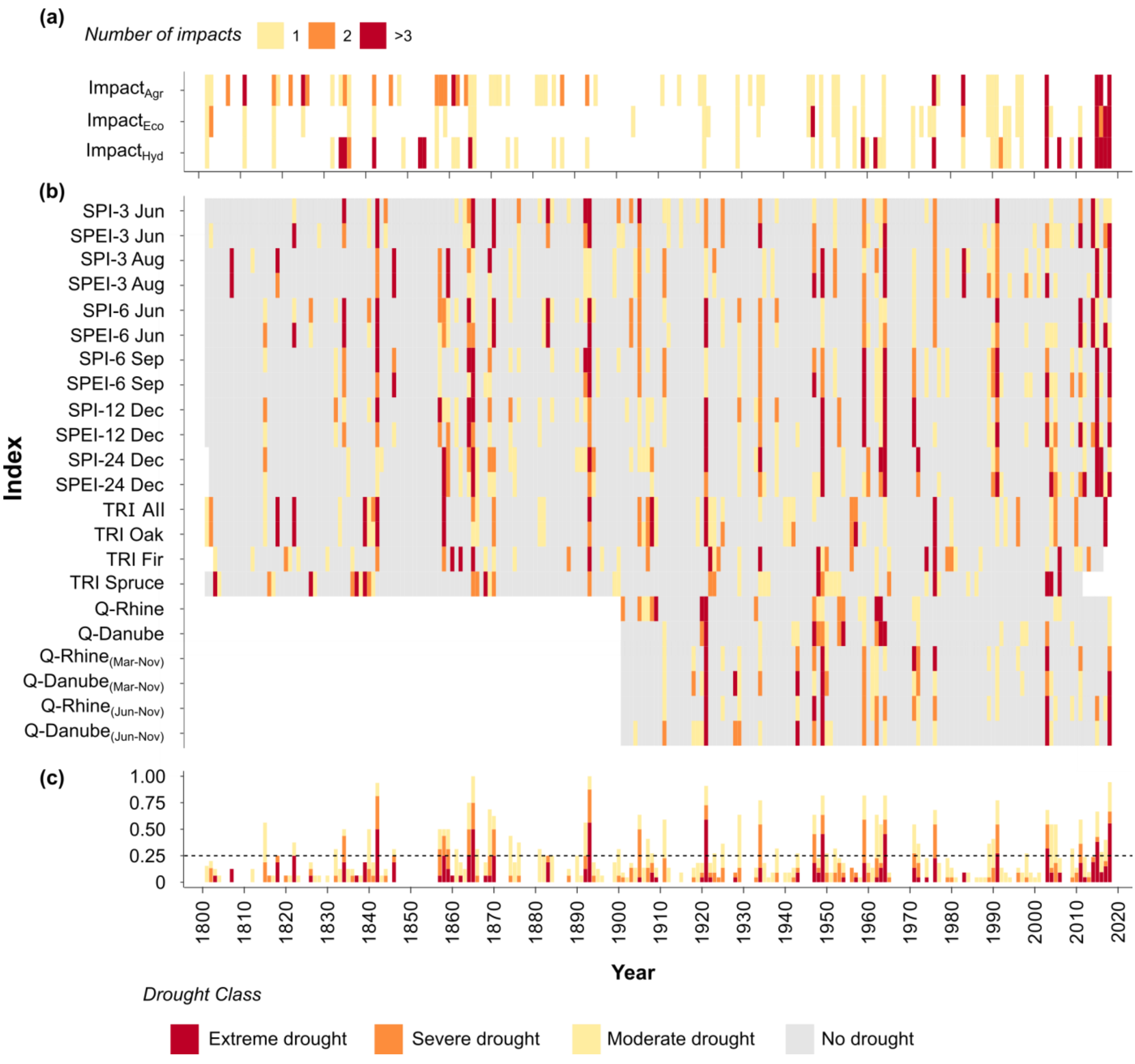


**Figure 3: Annual time series of drought occurrence in southwestern Germany according to different groups of indices (a) Drought impacts, (b) hydro-meteorological drought indices and tree ring data and (c) the percentage of indices indicating droughts.**

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### 3.2 Drought frequencies

To survey if drought occurrence has changed over time since 1801, the frequencies (C) for 5 and 15 years-long time windows were used to identify temporal patterns of drought occurrences (Fig. 4). The frequencies describe the average percentage of indicators classified as drought in a 5 or 15 year window prior to the year of interest. Both analyses reveal a high overall variability over the last 218 years. If using a 5 years-long window "drought hotspots" which occurred in the 1860s and in the most recent decade are revealed (Fig. 4a). The analysis with a 15 years-long window (Fig. 4a) picked up more long-term variations in drought frequencies.

During the decade from 1847 to 1857, no droughts occurred (Fig. 3a and Fig. 4b) while shortly after, 1860 and 1870, a high number of extreme droughts in tree-rings and meteorological datasets were identified (Fig. 4b). A major peak in drought occurrence was reached in 1865. A comparable increase of droughts was observed between the 1950s and the 1970s, with a peak around 1964. Also in the 1920s and towards the end of the 1940s the 5-year frequencies were high. Most droughts classified as extremes were found between 2014 and 2018 (Fig. 4b).

The frequency of a rolling 15-year window shows long-term periods of drought occurrence and absence (Fig. 4a). An increase of droughts was detected towards the 1840s. Most drought-prone periods were around 1870, the 1960s and with a steady increase in extreme droughts in the last decade.

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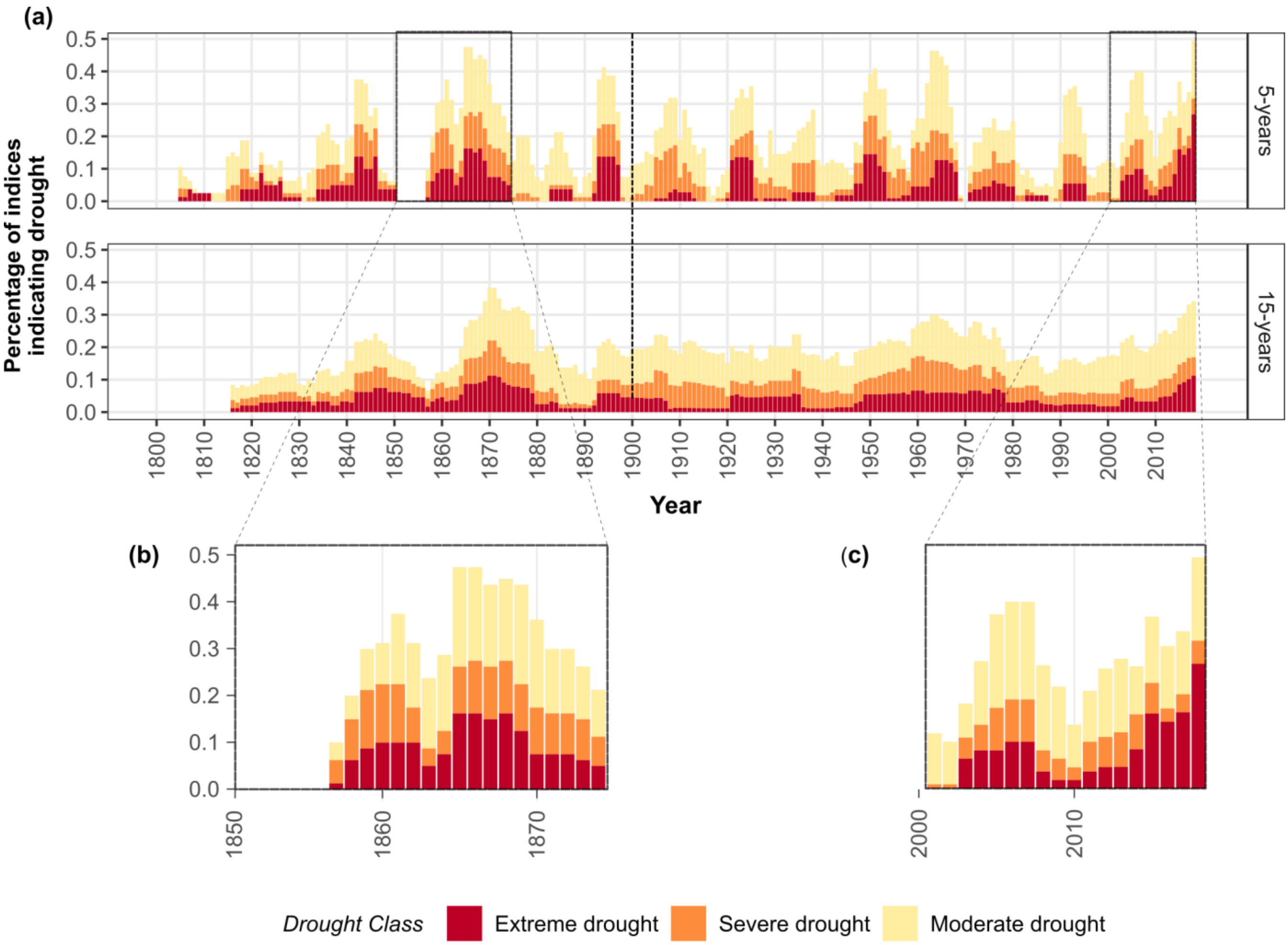


**Figure 4: Annual time series showing the fraction of indices in drought (different severities) smoothed with a 5 and 15 year backward smoothing window.**

### 3.3 Common drought events from different perspectives

To explore the different dimensions of droughts, we focused on the years, for which most indices point to a drought of any severity (Fig. 5). In all cases more than 25 % of the indices were classified as a moderate, severe or even an extreme drought. In all these years, drought appeared in both the indices and the impacts. All 17 years after 1900 (the period for which streamflow data was available) were identified as drought years based on streamflow indices. In 1911, 1971 and 2015 a drought signal was not observed in the tree-ring indices but in most other indices. Although we used a large number of meteorological drought indices (SPI and SPEI), these extreme years including 1921, 1976 and 2003, were identified in other index categories more or less equally (Fig. 5).

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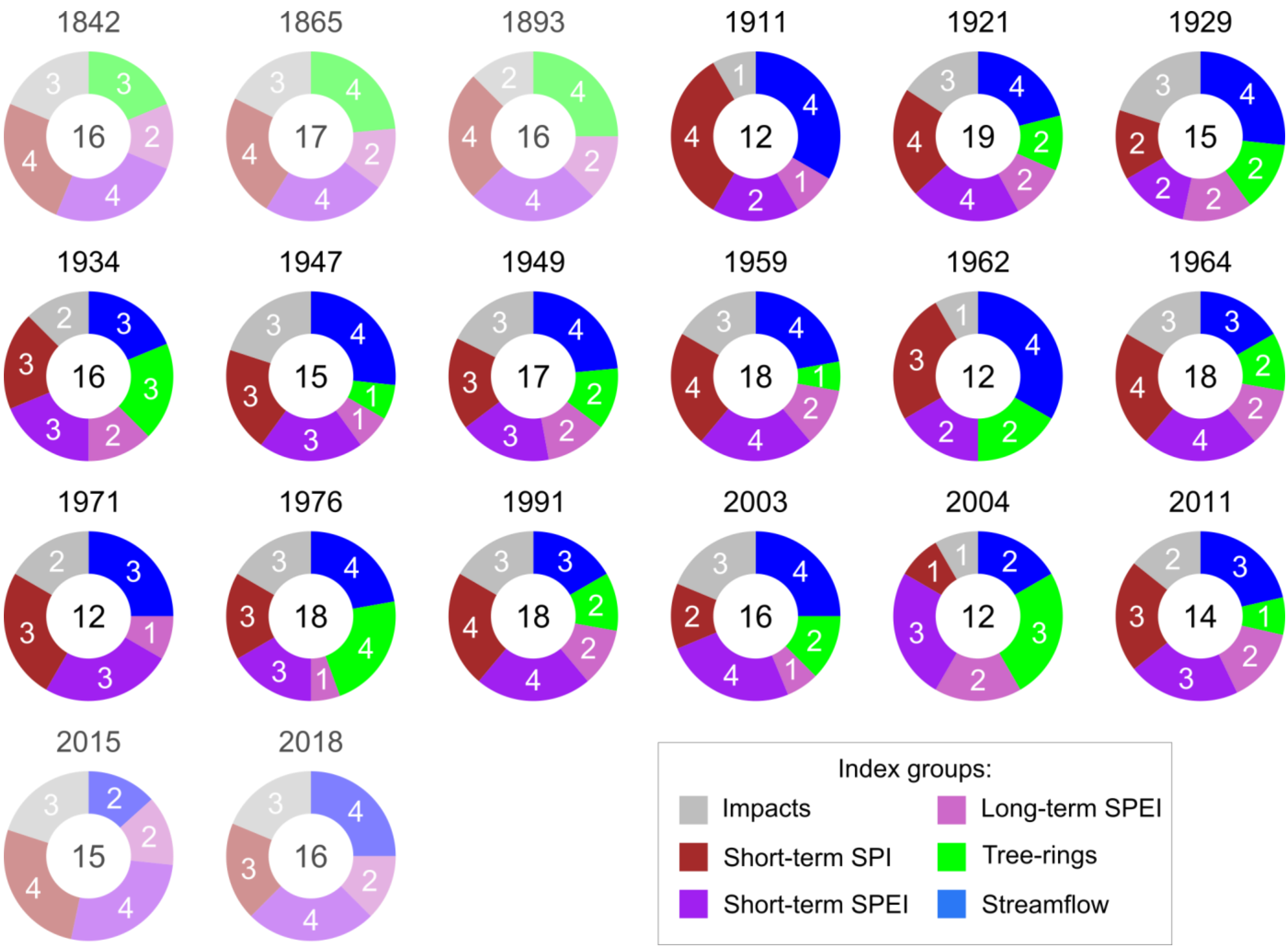


**Figure 5: Drought years in which more than ten indices (from different groups) point to a drought (the total number of indices pointing to a drought is written in the circle). Years without streamflow data (prior to 1900) or without tree ring data (after 2011) are displayed with paler colours.**

The ten most extreme drought years according to each indicator showed a large variation among indices (Table 1). Regarding its severity, the drought year 2018 ranked among the most extreme droughts in the last 118 years based on several indicators (Table 1a). In 11 out of the 18 indicators, 2018 was counted as a top ten event. Also 2003 stood out, in particular according to both meteorological and hydrological drought indicators. In 9 out of the 18 indicators, 2003 was counted as a top ten event. Considering two consecutive drought years (SPEI-24 of December) six of the top ten droughts occurred within in the last 18 years. For the other meteorological indicators, two to four droughts that occurred after the year 2000 were classified among the top ten. Events in the 1940s (1947 and 1949) ranked in the top ten across the two drought types. In the tree-ring dataset, only spruce was affected in the same year. Other extreme drought events occurred in 1921, 1971 and 1976. For tree-rings especially the years 1921 and 1976 stood out.

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When ranking the last 218 years, which is possible for the meteorological and tree-ring dataset, many of the top ten droughts occurred in the 19th century, e.g., 1842, 1865 and 1883 (Table 1b). More than half of the top ten drought events, identified by short term SPI and SPEI, occurred in the 19th century. Only for SPEI-6 of September and the long-term SPEIs (12 and 24 of December) less than half of the top ten events occurred in the 19th century. For these three indices 2018 remains still the top one event (Table 1b). Also the drought events in 2003 and 2015 were still among the top ten for the majority of meteorological indices.

**Table 1: Overview of the top ten most severe drought years. Drought years since the year 2000 are coloured purple and years between 1801 and 1900 are marked green. "-" = no data available.**

| Rank | SPI-3 Jun | SPEI-3 Jun | SPI-3 Aug | SPEI-3 Aug | SPI-6 Jun | SPEI-6 Jun | SPI-6 Sep | SPEI-6 Sep | SPEI-12 Dec | SPEI-24 Dec | TRI All | TRI Oak | TRI Fir | TRI Spruce | Q-Rhine(Mar-Nov) | Q-Danube(Mar-Nov) | Q-Rhine(Jun-Nov) | Q-Danube(Jun-Nov) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **(a) Top ten since 1900.** | | | | | | | | | | | | | | | | | | |
| 1 | 1905 | 2011 | 1983 | 1983 | 2011 | 2011 | 2018 | 2018 | 2018 | 2015 | 1976 | 1921 | 1976 | 2003 | 1921 | 1921 | 1949 | 2018 |
| 2 | 1991 | 2014 | 1949 | 2018 | 1991 | 2014 | 1959, 2015 | 2003 | 2015 | 2016 | 1921 | 1976 | 1922 | 1948 | 1949 | 1949 | 2018 | 1949 |
| 3 | 2014 | 2018 | 2018 | 2015 | 2014 | 2017 | 1964 | 1947 | 1959 | 2018 | 2017 | 2017 | 1948 | 2004 | 1976 | 2018 | 1947 | 1921 |
| 4 | 1934 | 1964 | 1964 | 2003 | 1921 | 1921 | 1991 | 2015 | 2003 | 1964 | 1908 | 1908 | 1974 | 1976 | 2003 | 1943 | 2003 | 1943 |
| 5 | 1925 | 1934 | 2015 | 1947 | 1903, 1929 | 1959 | 1947 | 1964 | 1971 | 2004 | 2010 | 1957 | 2006 | 2006 | 1971 | 1928 | 1921 | 2003 |
| 6 | 2011 | 1905 | 1947 | 1964 | 1905 | 1991 | 1905, 1971 | 1959 | 1949 | 1991, 2012 | 1956 | 1905 | 1934 | 1922 | 2011 | 1934 | 1964 | 1911 |
| 7 | 1964 | 1976 | 1962 | 1949 | 1938 | 1934, 1976 | 1949 | 1991 | 1921 | 1949 | 2005 | 1956 | 1956 | 1949 | 2018 | 1950 | 1976 | 1962 |
| 8 | 1921 | 1947 | 1905 | 1991 | 1959 | 1905 | 1911 | 1949 | 1964 | 2005 | 1905 | 2010 | 2013 | 1923 | 1947 | 1972 | 1959 | 1928 |
| 9 | 1900 | 1925 | 1991 | 1976 | 1934 | 1964 | 2003 | 2011 | 1991, 2011 | 1921, 1972 | 1907 | 1942 | 1907 | 1965 | 1943 | 1918 | 2015 | 1947 |
| 10 | 1976 | 2017 | 1911 | 1905 | 1976 | 1903 | 1990 | 1971 | 1934 | 1934 | 1996 | 2005 | 1950 | 1962 | 1972 | 2003 | 1971 | 1959 |
| **(b) Top ten since 1801.** | | | | | | | | | | | | | | | | | | |
| 1 | 1870 | 1870 | 1983 | 1983 | 1870 | 2011 | 2018 | 2018 | 2018 | 2015 | 1822 | 1822 | 1976 | 2003 | - | - | - | - |
| 2 | 1893 | 1865 | 1949 | 2018 | 1842 | 2014 | 1865 | 2003 | 2015 | 1865 | 1858 | 1858 | 1922 | 1948 | - | - | - | - |
| 3 | 1842 | 1893 | 1846 | 1846 | 1883 | 1870 | 1893 | 1947 | 1959 | 2016 | 1976 | 1921 | 1893 | 2004 | - | - | - | - |
| 4 | 1905 | 2011 | 2018 | 2015 | 1893 | 1893 | 1959, 2015 | 2015 | 2003 | 2018 | 1921 | 1976 | 1948 | 1837 | - | - | - | - |
| 5 | 1865 | 2014 | 1818, 1964 | 2003 | 2011 | 1842 | 1964 | 1865 | 1971 | 1964 | 2017 | 2017 | 1862 | 1976 | - | - | - | - |
| 6 | 1883, 1991 | 2018 | 1859 | 1807, 1947 | 1991 | 1834 | 1892, 1991 | 1964 | 1949 | 2004 | 1842 | 1842 | 1860 | 1803 | - | - | - | - |
| 7 | 1834 | 1822, 1842, 1964 | 1807 | 1964 | 1834, 1864 | 1822 | 1842 | 1959 | 1921 | 1991, 2012 | 1839 | 1908 | 1974 | 1839 | - | - | - | - |
| 8 | 2014 | 1934 | 1869 | 1859 | 2014 | 2017 | 1864 | 1991 | 1964 | 1949 | 1908 | 1839 | 2006 | 1826 | - | - | - | - |
| 9 | 1892 | 1834 | 2015 | 1949 | 1921 | 1921 | 1947 | 1846, 1893 | 1864 | 1858 | 1893 | 1818 | 1865 | 1868 | - | - | - | - |
| 10 | 1934 | 1905 | 1947 | 1991 | 1903, 1929 | 1883 | 1905, 1971 | 1949 | 1991, 2011 | 2005 | 1818 | 1957 | 1934 | 2006 | - | - | - | - |

### 3.4 Similarities and distinctiveness of drought in different datasets

Similarities and differences between datasets' extreme droughts calculated by the similarity index for each pair of datasets and for two periods partly showed some interesting patterns (Fig. 6). Streamflow percentiles from the two rivers and for the two different accumulation periods were very similar in terms of identified drought events in the early period (1901 to 1940). In the later period (1972 to 2011), the occurrence of below normal streamflows coincided less often in both rivers. The years classified as extreme drought events by the tree-ring chronologies of oaks and of combined tree species were identical for

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both periods. However, in the early period the two conifer chronologies (spruce and fir) did not show any similarity with the combined or the oak chronology in identifying drought events. On the contrary, in the later period approximately half of the identified droughts were commonly classified as extremes in all three different tree-ring chronologies. With a few exceptions (SPEI-6 of June – SPEI-12 December, SPI-6 of June – SPEI-12 December, SPEI-6 of June – SPI-6 of June), meteorological drought indicators were very dissimilar in identifying drought events during the early period. Their similarity however increased in the later period. The SPI/SPEI-3 classified only a single extreme drought in the early time period. Therefore, for this time period no similarities existed with other datasets. Streamflow and SPI-6 of June, SPEI-6 of June, and SPEI-12 of December showed almost identical extremes in the early period. Their similarity became weaker in the late period in the case of SPEI-12 December while no similarities were observed between streamflow series and SPI-6 of June or SPEI-6 of June. Low-flow series showed some similarity with SPEI-3 of August in the late period (except for Q. Danube Mar-Nov) which was not observed in the earlier period.

Relationships among different indices as well as temporal changes in their relationships computed by Pearson's correlation coefficients among all pairs of datasets and for two 40-year periods are presented in detail in the supplementary material (Fig. S5 and Fig. S6). Several correlations between the different indices over the whole period (1901-2011) and for two shorter time periods (1900 to 1940 and 1972 to 2011) were observed (Fig. S6). As expected, the strongest correlation was found between indicators belonging to the same type of dataset or time-scale (short-term SPI, short-term SPEI, long-term SPEI, tree-rings and riverflow) for both investigation periods. The two meteorological drought indices (SPI and SPEI), calculated for different accumulation periods and ending in different months, correlated strongly with each other (Fig. S6). In addition to the expected relationships between indicators belonging to the same group, strong correlations were also observed between indices belonging to different groups: Streamflow percentiles correlated most strongly with long accumulation periods (12 and 24 months) of meteorological indices both in the early and later period ($r > 0.6$). Tree-ring chronologies showed overall weak correlations with streamflow anomalies with the exception of oak and the combined tree-ring chronologies which were significantly correlated with the two streamflow series from the Rhine river. However, the combined tree-ring chronology as well as the oak chronology showed strong positive correlations with short-term meteorological drought indicators in both periods (Fig.. S5 and Fig. S6).

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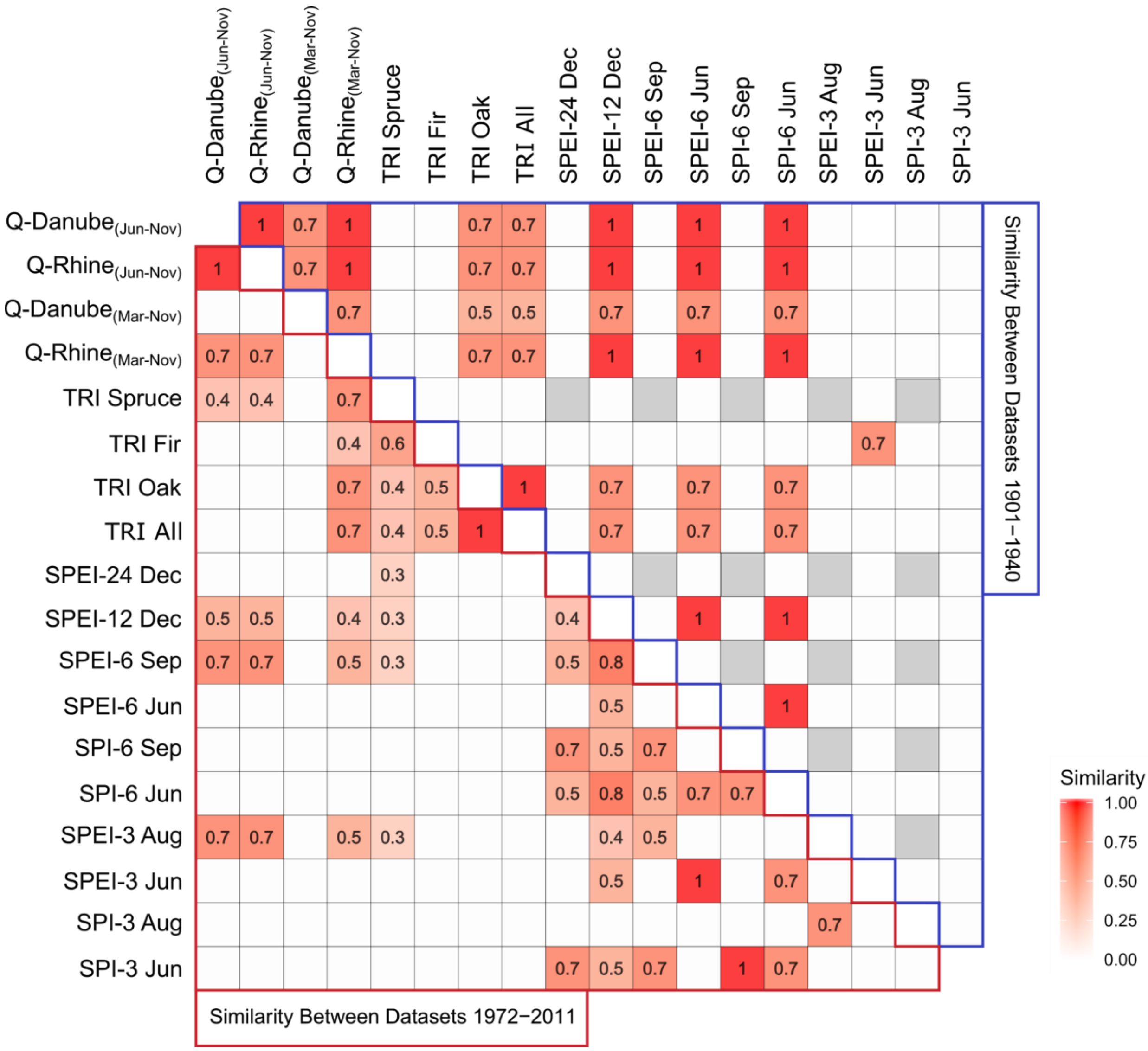


335 **Figure 6: Similarity index (*s*) between the different pairs of drought indices for two different time periods (1901 to 1940 and 1972 to 2011). Grey boxes = no extreme drought according to both indices.**

The distinctiveness value for groups of indices (Fig. 7) allowed to determine drought events we would have missed had we not included a specific type of dataset in the analysis. Including drought indices and impacts derived from different datasets in our drought catalogue resulted in the classification of 57 years throughout the period between 1800 and 2018, for which at least one drought index indicated extreme drought conditions (Fig. 3 and Fig. 7). Almost half of these drought events were
340 identified by a single group of datasets. Tree-rings showed the largest number of unique droughts (12 in total) while drought impact datasets identified seven extreme drought events that were not characterized as extreme in the other groups of

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datasets. Interestingly, 13 out of the 19 extreme droughts that we would have missed had we excluded both tree-ring and impact data, appear in the 19th century, while only 3 distinct droughts were observed in tree-ring and impact data after 1950. All groups of meteorological droughts had very low distinctiveness values (distinctiveness value, numbers of droughts excluded in Fig. 7) with short-term SPEI (accumulation periods of 3 and 6 months) showing no unique extreme drought events. This analysis indicates that different datasets provided distinct information on drought, which would be missed if only using one of the datasets.

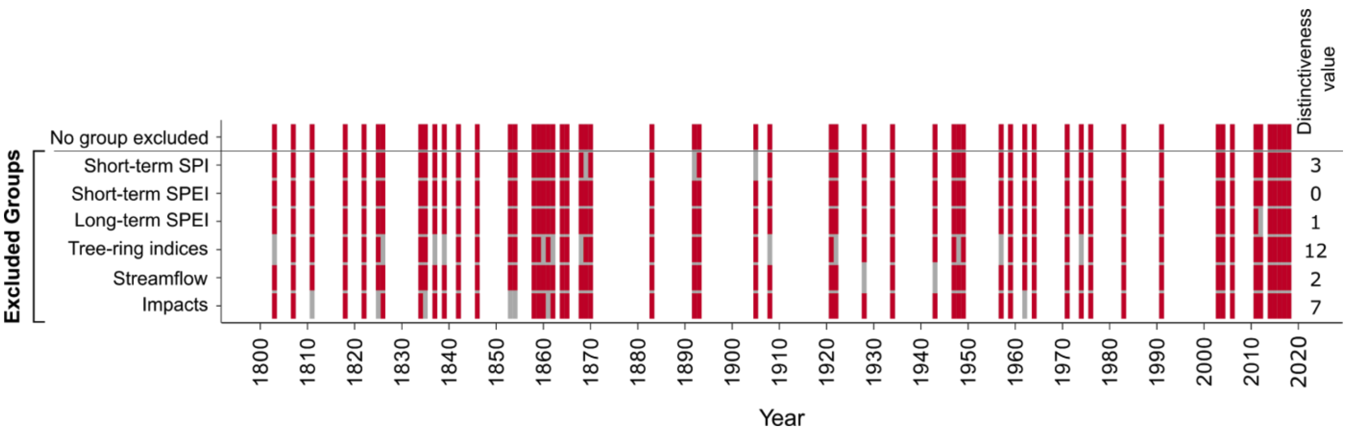


**Figure 7: Extreme drought events identified (red) or missed (grey) when excluding a certain group of drought indices. The total number of missed events (distinctiveness value) when excluding a certain group of indices is displayed on the right.**

## 4 Discussion

### 4.1 Assessment of the drought catalogue and underlying data

With the drought catalogue a unique dataset was created, which comprehensively identified drought events since 1801 in southwestern Germany from multiple datasets and drought indices. Events occurred in all decades, but a particular clustering was found in the mid-19th Century, some extreme double or triple drought years in the early 20th Century and during the most recent decade. Many of the major droughts that were apparent across all groups of indices, were also identified by other studies focusing on different European regions and using different datasets. Extreme droughts from the 19th century were also identified by Brazdil et al. (2019) for the Czech Republic (e.g., drought of 1842) using documents and measured data. Comparing our findings to the Old World Drought Atlas from Cook et al. (2015), which provides summer (June-August) reconstructions of the self-calibrating Palmer Drought Severity Index (PDSI), based on tree-ring data, the following extreme droughts from the 19th century were found in both datasets: 1842, 1834, 1858, 1864, 1865, 1893. Increased drought frequency in the years shortly before and after 1865 was also detected for an alpine-drought study by Haslinger et al. (2018) using meteorological data.

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Taking societal information into consideration (as we do from our impact sources), interpretation and discussion of droughts during the different historical periods opens another dimension. As Erfurt et al. (2019) have pointed out for the state of Baden-Wuerttemberg, the strength of a drought impact and the societal consequences strongly depend on the societal vulnerability and resilience as well as the possibilities to cope with and adapt to these impacts. The drought period identified in the mid 19th century (Fig. 4b), was also a time of growing population and manifold political changes. As the historical records underlying our dataset show, instability as well as drought relevant harvest failures and pricing led to hunger and diseases as well as an increase in mortality. As a consequence, people migrated to North America and to Russia as well as into south-eastern Europe. Similarly, the drought events in 1921-22 and 1947-49 were characterized by increased vulnerability. The damages and losses after the First and Second World War had increased the sensitivity towards drought related impacts. Even the high mortality in the context of the compound heatwave and drought event of 2003 event must be seen in the specific societal context of modern societies with their disregard and isolation of older people (Valtorta and Hanratty, 2012). In this sense, droughts and their impacts but especially the vulnerability and resilience are context-dependent. The many impacts reported in recent drought years (e.g., 2003, 2015, 2018) likely also reflect an increased awareness towards changing climate and changing policies, including climate change adaptation.

All data sources used have some uncertainties and hence, our results reflect some of the methodological choices made in this study: For example, we used hydro-meteorological averages aggregated over periods that we assumed are relevant for various drought related impacts, and compared those averages among the different years. However, using different aggregation periods or different methods (e.g., annual minimum flow or duration of which flow was below a fixed threshold) might have changed the ordering and classification of drought events. In addition, the long-term meteorological records of the stations Karlsruhe and Stuttgart are representative for the areas near these major civil centres for which drought would have had relevant impacts over the entire period of record. However, these meteorological records are not necessarily representative for the entire state of Baden-Wuerttemberg, which has a more diverse climate (especially in the more remote areas and at higher elevations). Furthermore, the rivers Rhine and Danube are major rivers flowing through the study area, which were important for, e.g., several of economic activities. However, these larger rivers are not necessarily representative for the variety of streamflow regimes found for the smaller tributaries in the study area.

Tree-ring records were a valuable source of information regarding the impacts of drought on forests. Indeed, most years that were identified by meteorological or streamflow drought indicators as severe or extreme droughts coincided with extremely reduced annual growth for all three species included in our analyses. Interestingly, we also observed unique differences in the drought response among some of the species. For example fir and spruce showed a delayed response to the drought in 1921 which was identified as drought by all other indices including the oak chronology. However, a detailed discussion of such differences in the timing of growth responses of trees to drought is beyond the scope of this study (but see for instance

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the study by Bhuyan et al., 2017 and discussion in Büntgen et al., 2010). In any case, delayed growth responses should be assigned to the drought years that triggered them so that they can be used for multi-indicator analyses such as presented here. Finally, the drought impact information used in this study stems from two different databases that originally were created for different purposes. Although care was taken in the re-coding into a much-simplified dataset of only the occurrence of drought impacts in the three different categories agriculture, ecology, and water use, the results of the identified droughts in the two centuries should be regarded with this difference in mind. Historical reports from tambora.org stem from a rather limited variety of sources such as city chronicles or analog statistical yearbooks and mostly focus on food security, economic losses or impacts on human health (Erfurt et al., 2019). From the 20th century onward, novel media such as newspapers but also scientific publications also became a source of information. The more recent years are dominated by a wealth of online mass media and a strong increase in drought research which now also considers ecological impacts (Blauhut et al., 2016, 2015b).

### 4.2 The added value of a long-term multidisciplinary dataset

The inclusion of different drought indices and impact information in this study allowed a comprehensive assessment of past extreme drought events. Based on all indices, 57 out of the past 218 years (26%), were characterized as extreme drought events in the region by at least one of the included indicators (Fig. 3). This result highlights the uniqueness of different drought years and at the same time questions the assessment of the most extreme droughts. The definition of an extreme drought event (which for this study ranged from 0 to 5 % of ranked values of each individual indicator) had to be redefined for a comprehensive assessment of droughts from multiple drought-related data sources. From this perspective a drought event was classified as extreme, when more than one group of indices indicated an extreme drought. Taking this definition of drought into account, 20 extreme events in the past 218 years (9% of all years) were identified as extreme droughts (Fig. 5). This indicates that using our approach it is more likely to identify an extreme drought event than if using only a single indicator (< 5% of all years).
Investigating the top ten drought events since 1900 and respectively since 1801 emphasized the importance of using datasets that go back as far as possible to the past to contextualize today's events. The analysis of different groups of drought indicators further showed some extreme droughts, that we would have missed when using only one group. For example, some years with extreme precipitation deficits and concurrent negative impacts for society were correctly detected by meteorological indicators but not identified as extreme by tree-rings or streamflow data. Hence, using a multidisciplinary dataset thus provided a more complete picture of droughts in the past.

In the present study several drought events might have been overlooked if we had excluded any of the assessed indicators (Fig. 7). Interestingly, we observed a change in the number of distinct extreme droughts (number of extreme drought events missed (grey) when excluding any group of indices in Fig. 7) over the last 200 years. The majority of these distinct droughts were identified by either tree-ring or impact data and appeared before 1900, while only three distinct events were found based on these indicators following 1950. One possible explanation for the decrease in distinct events could be an improved quality and accuracy of instrumental records in Germany, especially after the end of World War II.

Investigating the development of drought frequency and severity in the long-term (1801-2018) further allowed an assessment of the uniqueness of the recent drought events. If we only look at the past 100 years, the years 2003, 2011 and 2018 were among the most extreme and unique events, especially according to the drought indices that consider temperature (Table 1a). However including also drought events from the 19th century, we can see that drought events of similar severity appeared in earlier years (Table 1b). Two main periods of increased frequency and severity were identified in our dataset (Fig. 4b and c). Although these two periods were similar to each other in terms of overall percentage of indices pointing to drought, the recent period (starting in 2003) was characterized by higher frequency of extreme droughts. Looking at drought frequency in a 5-year window reveals that never before in the last 218 years that many indicators and impacts pointed to drought. This rise in severity in recent years is a result of increasing precipitation deficits and rising temperatures (Hänsel et al., 2019). At a European scale, studies have shown trends towards more droughts in Southern Europe and wetting trends in Northern Europe (e.g., Gudmundsson and Seneviratne, 2015, Vicente-Serrano et al., 2014), whereas for Central Europe the detection of drought trends is still an ongoing discussion (Seneviratne et al., 2012).

## 5 Conclusions

The main objectives of our analyses were a) to learn more about droughts in the region from a long-term perspective and b) to conduct a multidisciplinary analysis of drought events across various sectors using different datasets and hence combine knowledge from different disciplines. The different groups of drought information provide a novel, unique set of data on drought events in southwestern Germany for the past 218 years. Analysing drought from the point of view of different disciplines revealed that drought does not necessarily follow the classical propagation from precipitation deficit via soil moisture to streamflow deficits and finally causing impacts on ecosystems, society and economy. Each drought indicator rather provided a different dimension of the same drought event, which might or might not match the information obtained from other indicators. Time of occurrence of hydrometeorological water deficits is only one feature. Trees in the studied region are indeed sensitive to water deficits but their response might be highly variable depending on species. Incorporation of tree-ring information therefore resulted in years of drought in this catalogue that might lag the hydrometeorological events in time. Incorporating information on a range of drought impacts from documents provided historical context and identified certain years that were more severe due to post-war vulnerability than only a meteorological index may have suggested. Using a multidisciplinary dataset helped to improve our understanding about interactions between the different drought characteristics. The drought catalogue provides valuable information on long-term drought occurrence in southwestern Germany, which can be expanded in further drought studies.

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**Author contribution**: ME, GS, ET, VB and KS designed the study. ME and GS performed the analysis and prepared the manuscript with contributions from ET, VB. KS provided guidance and methodology suggestions throughout the process. All the authors read, reviewed, and approved all versions of the paper.

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### References

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K. R., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z., and Nieplova, E.: HISTALP - historical instrumental climatological surface time series of the Greater Alpine Region, International Journal of Climatology, 27, 17–46, https://doi.org/10.1002/joc.1377, 2007.

https://doi.org/10.5194/nhess-2019-424
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Natural Hazards and Earth System Sciences
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Bachmair, S., Kohn, I., and Stahl, K.: Exploring the link between drought indicators and impacts, Natural Hazards and Earth System Science, 15, 1381–1397, https://doi.org/10.5194/nhess-15-1381-2015, 2015.

Bachmair, S., Tanguy, M., Hannaford, J., and Stahl, K.: How well do meteorological indicators represent agricultural and forest drought across Europe?, Environ. Res. Lett., 13, 34042, https://doi.org/10.1088/1748-9326/aaafda, 2018.

Barker, L. J., Hannaford, J., Chiverton, A., and Svensson, C.: From meteorological to hydrological drought using standardised indicators, Hydrol. Earth Syst. Sci., 20, 2483–2505, https://doi.org/10.5194/hess-20-2483-2016, 2016.

Barker, L. J., Hannaford, J., Parry, S., Smith, K. A., Tanguy, M., and Prudhomme, C.: Historic hydrological droughts 1891-2015: systematic characterisation for a diverse set of catchments across the UK, Hydrol. Earth Syst. Sci. Discuss., 1–31, https://doi.org/10.5194/hess-2019-202, 2019.

Beguería S, Vicente-Serrano SM (2017) SPEI: Calculation of the Standardised Precipitation-Evapotranspiration Index.: R package version 1.7. https://CRAN.R-project.org/package=SPEI.

Bhuyan U, Zang C, Menzel A. Different responses of multispecies tree ring growth to various drought indices across Europe. Dendrochronologia 44:1-8, https://doi.org/10.1016/j.dendro.2017.02.002, 2017.

Blauhut, V., Gudmundsson, L., and Stahl, K.: Towards pan-European drought risk maps: Quantifying the link between drought indices and reported drought impacts, Environ. Res. Lett., 10, 14008, https://doi.org/10.1088/1748-9326/10/1/014008, 2015.

Blauhut, V., Stahl, K., and Kohn, I.: The dynamics of vulnerability to drought from an impact perspective, in: Drought - Research and Science-Policy Interfacing: Proceedings of the International Conference on Drought: Research and Science-Policy Interfacing, Valencia, Spain, 10-13 March 2015, edited by: Andreu, J., Solera, A., Paredes-Arquiola, J., Haro-Monteagudo, D., and van Lanen, H., CRC Press, Hoboken, 349–354, 2015b.

Blauhut, V., Stahl, K., Stagge, J. H., Tallaksen, L. M., Stefano, L. de, and Vogt, J. V.: Estimating drought risk across Europe from reported drought impacts, drought indices, and vulnerability factors, Hydrology and Earth System Sciences, 20, 2779–2800, 2016.

Brázdil, R., Dobrovolný, P., Trnka, M., Kotyza, O., Řezníčková, L., Valášek, H., Zahradníček, P., and Štěpánek, P.: Droughts in the Czech Lands, 1090–2012 AD, Clim. Past, 9, 1985–2002, https://doi.org/10.5194/cp-9-1985-2013, 2013.

Brázdil, R., Demarée, G. R., Kiss, A., Dobrovolný, P., Chromá, K., Trnka, M., Dolák, L., Řezníčková, L., Zahradníček, P., Limanowka, D., and Jourdain, S.: The extreme drought of 1842 in Europe as described by both documentary data and instrumental measurements, Clim. Past, 15, 1861–1884, https://doi.org/10.5194/cp-15-1861-2019, 2019.

Bunn, A. G.: A dendrochronology program library in R (dplR), Dendrochronologia 26, 115–124, doi: 10.1016/j.dendro.2008.01.002, 2008.

Büntgen, U., Trouet, V., Frank, D., Leuschner, H. H., Friedrichs, D., Luterbacher, J., and Esper, J.: Tree-ring indicators of German summer drought over the last millennium, Quaternary Science Reviews, 29, 1005–1016, https://doi.org/10.1016/j.quascirev.2010.01.003, 2010.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M,. Frank, D., Trouet, V., Kaplan, J., Herzig, F., Heussner, U., Wanner, H., Luterbacher, J., Esper, J. . 2500 years of European climate variability and human susceptibility. Science 331: 578–582, 2011.

Büntgen, U., Tegel, W., Kaplan, J. O., Schaub, M., Hagedorn, F., Bürgi, M., Brázdil, R., Helle, G., Carrer, M., Heussner, K. U., Hofmann, J., Kontic, R., Kyncl, T., Kyncl, J., Camarero, J. J., Tinner, W., Esper, J., Liebhold, A. Placing unprecedented recent fir growth in a European-wide and Holocene-long context. Frontiers in Ecology and the Environment 12: 100-106, 2014.

Cook, E. R., and Peters, K.: The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree Ring Bull., 41, 45–53, 1981.

Cook, E. R., Seager, R., Kushnir, Y., Briffa, K. R., Büntgen, U., Frank, D., Krusic, P. J., Tegel, W., van der Schrier, G., Andreu-Hayles, L., Baillie, M., Baittinger, C., Bleicher, N., Bonde, N., Brown, D., Carrer, M., Cooper, R., Čufar, K., Dittmar, C., Esper, J., Griggs, C., Gunnarson, B., Günther, B., Gutierrez, E., Haneca, K., Helama, S., Herzig, F., Heussner, K.-U., Hofmann, J., Janda, P., Kontic, R., Köse, N., Kyncl, T., Levanič, T., Linderholm, H., Manning, S., Melvin, T. M., Miles, D., Neuwirth, B., Nicolussi, K., Nola, P., Panayotov, M., Popa, I., Rothe, A., Seftigen, K., Seim, A., Svarva, H., Svoboda, M., Thun, T., Timonen, M., Touchan, R., Trotsiuk, V., Trouet, V., Walder, F., Ważny, T., Wilson, R., and Zang, C.: Old World megadroughts and pluvials during the Common Era, Science advances, 1, e1500561, https://doi.org/10.1126/sciadv.1500561, 2015.

Erfurt, M., Glaser, R., and Blauhut, V.: Changing impacts and societal responses to drought in southwestern Germany since 1800, Reg Environ Change, 6, 985, https://doi.org/10.1007/s10113-019-01522-7, 2019.

Glaser, R.: Klimageschichte Mitteleuropas: 1200 Jahre Wetter, Klima, Katastrophen, 3. Auflage, WBG Wissenschaftliche Buchgesellschaft, Darmstadt, 264 pp., 2013.

Glaser, R., Riemann, D., Kellersohn, A., Lentz, S., Hanewinkel, C., Beck, A., Vogt, S., Borel, F., Sidawi, W., Kahle, M., Vogt, J., Steller, H., Specht, S., and Koslitz, S.: Tambora - the climate and environmental history collaborative research environment, 2015.

Gudmundsson, L. and Seneviratne, S. I.: European drought trends, Proc. IAHS, 369, 75–79, https://doi.org/10.5194/piahs-369-75-2015, 2015.

Hänsel, S., Ustrnul, Z., Łupikasza, E., and Skalak, P.: Assessing seasonal drought variations and trends over Central Europe, Advances in Water Resources, 127, 53–75, https://doi.org/10.1016/j.advwatres.2019.03.005, 2019.

Haslinger, K., Koffler, D., Schöner, W., and Laaha, G.: Exploring the link between meteorological drought and streamflow: Effects of climate-catchment interaction, Water Resour. Res., 50, 2468–2487, https://doi.org/10.1002/2013WR015051, 2014.

Haslinger, K., Holawe, F., and Blöschl, G.: Spatial characteristics of precipitation shortfalls in the Greater Alpine Region — a data-based analysis from observations, Theor Appl Climatol, 27, 17, https://doi.org/10.1007/s00704-018-2506-5, 2018.

Kreibich, H., Blauhut, V., Aerts, J. C.J.H., Bouwer, L. M., van Lanen, H. A.J., Mejia, A., Mens, M., and van Loon, A. F.: How to improve attribution of changes in drought and flood impacts, Hydrological Sciences Journal, 64, 1–18, https://doi.org/10.1080/02626667.2018.1558367, 2019.

Mc Kee, T., Doesken, N. J., and Kleist, J.: The Relationship of Drought Frequency and Duration to Time Scales., Eight Conference on Applied Climatology, 17-22 January 1993, Anaheim, California., 6 pp., 1993.

Noone, S., Broderick, C., Duffy, C., Matthews, T., Wilby, R. L., and Murphy, C.: A 250-year drought catalogue for the island of Ireland (1765-2015), Int. J. Climatol, 37, 239–254, https://doi.org/10.1002/joc.4999, 2017.

Schwarz, J. A., and Bauhus, J.: Benefits of mixtures on growth performance of silver fir (Abies alba) and European beech (Fagus sylvatica) increase with tree size without reducing drought tolerance, Frontiers in Forests and Global Change, 2, 79, 2019.

Seneviratne, S.I., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Nicholls, N., and Rahimi, M.: Changes in climate extremes and their impacts on the natural physical environment, in: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, edited by: Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, New York, NY, USA, 109–230, 2012.

Skiadaresis, G., Schwarz, J. A., and Bauhus, J.: Groundwater Extraction in Floodplain Forests Reduces Radial Growth and Increases Summer Drought Sensitivity of Pedunculate Oak Trees (Quercus robur L.), Front. For. Glob. Change, 2, 267, https://doi.org/10.3389/ffgc.2019.00005, 2019.

Sohn, J. A., Gebhardt, T., Ammer, C., Bauhus, J., Häberle, K. H., Matyssek, R., & Grams, T. E.: Mitigation of drought by thinning: short-term and long-term effects on growth and physiological performance of Norway spruce (Picea abies), Forest Ecology and Management, 308, 188-197, 2013.

Speer, J. H.: Fundamentals of tree-ring research, Univ. of Arizona Press, Tucson, Ariz., 333 pp., 2010.

Spinoni, J., Barbosa, P., Jager, A. de, McCormick, N., Naumann, G., Vogt, J. V., Magni, D., Masante, D., and Mazzeschi, M.: A new global database of meteorological drought events from 1951 to 2016, Journal of Hydrology: Regional Studies, 22, 100593, https://doi.org/10.1016/j.ejrh.2019.100593, 2019.

Stagge, J. H., Kohn, I., Tallaksen, L. M., and Stahl, K.: Modeling drought impact occurrence based on meteorological drought indices in Europe, Journal of Hydrology, 530, 37–50, 2015.

Stahl, K., Kohn, I., Blauhut, V., Urquijo, J., Stefano, L. de, Acácio, V., Dias, S. M.A., Stagge, J. H., Tallaksen, L. M., Kampragou, E., van Loon, A. F., Barker, L. J., Melsen, L. A., Bifulco, C., Musolino, D., Carli, A. de, Massarutto, A., Assimacopoulos, D., and Van Lanen, H. A. J.: Impacts of European drought events: Insights from an international database of text-based reports, Nat. Hazards Earth Syst. Sci. Discuss., 3, 801–819, https://doi.org/10.5194/nhessd-3-5453-2015, 2016.

Teuling, A. J.: A hot future for European droughts, Nature Climate change, 8, 364–365, https://doi.org/10.1038/s41558-018-0154-5, 2018.

https://doi.org/10.5194/nhess-2019-424
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Tijdeman, E., Hannaford, J., and Stahl, K.: Human influences on streamflow drought characteristics in England and Wales, Hydrol. Earth Syst. Sci., 22, 1051–1064, https://doi.org/10.5194/hess-22-1051-2018, 2018.

Valtorta, N. and Hanratty, B.: Loneliness, isolation and the health of older adults: do we need a new research agenda?, Journal of the Royal Society of Medicine, 105, 518–522, https://doi.org/10.1258/jrsm.2012.120128, 2012.

van Lanen, H. A.J., Laaha, G., Kingston, D. G., Gauster, T., Ionita, M., Vidal, J.-P., Vlnas, R., Tallaksen, L. M., Stahl, K., Hannaford, J., Delus, C., Fendekova, M., Mediero, L., Prudhomme, C., Rets, E., Romanowicz, R. J., Gailliez, S., Wong, W. K., Adler, M.-J., Blauhut, V., Caillouet, L., Chelcea, S., Frolova, N., Gudmundsson, L., Hanel, M., Haslinger, K., Kireeva, M., Osuch, M., Sauquet, E., Stagge, J. H., and van Loon, A. F.: Hydrology needed to manage droughts: The 2015 European case, Hydrol. Process., 30, 3097–3104, https://doi.org/10.1002/hyp.10838, 2016.

van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., Gleeson, T., van Dijk, A. I. J. M., Tallaksen, L. M., Hannaford, J., Uijlenhoet, R., Teuling, A. J., Hannah, D. M., Sheffield, J., Svoboda, M. D., Verbeiren, B., Wagener, T., and Van Lanen, Henny A. J.: Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches, Hydrol. Earth Syst. Sci., 20, 3631–3650, https://doi.org/10.5194/hess-20-3631-2016, 2016.

Vicente-Serrano, S. M., Lopez-Moreno, J.-I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., Coelho, F., and Espejo, F.: Evidence of increasing drought severity caused by temperature rise in southern Europe, Environ. Res. Lett., 9, 44001, https://doi.org/10.1088/1748-9326/9/4/044001, 2014.