List of relevant changes

We would like to thank both Referees for their valuable comments and suggestions on this manuscript.
We largely followed their comments and recommendations. Relevant changes made are:

- The restructured and rewritten introduction,
- The better explanation of the drought severity classification scheme (section 2.2.5),
- The now separated sections 4.2 and 4.3 and the new section 4.4 in the discussion

Please find our responses (in green) to each point raised by the Referees (shown in black) and a marked-up manuscript version below.

List of Changes for Referee 1

We would like to thank Referee 1 for his/her constructive comments and feedback on this manuscript. We think that the suggested revisions based on the reviewers' comments helped improve the article. Please find our responses (in green) to each point raised by the reviewer (shown in black) below.

General comments

The study compiles a long-term drought dataset considering different types of droughts. It therefore addresses two important problems in hydrology: (1) the limited record length usually available for trend analyses in extremes and (2) the multifaceted nature of drought events, which propagate through the hydrological cycle. The study is generally well written and organized even though it may profit from rephrasing and slight restructuring now and then. The datasets chosen are suitable for the analysis and the methods chosen mostly appropriate. The results are presented in clear and nicely designed figures. I below point out the need for strengthening the research question, discuss a few methodological points that should in my opinion be improved, point out a few passages that need clarification, and provide some suggestions of how the conclusions could in my view be strengthened.
Response: We followed your suggestions and rephrased, restructured and focused the points you specify below.

Specific comments

1. Why not shorten the title to 'A multivariate drought catalogue for southwestern Germany dating back to 1801'? Would be a bit easier to read.
   Response: Thank you for the suggestion, we changed the title to the version you suggested (but with using the term "multidisciplinary").

2. I think that the manuscript needs a clear research question (see e.g. abstract, where it could be added in l.16). Currently, the aim is to present a long-term drought collection. This is a methodological goal, which is fair enough. However, the paper could go further than that by asking: 'is the clustering of extreme events during the past decade unprecedented in a historical context?' I personally would frame the introduction in a way that highlights the need of a long-term dataset to answer this question. This would provide motivation for the study and highlight the practical relevance and value of the long-term dataset. The results presented allow for answering this question and lead to the conclusion that the past decade experienced frequent extreme events which is, however, not historically unprecedented if looking back into the 19th century.
   Response: We think your suggestion of highlighting this thematic research question about the current drought cluster compared to the cluster in the past fits perfectly to our study. We therefore emphasized this point in the new version of the manuscript. Throughout the manuscript we now strengthened the need of long-term data in drought research. We included a new purpose point c) in the introduction (l. 79). We deepened the point in the result part of the manuscript (see section 3.1 and 3.2) and we emphasized the importance of this point in a new discussion section 4.2.

3. The introduction would profit from a clearer structure. I would first talk about the hazard component and the different drought types. In this first part, I would also shortly mention

different drought indices (indices such as SPI but also duration, deficit, intensity, see e.g. [*Van Loon and Laaha*, 2015; *Brunner et al.*, 2019]). In a second part, I would transition to the vulnerability and impact component. Then, one could highlight the necessity of long term records to determine the rarity of certain events or periods of events. This would nicely transition to the aim of the study of providing a long-term dataset. And I would definitely talk about the value of long-term datasets in the context of trend analyses.
Response: In the introduction, we aimed to highlight the need of multidisciplinary and long-term research on drought. We applied the suggested change to first write about the hazard component and indices, then the vulnerability and impact component, then the necessity of long-term records to further clarify our aim of this study.

4. Could you please provide a short overview of the homogenization procedure for precipitation and temperature data (l. 79)?
   Response: The homogenisation procedure was conducted by HISTALP. We added this information in the revised manuscript with the link to the study of Auer et al. (2007), where the homogenisation procedure is described in detail (l.102).

5. What is the temporal resolution of the tree-ring series (l. 102)?
   Response: Thank you for the comment, tree-ring series are annually resolved (please see l. 117).

6. The description of the impact dataset is a bit confusing and needs clarification (l. 105-118). Do you mean to say: 'Dataset 4 is based on reported textual information on the impacts of drought events contained in two databases'? What do you mean by 'additional reports recently collected (l. 116)? Would it be possible to provide a reference here? Could you provide a bit more information on the reasoning behind the choice of the three impact categories agriculture, ecology, and hydrological systems? Where do e.g. hydropower production and industrial water use belong to?
   Response: Yes, Database 4 is based on reported textual information on the impacts of drought events contained in the European Drought Impact Report Inventory and tambora.org. We used some additional sources (e.g. Alzenauer Wetterchronik), which are not yet included in the database tambora.org. We added the reference of the sources to the description (l. 139-140). The textual information was coded after the categorisation system of the EDII.
   The categorisation scheme of the EDII is elaborate and requires detailed information on the impact, which was not always available for impacts dating further back in time. Furthermore, with respect to historic drought events, certain impacts (such as tourism, ecology) did not play a major role in daily life, and hence have not been reported as such. Accordingly, we adapted the categorisation schemes to the "major" areas of drought hazards and concern: soil moisture, hydrology and ecology (including forestry) to pool comparable impact reports. We included a Table S2 in the Supplement material, where the specific impact categories and impact types used in this study, such as hydropower production and industrial water use, are listed.

7. Could you please pay attention to a consistent use of the terms 'variable', 'characteristic', 'index',… while revising the manuscript? In l. 125 e.g. do you really mean to talk about 'variables' or rather 'indices'? Or line 127: weren't indices computed from time series of anomalies?
   Response: We follow now the terminology in Figure 1. Indices were computed based on the

variables. In l. 125 we really meant variables (like precipitation data) that were used to calculate indices. In l. 127 we meant indices and corrected that in the revised manuscript (l. 153 now).

8. Drought definition section (l. 124-168): It remains unclear to me how exactly the drought events were determined based on the time series of indices (meteorological droughts) and percentiles (hydrological droughts). Currently, I see two aspects discussed: computation of index time series, and classification of years. Is it correct that the classification step corresponds to a threshold approach, in your case with three different thresholds? If so, could this be clarified?
Response: We now emphasize that we determined drought years and not drought events with a fixed start and end date. Drought years were derived from the anomaly time series of the different indices (SPI_n, $SPEI_n$, Q_P, $TRI_{species}$). A year was defined to be in drought whenever the variable of interest was abnormally low, in this study below the 20th percentile. Drought years were further classified according to three different severity classifications: D1 (moderate; <20th percentile), D2 (severe; <10th percentile) and D3 (extreme <5th percentile). We have now clarified how we defined drought years in section 2.2.

9. Computation of SPI and SPEI: why did you not use hydrological years for the computation of the index time series (l. 138)? This would be more consistent with a hydrological perspective than the use of calendar years.
Response: Thank you for the question. As you mentioned in comment 20, we have already included quite many meteorological drought indices, and did not want to give more weight to meteorological drought. Deriving meteorological drought indices for the hydrological year makes sense from a hydrological perspective, but probably not for other perspectives (e.g., tree-rings are time-stamped based on the calendar year). In fact, in hydrology some countries use a 'low flow year', starting in April for routine analyses (e.g. CH) - this is close to some of our accumulation periods. Further, our aim was to show the differences between the different perspectives and not to find the best link between the different drought types.

10. Choice of distribution functions for derivation of SPI and SPEI: please provide a reason for the specific choices made or a suitable reference (l. 140 and 145).
Response: For the SPI we selected the gamma distribution, because it best fits precipitation sums of different accumulation periods for Europe (Stagge et al., 2015). We clarified this and added a reference in the revised manuscript. For the SPEI we used the generalized logistic distribution as suggested by Beguería et al. (2014). We added the reference to the sentence (l. 169.173).

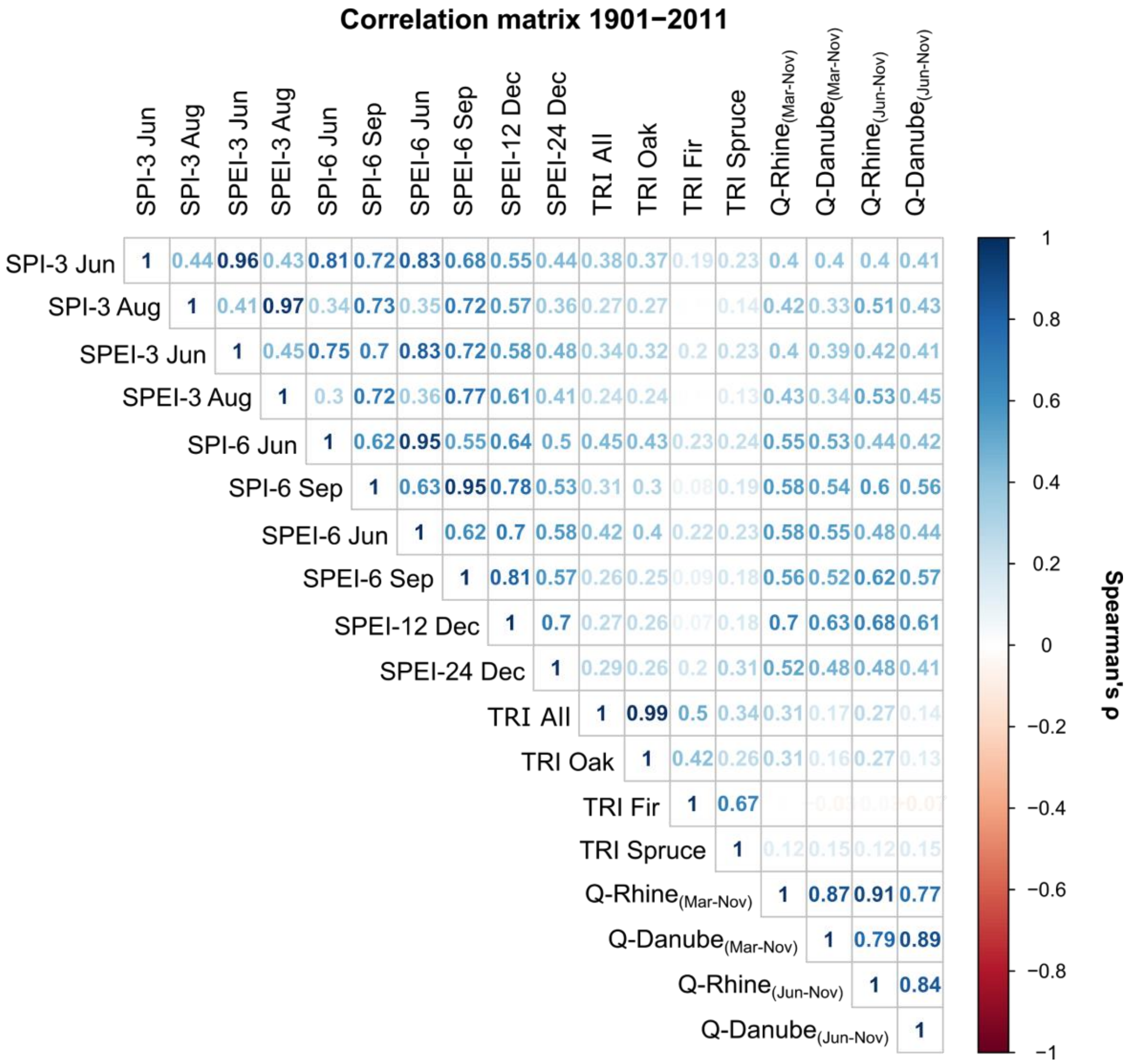
11. The vegetation drought section needs some additional explanation (l. 151-161) for non-dendrochronologists: provide a reference to the 'standard methods' (l. 151), explain what a 50% frequency cutoff is (l. 154), explain what a bi-weight robust mean is (l.156), explain what an expressed population signal is (l.159).
Response: We have now provided additional information on the dendrochronological methods and statistics used (l. 190-195).

12. Drought severity classification scheme (l. 169-178): In my understanding, this corresponds to the actual drought identification step. Could you please clarify this?
Response: We clarified how we defined drought years in section 2.2: "Drought years were

derived from the anomaly time series of the different indices (SPIn, SPEIn, QP, TRIspecies). A year was defined to be in drought whenever the variable of interest was abnormally low, in this study below the 20th percentile. Drought years were further classified according to three different severity classifications: D1 (moderate; <20th percentile), D2 (severe; <10th percentile) and D3 (extreme <5th percentile)." Please see our response to comment 8.

13. I think that the term 'frequencies of indices' (l. 176, l.240, l.251) is confusing (applies throughout the manuscript. If I understand this correctly, this is not a frequency but rather number of indices that co-detect a certain event. This whole part on the moving window is a bit unclear (l. 175-178). Why is this moving window approach even necessary?
    Response: With our "frequency" analysis we want to analyse how many D1, D2 and D3 Droughts occured in a specific unit of time. We see that the word "frequency" is not quite clear in that context. We therefore changed it throughout the manuscript to the word "combined drought index" and "occurrence" of droughts co-detect by several indices.
    For this analysis, we were not interested in the different drought types (we assume that but every perspective on drought is equally important) but instead we were interested in whether drought occurrence clusters in time, i.e., whether there were decadal hotspots of increased drought occurrences. By using a moving window instead of fixed decadal time blocks, we assure that we don't miss decadal drought hot-spots that happen at the end of one decade and the beginning of the following. We clarified that step in section 2.2 (l.214-219), in the figure description of Fig. 3, and in section 3.2.

14. Choice of Pearson correlation for correlation analysis (l. 186). Why use a linear correlation measure and not just a monotonic one, e.g. Kendall's or Spearman's rank correlation coefficient. Maybe there is a relationship which is just not linear.
    Response: Thank you for this comment. We have now repeated the analysis using Spearman's Rank-Order correlation (see figure below) and compared the results obtained from the two analyses. The correlation coefficients obtained from the two analyses are almost identical.



15. 'Similarity index' (l.186-187): It remains unclear to me what exactly this index does, and why it is called similarity index. Is the ratio you are talking about n_extreme/n_all? If so, did you compute this ratio for both indices and then compare the ratios to determine similarity? Please clarify.
Response: We will clarify in the revised manuscript that the similarity index is calculated as the total number of extreme drought years identified by two considered indices divided by the number of extreme drought years identified by index separately:

$$Similarity = \frac{total\ number\ of\ extreme\ droughts/2}{number\ of\ common\ extreme\ droughts}$$

It is used to describe the similarity between two indices to identify extreme drought events. We clarified this in the revised manuscript version and added the formula in line 232 to better explain our steps.

16. It would be nice to compute the similarity measures r and s not only for two periods but using a moving window approach allowing for an actual trend analysis (l.189-192). The problem with the two-period as opposed to a moving window approach is that one may compare a period located at the high end of an oscillation with one at the low end of an oscillation and therefore mistakenly interpret a trend even though these two periods are just located in two different parts of a cycle.
Response: We agree that the selection of two periods might seem arbitrary and a moving

window approach could be more appropriate here. The problem with a moving window approach, however, would be to demonstrate these results for all indices (153 combinations) and the long period examined here.

17. I do not understand why this second grouping is necessary (l. 196-200). Do you mean that you assign one or several reasons to the choice of an event?
Response: In Figures 5 and 7 grouping was necessary to identify similarities and differences among the datasets. Additionally we want to distinguish between short- and long-term meteorological drought indices (SPI and SPEI). There was almost no difference between the long-term SPEIs and the long-term SPIs, therefore we excluded the latter one for Fig. 5 and 7. We added more information on the grouping in order to clarify that point (line 243-245).

18. No actual trend analysis is performed in this study. I would therefore not talk about 'become more frequent' (l.209) but rather say that extreme droughts happened in clusters (e.g. 1860s and recent decade). Similarly I would say 'the last decade shows a high (not higher) severity of events' (219).
Response: Indeed we did not perform any trend analysis, so we changed the sentence to "several clusters of increased drought occurrence were identified" (line 252-254). With the sentence "the last decade shows a higher severity of drought events" we mean, that more drought events are classified as extreme (class D3). We changed the sentence accordingly (line 260-261).

19. Event clustering (l.240-249): I think that this temporal clustering aspect as opposed to a trend is interesting and deserves some more attention.
Response: We emphasized more on the temporal clustering in the revised manuscript in section 3.1 and 3.2.

20. Figure 3: Following the methods description, would it not be more logical to present the impact panel after panel b)? Why does panel a) not have a grey background for 'no events'? In the calculation of the percentages presented in panel c, aren't the meteorological indices getting much more weight than the other indices because there is so many of them?
Response: We decided to present the catalogue in this order, because the impacts were not included in panel c). Based on your comment, we see that this seems to be confusing, so we will change the order of the plot. In the revised manuscript we will present Figure 3 in the following order: (a) individual indices, (b) impacts, (c) composite information. We expanded the point on challenges with textual information in the discussion (line 444-447). In panel c) the meteorological indices make up a large proportion of the number of events per year, but this promotion does not change through time, so the 'weight' stays the same. The percentage of indices indicating droughts was calculated based on the number of available indices per year. This was corrected for the period following 1900 when Q was available.

21. Drought frequency (section 3.2): I do not see the added value of this moving window approach. What does it allow to demonstrate which is not already shown in Figure 3c? Wouldn't some temporal clustering approach be more beneficial here? E.g. group all events separated by less than 2 years without a drought?
Response: Please see also our response to comment 13. In Fig. 3c we only show the number of

drought events per severity class per year. In the next step, we were interested in the temporal clustering of droughts, i.e., decadal drought hot spots. Therefore we decided to calculate how many droughts per severity class occurred in 5 and 15-year periods. Instead of the moving windows, we could have used fixed timespans (e.g. for 5 years starting in 1801: 1801 to 1806, 1807 to 1811 and so on) but this is then biased by the starting point, so we found it more objective to use the moving window approach.

22. I would include Figure S5 in the main article and remove Figure 4 instead. What is the difference in the results derived from the correlation and similarity analysis? If both transport the same message, why not remove one of them?
Response: Do you mean Figure 6 instead of Figure 4? In the similarity analysis we used only extreme droughts (severity class D3), while in the correlation analysis (Figure S5) we included all severity classes. We now include the formula we provided in our response to point 15, we hope this now demonstrates the differences between the two metrics.

23. Section 4.1: It is interesting to note that the droughts identified by all indices seem to have a regional extent as illustrated by the references provided. I think it would be interesting to discuss this aspect a bit further.
Response: Indeed, that is an interesting point which we extended slightly in the revised manuscript (section 4.1).

24. I do not think that the statement 'the recent period was characterized by higher frequency of extreme droughts' (l. 435) is particularly well supported by the results. The results presented in Figure 3 rather show that there are temporal clusters of extreme events and that the cluster of extreme events observed in the recent decade is not unprecedented (e.g. 1855- 1870). I think that the strength of this study is exactly that it provides this context which is often missing when looking at short records (last 30-40) which bring us to conclusions such as 'extreme events become more frequent'. Your dataset nicely shows that periods of frequent extremes happen now but also happened in the past. I would add a discussion point on this temporal clustering aspect. Ideally, referring to existing literature.
Response: We agree and instead now wrote "was characterized by increased occurrence of extreme droughts." Nevertheless, within our dataset especially the last five years (see Fig. 4c, last bar: 2014 to 2018) we find more extreme droughts (severity class D3) then in the other timespans. But we agree with you, that the clustering of several years with extreme droughts is not unprecedented. Both points are important, so we distinguish between them and focus also on the temporal clustering in the discussion (see new Section 4.2).

25. I think that the conclusions could be much stronger than the ones currently presented (l.442-456). I suggest to add something along the lines of: 'Our long-term dataset shows that (1) extreme droughts cluster in time, (2) the recent decade experienced many extreme droughts similar to a period in the mid 19th century, (3) the last decade is less exceptional in a historical context than when looking at the last 30-40 years as often done in trend analyses.
Response: We included these points in the conclusion beside the points of using a multivariate dataset. We think this now underlines the main aspects of this study: I) using a long-term and II) multivariate dataset for regional drought research.

26. Could you provide some information on how the community can access the dataset?
    Response: Yes, we will provide access to the drought catalogue data. The doi is reserved and data will be uploaded upon acceptance of the paper.

Minor points

l. 26: with 'potentially' widespread negative consequences …
Response: We changed the sentence as suggested (l. 27).

l. 44: which 'can' affect all components …
Response: We changed the sentence (l. 28).

l.70: drought types such as …
Response: We added the drought types we referred to (l. 85).

l.71: drought indices such as …
Response: We added some examples (l. 87).

Figure 1: I would slightly extend the caption and provide a bit more information on the content of the figure. The equation within the blue box on streamflow percentiles is strange. I would remove it from the figure. Indexvalue should be 'index value'. Variable names should be in italic (e.g. T should be T).
Response: Thank you for the comment. We extended the caption. We removed the equation on streamflow percentiles. We also changed 'Indexvalues' to 'Index values' and made variable names italic.

l.75: 'the study employs and assembly…'. Rephrasing needed.
Response: We rephrased the sentence (l. 90).

Figure 2: I would use a gray scale for the relief as you are just displaying one variables which does not require the use of a rainbow color scheme. By 'Stand', do you refer to 'Standort'? If yes, I would use an English abbreviation instead such as 'Loc'.
Response: The term stand is used to refer to the location of forest stands (https://en.wikipedia.org/wiki/Forest_stand). We changed the figure and use a grey background now.

l.138: can you also provide a reason for June as you did with the other periods, analogous to the tree growth example for September?
Response: We now provide a reason for June as well (l. 164).

l. 140: The distribution is fitted to the data and not the data to the distribution. Sentence needs rephrasing.
Response: We rephrased the sentence (l. 166-167).

l. 142-143: reference period for what? I do not understand the meaning of this sentence.
Response: We rephrased the sentence (l. 169).

l. 149: provide a reference for the Weibull plotting position: [Weibull, 1938]
Response: We added the reference (l. 178).

l.181: do you mean from 1801-1900?

Response: We changed the sentence to "we ranked the ten most extreme years since 1900 onward for all indicators, and additionally since 1801 onward for the meteorological and the tree-ring dataset" and we hope it is now clear that we mean 1900-2017/18 and 1800-2017/18.
l. 184: two instead of 'three' metrics? I only see the Pearson correlation and the 'similarity index'.
Response: Here we refer to the three metrics (correlation, similarity and distinctiveness) used to quantify similarities and relationships among the different drought indices. We changed the text accordingly (l.225-229).

l. 196: by extreme, do you refer to set D3?
Response: Yes, we added D3 to the sentence in the revised manuscript (l. 239).

l. 197: which datasets were grouped?
Response: We meant 'indices'. We changed that in the revised manuscript (l. 240).

l. 208: I see a few more years in Figure 3b: 1964, 1949, 1991.
Response: Yes, there are more years. We listed only some examples. Nevertheless, we now include more examples (l. 252).

l. 222: Link this ET statement to literature on changes in temperature.
Response: We changed the sentence and included a reference to the ET statement in the discussion section 4.2 (l. 463).

l. 271-271: with most, do you mean more than 10 (see caption Figure 5)? And what does the sentence 'in all cases more than 25%...) mean?
Response: Yes, with 'most' we meant 'more than' 10. With 'more than 25%' we refer to the dotted line in Fig. 3c). We changed the sentence in the new version (l. 300 and the caption of Figure 5).

l. 288: which 'two' drought types?
Response: We rephrased the sentence to "meteorological and hydrological drought indicators" (l. 338).

Figure 5: Would it be possible to make the red color a bit more purplish to better fit into the overall color scheme?
Response: See new version of Figure 5.

l.304: When talking about the two different accumulation periods, do you refer to meteorological droughts?
Response: No, here we refer to the two average periods we used for stream flow (Q.March-November and Q.June-November). We clarified this in the text (l. 352-353).

l. 377: and due to more frequent reporting?
Response: Yes, the increased awareness (private, public and governmental) might be expressed by more frequent reporting (e.g. by an increase in reports on ecological impacts (Blauhut et al 2015). We clarified that in the new version of the manuscript (l. 446).

l. 405: how was this increase in reporting taken into account?
Response: We used binary information (annual value indicating 'impact' or 'no impact' occurrence in each category). We corrected the increase in reporting by converting every year before 1947 with one or more indicated impact into an impact year with 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 (see section 2.2.4).

l.424f: use of word ‘distinct’, do you mean ‘index-specific’. To me, the term distinct looks odd in this context.

Response: We changed the word to ‘unique’.

l. 433: specify which two periods.

Response: We specified the two periods (l. 451).

l.460: ‘all versions of the paper’. The readers just see one.

Response: Yes, that's true. We changed it to ‘the paper’.

References used in this review and the reply to this review

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.

Beguería, S., Vicente-Serrano, S. M., Reig, F., and Latorre, B.: Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring, Int. J. Climatol., 34, 3001–3023, https://doi.org/10.1002/joc.3887, 2014.

Brunner, M. I., K. Liechti, and M. Zappa (2019), Extremeness of recent drought events in Switzerland: Dependence on variable and return period choice, *Nat. Hazards Earth Syst. Sci.*, *19*(10), 2311– 2323, doi:10.5194/nhess-19-2311-2019.

Stagge, J. H., Tallaksen, L. M., Gudmundsson, L., van Loon, A. F., and Stahl, K.: Candidate Distributions for Climatological Drought Indices (SPI and SPEI), Int. J. Climatol., 35, 4027–4040, https://doi.org/10.1002/joc.4267, 2015.

Van Loon, A. F., and G. Laaha (2015), Hydrological drought severity explained by climate and catchment characteristics, *J. Hydrol.*, *526*, 3–14, doi:10.1016/j.jhydrol.2014.10.059.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, J. Climate, 23, 1696–1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.

Weibull, W. (1938), *Investigations into strength properties of brittle materials*, Generalstabens litografiska anstalts förlag, Stockholm.

List of Changes for Referee 2

We would like to thank Referee 2 for his/her constructive comments and feedback on this manuscript. We think that the suggested revisions based on the reviewers' comments improved the article. Please find our responses (in green) to each point raised by the reviewer (shown in black) below.

Major points

Although the title of the paper sets out the aim to explore the benefits of such a multidisciplinary approach for drought research, however I feel like the discussion would really benefit from a discussion of how these results and type of analysis is beneficial for real world applications or drought managers. In the UK for example, water companies must plan for droughts that are the worst on record (and actually now, worse than those on record using stochastic approaches), so having a good understanding of what droughts were severe, where and from what perspective is extremely important for the drought planning process. I am interested to see how this research will benefit water/drought management from the German perspective. The discussion could also be strengthened in terms out how the results compare to other studies in the region and how the droughts identified may differ in terms of their severity/impact – what was the effect of using multiple indices and the impacts here compared to these other studies?

Response: We like the idea of discussing the benefits or the potential of our study for drought management and included a new section 4.4. This is indeed crucial given the lack of a centralized drought management authority in southwestern Germany. Drought monitoring is dispersed: state level river situation monitoring existits and there are two federal level platforms by UfZ focusing on soil moisture anomalies for agricultural land and the DWD provides monthly maps of an aridity index for Germany but there is no overall, multi-sectoral drought management authority in place. With our drought catalogue we get a better understanding of past drought events. The worst case droughts can be used as benchmark events to inform future drought planning. We provide a discussion point 4.4 where we stress the need of a multi-sectoral regional drought management plan and how this or similar multidisciplinary studies could provide a basis and help to develop such a plan.
Further, we now focus in the discussion in section 4.1 on the data used and compare the identified droughts to other drought studies in Europe (most drought studies in the study region focus on methodological aspects and are only based on single variables). We discuss now separately the added value of long-term datasets in section 4.2, and the value of multidisciplinary studies in drought research in section 4.3.

Minor and technical points

L14: …Many studies have identified past drought events…

Response: We changed the sentence accordingly (L15).

L43: It might be nice to add another one/two examples of the types of individual indices used here, as well as tree-ring based ones

Response: We added some more examples to this part (paragraph beginning L56).

L45: it felt like there was a word missing here, suggestion: …Different drought types characterised using a variety of indices…

Response: We changed the whole paragraph (L40).

Section 2.1: It might be nicer to use un-numbered sub-headings for each of the datasets here to make it easier for the reader to refer back to the section of interest

Response: We inserted a third level of sub-headings for each dataset. We did the same in section 2.2.

Figure 1: Overall I like this diagram, however have a few comments. 1) in the combined drought frequency index box you mention S1, S2, S3 events, but it's not clear from the rest of the diagram where this categorisation has come from (and I don't think is mentioned elsewhere in the paper) is there a typo here? If not, perhaps clarify? 2) The red arrows on the right of the diagram show the outcome of the meteorological, hydrological and vegetation drought indices feeding into the distinctiveness analysis, but the impact data also feed in to this section – amend the arrows to show how the impacts feed into the final part of the analysis.

Response: 1) Indeed, that was a mistake. We changed the description to D1, D2 and D3 or the different drought classes. 2) We added the missing arrow.

L78: precipitation ~~sums~~ totals

Response: In literature we find both words for precipitation sums/totals. We decided to keep the word "sums".

L78-79: I think it makes sense for the station names to be earlier in the sentence, like this '…for two stations in Baden-Wuerttemberg (Rheinstetten-Karlsruhe and Stuttgart, Figure 2), which provide the longest continuous time-series of the required variables.'

Response: We change the sentence as suggested (L99).

L79: It's not clear whether the 'required variables' mentioned in the first sentence are the same as the precipitation and temperature data mentioned in the second sentence – please clarify.

Response: Yes, they are the same. We clarified this (L100).

L95-96: You state that pine was also tested but not included because of their weak climate signal – do you have a reference or some analysis you can show (perhaps in the supplementary info) to support this?

Response: Thank you for this comment. Indeed, this was not shown anywhere in our results and we believe this information is not necessary. We have, therefore, deleted this sentence in the revised version of the manuscript.

L100: what is meant by 'appx.'?

Response: We meant the appendix. But now we refer to the supplementary material with Table S1 and so on and therefore delete 'appx'.

L1157-119: You use three categories of impact (agriculture, ecology and hydrology), the EDII has ~14 categories, from what you've said I think that you have grouped EDII categories to create 3 groups of impacts, is this the case? Please clarify in the text.

Response: Yes, we have grouped the EDII categories into three new groups of impacts (agriculture, ecology and hydrology). We included a Table S2 in the supplements where we list which impact type from the EDII categorisation was used for the three groups and we clarified this in the text.

Figure 2: It is quite difficult to see the colour of the points for the tree locations against the elevation layer – you could either make the elevation slightly transparent to make it paler or change the colour of the points (or both) to make it easier to read

Response: We changed the figure. Elevation layer is now excluded, we use a grey background instead.

L127: …US Drought Monitoring and Drought Impact Rreporter… – capital R needed for Reporter

Response: We changed that (L153).

L133: … estimated using ~~with~~ the Thornthwaite equation (which only… [Space missing between 'equation' and opening bracket]

Response: We changed the sentence accordingly (L159).

L129-145: This section on the use and calculation of SPI and SPEI would benefit from a discussion of the distributions selected and the potential impact this choice may have had on the results – e.g. recent papers have tested appropriate distributions for such standardised indices Stagge et al. 2015 (https://doi.org/10.1002/joc.4267) and Svenssson et al. 2017 (https://doi.org/10.1002/2016WR019276). It isn't clear if a reference period was used, or whether data were standardised against the whole time series available – please clarify in the text.

Response: For the SPI we selected the gamma distribution, because it best fits precipitation sums of different accumulation periods for Europe and referred to Stagge et al., 2015. For the SPEI, we clarify that we used the generalized logistic distribution as suggested by Beguería et al. (2014, https://doi.org/10.1002/joc.3887) and refer to the latter paper. As reference period we used the longest available common period for both meteorological stations (which is 1810 to 2018). We clarified this.

L151: You mention that tree ring data were gathered from 70 locations, but from looking at Figure 2 there doesn't look to be 70 points representing tree stands – is this correct (or are there many overlapping points on the map?)

Response: That was indeed a mistake. The initial dataset consisted of tree-ring data from 70 locations. Following our selection procedure (L181) we included only tree-ring series from 55 locations. Still several points in Figure 2 are overlapping.

L174-176: This point isn't very clear (also mentioned in the comments for Figure 1) – perhaps worth adding a section to the diagram? If the diagram gets too big for the width of the page perhaps you could add it horizontally?

Response: We agree that this sentence needs clarification. However, it is already included in Fig. 1 (Drought Severity Classification). In this part we described that a year was defined to be in drought whenever the variable of interest was abnormally low, in this study below the 20th percentile. Drought years were further classified according to three different severity classifications: D1 (moderate; <20th percentile), D2 (severe; <10th percentile) and D3 (extreme <5th percentile). We clarified in the revised version how we defined drought years in section 2.2.

L154: remove space between 50 and % symbol

Response: In NHESS spaces must be included between number and unit. During the "typesetting" of NHESS, the "correct" spaces between symbols and numbers will probably be added.

L189: Both similarity measures, *r* and *s*, were…. (r and s in italics)
Response: We changed it to italics (L227).

L196-203: sorry this section is a bit unclear, particularly the last sentence of this paragraph. Do you mean that if one of the impact groups (e.g. tree rings) is removed, you identify 12 fewer events as these weren't identified in any of the other series? Please clarify.
Response: This is exactly what the distinctiveness value stands for. We have now clarified that in the text (L240).

L237-238: The order of the words in this sentence isn't quite right, suggestion: "For both the Rhine and the Danube, streamflow in the years 2003 and 2018 were marked as extremely low."
Response: We changed the sentence accordingly (L265).

L240: What is the significance of the bold text here?
Response: There is no significance, therefore we unbolded the text (L283).

Figure 3: I wonder if part b might be better grouped so that all the SPI indices are together, all the SPEI indices together, all Rhine and all Danube together, with a small break or line between each group. Please add a title (as in 3a) or a yaxis label to 3c.
Response: We think in this figure it is more important to have the accumulation periods together because we want to emphasize the difference between SPI and SPEI (which is more clearly visible by plotting the SPI-3 below the SPEI-3) and not the differences between accumulation periods (see Fig. below). In the revised manuscript we present Figure 3 in the following order: (a) individual indices, (b) impacts, (c) composite information.

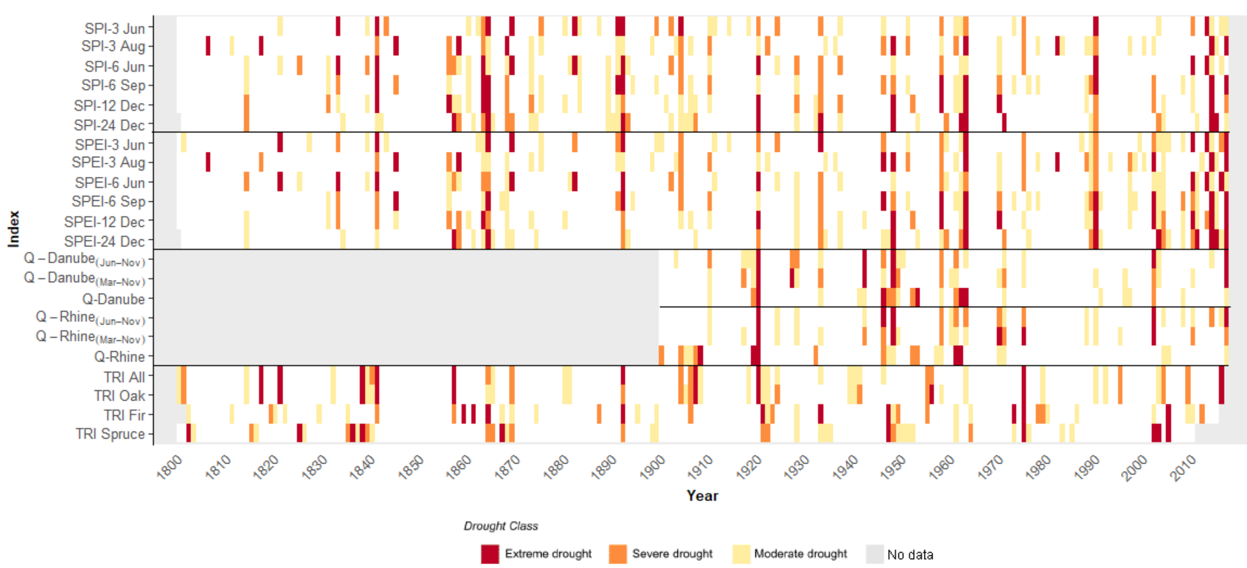


Fig.: Drought catalogue. Indices grouped by type (SPI, SPEI, Danube and Rhine) as well as the accumulation periods.

L270-276: It's not clear how you arrived at 17 years here from Figure 3c – please clarify. Perhaps you could mark on Figure 3c which years meet your criteria. (I think the criteria is more clearly explained in the caption for Figure 5).

Response: In the revised manuscript we included in L321, that we focused on the 20 drought years, in which most indices point to a drought. In L323 we rearranged the sentence to "After 1900 all 17 years (the period for which streamflow data was available) were identified as drought years based on streamflow indices."

L271: remove space between 25 and % symbol

Response: In NHESS spaces must be included between number and unit.

Figure 5: Please explain what the numbers within each section of the rings refers to in the caption.

Response: They refer to the number of indices per group pointing to a drought. We clarified this in the caption of Figure 5.

L302-303: This sentence doesn't read right, suggestion: The similarity index for each pair of datasets and the two periods showed some interesting patterns in the extreme droughts identified.

Response: We have now changed the sentence based on your suggestion (L351).

Figure 6 & Figure S7: group datasets/s as suggested for Figure 3 (and all other relevant figures in Supplement). There are two grey colours on the plot, the caption indicates that grey = no extreme drought, but it doesn't say which grey this refers to. There's also some white cells in the plot – what does this mean? Please add to the legend to include white, pale grey and dark grey. The colour scale doesn't show much differentiation between colours, I recommend you add a colour to the scale (e.g. yellow) so it is easier to visually see the difference in relationship.

Response: In Figure 6 and S7 we used only one grey color. The grey color used just seems darker when surrounded by dark red boxes. The white cells indicate 0 similarity while the grey boxes indicate that no extreme drought was identified by either of the two indices. We have added a black rectangle around the colour ramp which we believe clarifies this point.

Figure 7: the caption is a bit unclear, I think you need to make it clear that each row shows the droughts that are identified when the group of indices are excluded from the analysis and therefore show the events unique to this group indices

Response: We rewrote the caption of Fig. 7 and additionally use the word 'category' instead of 'group' now.

L355: what's meant by double or triple drought years?

Response: Here we meant 'two or three consecutive years of extreme drought'. We clarified the sentence (L405).

L386-388: can you comment on the changing anthropogenic influences in these catchments over time?

Response: We added a sentence on this in the discussion (L427-428). In general, human influences on river flow are susceptible to changes over time and further provide some detail and references how (changing) anthropogenic influences might have affected flow in the considered rivers.

L417: ...ten drought events since 1900 and ~~respectively~~ since 1801 emphasised…

Response: We changed the sentence as suggested (L450-451).

L420: you state here that you looked at negative impacts only, but I don’t think you mention this in the data/methods section – it would be good to point this out, but also perhaps mentioning that there can be positive impacts of drought (e.g. on particular crops like strawberries)

Response: We now mention it in the data section (L129).

L427: ‘’based on these indicators ~~following~~ 1950…

Response: We changed this sentence to “after 1950” (L477).

L428: could this also be a result of improved impact data in more recent times as well?

Response: We agree, the lack of distinct events in the last decades might be the result of both improved impact and hydrometeorological data. We added a comment on this (L478-479).

L449-450: …Trees in the study region are ~~indeed~~ sensitive to water deficiencies …

Response: We changed the sentence accordingly (L512).

L496: Update reference to accepted version of the paper

Response: We updated the reference to the accepted version of the paper (L569).

Figures S1-S4: perhaps these could be added as a single 4 panel plot (i.e. 2x2 grid)

Response: We made a single plot as suggested by you. See Fig. S1 in the supplementary material.

Figure S5: the numbers in the cells are a bit large and in some cases merge together – they would be made a bit clearer if the text was slightly smaller (for example, it is a better size in Fig S6). Also some of the colours are quite hard to read e.g. on the TIR Fir row (perhaps this is only an issue in the low quality review figure?) Please also add a label to the colour ramp legend to say what it is showing.

Response: We have decreased the size of the numbers and included a legend to the color ramp (see Fig. S2).

Figure S6: Please also add a label to the colour ramp legend to say what it is showing. Also some of the colours are quite hard to read e.g. on the TIR Fir row (perhaps this is only an issue in the low quality review figure?)

Response: We have included a legend to the colour ramp (see Fig. S3).

A multidisciplinary drought catalogue for southwestern Germany dating back to 1801

~~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 perspectives~~variables~~ need to be considered. Many studies have 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. However, it is not certain whether the increased frequency and severity of drought events in the past decade is unprecedented in recent history. There~~Here~~fore, we analyz~~s~~e different droughts and their impacts in a regional context using a multidisciplinary approach. We~~and~~ compile~~d~~ a comprehensive and long-term data set to investigate possible patterns in drought occurrence and 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 indices~~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 recent meteorological droughts in the 21st century.~~

1 Introduction

Droughts are natural hazards with potentially widespread negative consequences for environment and society. As droughts can affect different domains of the water cycle and water deficits often accumulate only slowly over time, they are commonly considered one of the most complex natural hazards (Wilhite 2000). The complexity of droughts is reflected in the numerous definitions of the hazard, developed by a variety of different disciplinary perspectives and needs for different drought management applications. Frequently these definitions are associated with one of several drought types, e.g., meteorological, hydrological, agricultural, and socioeconomic drought (Wilhite and Glantz 1985). To provide a quantitative assessment of different drought events a wealth of indices exists for each drought type (Zargar et al., 2011; WMO and GWP, 2016). For example, meteorological droughts are often evaluated using the Standardized Precipitation Index (SPI; McKee et al., 1993) at various timescales, hydrological droughts can be described calculating the Standardized Streamflow Index (SSFI), agricultural droughts can be assessed using the Soil Moisture Anomaly (SMA) index (for an overview of existing drought indices refer to WMO and GWP, 2016). These standardized indices can be used for large-scale monitoring as they allow comparison in space. In general, hydrometeorological variables and drought indices may be used to quantify drought event characteristics such as duration, timing, frequency and severity.

Often studies focus on one particular drought type or on the link between different types as droughts propagate, for example from precipitation deficit to soil moisture deficits and/or to surface and groundwater deficits (Haslinger et al., 2014; Bachmair et al., 2018, 2015; Blauhut et al., 2015; Stagge et al., 2015). A single variable assessment provides sector relevant information, e.g., analyzing the root zone soil moisture drought signal provides information relevant for agriculture. However, different types of drought are not necessarily linked in a similar way. For example, the propagation from meteorological anomalies to streamflow anomalies is affected by climate and catchment characteristics as well as by anthropogenic influences (Tijdeman et al., 2018). 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). Therefore, recent studies examine the simultaneous occurrence of different drought types (e.g., Brunner et al., 2019). In addition, below-normal anomalies in any hydro-meteorological variable 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, van Loon et al., 2016). ~~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 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.

The knowledge on past extreme droughts is not only critical for future drought management but also for climate change research. As droughts are rare and irregular extremes, a valid analysis of the extremes requires long-term records. The knowledge on past drought extremes can serve as a validation source for climate models and will increase the confidence in their projections of future changes in extremes. ~~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 can also help~~is needed~~ to assess the severity of current ~~and future~~ drought events (Hanel et al., 2018). 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) and Büntgen et al. (2010). 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; Mikšovský et al., 2019). A systematic characteriz~~s~~ation of historical hydrological droughts (1891 to 2015) for a diverse set of catchments exists for the UK (Barker et al., 2019). Jakubínský et al. (2019) developed a repository of drought impacts (between 1981 and 2016) across the Danube catchments countries. All these catalogues depict mainly one or two types of drought based on individual (e.g., precipitation~~, precipitation~~, streamflow or tree-ring based) indices~~indicators~~.

~~As droughts are multifaceted hazards which can 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.~~

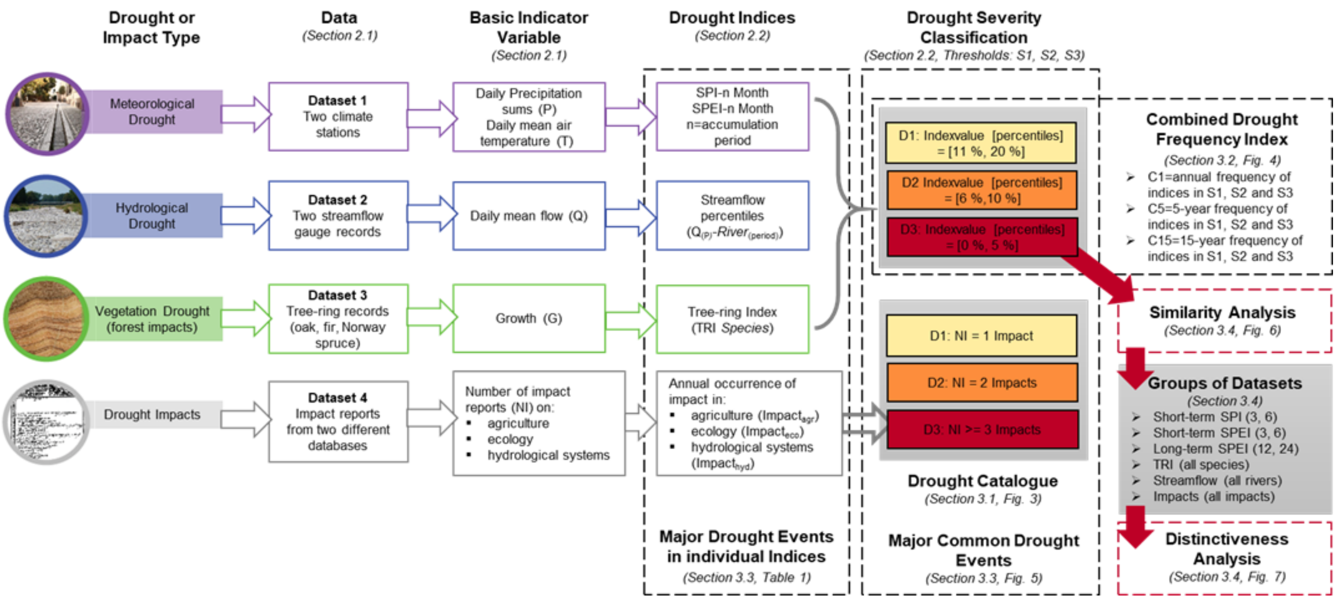
The purpose of this article is to catalogue and analyz~~s~~e historical drought events of the last 218 years at a regional scale, i.e. for the state of Baden-Wuerttemberg in southwestern Germany. Furthermore, this study explores multiple~~different~~ perspectives on drought and determines the added value of such ~~multi-dimensional~~ datasets for a comprehensive understanding of drought events from the year 1801~~0~~ onward. For this purpose, we:

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) investigate whether the recent clustering of extreme drought events is unprecedented in a historical context,
d~~c~~) identify strengths and weaknesses of the datasets and indices, and
e~~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 two major drought types - the meteorological and hydrological drought ~~and vegetation~~ ~~types~~ as well as past drought impacts on vegetation and society. Based on these datasets ~~and~~ multiple levels of classification of individual and combined drought indices such as the SPI, the Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010) and streamflow percentiles (QP) were calculated. 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). In this study, we use a compilation of several drought-related variables, herein referred to as datasets 1 to 4 (Fig. 1 and Fig. 2).



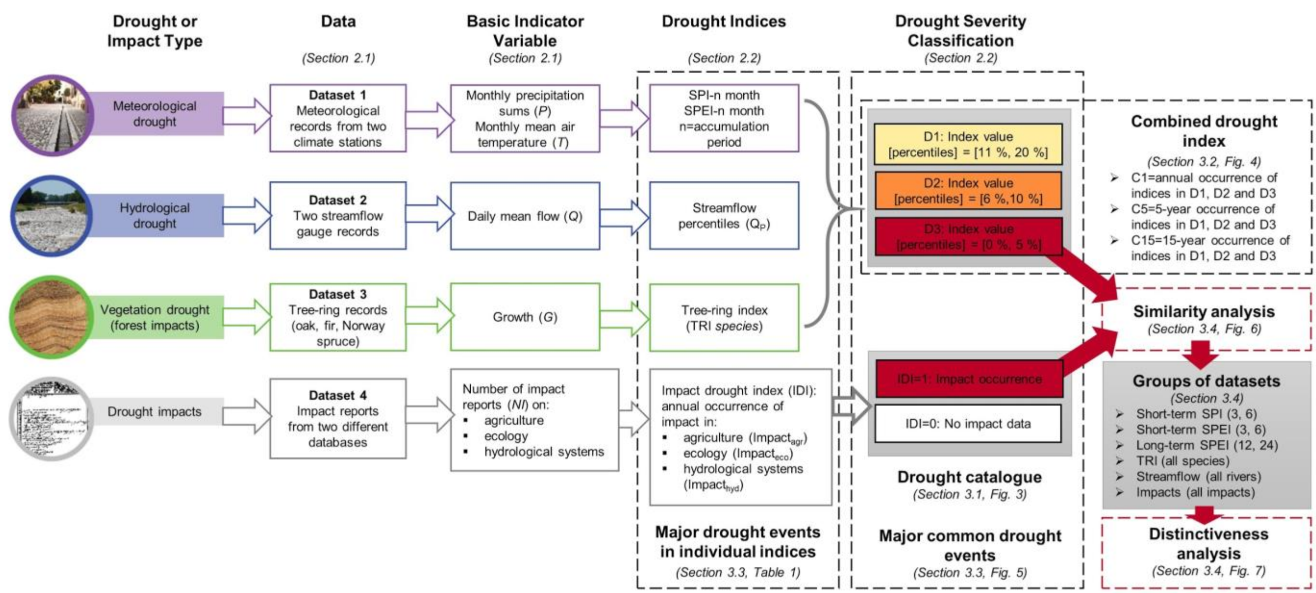


Figure 1: Conceptual overview of the multi-perspective approach of this study. The used multi-variable dataset is shown as well as the derived indices used to create the drought catalogue. ~~multi-variable dataset, variables and terminology used in this study.~~

~~The study employs an assembly of several drought-related variables, herein defined as datasets 1 to 4 (Fig. 1 and Fig. 2).~~

2.1.1 Dataset 1: Meteorological records

Dataset 1 comprises meteorological records from 1801 to 2018 of monthly mean air temperature ~~means~~ (*T*) and monthly precipitation sums (*P*) for two stations in Baden-Wuerttemberg (Rheinstetten-Karlsruhe and Stuttgart, only the first is presented in this paper), which provided the longest continuous time-series of the required variables~~, Rheinstetten-Karlsruhe and Stuttgart~~ (Fig. 2). These P and T ~~Pprecipitation and temperature~~ data were ~~homogenized and~~ retrieved from the project "Historical Instrumental Climatological Surface Time Series Of The Greater Alpine Region" (HISTALP, Auer et al., 2007). All HISTALP series undergo homogenization procedures, which try to detect and eliminate non-climatic breaks and outliers (for more information see 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/).

2.1.2 Dataset 2: Streamflow records

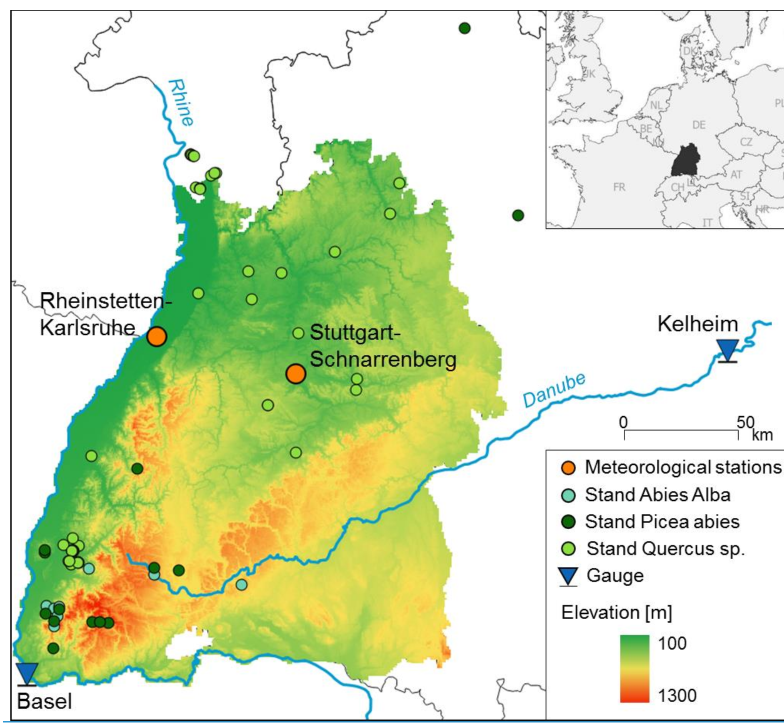
Dataset 2 consists of hydrometric records, namely daily streamflow records (*Q*) of the river Rhine (at Basel) and the river Danube (at Kelheim) (Fig. 2). Q ~~D~~data for the period of 1900-2018 were retrieved from the Bundesanstalt für Gewässerkunde (BfG, www.bafg.de). The selection of these two stations 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.

2.1.3 Dataset 3: Tree-ring records

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).

2.1.4 Dataset 4: Negative impact reports

Dataset 4 is based on reported textual information on the negative 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 the year 2000 onwards. Some additional sources not embodied in either of the two databases were included as well (Nees and Kehrer, 2002; Pfaff, 1846). All available information on reported impacts for southwestern Germany - from these databases and- the 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, ~~) (~~Table S2 lists the reclassification scheme of~~which impact types from~~ the EDII data~~categorisation scheme were used in this study~~).



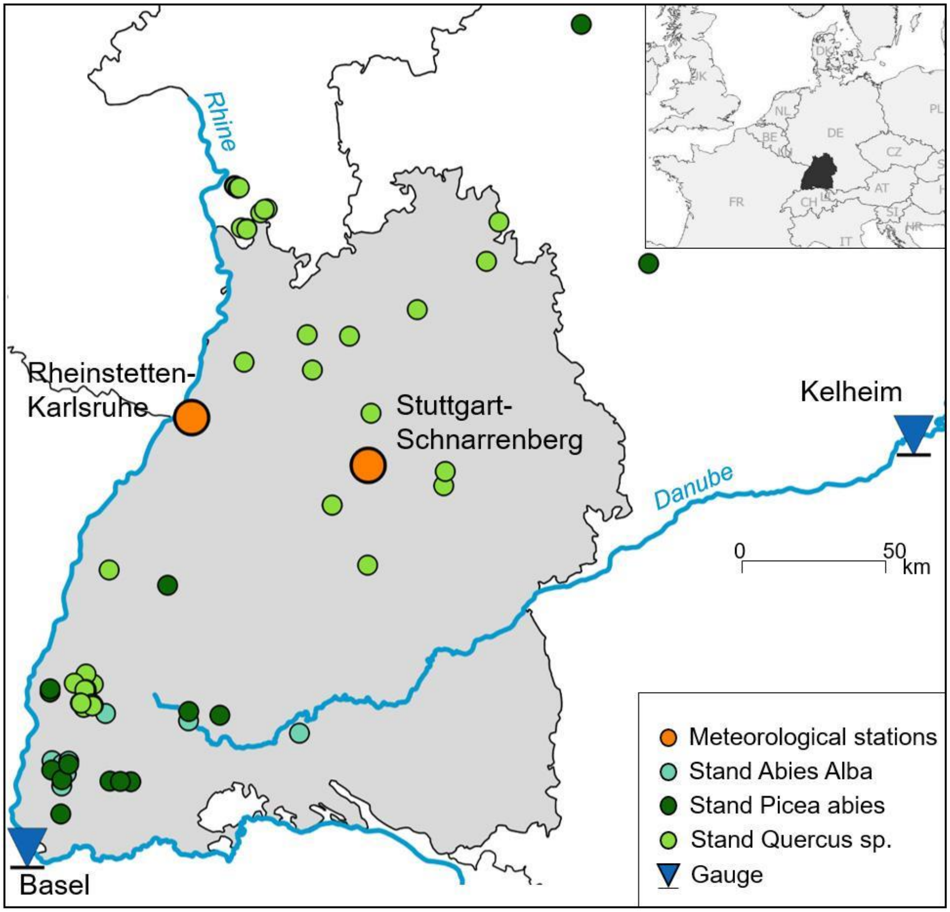


Figure 2: Baden-Wuerttemberg and location of various data sources considered in the study.

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 R~~r~~eporter, 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.

2.2.1 Meteorological drought

Meteorological d~~D~~rought, i.e. a lack of precipitation, was captured by the commonly used SPI ~~Standardizsed 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 an increased evaporative demand ~~higher evaporative demandevapotranspiration~~ (e.g., Teuling, 2018), we also used the SPEI ~~Standardizsed Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010)~~, which is based on the difference between precipitation and potential evapotranspiration. Potential evapotranspiration was estimated using~~with~~ the Thornthwaite equation (which only requires temperature and latitude as input), given that data to make more accurate potential evapotranspiration~~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 important for tree growth) and August (summer period important for impacts), SPI/SPEI-6 ending in June and September (vegetation period important 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, a gamma distribution was fitted to the precipitation series between 1810-2018 ~~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 (Beguería et al., 2014). The reference period for parameter fitting was set to the longest available period, in this case 1810 to 2018. ~~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 (Beguería et al., 2014).

2.2.2 Hydrological drought

Hydrological d~~D~~rought 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) (Weibull, 1938).

2.2.3 Vegetation drought

Vegetation d~~D~~rought indexing followed standard dendrochronological methods (e.g. Speer, 2010) in order to derive a t~~T~~ree-r~~R~~ing i~~I~~ndex (TRI) from Dataset 3. The 2089 different tree-ring series originated from 55~~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-response cutoff (the frequency at which 50 % of the amplitude of a signal is retained, see also Cook et al., 2013). 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 (whereby reducing the influence of outliers in the computation of the 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). The ~~expressed population signal (~~EPS~~)~~ is an indicator of how well a chronology represents a theoretical infinite population (Wigley et al., 1984). Low values of EPS (commonly <0.85) indicate that the chronologies are dominated by individual tree signals rather than a consistent regional signal (Speer, 2010). Rbar is the mean correlation between series within a chronology and is a measure of common signal strength of detrended chronologies. The signal to noise ratio (SNR) is a measure of the desired signal in each chronology versus the amount of unwanted information and random variation (Speer, 2010; Cook et al., 2013). ~~-~~Quality control, detrending and chronology development were performed using the 'dplR' package in R (Bunn, 2008).

2.2.4 Socio-economic drought

Socio-economic d~~D~~rought 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 occurrence' (IDI=1) or 'no impact data' (IDI=0) ~~occurrence~~ in each category. As the number of impact reports changed~~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 impacts into an impact year with 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.

2.2.5 Drought severity classification scheme

A drought severity classification scheme was then applied to the different individual drought indices to facilitate characterization and comparison of drought years~~events~~ across the continuous indices of datasets 1-3 (Fig. 1). Drought years were derived from the anomaly time series of the different indices (SPIn, SPEIn, QP, TRIspecies). A year was defined to be indicating drought whenever the variable of interest was abnormally low, in this study below the 20th percentile. Drought years were further classified according to three different severity classifications: D1 (moderate; <20th percentile), D2 (severe; <10th percentile) and D3 (extreme <5th percentile). ~~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~~. Dataset 4 was classified according to years with impact occurrence (IDI=1) and years with no impact reports available (IDI=0).

Events identified with their severities comprise our drought catalogue: all drought events identified in the individual indices~~variables~~ (for data availability see Erfurt et al., 2020). Based on these severity classes the relative amount of all indices indicating drought was calculated, hereafter referred to as the combined drought index (C). Since the amount of available indices changed over time, C was calculated as the number of indices indicating droughts in certain years relative to the total number of available indices for that year. Different smoothing windows (1, 5 and 15 years, resp. C1, C5 and C15) were used to identify temporal clusters (Fig. 1). ~~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).~~ By using a moving window instead of fixed decadal time blocks, we assure that we do not miss decadal drought hot-spots that happen at the end of one decade and the beginning of the following decade.

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 since~~from~~ 1900 ~~onward~~ for all indices,~~indicators,~~ and additionally since~~from~~ 1801~~ onward~~ for the meteorological and the tree-ring dataset.

2.3 Analysis of similarities and differences in drought variables

Three metrics were used ~~T~~to assess similarities and differences ~~distinctiveness uniqueness~~ in the ability of the multiple indices to identify 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. As a second metric,~~Additionally,~~ we developed a similarity index (*s*) ~~as a metric~~ for only the extreme events (D3). A third metric was used to assess the differences in the identification of extreme droughts, which is hereafter called distinctiveness analysis.

The similarity~~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 (Equation 1):

$$s = \frac{total\ number\ of\ extreme\ droughts/2}{number\ of\ common\ extreme\ droughts}$$

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 (D3) identified by the different datasets contained in the drought catalogue, we first grouped the indices~~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). Since there was almost no difference between the long-term SPEIs and the long-term SPIs (SPI-12 and SPI-24 of December) regarding the extreme droughts we excluded the latter from this analysis. Then, we investigated which extreme drought events would not be identified if excluding a single index category~~dataset~~. The number of extreme droughts, that our final catalogue would have failed to identify had we not included a specific index category~~dataset~~ (e.g., tree-rings), was defined as its~~the~~ distinctiveness value.

3 Results

3.1 Drought catalogue: drought events in individual indices~~variables~~

Figure 3 presents the temporal distribution of drought occurrence for the different indices~~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 e.g., 1842, 1865, 1993, 1921, 1947, 1949, 1964~~3~~, 1976, 1991, 2003, and 2018. No temporal trends of drought occurrences in general could be detected, but several clusters of increased drought occurrence were identified ~~but extreme droughts became more frequent~~ over the last 218 years (e.g. 1860s and recent decade, ~~last decade (~~Fig. 3a and c~~b~~). Further, the occurrence of a drought event in a certain year often is indicated by multiple indices~~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 indices~~variables~~.

~~The drought impact time series provided insights into the actual occurrence of socioeconomic consequences of drought (Fig. 3ba). 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 indices~~ndicators~~ used in the catalogue identify the degree of dryness at different time scales (Fig. 3a~~b~~). They are fairly distributed over the study period, although especially the recent~~last~~ decade and the period between 1857 to 1870 show~~s~~ a higher severity of drought events. W~~In particular w~~hen taking the potential evapotranspiration into account (SPEI for all different accumulation periods) in the recent decade more droughts are classified as extreme ~~extreme droughts became more frequent~~ (e.g., 2011, 2015, 2018). For the year 1991 all meteorological indices~~indicators~~ denoted severe to extreme precipitation shortfall yet this translates only into a moderate drought intensity based on indices of tree-rings and streamflow.

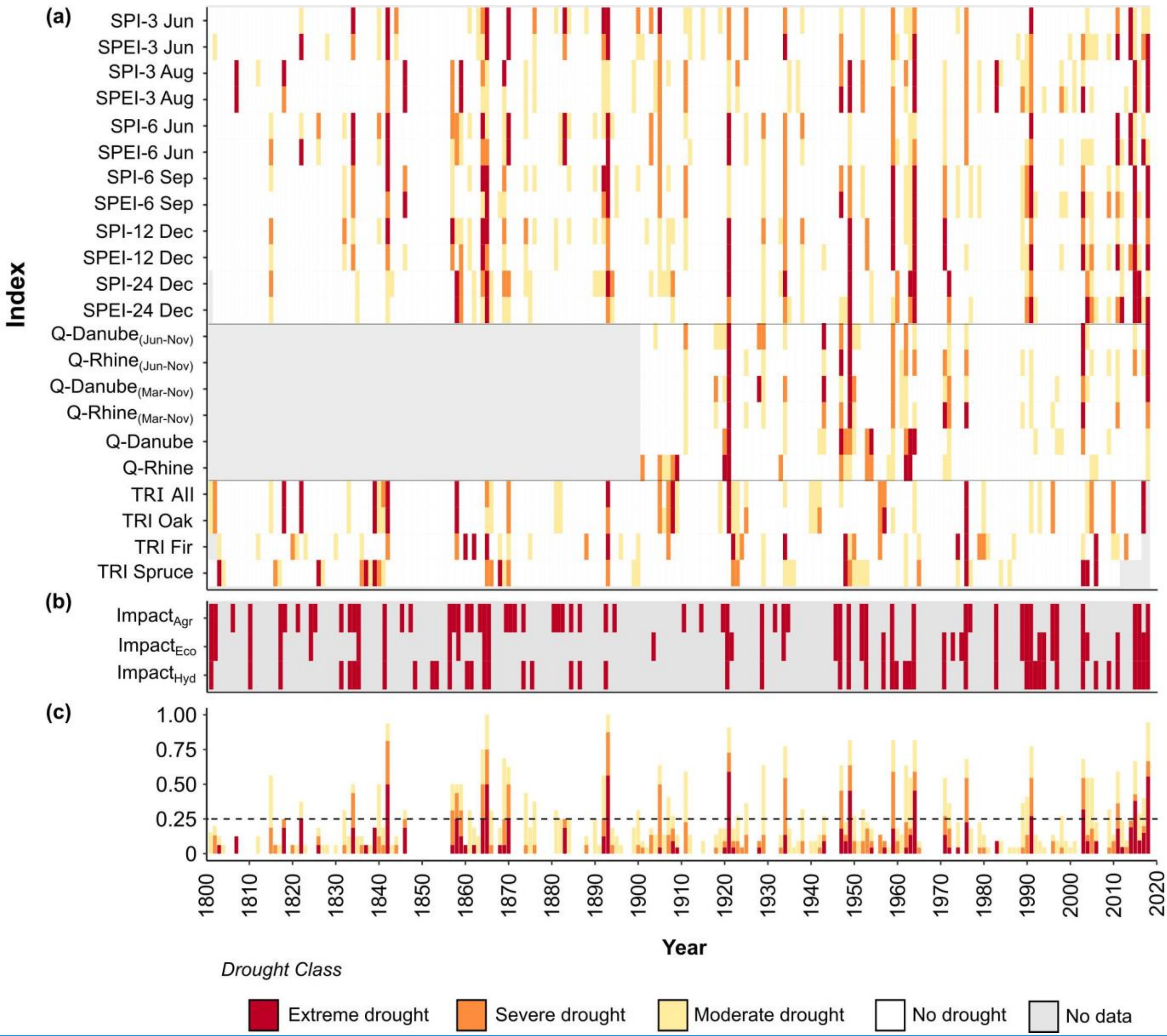
~~The hydrological view reflects the effects of precipitation shortfalls on streamflow (Fig. 3a). The s~~Streamflow indices revealed~~indicesdata revealed~~ that between 1976 and 2003, no severe or extreme drought was observed in the streamflow dataset. For both the Rhine and Danube, mainly the streamflow in 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.

In many cases, dendrochronological records show that years of extremely low tree~~-~~growth coincided with drought events identified by other indices (Fig. 3a~~b~~). 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 indices~~indicators~~ revealed that the lack of precipitation occurred mostly before the summer season. SPI/SPEI-6 of September and 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.~~ For~~In both~~ the~~, Rhine and~~ the ~~Danube, mainly the streamflow~~ in~~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.~~

The drought impact time series provided insights into the actual occurrence of socioeconomic consequences of drought (Fig. 3b). 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 annual time series of joint drought occurrence according to different indices is shown in Fig 3c. This annual combined drought index (C1) was~~Annual frequencies were~~ analyz~~s~~ed in order to explore the drought events from all perspectives (except the impacts) and examine how many D1, D2 and D3 droughts occurred in a specific unit of time (Fig. 3c). A cluster of extreme droughts between 2003 and~~to~~ 2018 was identified by all indices, with the SPEI accounting for the largest share. Through the analysis of a long-term dataset reaching back to 1801, it becomes evident that the cluster of recent droughts are not exceptional. 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. In addition,~~Also~~ the 1960s are marked by several consecutive drought years. 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).~~



(a)
(b)
(c)
Index
SPI-3 Jun
SPEI-3 Jun
SPI-3 Aug
SPEI-3 Aug
SPI-6 Jun
SPEI-6 Jun
SPI-6 Sep
SPEI-6 Sep
SPI-12 Dec
SPEI-12 Dec
SPI-24 Dec
SPEI-24 Dec
Q-Danube(Jun-Nov)
Q-Rhine(Jun-Nov)
Q-Danube(Mar-Nov)
Q-Rhine(Mar-Nov)
Q-Danube
Q-Rhine
TRI All
TRI Oak
TRI Fir
TRI Spruce
ImpactAgr
ImpactEco
ImpactHyd
1.00
0.75
0.50
0.25
0
1800 1810 1820 1830 1840 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
Year
Drought Class
Extreme drought
Severe drought
Moderate drought
No drought
No data

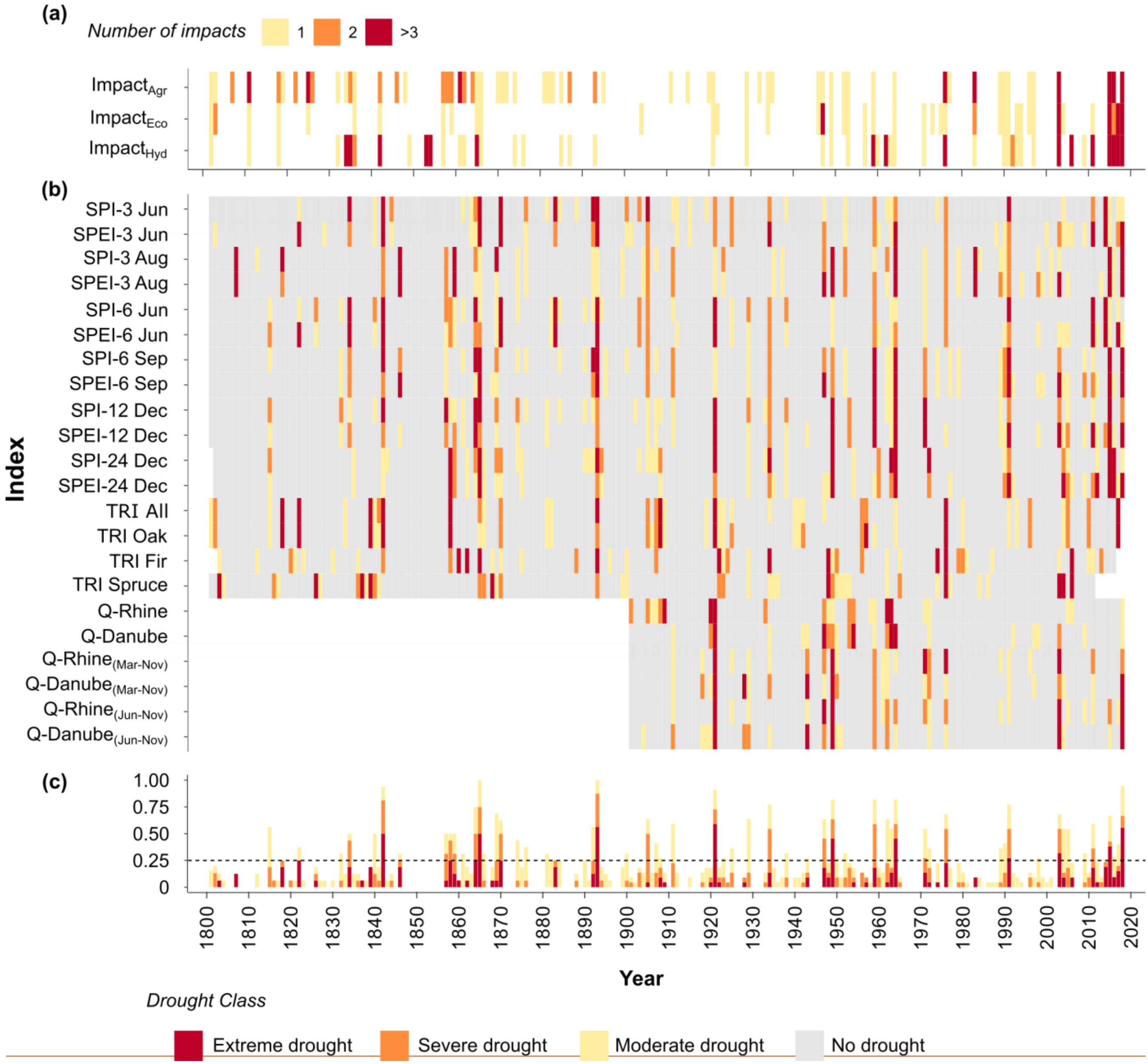
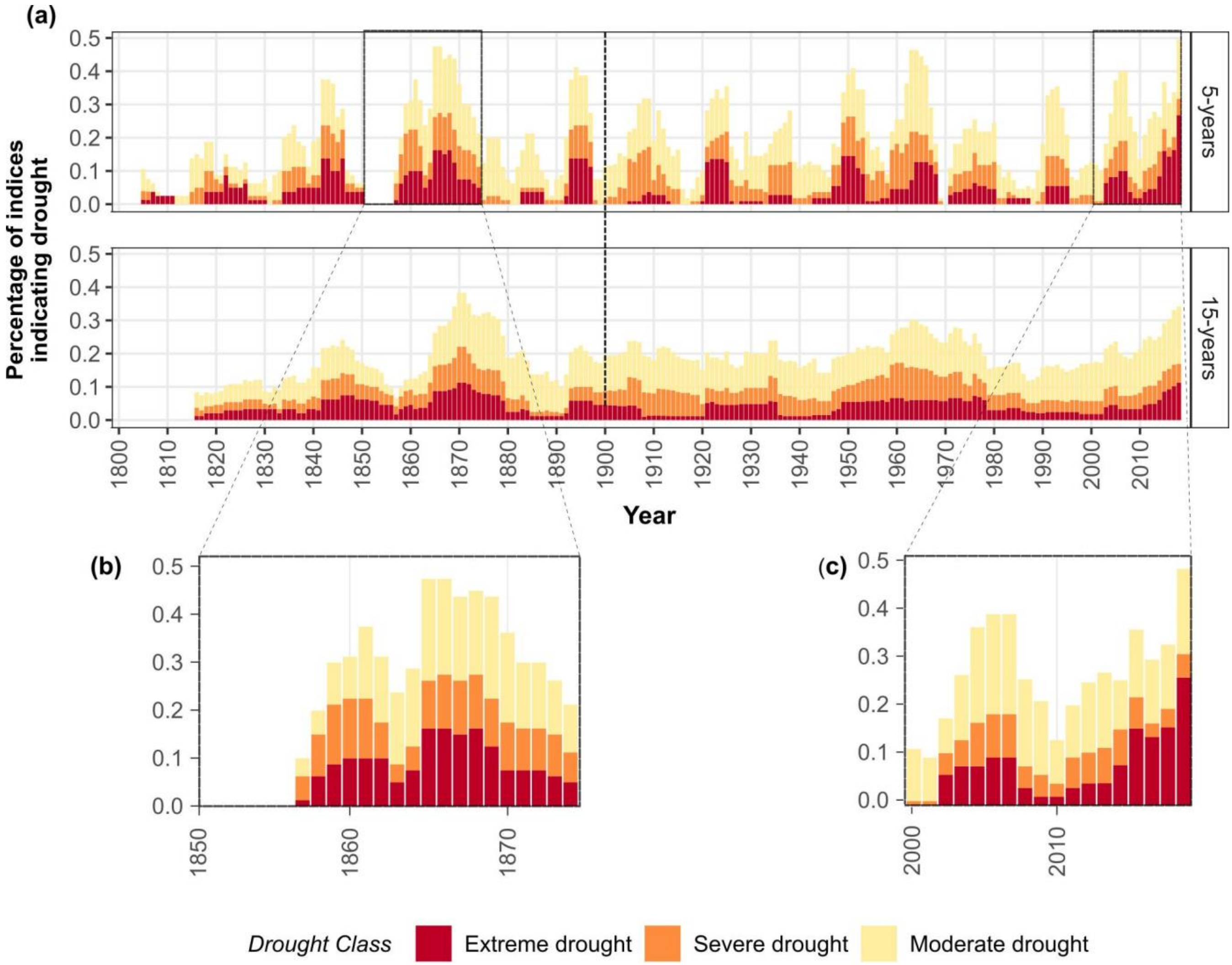


Figure 3: Annual time series of drought occurrence in southwestern Germany according to different groups of indices ~~(a) Drought impacts,~~ (a~~b~~) hydro-meteorological drought indices and tree-ring data, (b) drought impacts, and (c) the combined drought index C1, which shows the annual percentage of indices indicating droughts (impacts are excluded).

3.2 Combined ~~D~~drought occurrence ~~frequencies~~

To survey if drought occurrence has changed over time since 1801, the combined drought index~~frequencies~~ ~~(C)~~ for 5 (C5) and 15 (C15) years-long time windows was~~were~~ used to identify temporal patterns of drought occurrences (Fig. 4). The combined occurrence~~frequencies~~ describes the average percentage of indices~~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 occurrence~~frequencies~~.
According to the five year rolling window, most droughts classified as extreme were found between 2014 and 2018 (last bar in Fig. 4c). The fraction of extreme drought occurrence in these five years stands out when compared to any other 5-year window since 1801. Nevertheless, the clustering of several years with a high occurrence of moderate, severe and extreme droughts is not unprecedented in the study area. 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 occurrences~~frequencies~~ were high. ~~Most droughts classified as extremes were found between 2014 and 2018 (last bar in Fig. 4~~c~~b).~~

The combined drought index~~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.



(a)
Percentage of indices indicating drought
5-years
15-years
Year
(b)
(c)
Drought Class
Extreme drought
Severe drought
Moderate drought

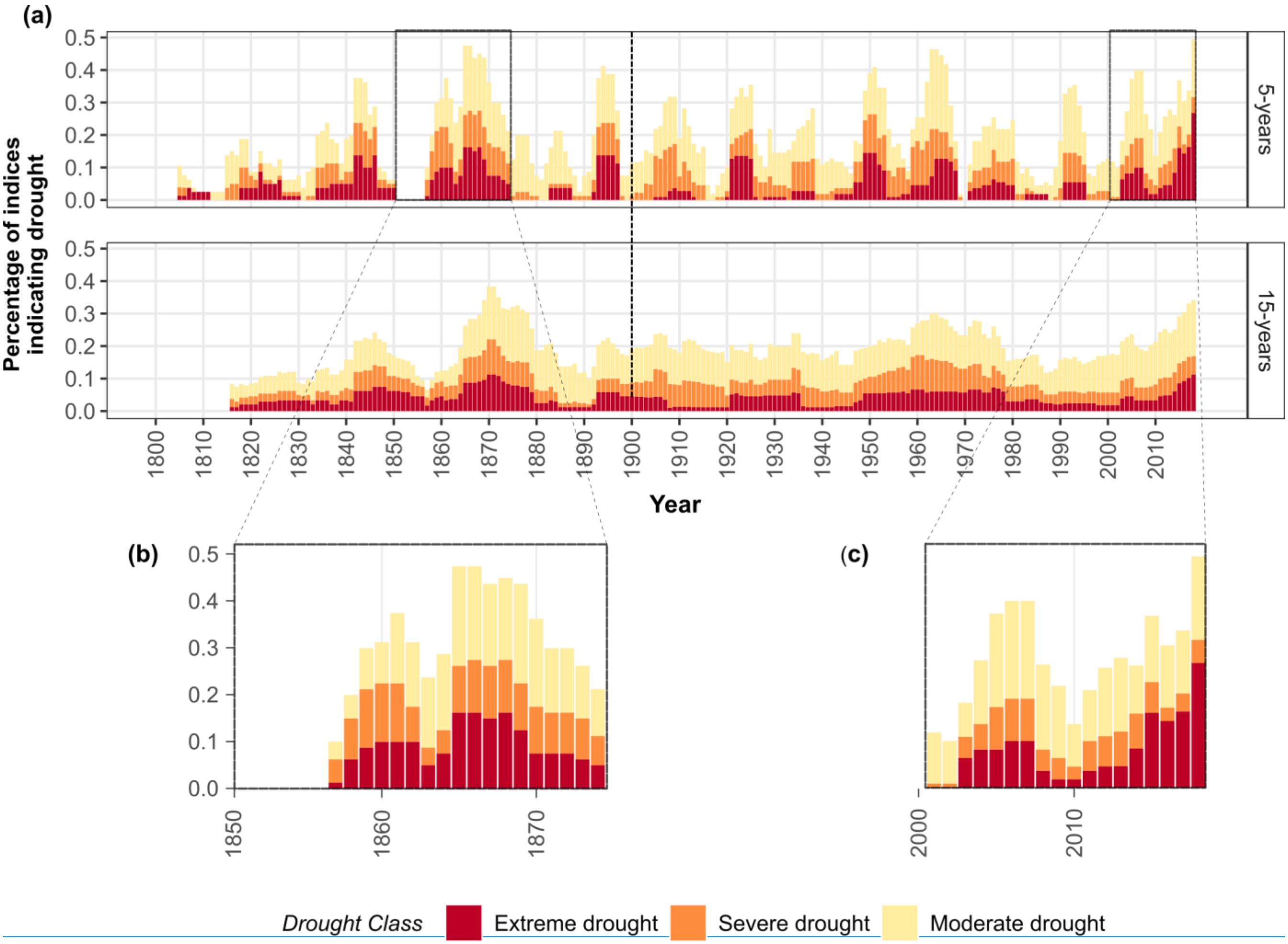
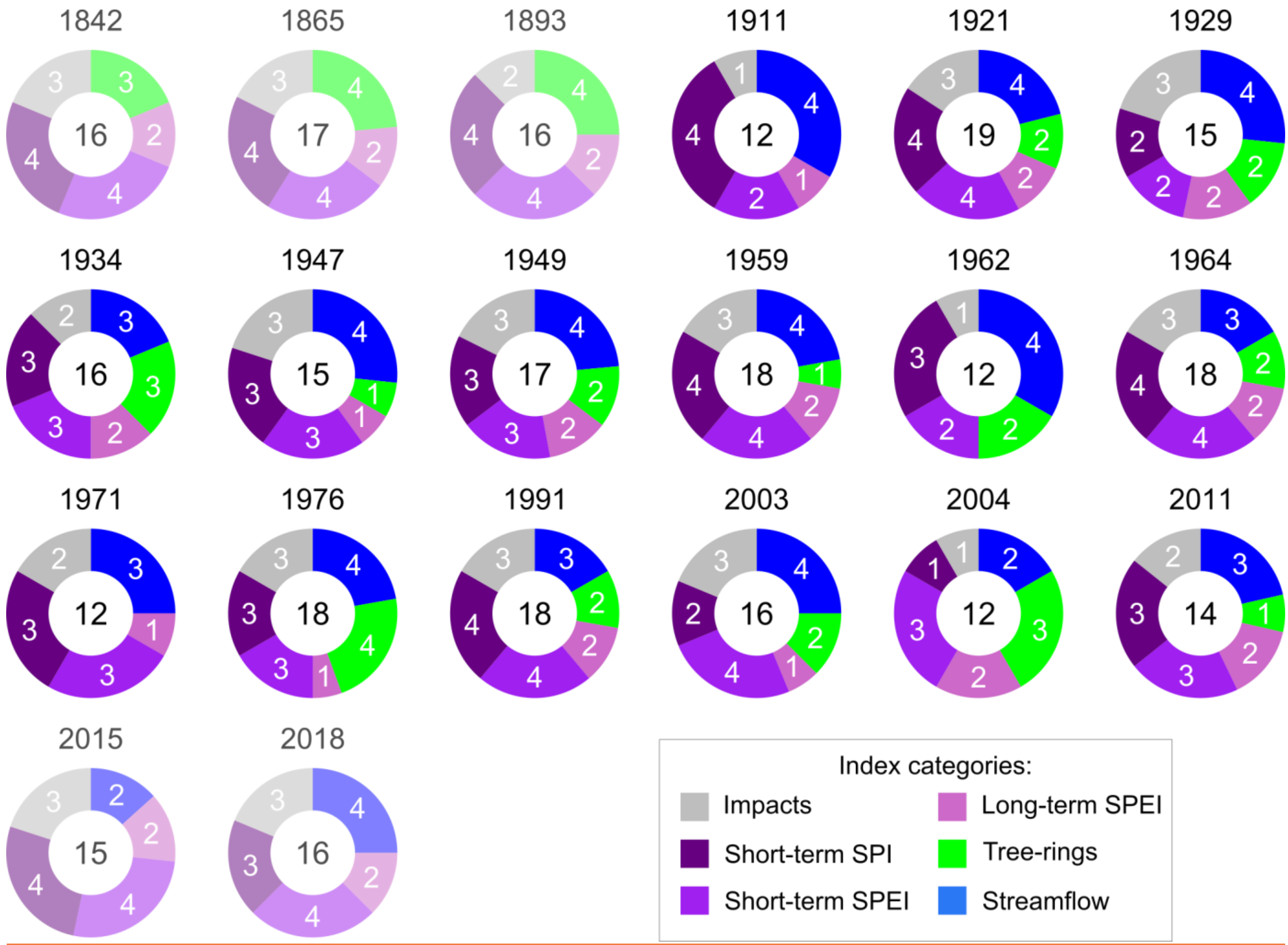


Figure 4: ~~Combined drought frequency index for A~~a~~nnual time series showing the fraction of indices in drought (different severities) smoothed with a 5 (C5) and 15 (C15) year backward smoothing window.~~ The combined drought index C5 and C15, showing the relative amount of all indices in drought (different severities) smoothed with a 5 (C5) and 15 (C15) year backward smoothing window.

3.3 Common drought events from different perspectives

To explore the different dimensions of droughts, we focused on the 20 years, for which more than ten ~~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 (Fig. 3c). In all these years, drought appeared in both the indices and the impacts. After 1900, all ~~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).


1842
16
1865
17
1893
16
1911
12
1921
19
1929
15
1934
16
1947
15
1949
17
1959
18
1962
12
1964
18
1971
12
1976
18
1991
18
2003
16
2004
12
2011
14
2015
15
2018
16
Index categories:
Impacts
Long-term SPEI
Short-term SPI
Tree-rings
Short-term SPEI
Streamflow

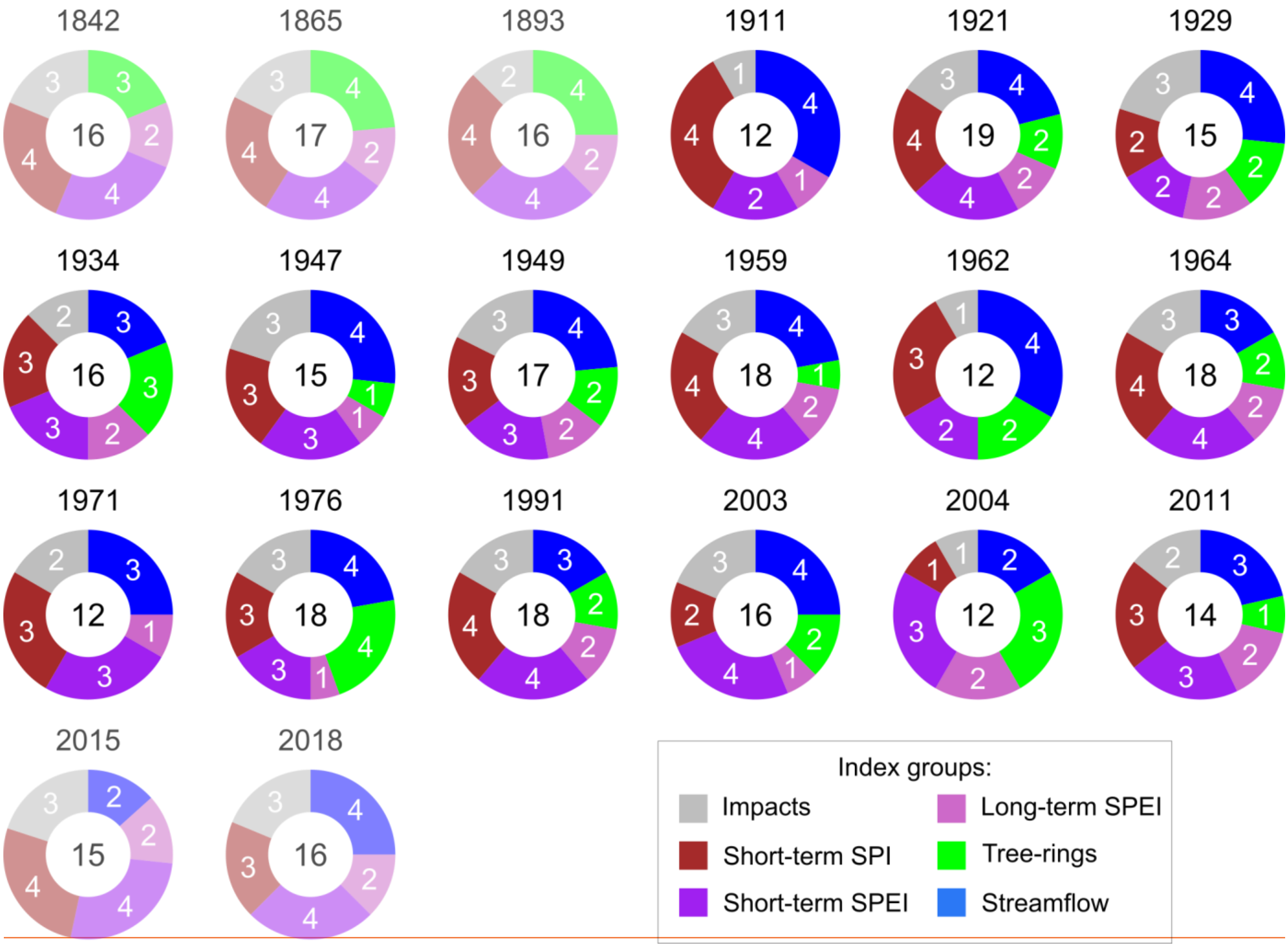


Figure 5: Drought years in which more than ten indices (from different categories~~groups~~) indicating ~~point to~~ a drought (the total number of indices pointing to a drought is written in the circle, the number of indices per group pointing to a drought is written in each section of the ring). Years without streamflow data (prior to 1900) or without tree-~~-~~ring data (after 2011) are displayed with paler colo~~u~~rs.

The ten most extreme drought years according to each index~~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 indices~~indicators~~ (Table 1a). In 11 out of the 18 indices~~indicators~~, 2018 was counted as a top ten event. Also 2003 stood out, in particular according to both meteorological and hydrological drought indices~~indicators~~. In nine~~9~~ out of the 18 indices~~ndicators~~, 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 indices~~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 meteorological and hydrological~~two~~ drought indices~~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.

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. * = years with the same value as the year before. "-" = no data available.

(a) Top ten since 1900.

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$_{(Jun-Nov)}$
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	**2003**	**2015**	**2016**	1921	1976	1922	1948	1949	1949	**2018**	1949
3	**2014**	**2018**	**2018**	**2015**	**2014**	**2017**	**2015***	1947	1959	**2018**	**2017**	**2017**	1948	**2004**	1976	**2018**	1947	1921
4	1934	1964	1964	**2003**	1921	1921	1964	**2015**	**2003**	1964	1908	1908	1974	1976	**2003**	1943	**2003**	1943
5	1925	1934	**2015**	1947	1903	1959	1991	1964	1971	**2004**	**2010**	1957	**2006**	**2006**	1971	1928	1921	**2003**
6	**2011**	1905	1947	1964	1929*	1991	1947	1959	1949	1991	1956	1905	1934	1922	**2011**	1934	1964	1911
7	1964	1976	1962	1949	1905	1934	1905	1991	1921	**2012***	**2005**	1956	1956	1949	**2018**	1950	1976	1962
8	1921	1947	1905	1991	1938	1976*	1971*	1949	1964	1949	1905	**2010**	**2013**	1923	1947	1972	1959	1928
9	1900	1925	1991	1976	1959	1905	1949	**2011**	1991	**2005**	1907	1942	1907	1965	1943	1918	**2015**	1947
10	1976	**2017**	1911	1905	1934	1964	1911	1971	**2011***	1921	1996	**2005**	1950	1962	1972	**2003**	1971	1959

(b) Top ten since 1801.

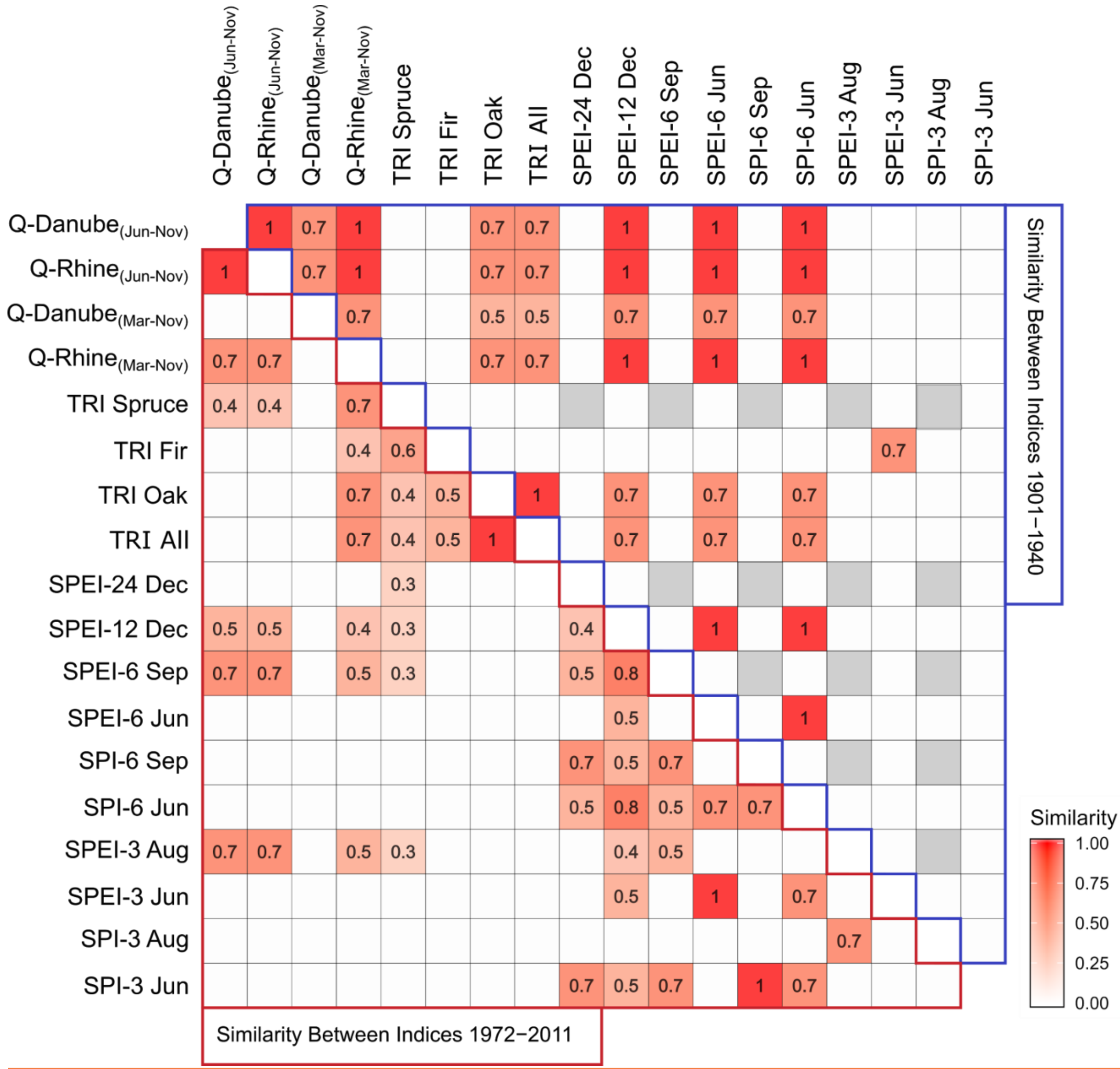
Rank	SPI-3 Jun	SPEI-3 Jun	SPI-3 Aug	SPEI-3 Aug	SPI-6 Jun	SPEI-6 Jun	SPI-6 Sep	SPEI-6 Sep	SPEI-12 Dec	SPEI-24 Dec	TRI All	TRI Oak	TRI Fir	TRI Spruce	Q-Rhine$_{(Mar-Nov)}$	Q-Danube$_{(Mar-Nov)}$	Q-Rhine$_{(Jun-Nov)}$	Q-Danube$_{(Jun-Nov)}$
1	**1870**	**1870**	1983	1983	**1870**	**2011**	**2018**	**2018**	**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**	**2003**	**2018**	1921	1976	1948	**1837**	-	-	-	-
5	**1865**	**2014**	**1818**	**2003**	**2011**	**1842**	**2015***	**1865**	1971	1964	**2017**	**2017**	**1862**	1976	-	-	-	-
6	**1883**	**2018**	1964*	**1807**	1991	**1834**	1964	1964	1949	**2004**	**1842**	**1842**	**1860**	**1803**	-	-	-	-
7	1991*	**1822**	**1859**	1947*	**1834**	**1822**	**1892**	1959	1921	1991	**1839**	1908	1974	**1839**	-	-	-	-
8	**1834**	**1842***	**1807**	1964	**1864***	**2017**	1991*	1991	1964	**2012***	1908	**1839**	**2006**	**1826**	-	-	-	-
9	**2014**	1964*	**1869**	**1859**	**2014**	1921	**1842**	**1846**	**1864**	1949	**1893**	**1818**	**1865**	**1868**	-	-	-	-
10	**1892**	1934	**2015**	1949	1921	**1883**	**1864**	**1893***	1991	**1858**	**1818**	1957	1934	**2006**	-	-	-	-

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

The similarity index, calculated for each pair of indices, showed some interesting patterns in the extreme droughts identified~~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 (March to November and June to November) 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 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 indices~~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. S~~5~~2 and Fig. S3~~6~~). 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. S3~~6~~). As expected, the strongest correlation was found between indices~~indicators~~ belonging to the same type of dataset or time-scale (short-term SPI, short-term SPEI, long-term SPEI, tree-rings and stream~~river~~flow) 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. S3~~6~~). In addition to the expected relationships between indices~~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 indices ~~indicators~~ in both periods (Fig.~~.~~ S2~~5~~ and Fig. S3~~6~~).


Q-Danube(Jun-Nov)
Q-Rhine(Jun-Nov)
Q-Danube(Mar-Nov)
Q-Rhine(Mar-Nov)
TRI Spruce
TRI Fir
TRI Oak
TRI All
SPEI-24 Dec
SPEI-12 Dec
SPEI-6 Sep
SPEI-6 Jun
SPI-6 Sep
SPI-6 Jun
SPEI-3 Aug
SPEI-3 Jun
SPI-3 Aug
SPI-3 Jun
Similarity Between Indices 1901−1940
Similarity Between Indices 1972−2011
Similarity
1.00
0.75
0.50
0.25
0.00

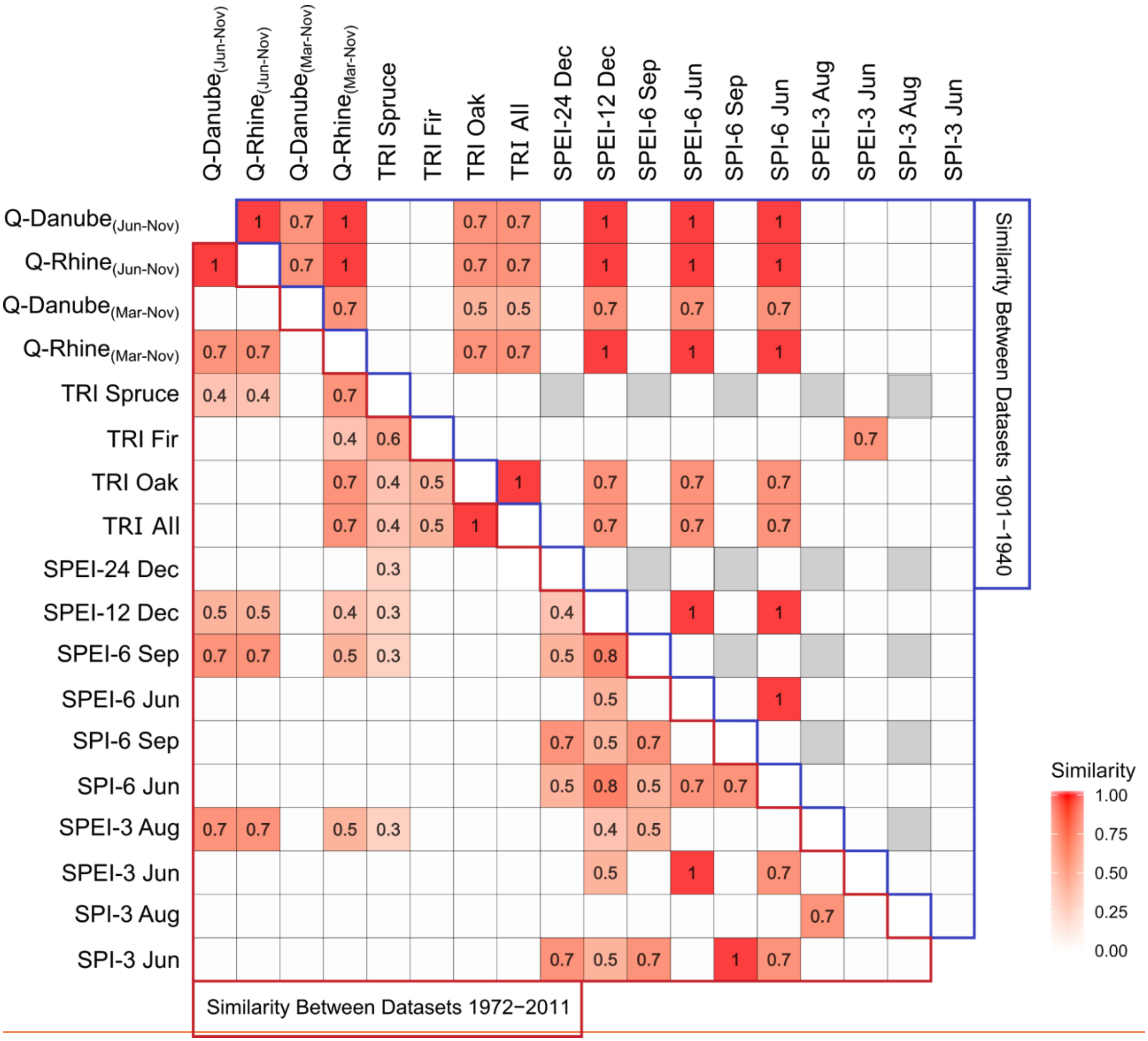
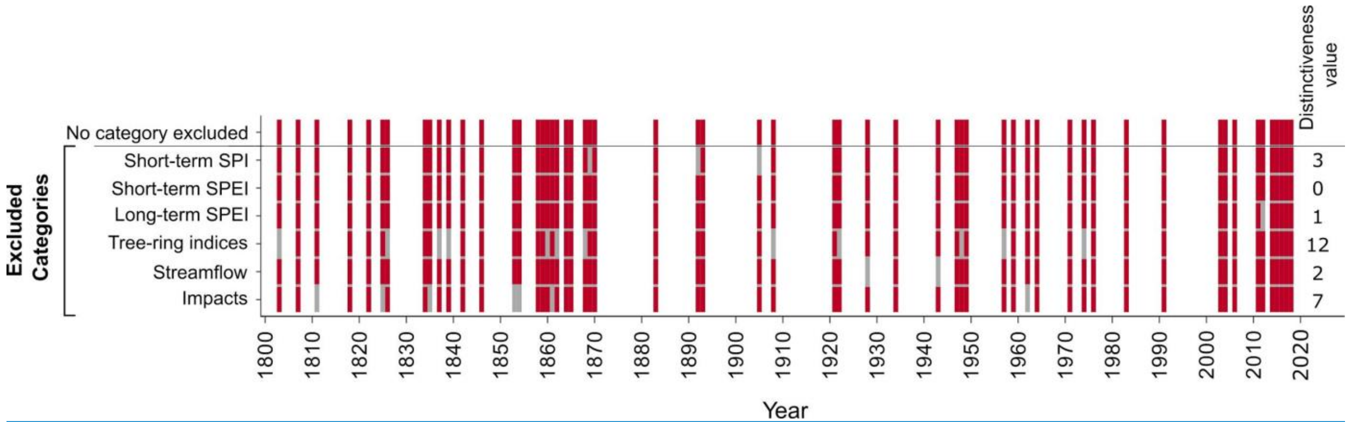


Figure 6: Similarity index (*s*) between the different pairs of drought indices for two different time periods (1901 to 1940 and 1972 to 2011). Grey boxes = no extreme drought according to both indices.

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 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 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 three~~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.



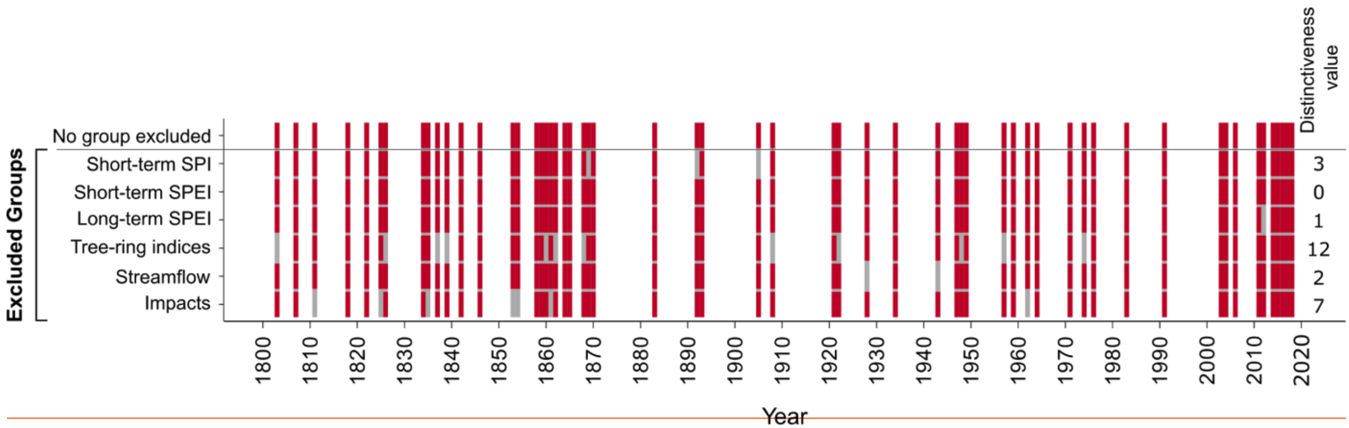


Figure 7: Extreme drought events identified (red) or missed (grey) when excluding a certain category ~~group~~ of drought indices. Each row shows the droughts that are identified when one of the categories are excluded from the analysis and therefore show the events unique to this category. The total 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 consecutive years of extreme droughts ~~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 occurrence~~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. The extreme drought events of the 21st century were also detected by several studies on an European scale (e.g., Brunner et al., 2019; Lahaa et al., 2017; Ionita et al., 2017; van Loon et al., 2017). These findings relate to the fact that especially persistent extreme droughts occur due to global weather patterns, dictated by ocean and land temperature fluctuations (Ault 2020).

~~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. The increased awareness (private, public and governmental) might be expressed by more frequent reporting (e.g. by an increase in reports on ecological impacts (Blauhut et al., 2015).~~

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 centers~~res~~ 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. In addition, stream~~river~~ flow, especially for larger river basins, is affected by direct and indirect human activities and thereby susceptible to changes over time (Tijdeman et al., 2018).

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 indices~~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 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-index~~dicator~~ 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 hydrology~~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). 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.

4.2 The added value of a long-term dataset

Investigating the development of drought occurrence and severity in the long-term (1801-2018) with independent observation data allowed an assessment of the uniqueness of the recent drought events. Investigating the top ten drought events since 1900 and ~~respectively~~ since 1801 emphasized the importance of using datasets that date back as far as possible in order ~~to the past t~~to contextualize today's event severity and frequency~~s~~. When o~~O~~~~If we o~~nly considering~~look at~~ the past 50 to 100 years, the years 2003, 2011, 2015 and 2018 were among the most extreme events, especially according to the drought indices that consider temperature (Table 1a). However, by considering the past 218 years~~including also drought events from the 19th century~~, it becomes evident that ~~we can see that~~ drought events of similar severity (e.g., 1842, 1865, 1870, 1893) also did ~~appeared~~occur in earlier years (Table 1b).

Two main periods, one in the 19th century (1857-1870) and a second in the 21st century (2003-2018), of increased occurrence and severity were identified in our dataset (Fig. 4b and c). The result highlights that the recent frequent occurrence of droughts in the study area is not unprecedented when looking back into the 19th century. This claims~~highlights~~ the need for long-term~~of long-term~~ data, especially when studying the development of drought trends in the future. Although these two periods of frequent drought events were similar to each other in terms of overall percentage of indices pointing to drought, the recent period (starting in 2003) was characterized by a larger number ~~n increased occurrence~~ of extreme droughts. This rise in severity in recent years is a result of increasing precipitation deficits and rising temperatures (Hänsel et al., 2019; Dai, 2013). 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).

4.3~~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 observations. 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 indices~~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 indexindicator) 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 indexindicator (< 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 categories~~groups~~ of drought indices~~indicators~~ further showed some extreme droughts that~~droughts, that~~ we would have missed when using only one category~~group~~. For example, some years with extreme precipitation deficits and concurrent negative impacts for society were correctly detected by meteorological indices~~ndicators~~ but not identified as extreme by tree-rings or streamflow data. U~~Hence, u~~sing 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 indices~~indicators~~ (Fig. 7). Interestingly, we observed a change in the number of unique~~distinct~~ extreme droughts (number of extreme drought events missed (grey) when excluding any category~~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 indices~~indicators~~ after~~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, between 1857 and 1870 and between 2003 and 2018, of increased frequency and severity were identified in our dataset (Fig. 4b and c). The result highlights that the recent high frequency of droughts in the study area is not unprecedented when looking back into the 19th century. This highlights the need of long-term data, especially when studying the development of drought trends in the future. 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 an increased occurrencehigher 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).~~

4.4 Applications for drought management

The integration of long time series showed the non-uniqueness of the recent drought period in time. For drought monitoring, going back further in time a longer reference has the advantage of placing ongoing events in a longer context of occurrence frequency. As a result, the recent droughts may not appear as severe as in studies with shorter term reference periods. As extremes are by definition, rare events, knowing more about historic events that could be used as “design events” (see e.g., Stoelzle et al., 2018) can help improve both short- and long-term drought planning and management. As a result of this long-term catalogue, we found that multi-year droughts may be a type of event that should be better prepared for even in the study area’s temperate humid climate.

The ~~identified~~ unique drought events identified in the different indices of our drought catalogue reveals the added value of considering different variables. Including drought impact information provides the necessary context to evaluate the severity of historic drought events, especially given the large changes in vulnerability over the past century. 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 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. 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. The recent drought of e.g., 2015 and 2018 in southwestern Germany that impacted multiple sectors (e.g. forestry, agriculture, energy and industry) could be tracked via some of the existing drought monitoring products available for the region. The State Institute for the Environment of Baden-Wuerttemberg (LUBW) offer a basic low flow monitoring system (www.hvz.baden-wuerttemberg.de) and the DWD provides monthly maps of an aridity index for Germany (https://www.dwd.de/EN/ourservices/klimakartendeutschland/klimakartendeutschland.html). However, the scarce amount of information is scattered around different places and there is no centralized drought management authority. The shown results suggest the added value of having multi-variable long-term drought information available in a central platform.

5 Conclusions

The main objectives of our analyz~~s~~es 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 drought catalogue provides valuable information on long-term drought occurrence in southwestern Germany, which can be expanded in further drought studies. Our long-term dataset reveals that recent drought clusters are less exceptional in a historical context than when looking at the last 30-40 years as often done in trend analyses. ~~The different groups of drought information provide a novel, unique set of data on drought events in southwestern Germany for the past 218 years.~~ Analyz~~s~~ing 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. E~~ each drought index~~indicator~~ rather provided a different dimension of the same drought event, which might or might not match the information obtained from other indices~~ndicators~~. Time of occurrence of hydrometeorological water deficits is only one feature. Trees in the study~~ied~~ 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.~~
The different groups of drought information provide a novel, unique set of data on drought events in southwestern Germany for the past 218 years.

Data availability: Erfurt, M., Skiadaresis, G., Tijdeman, E., Blauhut, V., Bauhus, J., Glaser, R., Schwarz, J., Tegel, W., and Stahl, K.: Drought Catalogue Dataset, Universitätsbibliothek Freiburg/FreiDok plus, doi: 10.6094/UNIFR/166056, 2020.

Supplement: The supplement related to this article is available online at: doi

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 and~~,~~ VB. KS provided guidance and methodology suggestions throughout the process. All the authors read, reviewed, and approved ~~all versions of~~ the paper.

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgements

We thank the team of Rüdiger Glaser for the provision of original text quotations of the collaborative research environment for climate and environmental history tambora.org. We acknowledge also the access to the European Drought Impact R~~r~~eport Inventory database, which has initially been funded by the EU FP7 project DROUGHT-R&SPI. We would also like to express our sincere gratitude to researchers that have contributed to the international tree-ring database ITRDB (www.ncdc.noaa.gov). We acknowledge Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (HISTALP, http://www.zamg.ac.at/histalp/) for providing us with long-term meteorological data. We further thank the following agencies of the German federal states for supplying meteorological data (German Weather Service, DWD, www.dwd.de) and streamflow data (Bundesanstalt für Gewässerkunde, BfG, www.bafg.de). Last, we thank the two anonymous referees for providing valuable suggestions and comments for improving the manuscript.

Financial support

This research was carried out within the interdisciplinary research project DRIeR. The project is supported by the Wassernetzwerk Baden-Württemberg (Water Research Network), which is funded by the Ministerium für Wissenschaft, Forschung und Kunst Baden-Württemberg (Ministry of Science, Research and the Arts of the State Baden-Wuerttemberg). The article processing charge was funded by the German Research Foundation (DFG) and the University of Freiburg in the funding programme Open Access Publishing.

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.

Ault, T. R.: On the essentials of drought in a changing climate, Science (New York, N.Y.), 368, 256–260, https://doi.org/10.1126/science.aaz5492, 2020.

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., Svensson, C., Hannaford, J., Barker, L. J., and Stahl, K.: A quantitative analysis to objectively appraise drought indicators and model drought impacts, Hydrology and Earth System Sciences, 20, 2589–2609, 2016.

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.~~

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., 23, 4583–4602, https://doi.org/10.5194/hess-23-4583-2019, 2019.

Beguería, S., Vicente-Serrano, S. M., Reig, F., and Latorre, B.: Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring, Int. J. Climatol., 34, 3001–3023, https://doi.org/10.1002/joc.3887, 2014.

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.

~~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.~~

Brunner, M. I., Liechti, K., and Zappa, M.: Extremeness of recent drought events in Switzerland: dependence on variable and return period choice, Nat. Hazards Earth Syst. Sci., 19, 2311–2323, https://doi.org/10.5194/nhess-19-2311-2019, 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., 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.

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.~~

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.

Cook, E., Briffa, K., Shiyatov, S., Mazepa, V., Jones, P. D.: Data Analysis. In: Cook E. R., Kairiukstis L. A., eds. Methods of Dendrochronology. Applications in the Environmental Sciences. Dordrecht: Springer Netherlands, 97–162, 2013.

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.

Dai, A.: Increasing drought under global warming in observations and models, Nature Climate change, 3, 52–58, https://doi.org/10.1038/nclimate1633, 2013.

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.

Erfurt, M., Skiadaresis, G., Tijdeman, E., Blauhut, V., Bauhus, J., Glaser, R., Schwarz, J., Tegel, W., and Stahl, K.: Drought Catalogue Dataset, Universitätsbibliothek Freiburg/FreiDok plus, doi: 10.6094/UNIFR/166056, 2020.

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.

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J., and Kumar, R.: Revisiting the recent European droughts from a long-term perspective, Scientific reports, 8, 9499, https://doi.org/10.1038/s41598-018-27464-4, 2018.

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., 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.~~

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.

~~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.~~

Ionita, M., Tallaksen, L. M., Kingston, D. G., Stagge, J. H., Laaha, G., Van Lanen, Henny A. J., Scholz, P., Chelcea, S. M., and Haslinger, K.: The European 2015 drought from a climatological perspective, Hydrol. Earth Syst. Sci., 21, 1397–1419, https://doi.org/10.5194/hess-21-1397-2017, 2017.

Jakubínský, J., Bláhová, M., Bartošová, L., Steinerová, K., Balek, J., Dížková, P., Semerádová, D., Alexandru, D., Bardarska, G., Bokal, S., Borojević, G., Bucur, A., Kalin, K. C., Barbu, A. C., Debre, B., Đorđević, M., Đurić, I., Mircea, B. F., Gatarić, S., Gregorič, G., Hasenauer, S., Ivanov, M., Kircsi, A., Labudová, L., Turňa, M., Marinović, I., Marković, M., Mateescu, E., Oblišar, G., Popescu, A., Srđević, Z., Savić-Šljivić, T., Supić, D., Sušnik, A., Pazin, N., Drljevic, M., Kuc, T., Mitrovic, L., Micev, S., Wagner, W., Eitzinger, J., Daneu, V., Blauhut, V., Stahl, K., and Trnka, M.: Repository of Drought Event Impacts Across the Danube Catchment Countries Between 1981 and 2016 Using Publicly Available Sources, Acta Univ. Agric. Silvic. Mendelianae Brun., 67, 925–938, https://doi.org/10.11118/actaun201967040925, 2019.

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.

Laaha, G., Gauster, T., Tallaksen, L. M., Vidal, J.-P., Stahl, K., Prudhomme, C., Heudorfer, B., Vlnas, R., Ionita, M., Van Lanen, Henny A. J., Adler, M.-J., Caillouet, L., Delus, C., Fendekova, M., Gailliez, S., Hannaford, J., Kingston, D., van Loon, A. F., Mediero, L., Osuch, M., Romanowicz, R. J., Sauquet, E., Stagge, J. H., and Wong, W. K.: The European 2015 drought from a hydrological perspective, Hydrol. Earth Syst. Sci., 21, 3001–3024, https://doi.org/10.5194/hess-21-3001-2017, 2017.

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.

Mikšovský, J., Brázdil, R., Trnka, M., and Pišoft, P.: Long-term variability of drought indices in the Czech Lands and effects of external forcings and large-scale climate variability modes, Clim. Past, 15, 827–847, https://doi.org/10.5194/cp-15-827-2019, 2019.

Nees G., Kehrer H.: Alzenauer Wetterchronik. Die interessantesten Wetterereignisse in Alzenau, im Kahlgrund und am Untermain von 265 bis 1999. Keim, Weil der Stadt, 2002.

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.

Pfaff K.: Geschichte der Stadt Stuttgart nach archival-Urkunden und anderen bewährten Quellen, Vol 2, Stuttgart, 1846.

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.

~~Stagge, J. H., Tallaksen, L. M., Gudmundsson, L., van Loon, A. F., and Stahl, K.: Candidate Distributions for Climatological Drought Indices (SPI and SPEI), Int. J. Climatol., 35, 4027–4040, https://doi.org/10.1002/joc.4267, 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.~~

Stahl, K., Kohn, I., Blauhut, V., Urquijo, J., De Stefano, L., Acácio, V., Dias, S., Stagge, J. H., Tallaksen, L. M., Kampragou, E., van Loon, A. F., Barker, L. J., Melsen, L. A., Bifulco, C., Musolino, D., de Carli, A., Massarutto, A., Assimacopoulos, D., and Van Lanen, Henny A. J.: Impacts of European drought events: insights from an international database of text-based reports: Insights from an international database of text-based reports, Nat. Hazards Earth Syst. Sci., 16, 801–819, https://doi.org/10.5194/nhess-16-801-2016, 2016.

Stölzle, M., Blauhut, V., Kohn, I., Krumm, J., Weiler, M., and Stahl, K.: Niedrigwasser in Süddeutschland. Analysen, Szenarien und Handlungsempfehlungen, KLIWA-Berichte, 23, 96 pp., 2018.

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.

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.

Trnka, M., Hlavinka, P., Možný, M., Semerádová, D., Štěpánek, P., Balek, J., Bartošová, L., Zahradníček, P., Bláhová, M., Skalák, P., Farda, A., Hayes, M., Svoboda, M., Wagner, W., Eitzinger, J., Fischer, M., and Žalud, Z.: Czech Drought Monitor System for monitoring and forecasting agricultural drought and drought impacts, Int J Climatol, https://doi.org/10.1002/joc.6557, 2020.

~~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., Kumar, R., and Mishra, V.: Testing the use of standardised indices and GRACE satellite data to estimate the European 2015 groundwater drought in near-real time, Hydrol. Earth Syst. Sci., 21, 1947–1971, https://doi.org/10.5194/hess-21-1947-2017, 2017.~~

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.

van Loon, A. F., Kumar, R., and Mishra, V.: Testing the use of standardised indices and GRACE satellite data to estimate the European 2015 groundwater drought in near-real time, Hydrol. Earth Syst. Sci., 21, 1947–1971, https://doi.org/10.5194/hess-21-1947-2017, 2017.

~~Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, J. Climate, 23, 1696–1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.~~

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.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, J. Climate, 23, 1696–1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.

Weibull, W.: Investigations into strength properties of brittle materials, Generalstabens litografiska anstalts förlag, Stockholm, 1938.

Wigley, T. M. L., Briffa, K. R., Jones, P .D.: On the Average Value of Correlated Time Series, with Applications in Dendroclimatology and Hydrometeorology, Journal of Climate and Applied Meteorology 23, 201–213, 1984.

Wilhite, D. A.: Drought as a Natural Hazard: Concepts and Definitions, Drought: A global assessment, edited by: Wilhite, D. A., Routledge, London u.a., 2000.

Wilhite, D. A. and Glantz, M. H.: Understanding: The Drought Phenomenon: The Role of Definitions, Water International, 10, 111–120, 1985.

World Meteorological Organization (WMO) and Global Water Partnership (GWP): Handbook of Drought Indicators and Indices (M. Svoboda and B.A. Fuchs), Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2, 52 pp., 2016.