Nat. Hazards Earth Syst. Sci. Discuss., 2, 7583–7620, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/7583/2014/
doi:10.5194/nhessd-2-7583-2014
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Natural Hazards and Earth System Sciences
Open Access
Discussions

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Exploring the link between drought indicators and impacts

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Received: 29 October 2014 – Accepted: 24 November 2014 – Published: 15 December 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Current drought monitoring and early warning systems use different indicators for monitoring drought conditions and apply different indicator thresholds and rules for assigning drought intensity classes or issue warnings or alerts. Nevertheless, there is little knowledge on the meaning of different hydro-meteorologic indicators for impact occurrence on the ground. To date, there have been very few attempts to systematically characterize the indicator–impact-relationship owing to the sparse and patchy data for ground truthing hydro-meteorologic variables. The newly established European Drought Impact report Inventory (EDII) offers the possibility to investigate this linkage. The aim of this study was to explore the link between hydro-meteorologic indicators and drought impacts for the case study area Germany and thus to test the potential of qualitative impact data for evaluating the performance of drought indicators. As drought indicators two climatological drought indices as well as streamflow and groundwater level percentiles were selected. Linkage was assessed though data visualization and correlation analysis between monthly timeseries of indicator–impact data at the federal state level, and between spatial patterns for selected drought events. The analysis clearly revealed a significant moderate to strong correlation for some states and drought events allowing for an intercomparison of the performance of different drought indicators. While several commonalities could be identified regarding "best" indicator, indicator metric, and time-scale of climatic anomaly, the analysis also exposed differences among federal states and drought events, suggesting that the linkage is time-variant and region specific to some degree. Concerning thresholds associated with drought impact onset, we found that no single "best" threshold value can be identified but impacts occur within a range of indicator values. While the findings strongly depend on data and may change with a growing number of EDII entries in the future, this study clearly demonstrates the feasibility of ground truthing hydro-meteorologic variables with text-based impact reports and highlights the value of impact reporting as a tool for monitoring drought conditions.

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1 Introduction

Drought is a complex natural hazard with severe environmental and socio-economic impacts. According to the UN Convention to Combat Drought and Desertification drought is a "naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels" (UN General Secretariat, 1994). Although little can be done to prevent this naturally occurring hazard, actions can be taken to reduce the societal vulnerability to drought. Such actions include the development of drought monitoring and early warning (M&EW) systems and drought plans to enhance drought preparedness (e.g. Wilhite et al., 2000; Wilhite and Knutson, 2008; Wilhite and Svoboda, 2000). Drought M&EW systems are based on different drought indicators or indices, which are variables describing drought conditions derived from predominantly meteorological or hydrological data. Knowledge on drought conditions expressed through an indicator, however, does not directly translate into understanding when and where drought impacts will occur given the complexity of how a prolonged precipitation deficit propagates though the hydrological cycle and interacts with environmental and socio-economic factors. Nevertheless, information on the occurrence, timing, and severity of a drought impact is usually what matters most to stakeholders. Therefore there is a vital need for research on the link between commonly used drought indicators and impacts (e.g. Kallis, 2008; Stagge et al., 2014a; Stahl et al., 2012).

Especially for the development of drought plans knowledge on the relationship between drought indicators and impacts is important to infer meaningful threshold values triggering a management response (Steinemann and Cavalcanti, 2006; Steinemann, 2003, 2014). A recent survey among state drought managers in the United States revealed that drought indicators and derived trigger values are often used without clarity about the relevance or effectiveness of this indicator (Steinemann, 2014). One reason for little consensus on the appropriateness of different indicators for drought M&EW is sparse and patchy data for ground truthing drought indicators. Since drought is a slow-onset "creeping" hazard (Gillette, 1950) with multifaceted impacts on different domains

NHESSD
2, 7583–7620, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

and sectors it is less visible than, for instance, earthquakes or floods. Apart from some exceptions (e.g. agricultural yield statistics) it is challenging to find information on the variety of drought impacts, which are mainly non-structural (not associated with physical damages to buildings, infrastructure, and other assets) and difficult to quantify in monetary terms (Logar and van den Bergh, 2013). To address these shortcomings, an online database for collecting user-based reports on drought impacts was launched in the United States some years ago (US Drought Impact Reporter (DIR), Wilhite et al., 2007). For Europe, a similar system has been recently established, however as a research database with a focus on past drought events, rather than as a real-time monitoring tool. This European Drought Impact report Inventory (EDII), which was broadly modeled after the US Drought Impact Reporter, compiles text-based reports on drought impacts from a variety of sources (Stahl et al., 2012). Inventories like the DIR or the EDII offer the possibility to evaluate drought indicators with information on impact occurrence.

A large body of literature exists on the vast amount of drought indicators (for recent reviews see Heim Jr., 2002; Keyantash and Dracup, 2002; Zargar et al., 2011) and many studies have assessed the linkage between different hydro-meteorologic indicators (e.g. Anderson et al., 2011; Hao and AghaKouchak, 2014; Haslinger et al., 2014; Keyantash and Dracup, 2002; Steinemann, 2003; Vicente-Serrano et al., 2012). While fewer studies explored the relationship between drought indicators and a quantitative impact variable, such as agricultural yield or a vegetation response proxy (e.g. Ceglar et al., 2012; Mavromatis, 2007; Potop, 2011; Quiring and Ganesh, 2010; Quiring and Papakryiakou, 2003; Rossi and Niemeyer, 2010; Sepulcre-Canto et al., 2012; Vicente-Serrano et al., 2012), only two studies have exploited text-based reports of drought impacts for evaluating the meaning of drought indicators (Dieker et al., 2010; Stagge et al., 2014a). The value of incorporating impact information into drought M&EW lies in moving from a hazard-based, reactive to a risk-based, proactive approach of drought management, as often postulated (Wilhite et al., 2000). Drought indicators only characterize the hazard, leaving room for interpretation whether and when this will trigger

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impacts. Depending on the vulnerability of a system a given hazard intensity will or will not evoke adverse environmental, economic or social effects. Vulnerability assessment is a common tool for closing the gap between hazard information and knowledge of risk of a certain region or exposed entity; its outcome, however, will strongly depend on the quality of available indicator data and assumptions made (Naumann et al., 2014). Directly evaluating drought indicators with impact occurrence allows, in theory, gaining insight into the cause–effect-relationship of a physical water deficit without any assumptions on vulnerability. Nevertheless, there are numerous challenges and potential sources of bias during the collection of drought impact information (Lackstrom et al., 2013); text-based impact reports thus only represent a proxy for impact occurrence.

Given the limited knowledge on the potential of qualitative impact data for evaluating the meaning of drought indicators, this study aims at exploring the link between hydro-meteorologic drought indicators and text-based information of drought impacts. To test the feasibility of linking indicators with impacts, Germany was chosen as a case study given its good coverage in the EDII and availability of hydro-meteorologic data. Specifically, we ask the following research questions:

- Is there a discernible link between drought impact occurrence derived from text-based information and different hydro-meteorologic indicators commonly applied for operational drought monitoring and early warning (M&EW) systems?

- If there is a link, which indicator or set of indicators best explain drought impact occurrence for the case study area Germany?

- Can impact occurrence be attributed to a specific indicator threshold?

NHESSD
2, 7583–7620, 2014

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2 Methods

2.1 Drought indicator data

Four indicators were selected representing drought propagation in different domains of the hydrological cycle: the standardized precipitation index (SPI) (McKee et al., 1993), the standardized precipitation evaporation index (SPEI) (Vicente-Serrano et al., 2010), and two hydrological indicators, namely streamflow percentiles (Q), and percentiles of groundwater levels (G). SPI-n and SPEI-n are statistical indicators that compare the total precipitation or climatic water balance at a particular location during a period of n months with its multiyear average (Vicente-Serrano et al., 2010; Zargar et al., 2011). As aggregation periods of SPI and SPEI we selected 1–8, 12, and 24 months. SPI and SPEI monthly timeseries are based on E-OBS gridded data (version 9.0; 0.25° regular spatial grid, Haylock et al., 2008) and were calculated using the R Package "SCI" (Gudmundsson et al., 2014; Stagge et al., 2014b). Standardization is based on the gamma distribution for SPI and the generalized logistic distribution for SPEI; potential evapotranspiration for SPEI is estimated using Hargreaves method (Hargreaves, 1994). As spatial units of drought indicator aggregation the 16 federal states, corresponding to European Union NUTS 1 regions, were chosen (Baden-Wuerttemberg (BW), Bavaria (BV), Berlin (BE), Brandenburg (BB), Hanseatic City of Bremen (HB), Hanseatic City of Hamburg (HH), Hessen (HE), Mecklenburg-Western Pomerania (MP), Lower Saxony (LS), North Rhine-Westphalia (NW), Rhineland Palatinate (RP), Saarland (SL), Saxony (SX), Saxony-Anhalt (ST), Schleswig-Holstein (SH), and Thuringia (TH)). See Fig. 1 for SPI or SPEI grid cell coverage per federal state. For the spatial aggregation of SPI or SPEI the following metrics were calculated per federal state: mean ($\overline{\text{SPI}}$ and $\overline{\text{SPEI}}$), 10th percentile (SPI_{10} and SPEI_{10}), and the percent area in drought (A_{SPI} and A_{SPEI}), which is defined as percent area with SPI or SPEI < -1.

Monthly streamflow percentiles are based on daily records of streamflow for several gauging stations per federal state. Timeseries of monthly groundwater percentiles

NHESSD
2, 7583–7620, 2014

Exploring the link between drought indicators and impacts

S. Bachmair et al.

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originate from weekly to monthly readings of groundwater levels or spring discharge for several monitoring stations per state. Figure 1 displays the spatial distribution of stations (amount of streamflow and groundwater gauging stations per federal state, respectively: 28/15 (BW), 69/26 (BV), 21/18 (BB), 19/18 (HE), 38/42 (LS), 7/4 (MP), 23/18 (NW), 20/18 (RP), 9/9 (SH), 3/0 (SL), 23/10 (SX), 16/14 (ST), 25/23 (TH), no data for BE, HB, and HH). Many of these stations are used for the federal states' hydrological forecasting systems and thus represent stations with good data quality. Note that streamflow gauging stations represent a variety of catchments varying in size and catchment characteristics, many of them being anthropogenically influenced. For more details on the selection of gauging stations per state see Kohn et al. (2014). The reference period for calculation of monthly percentiles is 1970–2011. Similar to the spatial aggregation of SPI or SPEI, different indicators metrics for streamflow or groundwater percentiles were calculated per federal state: mean ($\overline{Q}$ and $\overline{G}$), 10th percentile (Q_{10} and G_{10}), and percent stations under low flow conditions (percentile < 0.3; A_Q and A_G).

2.2 Drought impact data

Information on drought impacts originates from the European Drought Impact report Inventory (EDII) (Stahl et al., 2012). According to the EDII a "drought impact" is a negative environmental, economic or social effect experienced under drought conditions. Consequently, precipitation shortfalls, anomalously low levels of soil moisture, water levels or streamflow without negative consequences (for water uses, ecosystems, agricultural yields etc.) or at least serious concerns, are not regarded as drought impacts. EDII entries are based on text-based impact reports. These reports come from a variety of sources such as governmental or NGO reports, books, newspapers/digital media or journal articles. Each drought impact report in the inventory contains (1) a spatial reference (different levels of geographical regions including the European Union NUTS (Nomenclature of Territorial Units for Statistics) regions standard), (2) a temporal reference (at least the year of occurrence), and (3) an assigned impact category (there are 15 impact categories with further division into impact subtypes). More information on

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each drought impact report is available in the inventory but is not used for the analysis. See Stahl et al. (2012) for further information on the EDII and a description of impact categories.

About 30 % of the EDII entries represent impacts that occurred in Germany (761 impact reports as of August 2014). For the statistical analysis the qualitative information on drought impacts was converted into monthly timeseries of number of drought impact occurrences per state. The following decisions were made during the conversion of "drought impact reports" (EDII entries) into "drought impact occurrences" (hereafter termed *I*):

- Spatial reference: an impact report often contains information on drought impacts that occurred at several locations and/or impacts representing different impact subtypes. An impact report was converted into several *I* if (1) the impact report states impact occurrence in several federal states or (2) an impact falls into several impact subtypes. Note that an *I* assigned to a specific state may both represent an impact affecting the entire state (e.g. impact report states reduction of crop yield for the entire state) or an impact occurring at a smaller unit within that state (e.g. impact occurred in city X of state A). Both types of spatial reference have equal weight in the analysis (one *I*). Impact reports with country-level information without indication of affected states were not considered in the analysis.

- Temporal reference: impact reports indicating a month for start and end of drought impact occurrence were converted accordingly. If only the season was provided, drought impacts were assumed to have occurred during each month of that season (winter = DJF, spring = MAM, summer = JJA, fall = SON). Impact reports with only the year of occurrence stated were omitted from the analysis. Note that in the analysis we distinguish between months with *I* (months during which drought impacts occurred), and months with *I* onset (months where one or several drought impacts started to occur).

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For the analysis the time period 1970–2011 was chosen. Out of all impact reports for Germany, 685 fell into the time period 1970–2011; 38 % of these entries had either country-level information only or no month/season indicated and was thus discarded. The conversion of the remaining impact reports resulted in 1569 drought impact occurrences with spatial and temporal reference (state-level and month). In addition to the number of I of all impact categories we also considered the number of drought impact occurrences associated with hydrological drought (hereafter termed I_h), i.e. all impacts resulting from drought conditions of surface waters or groundwater. The temporal, spatial, and categorical distribution of I is displayed in Fig. 2. Due to very little impact data for the city states HB and HH these states are omitted from analysis.

2.3 Data analysis

The linkage between drought indicators and impacts is assessed through data visualization and correlation analysis. Two approaches are followed: (1) linkage between timeseries of indicator–impact data per state to gain insight into the spatial variability of the indicator–impact relationship, and (2) linkage between spatial patterns of indicator–impact data for selected drought events.

1. Linkage between timeseries of indicator–impact data per state: for this approach only years with at least one I within Germany were considered, which resulted in 17 years. The rationale behind this is to exclude years where drought conditions may have occurred but no impact reports are available given the undoubtedly biased temporal coverage of EDII entries. Note that all months of the respective years were considered ($n = 204$ months). Rank correlation coefficients and corresponding significance levels were computed for

   – timeseries of $\overline{\text{SPI}}$ or $\overline{\text{SPEI}}$ or $\overline{Q}$ or $\overline{G}$ vs. timeseries of I or I_h per federal state

   – timeseries of SPI_{10} or SPEI_{10} or Q_{10} or G_{10} vs. timeseries of I or I_h per federal state, and

NHESSD
2, 7583–7620, 2014

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– timeseries of A_{SPI} or A_{SPEI} or A_Q or A_G vs. timeseries of I or I_h per federal state. Note that for SPI or SPEI the aggregation periods 1–8, 12, and 24 months were considered.

We define strength of correlation as follows: 0–0.1 (no correlation), > 0.1–0.3 (weak), > 0.3–0.6 (moderate), > 0.6–0.9 (strong), and > 0.9 (perfect).Moreover, indicator values associated with drought impact onset were extracted from each drought indicator timeseries per federal state. Since indicator values associated with impact onset may represent thresholds for impact occurrence, we hereafter also use the term indicator "threshold" when referring to the former. Indicator threshold distributions were visualized and analyzed for their median values. Note that SPI and SPEI threshold distributions are based on I onset, while Q and G distributions are based on I_h onset.

2. Linkage between spatial patterns of indicator–impact data: for this approach the link between spatial patterns of indicator–impact data across the federal states was investigated for selected drought events. A drought event is defined as a time period of drought impact occurrence after a time with no impacts; we set a threshold of 35 I per event to be considered in the analysis. This resulted in seven selected events: 1971, 1976, 1983, 1992, 2003, 2006, and 2011. The reason for defining events via impact occurrence over exceedance of an indicator threshold is to focus on events with good coverage of impact data. Event duration is set to the time period of consecutive impact occurrence from first to last occurrence, which may be intermitted by one month with no impact. See Table 1 for duration and timing of drought events and number of I or I_h and I or I_h onsets. For each event, drought indicator timeseries were aggregated over the duration of the event, resulting in different indicator metrics per federal state and event: mean of $\overline{\text{SPI}}$ or $\overline{\text{SPEI}}$ or $\overline{Q}$ or $\overline{G}$, minimum of SPI_{10} or SPEI_{10} or Q_{10} or G_{10}, and maximum of A_{SPI} or A_{SPEI} or A_Q or A_G. Rank correlation coefficients and corresponding significance levels were computed between spatial patterns of

NHESSD
2, 7583–7620, 2014

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- mean $\overline{\mathrm{SPI}}$ or $\overline{\mathrm{SPEI}}$, minimum SPI_{10} or SPEI_{10}, maximum A_{SPI} or A_{SPEI} vs. number of I or I_h per event ($n = 14$; all states except the city states HB and HH)
- mean $\overline{Q}$, minimum Q_{10}, maximum A_Q vs. number of I or I_h per event ($n = 13$; no streamflow data for the city states BE, HB, and HH), and
- mean $\overline{G}$, minimum G_{10}, maximum A_G vs. number of I or I_h per event ($n = 12$; no groundwater data for the states BE, HB, HH, and SL).

Additionally, indicator values associated with drought impact onset during each event were extracted from the drought indicator timeseries. As for the linkage between timeseries approach, the resulting indicator threshold distributions per event were visualized and analyzed for their median values.

3 Results

3.1 Linkage between timeseries of indicator–impact data

Figure 3 displays correlation coefficients between timeseries of drought indicators and I or I_h per federal state, which range from −0.46 to 0.47. The indicator metrics mean, 10th percentile, and percent area in drought show differing directions of r. While the mean and 10th percentile are generally negatively correlated with I (lower indicator values coinciding with higher number of I), the percent area in drought is mainly positively correlated (larger area associated with higher number of I). However, there are some instances with an inverse direction of r (non-meaningful direction). The weak to moderate strength of correlation for several federal states clearly reveals a link between drought indicators and text-based information on drought impacts. Weak to moderate correlations are statistically significant ($p < 0.05$), as indicated by the white dots in Fig. 3. Figure 3 also reveals strong differences among states. While the states BW, BV, NW, RP and SX show a moderate correlation for several drought indicators, the states

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BE, BB, MP, LS, SL, and ST display predominantly weak correlations. The states SH and TH show no correlation for most indicators.

When focusing on commonalities in correlation patterns for I, the following findings become apparent: SPEI in most cases shows a slightly higher r than the corresponding SPI. The r for streamflow percentiles is for some states comparable to SPI, yet often shows lower values. Groundwater level percentiles show only a weak correlation with timeseries of drought impact occurrence. Regarding the accumulation period of SPI and SPEI the strongest correlation is found for intermediate accumulation periods. For half of the states the highest r is associated with a precipitation or water balance anomaly of 3 or 4 months. Notable is an inverse direction of r for SPI-24 and SPEI-24 for most federal states.The differences between indicator metrics (mean vs. 10th percentile vs. percent area in drought) are negligible (see vertical series of plots in Fig. 3). The picture for correlation with I_h is similar, yet some indicators display a higher r than with I, especially in the states with generally weak correlations (BE, BB, MP, and SH). The right panel of Fig. 3 highlights the difference in r between I and I_h for streamflow percentiles. As can be seen, there is no consistent picture of higher r between timeseries of Q and I_h than between Q and I.

In terms of thresholds for I or I_h onset it becomes evident that no single threshold value exists triggering the onset of drought impacts. The boxplots in Fig. 4 show that the interquartile range (IQR) of the $\overline{\mathrm{SPI}}$ or $\overline{\mathrm{SPEI}}$ distributions predominantly spans an absolute value of at least one. Apart from this, the boxplots and median of the $\overline{\mathrm{SPI}}$ or $\overline{\mathrm{SPEI}}$ and SPI_{10} or SPEI_{10} distributions, displayed in Table 2 and Table 3, reveal interesting differences among states and SPI or SPEI accumulation periods:

1. Differences among states: when neglecting the variability and complexity of the pattern within each state, there appears a pattern of some states showing more negative threshold values than others. In the states BV, BW, and RP, $\overline{\mathrm{SPI}}$ and $\overline{\mathrm{SPEI}}$ for accumulation periods 1–8 tend to be more negative (IQR between −1 and −2) than in the states BB, LS, and MP, where the IQR primarily lies between 0 and

NHESSD

2, 7583–7620, 2014

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−1. If only considering the indicator showing the highest correlation with drought impact occurrence, a threshold (median of $\overline{SPI}$ or $\overline{SPEI}$ distribution) of −1.7 (BV), −1.5 (BW), −1.53 (RP), −0.5 (BB), −0.93 (LS), and −0.37 (MP) can be identified (see Table 2 for median values of all indicator distributions). The former states are located in the south/southwest of Germany, whereas the later are situated in the north/north-east. Other states such as HE, NW, SN, or ST show more variability and cannot be clearly assigned to one group or the other. Some states only have very limited impact data not allowing for a robust characterization (BE, SL, SH, and TH, see Table 2 and Fig. 2). The findings above also apply to SPI_{10} and $SPEI_{10}$, yet the threshold values are generally more negative (not shown).

2. Differences between SPI and SPEI and among accumulation periods: notable as well is that $\overline{SPEI}$ or $SPEI_{10}$ values triggering I onset are in most cases more negative than the corresponding $\overline{SPI}$ or SPI_{10} (see Fig. 4 and Table 2). Regarding timescales of SPI and SPEI, longer accumulation periods, especially 12 and 24 months, show less negative threshold values than shorter accumulation periods.

For streamflow and groundwater percentiles the onset of drought impacts is also attributable to a range of threshold values (see Table 2). However, for many states only very few months with I_h onset exist. This does not allow for an intercomparison among states.

3.2 Linkage between spatial patterns of indicator–impact data for selected drought events

The maps in Fig. 5 reveal that there is a reasonable agreement between the spatial distribution of two exemplarily selected drought indicators ($SPEI_{10}$-3 and $\overline{Q}$) and number of I or I_h per drought event. Nevertheless, there are differences among drought events. During the events of 1976, 1992, and 2011 the spatial patterns of $SPEI_{10}$-3 vs. I match well apart from some exceptions (e.g. similarly negativ $SPEI_{10}$-3 values in

Thuringia as in neighboring states 2011, yet no drought impact occurrence). Opposed to that, the agreement between spatial patterns of indicator–impact data is lower for the events 1971, 1983 (only for $SPEI_{10}$-3), and 2006. There, federal states with similar drought indicator values show dissimilar I or I_h patterns (e.g. 1971: SL and BV similar $\overline{Q}$ as NW, RP, and BW but no hydrological drought impact occurrence).

The correlation between spatial patterns of drought indicators and I or I_h per event is displayed in Fig. 6. Rank correlation coefficients lie between −0.88 and 0.84. When only considering the "best" indicator per drought event, i.e. the indicator with the highest absolute value of r, correlations range from 0.53 (1971) to 0.88 (2011). All strong correlations are statistically significant ($p < 0.05$), as indicated by the white dots in Fig. 6. Noticeable are a number of insignificant correlations with non-meaningful direction of r, especially for the events 1971, 1983, and 2003 (positive r for the metrics mean and 10th percentile; negative r for percent area in drought). One commonality of all events is more pronounced differences between indicator metrics (mean vs. 10th percentile vs. percent area in drought) compared to the linkage-between-timeseries approach (Sect. 3.1). For some events the 10th percentile performs slightly better the mean, highlighting the importance of variability for the strength of correlation between spatial patterns. Apart from this, Fig. 6 reveals clear differences among drought events. Drought events with geographical concentration and thus higher spatial variability of indicator and/or impact data (1976/1992/2011) exhibit a higher number of indicators with a significant moderate or strong correlation (see Figs. 5 and 6). In contrast, the events of 2003 and 2006, where drought impacts occurred more evenly distributed in nearly all federal states, show weaker and mostly insignificant correlations, many of them with a non-meaningful direction of r. A weak and insignificant r between drought indicators and I also applies to the events of 1971 and 1983.

Regarding the "best" indicator there is a tendency of SPEI performing better than SPI, and SPEI or SPI outperforming streamflow and groundwater percentiles. Nevertheless, there is much variability among events, which also applies to the "best" SPI or SPEI timescale. Intermediate accumulation periods (roughly 3–8 months) best cor-

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relate with impact occurrence for the events of 1976 and 2006; shorter accumulation periods (2–4 months) yield the highest r for 1992. For the 2011 event all accumulation periods show a moderate to high correlation with spatial patterns of impact data. In contrast to the linkage between timeseries, the difference in r between I and I_h is more pronounced, especially for the events in 1971, 1983, and 2006 (see Fig. 6). While for most events I and I_h mostly differ in number of impact occurrences (decrease of I_h), the spatial distribution of I or I_h also changes for the above named events due to some states with no hydrological drought impacts (see maps in Fig. 5). A pattern of stronger correlation between streamflow/groundwater percentiles and I_h, however, does not exist; often correlations are lower.

Indicator thresholds associated with I or I_h onset also reveal differences among events, highlighting the difficulty of identifying a single, time-invariant "best" threshold (see Fig. 7 and Table 3). For intermediate accumulation periods of SPI or SPEI (3–8 months) the longer-duration events 1976, 2003, and 2011 show more negative threshold values than the other, shorter-duration events (median of $\overline{\text{SPI}}$ or $\overline{\text{SPEI}}$ distribution generally < -1 (Table 4); median of SPI_{10} or SPEI_{10} distribution generally < -1.5 (not shown)). For both short and long accumulation periods the differences in threshold values among events are less pronounced or disappear.

For streamflow and groundwater percentiles weak differences among events are discernible. However, the events are hardly comparable given the small number of data points for 1971, 1983, and 2006 due to barely any I_h onsets (see Table 1 for number of I or I_h onsets).

NHESSD
2, 7583–7620, 2014

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4 Discussion

4.1 Is there a discernible link between drought impact occurrence derived from text based information and different hydro-meteorologic indicators?

The analysis clearly revealed a relationship between the selected hydro-meteorologic drought indicators and drought impact occurrence inferred from text-based reports. The linkage-between-timeseries approach (Sect. 3.1) showed a significant moderate strength of correlation for several federal states, allowing for intercomparing the performance of different drought indicators. The event based approach (Sect. 3.2) also exposed a significant moderate to strong correlation between spatial patterns of indicator–impact data for some drought events. From these results one can infer that qualitative information on drought impacts has strong potential for evaluating the meaning of hydro-meteorologic drought indicators. This is highly relevant for improving drought M&EW systems, since drought indicators are often used without having explicitly tested their representativeness for drought impact occurrence. Despite this promising outcome, it needs to be emphasized that for some federal states and drought events only a weak or no correlation was found, and sometimes a correlation with non-meaningful direction. For some states no to weak correlation may be an effect of very few months with impact occurrence (TH and SL), while this is not the case for the states MP, BB, and LS, which are comparable to SX and HE regarding the number of impact occurrences. The underlying mechanisms of these differences are not clear; they may simply result from less representative impact data for these states.

Generally, there are many potential sources of error or bias concerning drought impact data. As described in Lackstrom et al. (2013), drought impact reporting is associated with numerous challenges, creating a “patchwork” of impact information. Concerning our analysis the following sources of uncertainty need to be pointed out: first, not all drought impacts become published in reports, newspaper articles or other sources; if they are published, the level of detail regarding the spatial and temporal reference likely differs. Second, not all published information will make it into the inventory if not easily

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found or accessible; when entering information about spatial and temporal reference and impact category further bias may be introduced. Third, the assumptions during the process of impact report quantification for this study are subjective. For instance, we simply sum up (hydrological) drought impact occurrences per month independent of impact severity or spatial extent of the impact. All drought impacts have equal weight. At the same time, we think that the amount of reported drought impacts may represent some measure of impact severity. Hence, the number of impact occurrences may provide more information than a binary target variable (impact vs. no impact).

Despite these limitations, the impact data used in this study provided a reasonable proxy for the linkage with hydro-meteorologic indicators. Given the "patchwork" nature of impact information, uncertainty associated with the indicator data seems of lower importance (e.g. dissimilar amount of streamflow and groundwater gauging stations per state; choice of probability distribution for SPI or SPEI calculation, e.g. Stagge et al., 2014b). The reasons for weak correlations for some drought events could also go back to the method of event delineation (e.g. impact occurrence in summer according to impact report, assignment of start month June during automatic data processing, yet start of meteorological/hydrological drought conditions in August), or low spatial variability of impact and/or indicator data not allowing to detect a cause–effect-relationship. Especially for the events 1971, 1983, 2003, and 2006, low spatial variability of impact and/or indicator data may explain the frequent occurrence of insignificant, weak correlations, often with non-meaningful direction of r. In 2003, drought conditions and heatwaves dominated entire central Europe (Fink et al., 2004). For relatively homogenous drought events like 2003 the linkage-between-spatial-patterns approach does not yield useful insights into the indicator–impact relationship.

4.2 Which indicator or set of indicators best explain drought impact occurrence for the case study area Germany?

Generally speaking, the complementary approaches of linkage-between-timeseries and linkage-between-spatial-patterns of indicator–impact data revealed that (1) SPEI

NHESSD
2, 7583–7620, 2014

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often correlates slightly better than SPI, (2) intermediate accumulation periods of SPI or SPEI show the highest correlation, (3) streamflow percentiles are comparable to SPI in the linkage in many cases, and (4) the choice of indicator metric (mean vs. minimum vs. percent area in drought) does not make a difference for the between-timeseries approach, but matters for the event based approach (10th percentile often outperforms mean/percent area in drought).

The finding that SPEI performed slightly better than SPI is in line with of other studies assessing the correlation between SPI or SPEI and different hydrological, agricultural, and ecological response variables (Haslinger et al., 2014; Potop, 2011; Stagge et al., 2014a; Vicente-Serrano et al., 2012). Also in terms of the "best" time-scale of SPI or SPEI similar results were obtained as in other studies. Stagge et al. (2014a), who modeled drought impact occurrence for five European countries based on logistic regression with different climatological drought indicators, identified an SPEI aggregation time of 3 months as best predictor for agricultural impact occurrence in Germany. For other impact categories in Germany, e.g. energy and industry, they obtained more complex results promoting a combination of shorter and longer accumulation periods (Stagge et al., 2014a). Our finding that the "best" SPI or SPEI accumulation period differs among drought events could result from a shift in dominant impact type. For instance, the events in 1971, 1983, 1992, and 2006 show a higher fraction of agricultural impacts (see Fig. 2) as opposed to the other events with more diverse impact types, many of them evoked by lowflows (e.g. impacts on waterborne transportation and energy production). Different impact types are known to have specific response times and could thus be attributed to different "best" SPI or SPEI timescales (e.g. shorter-term impacts on rain-fed agriculture vs. longer-term impacts on water supply systems evoked by groundwater drought) (e.g. Stagge et al., 2014a; Vicente-Serrano et al., 2013). Overall, similar results as by Stagge et al. (2014a) are not surprising given that they also exploited EDII data to obtain binary impact information at the country-level. However, it is important to test, where simple and intuitive approaches like correlation and visualization of linkage patterns can yield similar results as more complex

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statistical models. The identified similar strength of correlation for streamflow as for SPI is noteworthy given the more complex streamflow signal stemming from several sources such as catchment area outside of the administrative area and human alteration through streamflow abstraction or augmentation. The weak correlation between groundwater levels and drought impact occurrence could be an effect of longer lag times of the groundwater response.

Apart from the above named commonalities, we observed differences in correlation patterns among federal states and drought events, highlighting the complexity of identifying a "best" indicator. It is known that an individual indicator is not capable of representing the diversity and complexity of drought conditions across space and time for different sectors (Botterill and Hayes, 2012; Hayes et al., 2005). Nevertheless, drought M&EW systems rely on the use of meaningful indicators and associated triggers. Usually drought M&EW systems operate on a national or continental scale and apply fixed rules for assigning drought intensity classes or issue warnings or alerts. One example is the European Drought Observatory (http://edo.jrc.ec.europa.eu), which assigns different alert levels inferred from a combination of drought indicators for entire Europe (European Drought Observatory, 2013). Another example is the US Drought Monitor (http://droughtmonitor.unl.edu; USDM). The USDM produces nationwide weekly maps of drought severity categories based on a percentile approach of six key physical indicators and many supplementary indicators (Hayes et al., 2005; Svoboda et al., 2002). In addition, the USDM incorporates judgment from climate and water experts as a reality check at the state and local level, making it a "state-of-the-art blend of science and subjectivity" (http://droughtmonitor.unl.edu). Our analysis showed that a single "best" indicator for Germany could not be identified. Instead, the spatial variability in correlation patterns suggests that fixed rules representative for a larger area need to be selected with care. This is especially true since Germany is a comparably small country per se with lower spatial variability in climate and geographical properties as opposed to the whole of Europe or the US, for instance. Our study thus calls for evaluating the meaning of drought indictors at smaller spatial scales.

NHESSD
2, 7583–7620, 2014

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Furthermore, the linkage-between-spatial-patterns approach revealed clear differences among drought events. The drivers of the inter-event variability of correlation patterns and thus "best" indicators are less clear. Likely a combination of (1) dissimilar hazard characteristics (duration and evolution of drought severity and related hazards such as heat weaves) triggering different impact types, (2) differences in geographic extent and vulnerability of affected regions, and (3) potentially an impact reporting bias for certain events and/or regions cause the differences among events. Common to all events except 2011 is that they represent summer droughts with respect to peaks of drought impacts (see Table 1). Most drought impacts receded in fall (1971, 1976, 1983, and 1992) while the 2003 drought was more persistent with longer-term drought impacts tapering off only in early 2004. From the hazard side, however, the droughts of 1976 and 1992 were more prolonged (e.g. Bradford, 2000; Hannaford et al., 2011; Zaidman et al., 2002). The 2011 drought was exceptional with regard to its unusual timing: after a flood in January two drought periods occurred in spring and late autumn, with November 2011 being the driest November recorded (Kohn et al., 2014). This may explain the comparably different correlation pattern for 2011, with SPI or SPEI from 1 to 8 months, streamflow and groundwater percentiles all performing similarly well showing strong correlation with impacts. While the reasons for the differences among events remain speculative, the inter-event variability suggests that the "best indicator" for drought impact occurrence is event-dependent.

4.3 Can impact occurrence be attributed to a specific indicator threshold?

Regarding indicator thresholds triggering the onset of drought impacts we found that (1) no single "best" threshold value can be identified but impacts occur within a range of indicator values, (2) SPEI often shows slightly lower values than the corresponding SPI, and (3) there are differences among federal states and drought events.

Our analysis revealed that a single "one size fits all" indicator threshold does not exist. Instead, the interquartile range of the SPI or SPEI distributions was found to span at least an absolute value of one. This is not surprising given the differences in impacts

NHESSD
2, 7583–7620, 2014

both regarding impact type and severity. We currently do not differentiate between impact types due to the small sample size; we only consider all drought impacts vs. hydrological drought impacts. However, thresholds are likely specific to a certain impact category and affected sector, as already pointed out by Botterill and Hayes (2012). A split into more homogenous groups could lead to condensed threshold ranges, a prerequisite for inferring meaningful triggers. The Combined Drought Indicator by the European Drought Observatory, for instance, which is based on SPI-1, SPI-3, anomalies of soil moisture and fAPAR (fraction of Absorbed Photosynthetically Active Radiation), builds on combinations of threshold values of −1 and −2 for assigning the agricultural drought levels "Watch", Warning", and "Alert" (for details see corresponding product fact sheet, European Drought Observatory, 2013). The combined indicator geared towards agricultural drought detection was evaluated against data from the EM-DAT International Disaster Database and yield statistics, suggesting a robustness of the method against false alarms (Sepulcre-Canto et al., 2012). Information on impact onset derived from EDII reports could serve as valuable tool to derive meaningful warning thresholds for other types of drought.

A notable outcome of the analysis is differences in threshold values between southern/southwestern (hereafter called southern) and northern/northeastern (hereafter called northern) states of Germany. The differences coincide with stronger and weaker correlation between indicator–impact timeseries of the southern and northern states, respectively. Care needs to be taken regarding any interpretations given the "soft" text-based impact data and small sample size. However, one could speculate that these differences are attributable to differences in geographic properties, manifesting in different vulnerabilities to reduced precipitation input. The northern states generally exhibit soils with higher sand content and thus lower water holding capacity than in the south (Bundesanstalt für Geowissenschaften und Rohstoffe, 2007). Additionally, there is lower natural water availability in the northern federal states (Bundesamt für Gewässerkunde, 2003). This could serve as explanation for impact onset during less negative SPI or SPEI values than in the south. Lower SPI or SPEI values associated with impact occurrence and hence lower variability of these timeseries could also explain the weaker correlation patterns for these states. Other studies also report on lower soil moisture availability and higher drought vulnerability of the northeast of Germany (Samaniego et al., 2013; Schindler et al., 2007; Schröter et al., 2005). Regardless of the drivers of differences among states one could argue that assuming a fixed trigger applied to a large area varying in geographic properties may not be appropriate. For continental-scale drought M&EW a systematic assessment of differences in threshold behavior could be useful.

In addition, the inter-event variability of thresholds associated with impact onset suggests that a "best" threshold is time-variant. The analysis revealed comparably lower values associated with drought impact onset for the longer-duration, more severe events of 1976, 2003, and 2011. However, some events did not affect all states but were spatially concentrated (1992: focus on north-eastern Germany; 1976/2011: focus on the southwest). Differences in indicator thresholds among events could hence be a result of drought event characteristics, or an effect of location given the differences in threshold values between the south/north. For drought management plans aiming at withstanding a certain "design" drought, historical droughts of similar severity and duration could be jointly analyzed to derive reference thresholds triggering certain management actions during future events. While the visualization of indicator values corresponding to impact onset is a very simple approach, the suitability of threshold ranges can be easily judged, which was shown to be an important criterion for effective communication with stakeholders (Steinemann and Cavalcanti, 2006; Steinemann, 2014).

5 Conclusion

We explored the link between hydro-meteorologic indicators and drought impacts for the case study area Germany to illustrate the potential of qualitative impact data for evaluating the meaning of drought indicators. The analysis clearly revealed a rela-

NHESSD
2, 7583–7620, 2014

tionship between selected drought indicators (SPI, SPEI, streamflow and groundwater level percentiles) and drought impact occurrence inferred from text-based reports of the European Drought Impact report Inventory (EDII). Through data visualization and correlation analysis several general conclusions concerning the performance of indicators, "best" indicator time-scale, and thresholds associated with impact onset can be drawn. The notable differences in indicator–impact relationship among the federal states in Germany and among drought events, however, suggest that the linkage is time-variant and region specific to some degree. We think that this study is a proof of concept and a first step in the direction of systematically characterizing the relationship between drought indicators and text-based impact reports. While the findings on "best" indicators and thresholds for impact onset strongly depend on data and may change with a growing number of impact reports in the future, the aim was to demonstrate the feasibility of evaluating hydro-meteorologic variables used for drought M&EW with text-based impact reports. The complementary approaches of linkage between timeseries of indicator–impact data per state and linkage between spatial patterns for selected drought events proved to be a simple, yet effective methodology for deriving strong hypotheses on general patterns of the indicator–impact-relationship. Consequently, this study highlights the value of impact reporting as a tool for monitoring drought conditions and stresses the necessity to further develop drought impact inventories.

Acknowledgements. Funding to the project DrIVER by the German Research Foundation DFG under the international Belmont Forum/G8HORC's Freshwater Security programme (project no. STA-632/2-1) and to the EU-FP7 DROUGHT R&SPI project (contract no. 282 769) is gratefully acknowledged. We thank Lukas Gudmundsson for the provision of SPI and SPEI gridded data developed within the DROUGHT R&SPI project. We further thank the following agencies of the German federal states for supplying streamflow and groundwater level data through the Bundesanstalt für Gewässerkunde-funded project "Extremjahr 2011": Bayerisches Landesamt für Umwelt (LfU), Hessisches Landesamt für Umwelt und Geologie (HLUG), Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (LANUV), Landesamt für Umwelt und Arbeitsschutz Saarland (LUA), Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern (LUNG), Landesamt für Umwelt, Wasserwirtschaft und Gewer-

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beaufsicht Rheinland-Pfalz (LUWG), Landesanstalt für Umwelt, Gesundheit und Verbraucherschutz Brandenburg (LUGV, Regionalabteilungen Ost, Süd, West), Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), Landesbetrieb für Hochwasserschutz und Wasserwirtschaft Sachsen-Anhalt (LHW), Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein (LKNM), Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN), Ruhrverband, Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (LfULG), Staatliches Amt für Landwirtschaft und Umwelt Vorpommern (StALU-VP), Thüringer Landesamt für Umwelt und Geologie (TLUG), Landesamt für Landwirtschaft, Umwelt und ländliche Räume (LLUR), Wasser- und Schifffahrtsverwaltung des Bundes (WSV).

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Table 1. Information on selected drought events: duration and number of drought impact occurrences and onsets.

Drought event	Jun–Dec 1971	Feb–Aug 1976	Jun–Aug 1983	Mar–Aug 1992	Feb 2003–Feb 2004	Jun–Aug 2006	Jan–Dec 2011
Duration (months)*	7	7	3	6	13	3	12
nI	54	149	42	72	954	36	155
nI_h	18	82	3	18	757	12	111
nI onset	11	17	4	14	49	14	29
nI_h onset	5	11	1	4	38	6	23

* Event delineation based on impact occurrence (see Sect. 2.3).
nI = number of drought impact occurrences,
nI_h = number of hydrological drought impact occurrences,
nI onset = number of months with I onset,
nI_h onset = number of months with I_h onset.

NHESSD
2, 7583–7620, 2014

Exploring the link between drought indicators and impacts

S. Bachmair et al.

Table 2. Median of indicator distribution ($\overline{\mathrm{SPI}}$ or $\overline{\mathrm{SPEI}}$ or $\overline{Q}$ or $\overline{G}$) associated with drought impact onset per federal state. The bold values represent the indicator with highest absolute value of r between timeseries of drought indicators and I per federal state.

	Acc.	SH	MP	LS	ST	BB	BE	NW	HE	TH	SX	RP	SL	BW	BV
$\overline{\mathrm{SPI}}$	1	−1.05	−0.56	−0.9	−0.74	−0.81	−0.31	−0.92	−0.66	–	−1.06	−0.71	−0.56	−1.15	−1.16
$\overline{\mathrm{SPEI}}$	1	−1.31	−0.83	−1.07	−0.99	−1.02	−0.92	−1.39	−0.72	–	−1.19	−1.14	−1.41	−1.56	−1.45
$\overline{\mathrm{SPI}}$	2	−0.5	−0.3	−0.83	−1.14	−0.7	−0.81	−1.09	−0.64	–	−1.19	−1.06	−1.06	−1.4	−1.37
$\overline{\mathrm{SPEI}}$	2	**−0.69**	−0.58	**−0.93**	−1.32	−0.93	−1.05	−1.31	−0.9	–	−1.38	−1.55	−1.48	−1.61	−1.66
$\overline{\mathrm{SPI}}$	3	0	−0.74	−0.76	−0.93	−0.61	−0.67	−0.85	−0.79	–	−1.75	−1.19	−1.3	−1.32	−1.33
$\overline{\mathrm{SPEI}}$	3	−0.1	−1.15	−0.94	**−1.27**	−0.97	−0.81	**−1.15**	−0.82	–	−1.69	**−1.53**	−1.8	**−1.5**	−1.65
$\overline{\mathrm{SPI}}$	4	−0.07	−0.56	−0.69	−0.46	−0.52	−0.69	−0.79	−0.9	–	−0.85	−1.01	−1.16	−1.55	−1.54
$\overline{\mathrm{SPEI}}$	4	−0.51	−0.81	−1.01	−0.87	−0.79	−0.95	−0.96	−1.09	–	**−1.22**	−1.39	**−1.75**	−1.61	**−1.7**
$\overline{\mathrm{SPI}}$	5	−0.45	−0.1	−0.79	−0.49	−0.22	−0.53	−0.85	−1.13	–	−0.63	−1.12	−1.41	−1.24	−1.09
$\overline{\mathrm{SPEI}}$	5	−0.77	−0.26	−0.85	−0.79	−0.58	−0.76	−0.89	−1.14	–	−1.03	−1.27	−1.79	−1.27	−1.23
$\overline{\mathrm{SPI}}$	6	−0.6	−0.29	−0.74	−0.33	−0.08	−0.64	−0.71	−1.33	–	−0.46	−0.93	−1.73	−1.21	−0.97
$\overline{\mathrm{SPEI}}$	6	−0.99	−0.44	−0.94	−0.55	−0.59	−0.94	−0.94	**−1.3**	–	−0.75	−1.04	−1.8	−1.39	−1.08
$\overline{\mathrm{SPI}}$	7	−0.64	−0.1	−0.89	−0.4	−0.14	−0.69	−0.99	−1.08	–	−0.29	−1.1	−1.23	−1.35	−1.05
$\overline{\mathrm{SPEI}}$	7	−0.81	−0.25	−1.02	−0.74	−0.45	−0.82	−1.14	−1.27	–	−0.43	−1.35	−1.45	−1.52	−1.23
$\overline{\mathrm{SPI}}$	8	−0.82	−0.18	−0.74	−0.21	−0.22	−0.6	−1.03	−0.91	–	−0.3	−1.11	−1.1	−1.14	−0.85
$\overline{\mathrm{SPEI}}$	8	−0.94	**−0.37**	−0.9	−0.67	−0.53	**−0.93**	−1.14	−1.19	–	−0.72	−1.25	−1.31	−1.41	−1.04
$\overline{\mathrm{SPI}}$	12	−0.59	−0.2	−0.38	−0.08	−0.21	0.08	−0.44	−0.64	–	−0.03	−0.43	−0.4	−0.73	−0.2
$\overline{\mathrm{SPEI}}$	12	−0.79	−0.24	−0.47	−0.49	**−0.5**	−0.37	−1	−0.8	–	−0.2	−0.99	−0.94	−0.97	−0.18
$\overline{\mathrm{SPI}}$	24	0.24	0.06	−0.48	0.11	0.05	0.23	−0.26	−0.35	–	0.6	−0.43	0.13	−0.47	0.42
$\overline{\mathrm{SPEI}}$	24	0.18	0.12	−0.37	0.15	0.07	0.05	−0.56	−0.46	–	0.46	−0.62	−0.21	−0.35	0.5
$\overline{Q}$		–	–	0.23	–	0.13	–	0.16	0.31	–	–	0.14	–	0.15	0.16
$\overline{G}$		–	–	0.3	–	0.34	–	0.38	0.42	–	–	0.42	–	0.32	0.37
nI onset		7	9	18	10	14	7	16	14	3	10	17	5	18	14
nI_h onset		4	2	9	3	5	2	14	10	0	4	14	3	17	12

Acc. = Accumulation period of SPI or SPEI (months).

nI or I_h onset = number of months with drought impact onset or with hydrological drought impact onset; $\overline{\mathrm{SPI}}$ and $\overline{\mathrm{SPEI}}$ distributions are based on I onset; $\overline{Q}$ and $\overline{G}$ distributions are based on I_h onset; no data if $n < 5$.

Table 3. Median of indicator distribution ($\overline{\mathrm{SPI}}$ or $\overline{\mathrm{SPEI}}$ or $\overline{Q}$ or $\overline{G}$) associated with drought impact onset per drought event. The bold values represent the indicator with highest r between spatial patterns of drought indicators and I per drought event.

	Acc.	1971	1976	1983	1992	2003	2006	2011
$\overline{\mathrm{SPI}}$	1	0.99	−1.53	–	−0.75	−0.64	−1.07	−0.91
$\overline{\mathrm{SPEI}}$	1	1.05	−1.47	–	−0.93	**−1.08**	−1.36	−1.23
$\overline{\mathrm{SPI}}$	2	**0.86**	−1.69	–	−1.17	−0.93	−0.81	−1.52
$\overline{\mathrm{SPEI}}$	2	0.81	−1.58	–	−1.25	−1.29	**−1.03**	−1.71
$\overline{\mathrm{SPI}}$	3	0.43	−1.88	–	−0.61	−1.01	−0.6	−1.32
$\overline{\mathrm{SPEI}}$	3	0.42	−1.7	–	**−0.97**	−1.32	−0.86	−1.58
$\overline{\mathrm{SPI}}$	4	0.04	−2.34	–	−0.41	−1.07	−0.25	−1.15
$\overline{\mathrm{SPEI}}$	4	0.1	−1.96	–	−0.91	−1.43	−0.67	−1.45
$\overline{\mathrm{SPI}}$	5	−0.19	−2.48	–	−0.45	−1.28	−0.01	−0.84
$\overline{\mathrm{SPEI}}$	5	−0.12	−1.92	–	−0.82	−1.61	−0.35	−1.01
$\overline{\mathrm{SPI}}$	6	−0.53	−1.35	–	−0.22	−1.41	−0.46	−0.85
$\overline{\mathrm{SPEI}}$	6	−0.42	−1.41	–	−0.62	−1.67	−0.6	−1.06
$\overline{\mathrm{SPI}}$	7	−0.56	−1.45	–	−0.1	−1.31	−0.5	−1.03
$\overline{\mathrm{SPEI}}$	7	−0.47	**−1.49**	–	−0.59	−1.64	−0.63	−1.28
$\overline{\mathrm{SPI}}$	8	−0.61	−1.61	–	−0.22	−1.02	−0.77	−1.02
$\overline{\mathrm{SPEI}}$	8	−0.53	−1.68	–	−0.58	−1.42	−0.94	**−1.3**
$\overline{\mathrm{SPI}}$	12	−0.45	−1.48	–	−0.68	0.07	−0.42	−0.43
$\overline{\mathrm{SPEI}}$	12	−0.37	−1.55	–	−1.02	−0.36	−0.56	−0.79
$\overline{\mathrm{SPI}}$	24	−0.49	−0.56	–	−0.86	0.92	−0.27	−0.54
$\overline{\mathrm{SPEI}}$	24	−0.54	−0.44	–	−0.88	0.63	−0.6	−0.84
$\overline{Q}$		0.14	0.16	–	–	0.17	0.22	0.15
$\overline{G}$		0.35	0.2	–	–	0.41	0.33	0.38

Acc. = Accumulation period of SPI or SPEI (months).
$\overline{\mathrm{SPI}}$ and $\overline{\mathrm{SPEI}}$ distributions are based on I onset, while $\overline{Q}$ and $\overline{G}$ distributions are based on I_h onset; no data if $n < 5$. For number of I and I_h onsets per event see Table 1.

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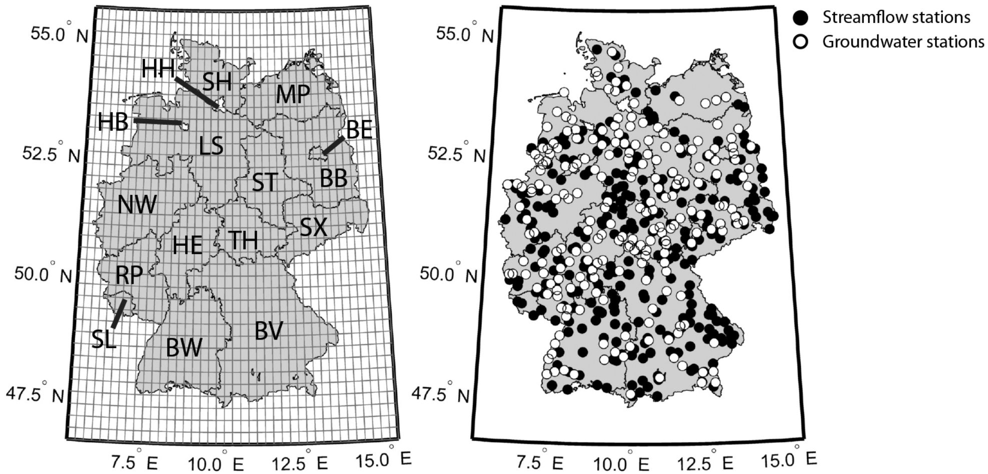

Figure 1. Overview on study area and data. Left map: federal states of Germany overlain by raster displaying SPI or SPEI resolution (0.25°). The city states HB and HH (displayed in white) are not considered in the analysis due to very little impact data. Right map: distribution of streamflow and groundwater monitoring stations.

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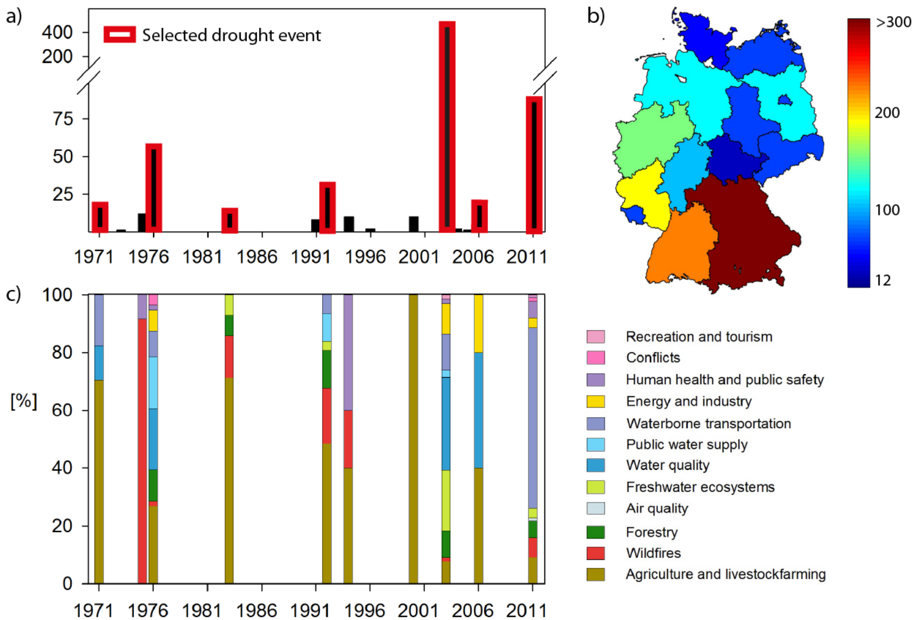

Figure 2. (a) Number of drought impact onsets in Germany per year. The bars outlined in red represent the drought events selected for analysis. **(b)** Spatial distribution of number of drought impact occurrences. **(c)** Distribution of impacts by impact category.

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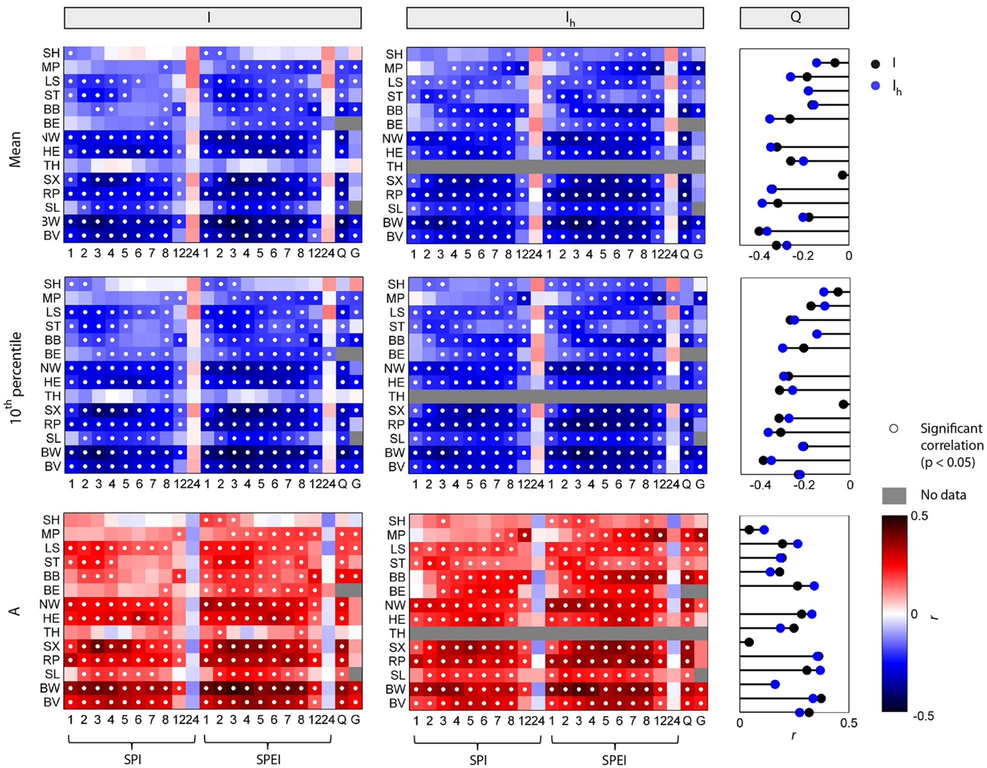

Figure 3. Rank correlation coefficients (r) between timeseries of drought indicators (SPI or SPEI or streamflow (Q) or groundwater level (G) percentiles) and drought impact occurrences (I or I_h) per federal state sorted by approximate geographical location (NW to SE). Mean, 10th percentile, and A (percent area in drought) represent different indicator metrics. The right panel highlights the difference in r between I and I_h for streamflow percentiles.

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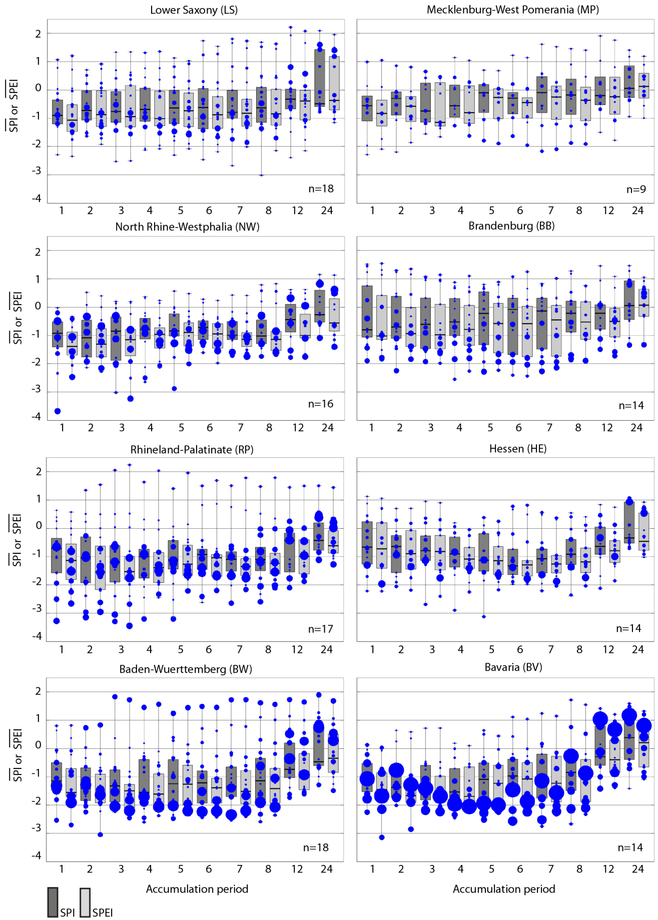

Figure 4. Distribution of $\overline{\text{SPI}}$ or $\overline{\text{SPEI}}$ associated with *I* onset in eight selected federal states; *n* = number of months with *I* onset. The size of data points corresponds to the number of *I* onsets per month.

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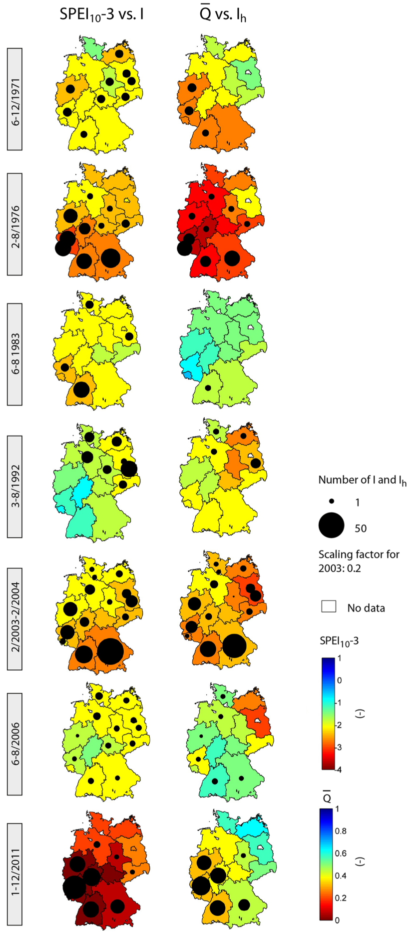

Figure 5. Thematic maps showing selected drought indicators ($SPEI_{10}$-3 and $\overline{Q}$) vs. number of drought impact occurrences (I and I_h) per federal state and drought event.

NHESSD
2, 7583–7620, 2014

Exploring the link between drought indicators and impacts

S. Bachmair et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

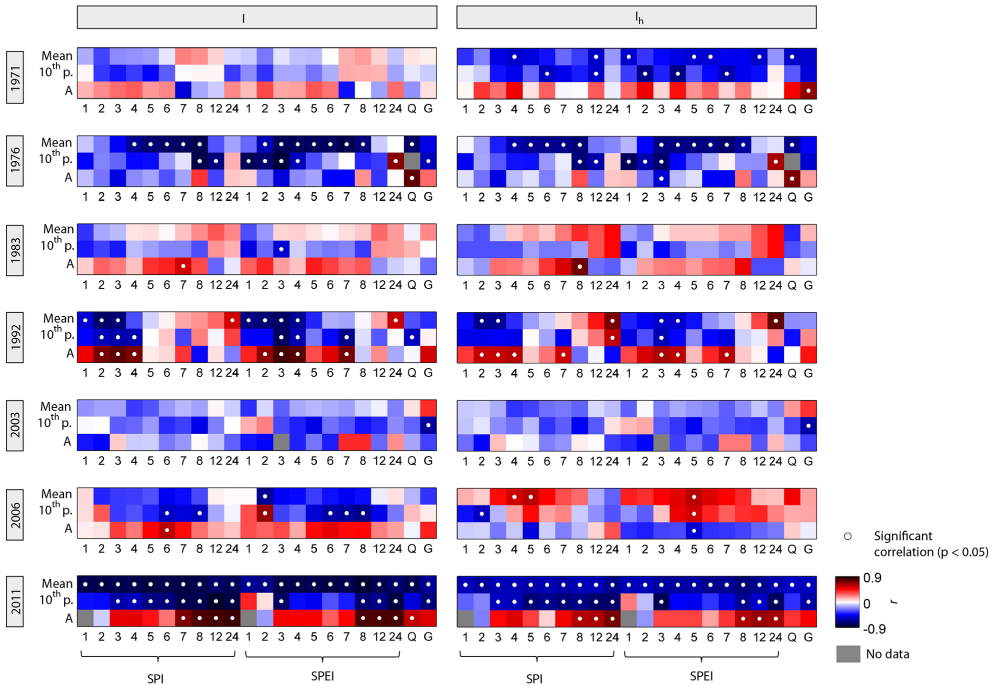

Figure 6. Rank correlation coefficients (r) between spatial patterns of drought indicators (SPI or SPEI or streamflow (Q) or groundwater level (G) percentiles) and drought impact occurrences (I or I_h) per drought event. Mean, 10th percentile, and A (percent area in drought) represent different indicator metrics.

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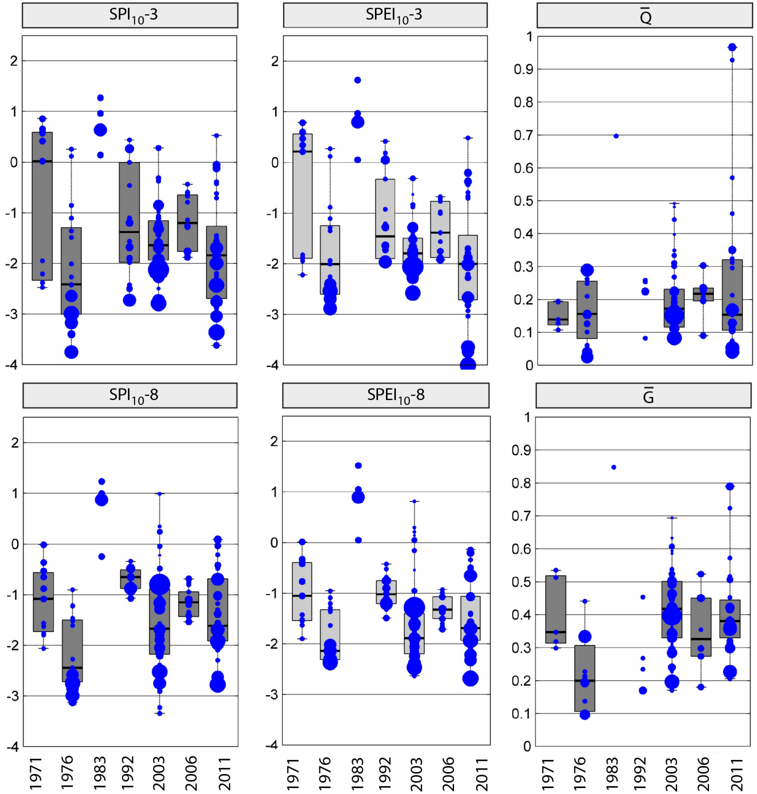

Figure 7. Distribution of selected drought indicators associated with I or I_h onset per drought event. The size of data points corresponds to the number of drought impact onsets per month.

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