ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Flash droughts and their impacts—using newspaper articles to assess the perceived consequences of rapidly emerging droughts

To cite this article: Pedro Henrique Lima Alencar *et al* 2024 *Environ. Res. Lett.* **19** 074048

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
4 March 2024

REVISED
5 June 2024

ACCEPTED FOR PUBLICATION
17 June 2024

PUBLISHED
25 June 2024

LETTER

Flash droughts and their impacts—using newspaper articles to assess the perceived consequences of rapidly emerging droughts

Pedro Henrique Lima Alencar[1], Jan Sodoge[2], Eva Nora Paton[1] and Mariana Madruga de Brito[2,*]

[1] Technical University Berlin, Institut of Ecology, Ernst-Reuter-Platz 1, 10587 Berlin, Germany
[2] Helmholtz Centre for Environmental Research, Department of Urban and Environmental Sociology,Permoserstr. 15, 04318 Leipzig, Germany
[*] Author to whom any correspondence should be addressed.

E-mail: mariana.brito@ufz.de

Keywords: digital trace data, time series, validation, trend analysis, correlation analysis, flash drought

Supplementary material for this article is available online

Abstract

Flash droughts (FDs) have attracted increasing attention in the past decade. They are characterised by a rapid depletion of soil moisture resulting from interactions between the soil and atmospheric conditions. To date, there is a lack of consistent FD definitions and an understanding of their socio-economic impacts. Here, we explore the relationship between biophysical FD conditions and the perceived impacts of FDs in Germany between 2000 and 2022. We measured perceived impacts by analysing consequences reported in newspaper articles (2000–2022) and online search behaviour using Google trends data (2004–2022). To characterise the physical process, we considered root zone soil moisture data. Our results show that FDs are becoming increasingly frequent in Germany, occurring once every two years on average. Despite the lack of knowledge from the general public regarding the phenomenon of FDs, the peaks of interest in drought impacts correspond to the physical occurrence of FDs across the country. We identified an average time gap of four weeks between FD onset and the reporting of perceived impacts. This gap is longer than the average duration of FDs' onset. Consequently, our findings highlight that consistent monitoring of FD conditions and drivers is necessary to guarantee effective preparedness. As impact perception is too slow to allow the adoption of mitigation measures, FDs require new schemes for response measures compared with slowly emerging (conventional) drought events. The novel method also allows the consistent and impact-based validation of FD identification methods.

1. Introduction

Recently, the scientific community has shown an increased interest in studying flash droughts (FDs). In particular, the 2012 FD that started in late May and by July affected over 75% of croplands in the USA Midwest. This disastrous event devastated central areas in the USA and produced increased attention from scholars on a term that was rarely used before (Basara *et al* 2019, Lisonbee *et al* 2021). The 2012 USA FD led to over US$30 billion in losses across the country because the rapid change from wet-to-dry soil moisture hindered timely prevention and mitigation (Christian *et al* 2019). The 2012 FD made the public aware of a new threat to the water-food nexus posed by rapid onset drought conditions (Pendergrass *et al* 2020), which is expected to occur more frequently worldwide under climate change (Yuan *et al* 2023).

FDs are a particular type of drought characterised by the rapid onset, in contrast to the slow-evolving attribute of conventional droughts. Multiple methods to define and identify FD have been proposed in the academic literature (Alencar *et al* 2022). An initial debate focused on whether FDs were short-lived droughts (Mo and Lettenmaier 2016), or intense evolving droughts (Ford and Lobosier 2017). The current consensus supports the latter (Christian *et al* 2024). A leading understanding describes FDs as emerging rapidly by transitioning from average to high soil moisture to dry conditions (Yuan *et al* 2023). However, seminal questions remain concerning what should be considered an FD. Although clear thresholds have been proposed (Christian *et al* 2019, Li *et al* 2020, Osman *et al* 2021, Yuan *et al* 2023), their transferability across case studies is limited (Alencar *et al* 2022). The lack of well-established criteria has led to a growing diversity of definitions and monitoring tools for FDs. However, these definitions and tools still lack validation and transferability (Lisonbee *et al* 2021, Alencar *et al* 2022). Hence, FD research would benefit from studies applying multiscale and multivariable frameworks (Liang and Yuan 2021).

Here, we propose a different perspective for FD identification. Similar to their slower counterparts (i.e. longer and slow-evolving droughts; henceforth referred to as *conventional droughts*), FDs affect multiple sectors of society, such as agriculture, animal husbandry, energy and water supply, and social activities (Christian *et al* 2020, Walker *et al* 2024). Although various existing FD indices are centred on hazards (Alencar *et al* 2022), they may not consistently translate into socioeconomic impacts. Therefore, the conditions leading to impactful FDs are still uncertain. Here, we suggest that understanding society's perception of the impacts of FDs can assist in diminishing these uncertainties.

We present a novel approach to studying FDs by considering the link between the biophysical occurrence of FDs and their perceived impacts. We assess the impacts based on impacts reported in newspaper articles and the internet search behaviour of local populations which represent two popular approaches for measuring local drought awareness.

Newspapers often serve as real-time recorders of societal responses and reactions to extreme weather events (e.g. Sodoge *et al* 2024, Bogdanovich *et al* 2024), offering a unique perspective on the social impacts of FDs. Similarly, internet searches can approximate public awareness of a specific topic (Kam *et al* 2019, Kim and Kim 2023). This approach can help researchers gain a more comprehensive understanding of the socio-economic implications of FDs, enhancing their ability to develop effective strategies for preparedness, mitigation, and adaptation.

To test whether digital trace data (e.g. news articles and Google searches) can support the identification of FD occurrence, we considered the case of Germany from 2000 to 2022. Germany was chosen as a case study because of its recent history of major conventional droughts (2003, 2015, and 2018–2022) that had widespread impacts on sectors such as agriculture, forestry, livestock, and waterways navigation, which have gained public attention (Tijdeman and Menzel 2021, Rakovec *et al* 2022, Sodoge *et al* 2024). We obtained daily time series for biophysical FD occurrence, reported impacts in newspapers, and online search behaviour on a district level in Germany. Thus, we investigate three hypotheses:

- H1 – FD is a common phenomenon in Germany, and its occurrence has increased over the last few decades.
- H2 – Impacts reported in the media and searched by internet users are a source of information for risk assessment that can be used to identify when FDs impact society
- H3 – There is a delay between FD onset and impact reporting due to latency time for water/plant/soil/society response to drier conditions.

2. Data and methods

Our research design comprises multiple steps that involve three distinct datasets: soil moisture, online search behaviour measured using Google trends, and reported drought impacts in newspaper articles (figure 1). For each, we obtained daily time series on a district-level using the statistical regions of Germany defined by the Nomenclature of Territorial Units for Statistics (NUTS) levels 1, 2, and 3. We used the most fine-grained NUTS level available for each dataset for the main analysis and provided the results for all NUTS levels in the supplementary material. To explore the relationship between hazard and impact-related indicators, we employed time-series cross-correlation analysis. The following sections provide a detailed description of each step in the research design.

2.1. Soil moisture data and FD identification

For identifying FDs, we used the method suggested by Ford and Labosier (2017) which is based on root-zone soil moisture and was successfully applied in multiple case studies (Otkin *et al* 2018, Lesinger and Tian 2022). This method was chosen due to its use of soil moisture in shallow compartments, which has been pointed as the most important variable for FD occurrence and that best relates to impacts (Lisonbee *et al* 2021, Alencar *et al* 2022, Christian *et al* 2024). For soil moisture, we used data for Germany from Boeing *et al* (2022) which covers 1980–2022 and has daily soil moisture at different soil depths (0-25, 25-60 and 60-200 cm) and a 4 km spatial resolution. The data was generated through the mesoscale hydrological model (mHM—Samaniego *et al* (2017)) and demonstrated a robust correlation ($\rho > 0.7$; p-value < 0.05) with observed soil moisture by the German network of terrestrial environmental observatories at (TERENO—Bogena *et al* (2022)) and FluxNET (Pastorello *et al* 2020) stations across Germany. The optimal performance of the soil moisture model was observed from April to November, corresponding to the primary FD season in Central Europe (Alencar *et al* 2022, Boeing *et al* 2022). We focused on the soil moisture data at 40 cm depth and accumulated soil moisture values at five-day intervals (*pentads*), as described by Ford and Lobosier (2017). A FD was considered to occur

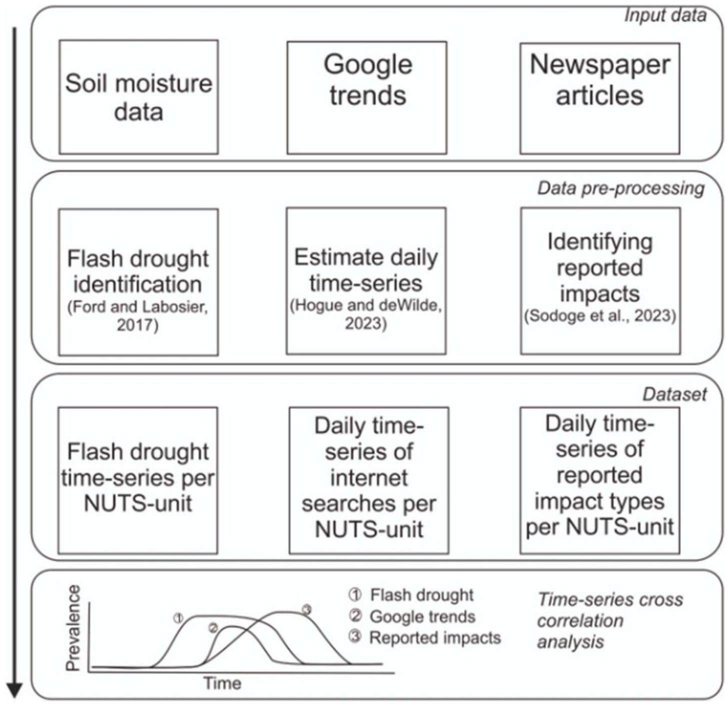

Figure 1. Overview of the research design: based on the three datasets for soil moisture, reported drought impacts, and online search behaviour, daily time series are obtained on a district level in Germany. Cross-correlation analysis is then employed to analyse the relationship between hazard indicators and consequent impacts.

if (1) the soil moisture dropped from at or above the 40th percentile to at or below the 20th percentile within four pentads, (2) the soil moisture remained below the 30th percentile for at least three pentads after the onset to avoid classifying very short events, and (3) the event ended after soil moisture reached the 40th percentile. Percentiles were computed based on a grouping of pentad-years, wherein each pentad (1 to 73) was juxtaposed with its corresponding *i*th pentad for each year within the 1980–2022 period. This means that the percentile distributions were calculated separately for each pentad across all years in the dataset. For instance, all data points corresponding to the 1st pentad of each year were used to compute the percentile distribution for the 1st pentads, all data points for the 2nd pentad were used to compute the percentile distribution for the 2nd pentads, and this process was repeated for all 73 pentads. These criteria were computed using the detailed soil moisture dataset by Boeing *et al* (2022) and the method of Ford and Lobosier (2017) implemented in the R-package *fdClassify* (Alencar *et al* 2022). Criterion 1 defines the intensification phase, which ends at the FD onset. Criterion 2 defines a minimum persistence after onset to avoid overidentification of events (Pendergrass *et al* 2020), and criterion 3 establishes the end of the event, indicating a return to normal conditions.

Although the spatial resolution of the FD dataset corresponded to 4 km, we aggregated the occurrences at NUTS-1, NUTS-2, and NUTS-3 levels. For each NUTS level, the percentage of the area under FD conditions was computed at each pentad. At the NUTS-1 level, the three German city-states (Berlin, Bremen, and Hamburg) joined the surrounding states (Brandenburg, Niedersachsen, and Schleswig–Holstein, respectively) because of their relatively small size compared to the other states.

2.1.1. Trend analysis

To explore the temporal patterns in the occurrence of FDs in Germany (H1), we assessed the trends in their intensity, duration, and frequency from 1980–2022. Here, we define FD intensity as the mean drop in soil moisture percentiles over the intensification phase, measured in percentile.day^{-1}. Duration refers to the period from the start of intensification until the return to normal conditions. Frequency is considered as the expected number of years with an occurrence of at least one FD, ranging from 0–1.

We used the regional Mann–Kendall test to perform this trend analysis and to compute and identify possible changes in FD intensity, duration, and frequency (Mann 1945, Helsel *et al* 2020). This test evaluates the monotonic trend in the time series data to identify the significance of increasing or decreasing trends. We used the data on identified FDs (section 2.1) at the NUTS-2 level to assess whether the frequency, duration, and intensity of FDs in Germany increased considerably during the study period (H1). Furthermore, we computed the regional Theil-Sen estimator (Sen 1968, Theil 1992) to estimate the slope of these trends (i.e. the trend direction and magnitude). The Theil-Sen estimator, known for its robustness in assessing rates of changes in time-series, is less sensitive to outliers, and does not rely on assumptions regarding the distribution of data and residuals (Wang and Yu 2005). It is computed as the median of the slope of all lines that connect all pairs of points in the data series (Helsel *et al* 2020).

2.2. Digital trace data on perceived impacts and public awareness

2.2.1. Socio-economic impact data

To assess the perceived impacts of FDs on different socio-economic sectors, we used information on reported socio-economic impacts in newspaper articles. Specifically, we used the approach and data by Sodoge *et al* (2024), which consider the frequency of newspaper articles reporting on a specific drought impact using text-mining approach as follows. We examined approximately 50 000 newspaper articles that included terms related to conventional drought (e.g. Dürre* and Trockenheit in German). These were published between 2000 and 2022 in 250 national, regional, and local German newspaper outlets included in the genios.de newspaper aggregator database. Articles were automatically reviewed using text-mining techniques to detect reported impacts in each article and its geographic scope using NUTS levels 1, 2, and 3. First, duplicate articles were automatically removed by considering the Jaccard similarity score (Mullen 2020). To this end, a threshold of 95% was defined, where 100% indicates full similarity. We then categorized the types of impacts using lasso logistic regression models. These models were trained and assessed using a set of 1800 manually annotated newspaper articles (Madruga de Brito *et al* 2020). Hyperparameter tuning was conducted using cross-validation within the training sample. A median accuracy of 89% was obtained for these models compared to the manually annotated data. The following impact types were covered: agriculture (crop yield losses), energy (impacts on reduced energy production in nuclear power plants), fire (forest wildfires or fires in other areas due to drought conditions), livestock (impacts on livestock farming and animal populations), and social (impacts on places and activities used for recreation, tourism, and leisure). To locate impact areas, we identified the cities, regions, and districts mentioned in each article using named-entity recognition. We then selected the regional cluster with the highest frequency of detected locations. A previous study by Sodoge *et al* (2024) provides a detailed description of this procedure, including extensive validation with external indicators and observed impacts such as crop yield losses, forest fire statistics, and precipitation deficit.

The resulting dataset contains daily time-series data for each NUTS unit (levels 1,2, and 3) of the number of reported impacts. We further aggregated the time series into pentads to compare the data with the FD measurement. At the NUTS-1 level, the three German city-states (Berlin, Bremen, and Hamburg) joined the surrounding states (Brandenburg, Niedersachsen, and Schleswig–Holstein, respectively) because of their small size compared to the other states.

2.2.2. Public awareness data

To determine public awareness of FDs, we collected information on spatio-temporal patterns of internet search frequency for the topic 'drought' using Google trends data. This service provides an index of how many Google users on a particular day and region search for a specific term, where a higher value (maximum 100) corresponds to the maximum interest for a term. Previous studies have shown the capabilities of Google trends data to monitor the awareness of droughts from a spatio-temporal perspective (Kam *et al* 2019). However, Google does not reveal details and changes in the underlying algorithms. We extracted the daily time series for 2004–2022 for each NUTS-1 (only scale available) unit using the PyTrends Python package (Hogue and DeWilde 2023). We then aggregated the time series into pentads to compare the different datasets in subsequent analyses.

2.3. Correlation analysis

To identify whether the reported impacts in the news media and internet search behaviour were influenced by the occurrence of FDs (H2), we performed a cross-correlation analysis between the datasets. This allowed us to assess the temporal delays between the occurrence of FDs and impact perception (H3). Specifically, we employed cross-correlation functions (CCF—Shumway and Stoffer 2019) that can identify delays between two variables, offering insights into whether one variable can predict the other. In this study, these delays represent the asynchronous behaviours expected between the peaks of FD onset and impact reporting (hypothesis H3). CCFs are commonly used to assess the similarity between two series (waveforms) as a function of their relative delay (equation 1)

$$\rho_{xy}\left(i,j\right) = \frac{\gamma_{xy}\left(i,j\right)}{\sqrt{\sigma_x\left(i,i\right)\sigma_y\left(j,j\right)}} \tag{1}$$

where x and y are time series, γ is the co-variance between x and y, ρ_x and ρ_y are the standard deviations of x and y, respectively, and i and j are time indexes. It is important to notice that i and j are related, being $j = i + h$, where h is the delay between the time series. Using equation (1), we can identify the delay between both time series x and y (e.g. FD onset and impact reporting) as being the h that maximizes $\rho_{x,y}(i, i + h)$.

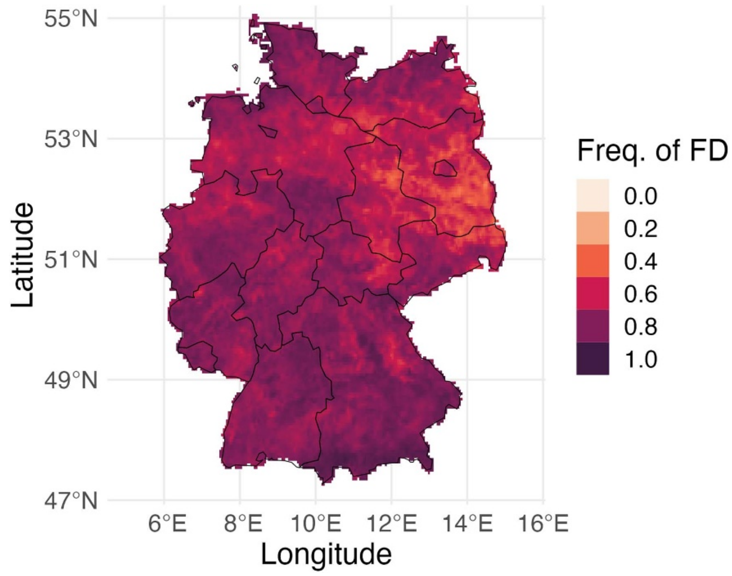

Figure 2. Ratio of years with FD occurrence in Germany from 1980–2022. Events were identified using the Ford and Lobosier (2017) approach, which is based on soil moisture percentile changes at a depth of 40 cm. Soil moisture was assessed using the Helmholtz Centre for Environmental Research (UFZ) drought monitor dataset (Boeing *et al* 2022). The soil moisture data is generated through the mesoscale hydrological model (mHM—Samaniego *et al* 2017) and validated with TERENO and FLUXNET stations (Pastorello *et al* 2020, Bogena *et al* 2022) at a resolution of 4 kilometers.

3. Results

H1–FD is a frequent and intensifying phenomenon in Germany

Using a high-resolution soil moisture dataset (Boeing *et al* 2022) and the method described by Ford and Lobosier (2017), we assessed the occurrence of FDs in Germany from 1980–2022 (see figure 2). The results showed that FDs are a frequent phenomenon in Germany, with an average frequency of one event every 1.5 years. Particularly, the southern and southwestern regions experience the highest frequency of events, with FDs occurring almost every year (frequency of approximately 0.87). Conversely, the northeast, including the federal states of Saxony–Anhalt, Brandenburg, and Berlin, has a lower rate of FD occurrence. Here, FDs occurred in approximately 55% of the analysed years.

Temporal trend analysis revealed that FDs have increased in frequency and affected areas over the last few decades (see figure 3). From 1980–2022, Germany experienced FD events every year, at least in parts of its territory, with the minimum values of affected areas ranging from 10% (e.g. 1987 and 2002) to a notable maximum of approximately 99% (in 2020). The affected area has consistently increased at a rate >9% per decade. Hence, the average annual affected area by FDs in Germany increased from approximately 40% at the beginning of the 1980 s to approximately 80% in the 2020 s. In particular, 2007, 2012, 2020, and 2022 had major FD occurrences in Germany.

Using the regional Mann–Kendall test, we assessed the spatial distribution of trends in FD intensity, duration, and frequency (figure 4). Only positive trends were identified across the NUTS-2 regions in Germany for all three variables. Furthermore, most trends were statistically significant, as indicated by the hatched areas. These findings indicate that FD is not only a frequent phenomenon (occurring almost yearly in some regions) in Germany (H1), but also an intensifying one. Figure 4(a) shows that FDs intensified across southern Germany, with rates increasing up to 1 percentile.day^{-1}.decade^{-1}. Meanwhile, figure 4(b) illustrates changes in the duration of FDs, showing particularly major trends in the southern and western regions. Here, FDs have become notably longer over the 2000 s and 2010 s, with durations increasing up to 30 days.decade^{-1}. These two results underscore the heightened hazard posed by FDs in the south and southwest of the country, where soil is rapidly drying at a faster rate and persisting for longer durations.

Figure 4(c) presents the changes in FD occurrence in terms of events per year. These events have become more frequent across all regions, with an average frequency of 5%.decade^{-1}. The region with the largest increase was Berlin (11%.decade^{-1}). In contrast to the patterns observed for the other two variables analysed, NUTS 2 regions in the south presented a slightly lower trend in FD occurrence than their northern counterparts.

H2–The blind perception of FDs

The term '*Blitzdürre*' (FD, in German) is not widespread in the news or is common knowledge in

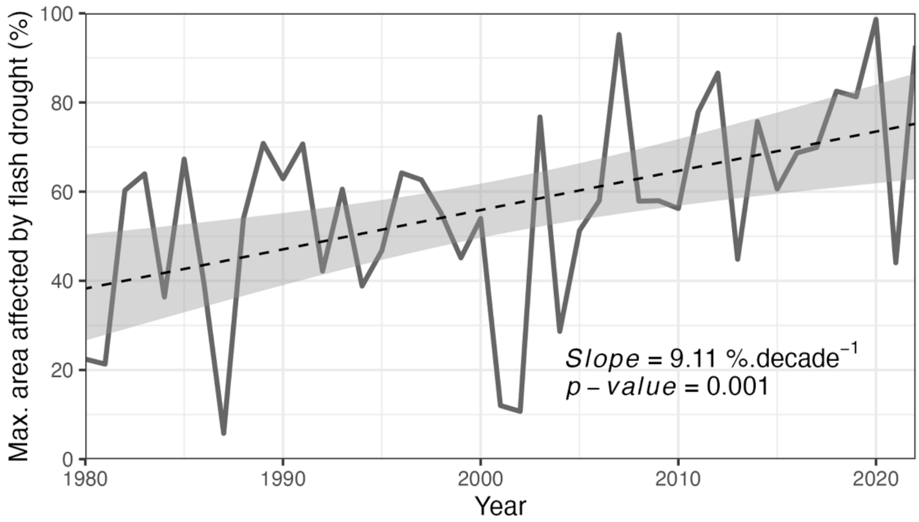

Figure 3. Annual percentage of areas affected by FDs in Germany. Using the Mann–Kendall test, we found strong evidence (p-value < 0.01) of an upward trend in the yearly affected area, with an increase of >9% per decade. Grey shaded area indicates the 95% confidence interval.

German society. In fact, of the over 260 million articles in the *genios.de* newspaper aggregator database, only 21 mentioned this term after 2023. Comparing the interest in searches using the keywords *Blitzdürre* and *Dürre* (the term for conventional drought, in German), we find that interest in FDs is, on average, 14 times lower (figure 5). During peak periods of interest in FDs in the early 2000 s, this accounted for only 16% of the searches using the keyword drought. Over the last five years, searches focusing on FDs have decreased to 0.5%. The keywords used to assess impact perception from news articles and public awareness from Google searches focused solely on *drought*-related terms because of the absence of the term *FD* in public discourse. Nevertheless, there is a common pattern of FD emergence and an increase in drought-related report impact on the media illustrated in figure 6. This consistent pattern of acknowledging FD occurence via the impact perception and their reporting as conventional droughts (i.e. *Dürre*) is what we call here as a 'blind perception'.

H3–Relationship between FD occurrence, perceived impacts, and public awareness

Comparing the time series of FD indices and reported impacts in newspapers, we found positive correlations ($r = 0.65$) and that following a rapid increase in areas affected by FD, there is a wave of impact reporting. Using CCF, we assess time lags between the occurrence of FDs and the reporting of their impacts on the news media (figure 7(a)).

The results for Germany as a whole show a uniform baseline awareness of droughts (see the blue line in figure 7(a)). We interpret this as reflecting the cultural and social perceptions of droughts, encompassing the expectation of future events and the recollection of past events. The baseline value was derived from the CCF computation, where the horizontal axis can be arbitrarily long in the positive and negative directions. To assess the media's baseline awareness of drought impacts, we used CCF values for long delays (above 15 weeks, a period longer than usual FDs) and negative delays under two weeks (to exclude potential forecast reports). The concept of negative delay results from the mathematical nature of CCF, which allows the identification of synchronicity independent of causality.

When examining the relationship between media-reported impacts and FD occurrences, we found that there was a consistent delay of four weeks before the impacts peaked. This suggests persistence of interest and reported impacts long after the onset of FDs. The four-week delay can be interpreted as the average time between FD onset and the perception and reporting of socioeconomic impacts. However, there were spatial differences between the changes in impact reporting under FD occurrence. In NUTS-2 and NUTS-3 regions, there was a notably higher frequency of impact reporting within the first two weeks compared to the NUTS-1 region (supplementary material). This highlights the effectiveness of localized news sources in monitoring and reporting the local conditions and impacts of droughts and FDs.

Comparing FD occurrence and online search behaviour data from Google Trends, we found similar correlations ($r = 0.61$) and trends in public awareness in response to the occurrence of FDs (see figure 7(b)). Overall, the value of the baseline awareness aligns

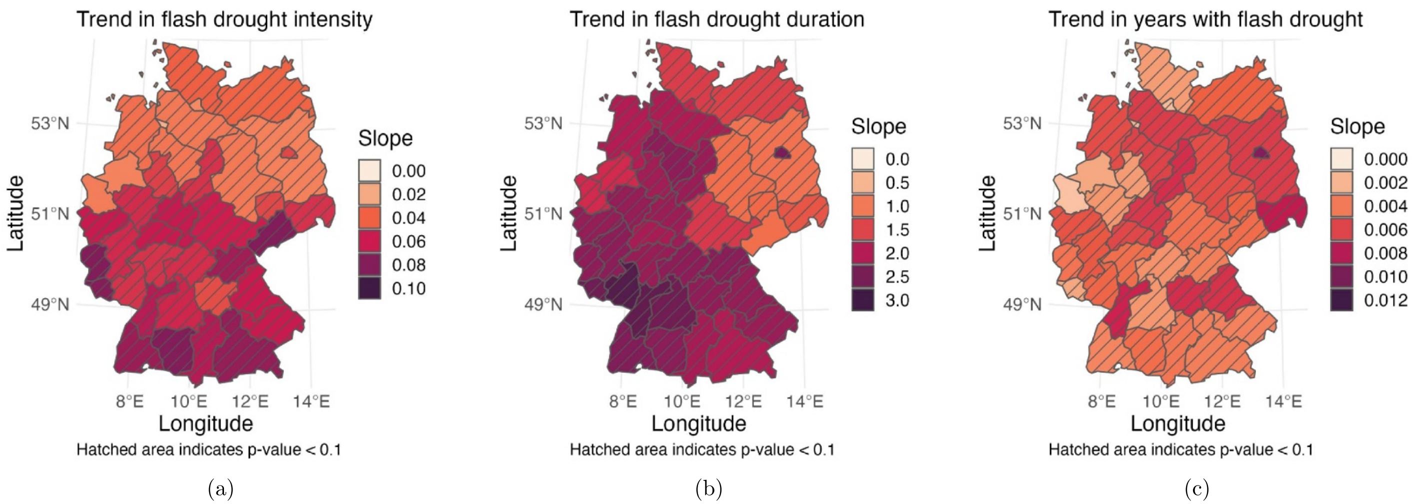

Figure 4. Regional Kendall tests to assess trends in (a): intensity (drop in soil moisture percentiles per day during the onset phase), (b): duration (total event duration in days), and (c): frequency (years with events) of occurrence of FDs in Germany at NUTS-2 level from 1980–2022. Most regions presented statistically significant trends for all variables.

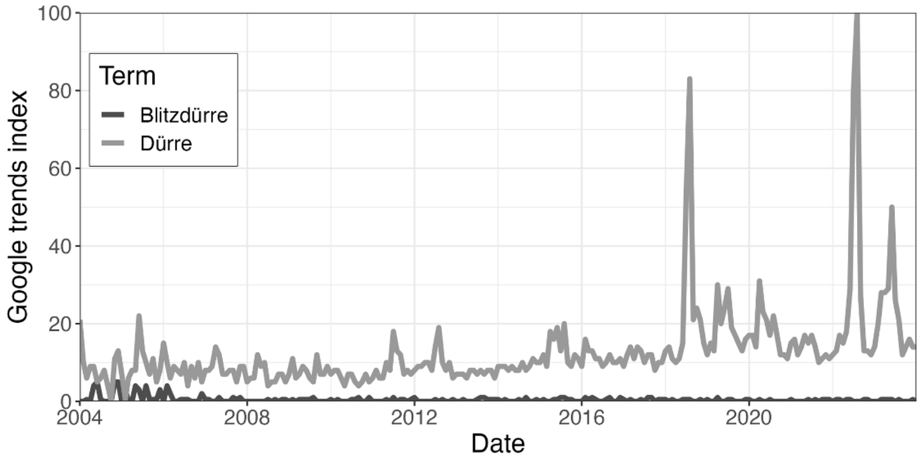

Figure 5. Comparison of searches on Google for the terms 'Dürre' (*Drought*—light grey) and 'Blitzdürre' (*Flash drought*—dark grey) in Germany, from 2004 to 2023. Searches in Google Trends are reported as a percentage of the maximum observed in the monitored period.

with our previous observation (figure 7(a)). However, the peak delay was shorter (three weeks) compared to the response of reported impacts in newspaper articles (four weeks). This shorter timeframe indicates that the general community engaging in online searches has a quicker perception of the impacts of FDs. One possible explanation for this is the time required between perception and reporting of the news, as there is an intrinsic interval necessary to collect, verify, and write news compared to online search behaviour.

4. Discussion

FDs are becoming increasingly frequent under climate change, and require different adaptation schemes owing to their rapid emergence (Yuan *et al* 2023, Christian *et al* 2024). In this regard, we investigated the occurrence of FDs in Germany, as well as societal awareness (Kam *et al* 2019) and perceived impacts (Sodoge *et al* 2024). Using these digital trace data, our study shows the delayed response of social perception to FDs as reported in the media and according to online search behaviour. Expanding on the results of our study, we contextualize them within the structure of our hypothesis presented in the Introduction.

Hypothesis 1–FD is a common phenomenon, and its occurrence has increased over the last few decades in Germany

Our analysis revealed that FDs have become increasingly frequent in Germany, occurring once every two years on average (figure 2). Notably, they are more prevalent in the southern and western parts of the country. In contrast, northeast Germany (e.g. Berlin and Brandenburg), which has sandier soils and lower plant-available water (Kruse 2015, Gebauer *et al* 2022), exhibited faster variations in soil moisture in terms of percentiles (Alencar *et al* 2022). This characteristic leads to a lower rate of FD intensification, which may explain the lower occurrence of FDs in the region. This does not necessarily imply that regions like Brandenburg experience less rapid drying such as FDs (Shah *et al* 2022). Rather, this suggests a limitation in the method used to identify these local events (Alencar *et al* 2022). Impact-based and multivariate indices and analysis are possible solutions for overcoming the limitations of traditional methods of identifying FDs (Mukherjee and Mishra 2022, Zhang *et al* 2022, Shyrokaya *et al* 2023).

Furthermore, the trend analysis showed that in addition to being a common phenomenon, FDs are becoming more intense, longer, and more frequent across Germany, with positive trends in all three variables observed in all regions (NUTS-2). However, these trends are not uniform and can be linked to different factors. Specifically, FD intensity increased in the southern region, which is consistent with previous reports (Brunner *et al* 2023, Yuan *et al* 2023), especially in mountainous regions. The results indicated that the western and southern regions of Germany experienced an increase in the duration of FDs. These trends might be a consequence of differences in the regional climate. The western and southern regions have a temperate oceanic climate (Cfb—Köppen-Geiger classification; Beck *et al* 2018) whereas the eastern regions have a colder humid continental climate (Dfb). Moreover, east Germany has sandier soils, with lower organic matter content and plant-available water (Kruse 2015, Gebauer *et al* 2022). The city of Berlin shows large trends

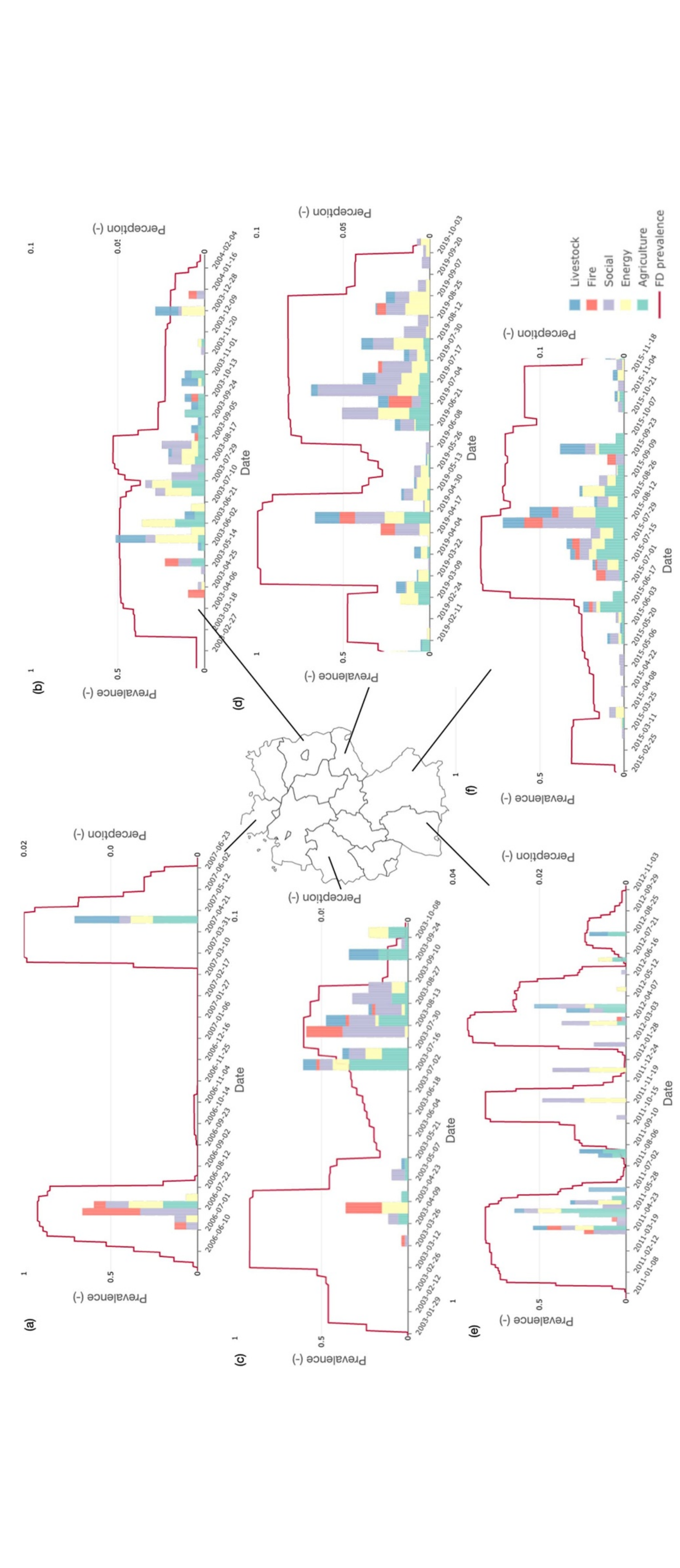

Figure 6. Examples of synchronicity between FD occurrence and impact reporting. These examples show the patterns of synchronicity at multiple locations (a) Schleswig–Holstein; (b) Brandenburg; (c) Nordrhein–Westfalen; (d) Sachsen; (e) Baden–Wüttemberg; (f) Bayern). *Prevalence* indicates the percentage of the area affected by FDs, and *Perception* is the reporting of drought-related impacts according to news articles. For more examples, visit the open application PerceptionFD, used to generate the multiple plots in this figure.

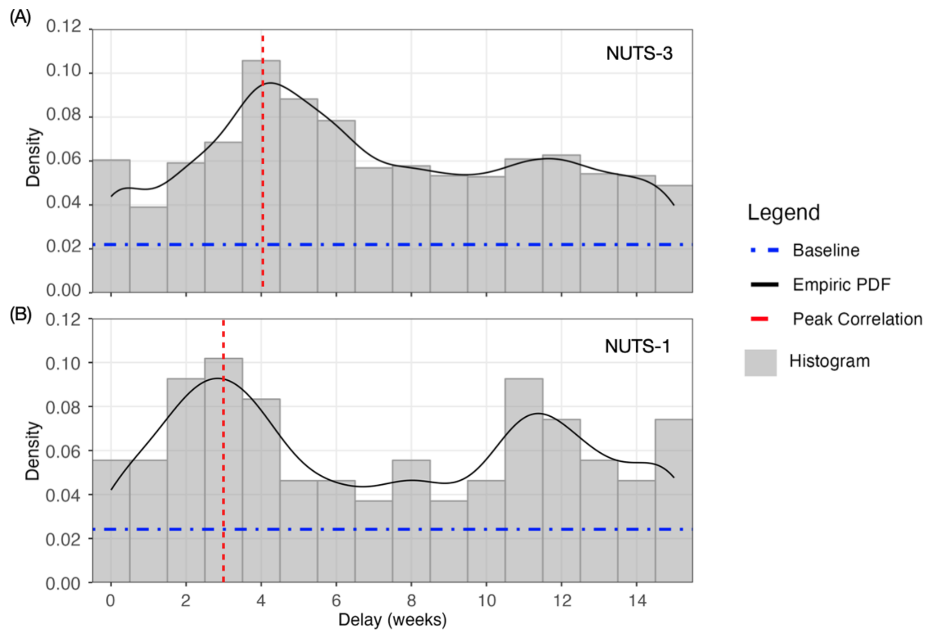

Figure 7. Results of the cross-correlation function (CCF) between A: Impact reporting in news articles and FD occurrences (NUTS-3) and B: searches on Google and FD occurrences (NUTS-1). We observe a baseline of correlation, which reflects noise and pre-existing awareness or discussions regarding drought impacts in the media. The red line indicates the peak in the delay of FDs and impact reporting. Graphs for all NUTS levels are provided in the supplementary material.

in all three variables, possibly induced by urban anthropogenic causes, such as soil sealing and water multiple water abstractions (Kuhlemann *et al* 2020), as well as land use changes upstream, particularly in Lausitz, where Lignite mining which artificially added water to the Berlin system and has progressively being reduced, with projection to complete phase-out by 2030 (Gerwin *et al* 2023). Nevertheless, the exact cause of the different trends in FD features is beyond the scope of this study, and further investigation is required.

Hypothesis 2–The impacts reported in the media and searched by internet users are a source of risk assessment that can be leveraged to identify when FDs impact society

While prior studies focused on hazard-centric indicators (Ford and Lobosier 2017, Pendergrass *et al* 2020, Noguera *et al* 2021, Ho *et al* 2023) to identify FDs, our study demonstrates the effectiveness of using digital trace data to track FDs and their societal impacts.

We found that the use of the term 'FD' is not widespread in the German public discourse. Consequently, terms associated with drought were used to evaluate impact perception and public awareness. Despite the distinct nature and drivers of droughts and FDs, they are often perceived as a single phenomenon, as evidenced by the positive cross-correlation values (figure 7). Additionally, negative correlations between event occurrence, impact perception, and public awareness may be attributed to the semantic blending of flash and conventional droughts in public discourse. This blending results from drought-related impacts that are examined for synchronicity with FD events, as well as FDs that eventually become longer (conventional) droughts (Basara *et al* 2019). Additionally, while previous studies used Google Trends and newspaper data to enhance the modeling of social awareness in response to droughts (Kam *et al* 2019, Kim and Kim 2023), this study is the first to model FDs using innovative digital trace data and relate the results to hazard events. Thus, while modeling for larger, less-fine-grained temporal resolutions of heatwaves has been shown in previous studies (Polt *et al* 2023), we highlight how shorter drought hazards, such as FDs, can be monitored for short-term responses. These results underscore the value of digital trace data in comprehending the impacts of FDs, unraveling the distinct characteristics that differentiate them from more gradually unfolding droughts.

Hypothesis 3–There is a delay between FD onset and impact reporting due to latency time for water/plant/soil/society response to drier conditions

Using high-resolution soil moisture data and digital trace data at multiple levels of spatial aggregation (NUTS1, 2, and 3), we found a correlation between FD occurrence, impact reporting ($r = 0.65$), and Google searches ($r = 0.61$). The analysis of these digital trace data revealed a consistent delay between FD occurrence and the reporting of its impacts on the media (four weeks), as well as in Google searches (three weeks). Hence, these correlations and observed delays support H3 and H2. However, these delays are too long to be actionable because they are longer than the usual onset duration for FDs (up to 20 days—Ford and Lobosier 2017, Pendergrass *et al* 2020, Lisonbee *et al* 2021). There are two consequences of this finding. First, it reinforces the necessity of early-warning and early-action systems to inform stakeholders about the occurrence of FDs (Sehgal *et al* 2021, Otkin *et al* 2022). Second, it provides a consistent metric for identifying impactful FDs that can be used to validate hazard identification methods, monitoring, and early warning systems (Alencar *et al* 2022).

Although recent studies have attempted to monitor and forecast FDs (Mukherjee and Mishra 2022, Ho *et al* 2023, Christian *et al* 2024), these efforts often fail to identify impactful events and validate their metrics and indices with observed societal consequences, leading to misidentification and misinformation (Alencar *et al* 2022). This study provides a novel technique to bridge this gap and allows the production of more reliable methods for FD identification and monitoring based on validated events. Currently, Germany does not monitor FDs, although German drought monitoring provides daily assessments of drought conditions (Zink *et al* 2016). Moreover, there is no tool in place for alert or early warning, despite the frequent occurrence of FDs and their major impact on multiple sectors, particularly agriculture.

5. Conclusions

Since 1980, we have observed an increase in the frequency and intensity of FDs. Different adaptation strategies are necessary to cope with their rapid emergence. We investigated the occurrence of FDs and their relationship to societal awareness in Germany. By analysing digital trace data on the perception of drought impacts, our study shows a delayed response of social perception to FDs in newspaper media and online searches.

We found that FD occurrence in Germany has been increasing over the past few decades, making FDs a common phenomenon. Synchronicities were observed between the reporting of drought-related impacts in the newspaper media and the incidence of FDs in Germany. However, societal awareness, measured by online search behaviour and reported impacts in newspapers, was dampened by a delay of, on average, four weeks compared to the emergence of the FD. These findings have two key implications: (1) digital trace data coupled with high-quality soil moisture data can successfully assist modelers in accurately validating designed metrics for FD identification, (2) although digital trace data serve as a rich source of information to determine when and where impactful FDs occur, it is insufficient to provide actionable information owing to delays in the publication of data. With the increasing threat posed by FDs in a changing climate, it is necessary to design information systems capable of integrating forecast assessments with potential impacts in vulnerable areas.

Data availability statements

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.11 185 331.

All code and data are available at 10.5281/zenodo.11 185 331. The interactive data exploration app in R-Shiny is also available via the GitHub repository and can be run locally. An independent and publicly hosted version is accessible at pedroalencar.shinyapps.io/Impact_perception/

The authors are members of the Einstein Research Unit 'Climate and Water under Change'. The Einstein Research Unit 'Climate and Water under Change' is funded by the Einstein Stiftung Berlin and the Berlin University Alliance

Acknowledgment

This research was funded through the Einstein Research Unit 'Climate and Water under Change' from the Einstein Foundation Berlin and Berlin University Alliance (ERU-2020-609).

Conflict of interest

The authors have no conflict of interests

Authors' contributions

PHLA contributed with conceptualization, data acquisition, processing, and analysis, script and manuscript writing. J S contributed with data acquisition, processing, and analysis, and manuscript writing. ENP contributed with results interpretation and manuscript writing. MMdeB contributed with conceptualization, results interpretation and manuscript writing.

ORCID iDs

Pedro Henrique Lima Alencar https://orcid.org/0000-0001-6221-8580
Mariana Madruga de Brito https://orcid.org/0000-0003-4191-1647

References

Alencar P H L and Paton E N 2022 How do we identify flash droughts? a case study in central european croplands *Hydrol. Res.* **53** 1150–65

Basara J B, Christian J I, Wakefield R A, Otkin J A, Hunt E H and Brown D P 2019 The evolution, propagation and spread of flash drought in the central united states during 2012 *Environ. Res. Lett.* **14** 084025

Beck H E, Zimmermann N E, McVicar T R, Vergopolan N, Berg A and Wood E F 2018 Present and future köppen-geiger climate classification maps at 1-km resolution *Sci. Data* **5** 180214

Boeing F *et al* 2022 High-resolution drought simulations and comparison to soil moisture observations in germany *Hydrol. Earth Syst. Sci.* **26** 5137–61

Bogdanovich E, Brenning A, Reichstein M, De Polt K, Guenther L, Frank D and Orth R 2024 Official heat warnings miss situations with a detectable societal heat response in european countries *Int. J. Disaster Risk Reduct.* **100** 104206

Bogena H R *et al* 2022 Cosmos-europe: a european network of cosmic-ray neutron soil moisture sensors *Earth Syst. Sci. Data* **14** 1125–51

Brunner M I, Götte J, Schlemper C and Van Loon A F 2023 Hydrological drought generation processes and severity are changing in the alps *Geophys. Res. Lett.* **50** e2022GL101776

Christian J, Basara J B, Hunt E, Otkin J A and Xiao X 2020 Flash drought development and cascading impacts associated with the 2010 russian heatwave *Environ. Res. Lett.* **15** 094078

Christian J, Basara J B, Otkin J A, Hunt E, Wakefield R, Flanagan P and Xiao X 2019 A methodology for flash drought identification: application of flash drought frequency across the united states *J. Hydrometeorol.* **20** 833–46

Christian J, Hobbins M, Hoell A, Otkin J A, Ford T, Cravens A, Powlen K, Wang H and Mishra V 2024 Flash drought: a state of the science review *WIREs Water* **11** e1714

Ford T W and Labosier C F 2017 Meteorological conditions associated with the onset of flash drought in the eastern united states *Agri. Forest Meteorol.* **247** 414–23

Gebauer A, Sakhaee A, Don A, Poggio M and Ließ M 2022 Topsoil texture regionalization for agricultural soils in germany-an iterative approach to advance model interpretation *Front. Soil Sci.* **1** 770326

Gerwin W *et al* 2023 Perspectives of lignite post-mining landscapes under changing environmental conditions: what can we learn from a comparison between the rhenish and lusatian region in germany? *Environ. Sci. Europe* **35** 36

Helsel D R, Hirsch R M, Ryberg K R, Archfield S A and Gilroy E J 2020 *Statistical Methods in Water Resources: U.S. Geological Survey Techniques and Methods* ch A3, p 458

Ho S, Buras A and Tuo Y 2023 Comparing agriculture related characteristics of flash and normal drought reveals heterogeneous crop response *Water Resour. Res.* **59** e2023WR034994

Hogue J and DeWilde B 2023 Pytends: pseudo api for google trends Online (available at: https://pypi.org/project/pytrends/)

Kam J, Stowers K and Kim S 2019 Monitoring of drought awareness from google trends: a case study of the 2011-17 california drought *Weather Clim. Soc.* **11** 419–29

Kim Y and Kim Y 2023 Global regionalization of heat environment quality perception based on k-means clustering and google trends data *Sustain. Cities Soc.* **96** 104710

Kruse K 2015 Bodendaten der bgr und der neue bodenatlas deutschland *Technical Report* Bundesanstalt für Geowissenschaften und Rohstoffe

Kuhlemann L, Tetzlaff D and Soulsby C 2020 Urban water systems under climate stress: an isotopic perspective from berlin, germany *Hydrol. Process.* **34** 3758–76

Lesinger K and Trends T D 2022 Variability and drivers of flash droughts in the contiguous united states *Water Resour. Res.* **58** e2022WR032186

Li J, Wang Z, Wu X, Chen J, Guo S and Zhang Z 2020 A new framework for tracking flash drought events in space and time *CATENA* **194** 104763

Liang M and Yuan X 2021 Critical role of soil moisture memory in predicting 2012 central USA flash drought *Front. Earth Sci.* **9** 46

Lisonbee J, Woloszyn M and Skumanich M 2021 Making sense of flash drought: definitions, indicators and where we go from here *J. Appl. Service Climatol.* **2021** 1–19

Madruga de Brito M, Kuhlicke C and Marx A 2020 Near-real-time drought impact assessment: a text mining approach on the 2018/19 drought in germany *Environ. Res. Lett.* **15** 1040a9

Mann H B 1945 Nonparametric tests against trend *Econometrica* **13** 245

Mo K C and Lettenmaier D P 2016 Precipitation deficit flash droughts over the united states *J. Hydrometeorol.* **17** 1169–84

Mukherjee S and Mishra A K 2022 A multivariate flash drought indicator for identifying global hotspots and associated climate controls *Geophys. Res. Lett.* **49** e2021GL096804

Mullen L 2020 textreuse: detect text reuse and document similarity (available at: https://docs.ropensci.org/textreuse)

Noguera I, Domínguez-Castro F and Vicente-Serrano S M 2021 Flash drought response to precipitation and atmospheric evaporative demand in spain *Atmosphere* **12** 165

Osman M, Zaitchik B F, Badr H S, Christian J I, Tadesse T, Otkin J A and Anderson M C 2021 Flash drought onset over the contiguous united states: sensitivity of inventories and trends to quantitative definitions *Hydrol. Earth Syst. Sci.* **25** 565–81

Otkin J A *et al* 2022 Getting ahead of flash drought: from early warning to early action *Bull. Am. Meteorol. Soc.* **103** E2188–202

Otkin J A, Svoboda M, Hunt E D, Ford T W, Anderson M C, Hain C and Basara J B 2018 Flash droughts: a review and assessment of the challenges imposed by rapid-onset droughts in the united states *Bull. Am. Meteorol. Soc.* **99** 911–9

Pastorello G *et al* 2020 The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data *Sci. Data* **7** 225

Pendergrass A G *et al* 2020 Flash droughts present a new challenge for subseasonal-to-seasonal prediction *Nat. Clim. Change* **10** 191–9

Polt K D, Ward P J, de Ruiter M, Bogdanovich E, Reichstein M, Frank D and Orth R 2023 Quantifying impact-relevant heatwave durations *Environ. Res. Lett.* **18** 104005

Rakovec O, Samaniego L, Hari V, Markonis Y, Moravec V, Thober S, Hanel M and Kumar R 2022 The 2018–2020 multi year drought sets a new benchmark in europe *Earth's Future* **10** e2021EF002394

Samaniego L *et al* 2017 Toward seamless hydrologic predictions across spatial scales *Hydrol. Earth Syst. Sci.* **21** 4323–46

Sehgal V, Gaur N and Mohanty B P 2021 Global flash drought monitoring using surface soil moisture *Water Resour. Res.* **57** e2021WR029901

Sen P K 1968 Estimates of the regression coefficient based on Kendall's tau *J. Am. Stat. Assoc.* **63** 1379–89

Shah J, Hari V, Rakovec O, Markonis Y, Samaniego L, Mishra V, Hanel M, Hinz C and Kumar R 2022 Increasing footprint of climate warming on flash droughts occurrence in europe *Environ. Res. Lett.* **17** 064017

Shumway R H and Stoffer D S 2019 *Time Series: A Data Analysis Approach Using R* (Chapman and Hall/CRC)

Shyrokaya A, Pappenberger F, Pechlivanidis I, Messori G, Khatami S, Mazzoleni M and Di Baldassarre G 2023 Advances and gaps in the science and practice of impact based forecasting of droughts *WIREs Water* **11** e1698

Sodoge J, Kuhlicke C, Mahecha M D and de Brito M M 2024 Text mining uncovers the unique dynamics of socio-economic impacts of the 2018–2022 multi-year drought in Germany *Nat. Hazards Earth Syst. Sci.* **24** 1757–77

Theil H 1992 *A Rank-Invariant Method of Linear and Polynomial Regression Analysis* (Springer) pp 345–81

Tijdeman E and Menzel L 2021 The development and persistence of soil moisture stress during drought across southwestern germany *Hydrol. Earth Syst. Sci.* **25** 2009–25

Walker D W *et al* 2024 Flash drought typologies and societal impacts: a worldwide review of occurrence, nomenclature and experiences of local populations *Weather Clim. Soc.* **16** 3–28

Wang X and Yu Q 2005 Unbiasedness of the theil-sen estimator *J. Nonparametric Stat.* **17** 685–95

Yuan X, Wang Y, Ji P, Wu P, Sheffield J and Otkin J 2023 A A global transition to flash droughts under climate change *Science* **380** 187–91

Zhang Y, Liu X, Jiao W, Zhao L, Zeng X, Xing X, Zhang L, Hong Y and Lu Q 2022 A new multi-variable integrated framework for identifying flash drought in the loess plateau and qinling mountains regions of china *Agric. Water Manage.* **265** 107544

Zink M, Samaniego L, Kumar R, Thober S, Mai J, Schäfer D and Marx A 2016 The german drought monitor *Environ. Res. Lett.* **11** 074002