

Drought Propagation and Ecosystem Resilience in a Peri-Urban Catchment of Berlin-Brandenburg

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Abstract. Climate change intensifies pressure on water resources, making it essential to understand how drought severity affects both surface and groundwater systems and their impact on vegetation. Local studies can offer critical insights into ecosystem responses and help to support targeted adaptation strategies. This study investigates the drought dynamics and their effects on surface water, groundwater, and vegetation across the Tegeler Fließ catchment in Berlin/Brandenburg from November 2008 to April 2021. Calculating drought indices for atmospheric, hydrological and groundwater drought, namely the Standardised Precipitation Index (SPI), the Standardised Surface Water Level Index (SSWLI) and the Standardised Groundwater Level Index (SGLI), respectively, the analysis identifies station-specific drought events and their propagation across three locations: Schildow, Luebars, and Tegel. The three indices allow us to take a closer look into the differences and the propagation of drought processes over different parts of the hydrological system. The study also assesses the impact of drought on vegetation health using the Normalized Difference Vegetation Index (NDVI). Our results strongly differ at different locations: the peri-urban area (Tegel) experienced the most extreme severe and prolonged groundwater droughts. In contrast, while the groundwater in the nature reserve and fen meadow area (Schildow) experienced more moderate occurrences of drought. Thus, this area remained more resilient, but faced significant surface water stress. Agricultural land (Luebars) displayed variability in both surface and groundwater responses, with surface water systems being more resilient. NDVI analysis revealed little to no observable effect with only moderate changes in vegetation that vegetation remained largely within moderate to dense classes throughout the study period, showing resilience despite severe drought conditions from 2018 to 2020. Spearman correlation tests did not show any significant relationship between NDVI and drought indices, while Granger causality tests revealed that SPI, and for some stations also SSWLI, significantly Granger-caused NDVI with a lag of one month. These findings highlight the need for localized drought management strategies tailored to both surface and groundwater resources, alongside enhanced vegetation monitoring that goes beyond traditional indices like NDVI.

1 Introduction

The phenomenon of global warming is having a significant impact on our planet, with observable consequences already affecting the Berlin/Brandenburg region and it is evident that the Berlin/Brandenburg region will not be spared from the consequences of climate change^{PF}. Studies show that extreme heat waves and dry spells will likely^{PF} become increasingly frequent and in-

25 tense across Europe by the end of the 21st century (Spinoni et al., 2018; Grillakis, 2019). The increasing pressure of climate
change on water resources highlights the importance of understanding how it will affect both surface and groundwater systems
and what the impact will be on vegetation. Understanding the relationship between drought severity and vegetation response
as climate change intensifies is critical for ensuring ecosystem resilience and managing precious water resources. Ecosystems
show varying capacities in withstanding frequent drought occurrences. However, as droughts become longer and more spatially
30 extended under climate change, in the long run, they will likely lead to ecosystem degradation and the disappearance of crucial
ecosystem services (Crausbay et al., 2017).

Droughts affect regions all over the world. Local studies provide valuable insights into the impacts within specific study ar-
eas, thus gaining context and understanding for targeted adaptation strategies. ~~As a historically water-rich region, Berlin/Brandenburg
must now adapt to a drier future (Kahlenborn et al., 2021).~~^{PF} Although often associated with abundant surface water bodies,
35 Berlin/Brandenburg is characterized by a tight water budget, with low annual precipitation relative to its temperate humid cli-
mate and high atmospheric demand through evapotranspiration, especially in the spring and summer months (Köstner et al.,
2007; Germer et al., 2011; Kahlenborn et al., 2021). This makes this inherently water-limited region, which is heavily reliant
on both surface and groundwater systems, ~~its distinct natural environment, heavily reliant on both surface and groundwater
systems, makes it~~ particularly vulnerable to droughts (Cullmann et al., 2022), presenting a compelling case for an empirical
40 study.

Brandenburg is one of the states with the strongest water deficit and highest drought risk in Germany (Schindler et al., 2007).
The 2018 drought was the most severe on record since 1951 (Helmholtz Centre for Environmental Research, 2023), with over
90 percent of the agricultural area being severely or highly affected (Ihinegbu and Ogunwumi, 2022). Droughts in the region
have cascading effects, including ~~declining groundwater tables,~~^{PF} water stress, ~~declining groundwater tables,~~ increased fire
45 risk, and significant reductions in agricultural productivity (Reyer et al., 2012). For example, Bloch et al. (2015) reported a 20
percent annual yield loss in legume-grass swards due to drought. Small catchments, such as the Tegeler Fliess in Brandenburg,
are more vulnerable to climate change than larger river systems (Blöschl et al., 2007). However, despite these impacts, research
on the hydrological and hydrogeological aspects of droughts and their combined effects on vegetation health in Brandenburg
remains limited, highlighting the need for more interdisciplinary and region-specific studies (Germer et al., 2011). This study
50 aims to fill this gap by analysing short-term drought variability at three sites along the Tegeler Fliess – Schildow, Luebars and
Tegel – over 13 hydrological years from November 2008 to April 2021.

The Tegeler Fliess is a tributary of the river Havel located in the north of Berlin. This stream crosses a diverse landscape of
different land uses consisting of various nature reserves, fen meadows, calcareous tufa terrain, agricultural land and peri-urban
settlements (Berliner Senatsverwaltung für Stadtentwicklung, 2025). There are several surface and groundwater monitoring
55 stations along the stream, so data availability is good, but ~~surprisingly few studies have dug into the specifics of drought in
this particular region, though we have some important pieces of the puzzle. For instance, looking at the 2018–2019 drought,
Kuhlemann et al. (2022) used stable isotope analysis to trace water balances across Berlin. Their work points to strong evap-
orative losses and suggests the fundamental interactions between groundwater and surface water were altered. Looking at the
wider Brandenburg area, the picture appears even more concerning. A remote sensing study from that same period by Ihinegbu~~

60 and Ogunwumi (2022) is pretty alarming, suggesting that over 90 percent of the territory was grappling with high to extreme drought. While any satellite-level analysis might gloss over local realities, their finding that agricultural regions were seemingly the hardest hit is difficult to ignore. This wasn't just a snapshot of a single bad year, either. It seems to fit a troubling pattern flagged by Helmholtz Centre for Environmental Research (2023), which has noted a string of damaging dry spells over the last decade. This broader context really brings the potential vulnerability of the Tegeler Fliess landscape into sharp focus. It provides a crucial backdrop for understanding just how the connection between surface and groundwater holds up in a peri-urban landscape so thoroughly dependent on both. ~~to the best of our knowledge, there are only a few studies that have investigated drought in this particular region. In the last decade, this area has experienced several dry spells leading to significant effects on the environment (Helmholtz Centre for Environmental Research, 2023). This setting provides a chance to examine how surface water and groundwater levels interact in a peri-urban landscape in an area that is heavily reliant on both surface water and groundwater sources.~~^{AG}

Given its multifaceted nature, a universal drought definition does not exist; rather, it depends on the perspective and objective of a study (Van Loon, 2015)^{PF}. To capture this complexity, a range of indices has been developed for different components of the hydrological cycle (Heim Jr, 2002; Smakhtin and Schipper, 2008; Yihdego et al., 2019).^{PF}

75 Meteorological drought is commonly assessed using indices such as the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI). The SPI, introduced by McKee et al. (1993), is valued for its simplicity and effectiveness. It only requires precipitation data and is widely used to detect meteorological droughts across various timescales. However, its main limitation is that it does not take into account the effects of temperature or evapotranspiration, which have become increasingly important factors in the context of climate change. In contrast, the SPEI developed by 80 Vicente-Serrano et al. (2010) incorporates both precipitation and potential evapotranspiration, offering a more comprehensive assessment of drought severity. The added complexity and data requirements of the SPEI, however, can restrict its application in regions where such data are scarce. SPI and SPEI are both recommended by the World Meteorological Organization for drought assessment (Svoboda and Fuchs, 2016). Studies show that although SPEI is more accurate due to its consideration of temperature, SPI and SPEI often provide comparable results (Pei et al., 2020; Ojha et al., 2021; Abu Arra and Şişman, 2024).^{PF}

85 Hydrological drought indices include the Streamflow Drought Index (SDI) and the Standardized River Stage Index (SRSI). The SDI, as described by Nalbantis and Tsakiris (2009), monitors droughts characterised by reduced cumulative streamflow volumes over predefined time intervals. Though its effectiveness depends on the availability of reliable discharge data, which may not be available in certain catchments. When discharge data is unavailable, the SRSI offers an alternative by utilizing level data as a proxy and thereby enabling drought monitoring in ungauged basins (Zhong et al., 2022). It is important to note that 90 water level measurements can be influenced by local channel morphology and may not always accurately reflect actual flow conditions.^{PF}

For groundwater droughts, which are slow to develop but often take the longest to recover from, the Groundwater Drought Index (GDI) is commonly used. This index standardizes groundwater level anomalies to assess hydro-geological droughts

(Bloomfield and Marchant, 2013). While the GDI is valuable for quantifying groundwater drought, its application is often limited by the sparse availability of groundwater data.^{PF}

Each of these indices provides a different perspective on drought, and their combined use enables a more holistic understanding of drought dynamics across meteorological, hydrological, and hydrogeological domains.^{PF}

Usually, below-normal hydro-/meteorological anomalies are understood as droughts, where "normal" depends on space, time, and the variable of interest (Van Loon, 2015). Various indices have been created to uncover this complexity, including the Standardised Precipitation Index (SPI), which measures meteorological droughts, the Streamflow Drought Index (SDI), which focuses on hydrological droughts, and the Groundwater Drought Index (GDI), which looks at hydrogeological droughts (Smakhtin and Schipper, 2008; Smakhtin and Schipper, 2019). For catchments without discharge information the Standardised River Stage Index has been developed as an alternative to SDI (Zhong et al., 2022). The SPI, first proposed by McKee et al. (1993), is a method utilised for assessing drought by normalising precipitation across different time scales. A similar index to the SPI is the SDI. It is used to monitor droughts characterised by reduced reservoir levels (Nalbantis and Tsakiris, 2009). Groundwater droughts, which are slow to develop but often take the longest to recover from, are measured using the GDI (Bloomfield and Marchant, 2013). Each of these indices offers a different perspective on droughts and together they provide a more holistic approach to understanding different drought dynamics. The SPI and the Standardised Precipitation Evapotranspiration Index (SPEI) are both recommended by the World Meteorological Organization for drought assessment (Svoboda and Fuchs, 2016). While the SPI relies solely on precipitation data, making it a simple and effective index for identifying meteorological drought, the SPEI includes potential evapotranspiration to account for temperature effects. This provides a more comprehensive view of drought conditions (Vicente-Serrano et al., 2008). Studies show that although SPEI is more accurate due to its consideration of temperature, SPI and SPEI often provide comparable results (Pei et al., 2020; Pei et al., 2021; Pei et al., 2024). However, the complexity and additional data requirements limit the use of SPEI.^{PF}

In this study, we use ^{PF}a three-month accumulation period ~~was used~~ to evaluate drought conditions, based on the ~~works studies~~^{PF} of McKee et al. (1993) and Bloomfield and Marchant (2013). ~~By using t~~^{PF}This approach, ~~lets us we were able to~~ analyse short-term drought patterns ~~in the area~~, compare indices across sites ~~making the indices comparable with one another and across study sites~~, and examine how meteorological factors influence ~~while also gaining valuable insights into various aspects of drought dynamics such as meteorological influences and how they affect~~ surface and groundwater systems. We ~~then combine~~ ^{PF}By combining these drought indices with ~~an examination of~~ long-term trends ~~analysis~~ and ~~conducting~~ Granger Causality tests (Granger, 1969) to identify ~~the research seeks to uncover trends in~~ how droughts propagate and impact vegetation health (Zolghadr-Asli et al., 2021; Li et al., 2024; Xiao et al., 2025).

The objectives are twofold: to identify specific drought events and examine their propagation at individual stations as well as between stations, and to assess the impact of these droughts on vegetation health using the Normalised Difference Vegetation Index (NDVI) as an indicator of vegetation stress. By conducting a long-term trend analysis, we aim to ~~better understand~~ ^{PF}uncover persistent drought-vegetation dynamics ~~that have emerged~~ over the study period. ~~Our~~^{PF}This study addresses the following research questions:

1. How do meteorological, hydrological, and hydrogeological droughts interact in the Tegeler Fliess catchment?

2. What long-term drought trends can be observed, and how do they impact vegetation stress?

130 3. Can time-lagged relationships between drought indices and vegetation health be identified?

By addressing these questions, this study contributes to a deeper understanding of drought dynamics and their implications for water resource management and ecosystem resilience along the Tegeler Fliess. The findings of this study are transferable to other peri-urban regions with similar environmental conditions, which may have a poorer data availability.

2 Methodology

135 2.1 Study Area

The Tegeler Fliess is an approximately 30 km long stream that crosses the northern border between Berlin and Brandenburg. It is the tributary of the Havel river, and part of the Elbe river system.^{PF} Its catchment area spans 126 km². Most of the area lies within the Barnim Nature Park and touches the Westbarnim Landscape Conservation Area (LSG) in Brandenburg and the Tegeler Fliess LSG in Berlin, as well as the Tegeler Fliess Calcareous Tufa Nature Conservation Area (NSG) and the Tegeler Fliess Fens Nature Conservation Area (NSG). The river valley is registered as a Natura 2000-site in both federal states (NABU Berlin, n.d.). The river valley was formed after the last glacial maximum as a post-glacial meltwater channel. The main aquifer in the area consists of fine sand underneath the boulder clay and the area is highly dependent on surface and groundwater systems (Baugenossenschaft Freie Scholle zu Berlin eG, 2024; Berliner Senatsverwaltung für Stadtentwicklung, 2025). The selected sites - Schildow, Luebars and Tegel - represent key points along the Tegeler Fliess. The sites were selected not only due to long-term data availability but also because they represent key ecological and land-use zones along the Tegeler Fliess, as shown in Fig. 1 and Fig. 2. Based on a high-resolution land cover analysis, the areas look something like this: Luebars is largely characterized by open agricultural fields and shrubland, with only sparse tree cover. While we don't have specific crop-type metadata—a notable limitation of our data sources—the landscape suggests seasonal crops common to the Berlin-Brandenburg area, likely cereals and fodder grasses. This interpretation, however, remains an educated guess on our part. Schildow, in contrast, offers a much more varied landscape. It's a patchwork of small-scale agriculture, considerable tree cover, and remnants of fen meadow supporting semi-natural flora. This inherent structural complexity appears to be a critical factor, as it probably fosters a more nuanced ecosystem response than we would expect to find in a more uniform environment. Tegel represents the peri-urban end of the spectrum. The environment here is a hybrid, blending managed green spaces and tree-lined infrastructure with the nearby pressures of developed land. One gets the sense that the vegetation is heavily influenced by municipal upkeep, such as regular irrigation, which likely makes its ecological dynamics quite different from those of the more rural sites. They are characterised by natural landscapes, agricultural areas and peri-urban development respectively, and were selected based on the availability of long-term datasets for both surface and groundwater monitoring sites in close proximity (see Fig. ??).^{AG}

Groundwater profiles from the three sites reveal a diverse geological landscape. At the monitoring station in Luebars, the well filter is located beneath over 10 m of shale, in an isolated by a local aquifer formed by regional geological processes.

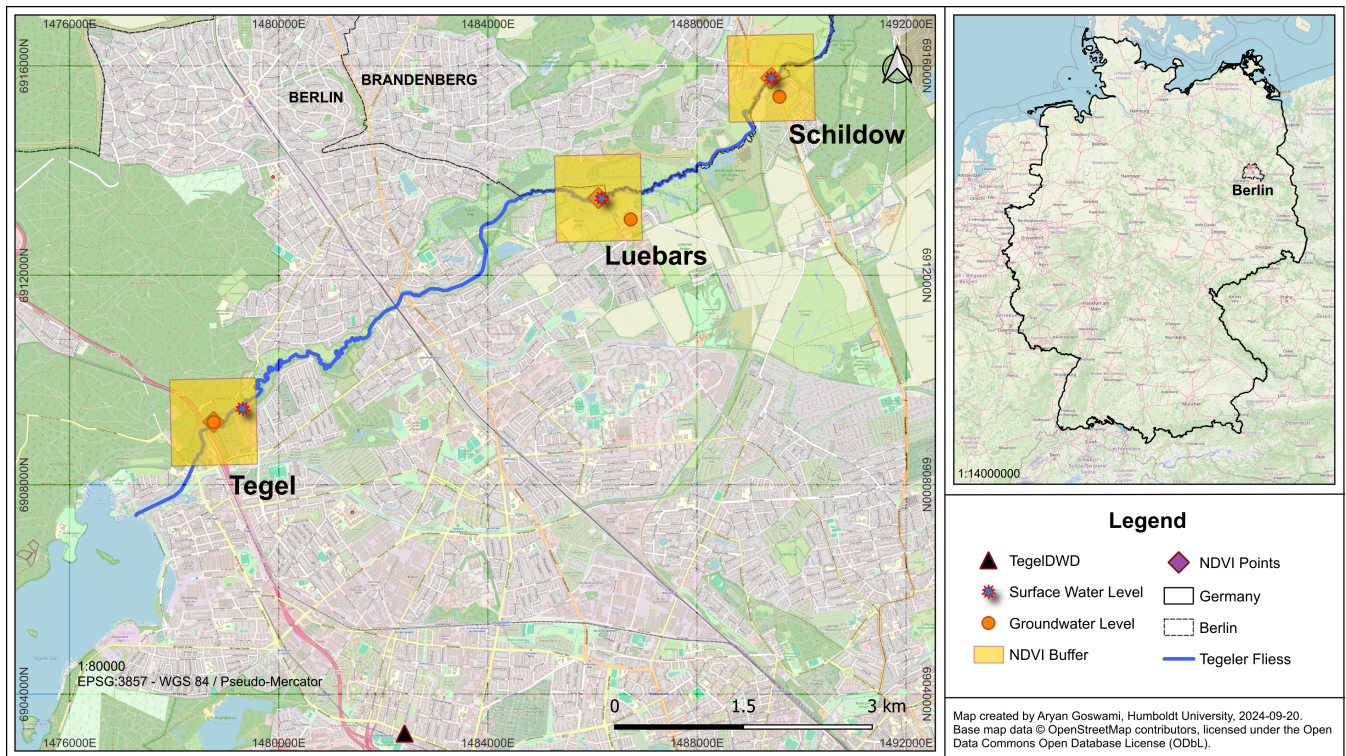


Figure 1. Map of Study Area.

This isolation limits its connection to recharge, contrasting with the other two sites. Schildow also features a thick sand layer with some silt, potentially offering a similar, though less pronounced, isolation effect and contributing to greater resilience. In contrast, the Tegel aquifer lacks a confining layer and consists of layered sand deposits. This suggests a more direct connection to atmospheric processes. Unfortunately, porosity logs were unavailable for these locations, making it difficult to definitively assess their impact on drought index calculations. However, all three aquifers are primarily composed of similar middle-sized sand, suggesting comparable porosity. The Tegel aquifer, with its greater sand volume, may have higher storage capacity, potentially explaining the smaller annual oscillation in groundwater levels.

2.2 Data Collection and Processing Tools

R statistical software (version 4.4.1) (R Core Team, 2024) was used for data pre-processing and all analysis steps (see 2.5).^{PF} The study period covers 13 hydrological years from November 2008 to April 2021, chosen after data availability. An overview of the data used, the data sources and the official names of the measurement sites as called by the data provider - or in the case of the NDVI data, the coordinates used to extract mean NDVI values - are summarized in Table 1.

Daily precipitation measurements were obtained from the Berlin-Tegel station via the German Weather Service (Deutscher Wetterdienst, DWD) using the R package 'rdwd' (Boessenkool, 2023). The dataset is assigned DWD's quality measure QN9,

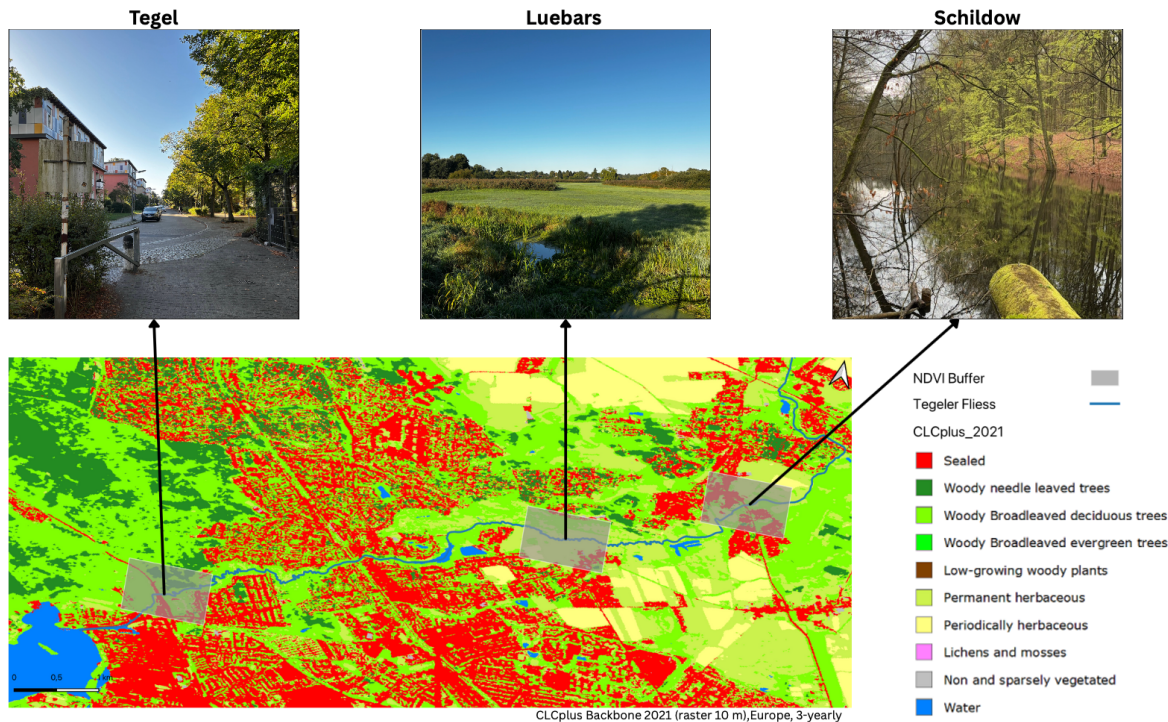


Figure 2. Overview of the study area. The photos above show the typical landscapes near the study sites, the map below shows the land cover distribution along the river.

175 indicating that while it is complete, some parameters may still require correction. Given the short distances between stations within the Tegeler Fliess catchment area, this single station is used to represent precipitation over the entire study area. This approach is taken for the sake of simplicity, but also due to lack of other measurement sites in close proximity to data records over the study period.

~~The R-statistical software version 4.4.1 (R Core Team, 2024) was used for data pre-processing and all analysis steps (see~~
180 ~~2.5).~~^{PF}

Daily surface water and groundwater level measurements were obtained from ~~two~~^{various} regional water management authorities (see Table 1) depending on the station's location. ~~Data integration was a challenge due to different data collection strategies.~~ The groundwater measurement station at Schildow only provided weekly data, whereas groundwater records at Tegel and Luebars were more complete but contained some minor gaps. ~~measurements, while groundwater data at Tegel and~~
185 ~~Luebars showed minor gaps with no measurements (see Fig. S1 in Supplementary Material).~~ To address these gaps and improve data resolution, all data sets with missing values were linearly interpolated to the same daily temporal resolution.

Vegetation health was assessed using MODIS NDVI (product MOD13Q1, L3 validation stage) at a spatial resolution of 250 m and a temporal resolution of 16 days, accessed using the R package 'MODISTools' (Hufkens, 2023). ~~The 250m resolution~~

Table 1. Overview of data used, data sources and data quality.

Data	Location/Name	Official Name/Coordinates	Provider
Precipitation	Tegel-DWD	00430 Berlin-Tegel	German Weather Service (DWD)
Surface Water	Schildow	Schildow, 5819801	Brandenburg State Office for the Environment (LfU)
	Luebars	5819901, Lübars	Berlin Water Portal, Berlin Senate
	Tegel	5820000 St.-Joseph-Steg	Berlin Water Portal, Berlin Senate
Groundwater	Schildow	33465504, Schildow OP	Brandenburg State Office for the Environment (LfU)
	Luebars	9	Berlin Water Portal, Berlin Senate
	Tegel	809	Berlin Water Portal, Berlin Senate
NDVI	Schildow	N 52° 38' 60 E 13° 22' 47	MODIS, NASA
	Luebars	N 52° 37' 21 E 13° 20' 60	
	Tegel	N 52° 35' 57 E 13° 17' 2	

data is, of course, a compromise at the sub-catchment level. The main issue is the "mixed-pixel" problem in peri-urban zones, where one cell can easily merge signals from infrastructure, trees, and farmland. Chen et al. (2018) and Jimenez et al. (2022) showed this can weaken the NDVI response in such areas.^{AG} A point was selected near each site, the coordinates of which are given in Table 1, and the mean NDVI value within a 500 m buffer (see Fig. 1) was calculated to represent vegetation health. We attempted to account for this by carefully placing our three NDVI points in locations within the 500m buffer that were dominated by vegetation.^{AG}

We assessed land cover within a 500 m buffer around each station to account for the influence of local vegetation and land cover on the NDVI signal. Our primary classification relied on the European Environment Agency’s CLCplus Backbone 2021 dataset, a 10 m resolution raster (European Environment Agency, 2021). To refine this classification, we conducted a visual assessment using the HCMGIS plugin in QGIS, since automated classifiers can miss small-scale features. High-resolution Google Satellite imagery allowed us to verify field structures, vegetation patterns, and built-up areas at each site, ensuring a more accurate representation of factors influencing the NDVI signal.^{AG}

To evaluate the potential impact of localized anthropogenic factors—specifically construction and land use change—on surface and groundwater dynamics, we visually inspected high-resolution historical satellite imagery using Google Earth covering the study period (November 2008–April 2021). Our inspection confirmed that despite the sites being located in or near urban/peri-urban settings, no significant construction activity, large-scale urban expansion, or extensive surface sealing was observed in the immediate vicinity of the groundwater wells at Schildow, Luebars, or Tegel.^{AG}

2.3 Conceptual model of drought propagation

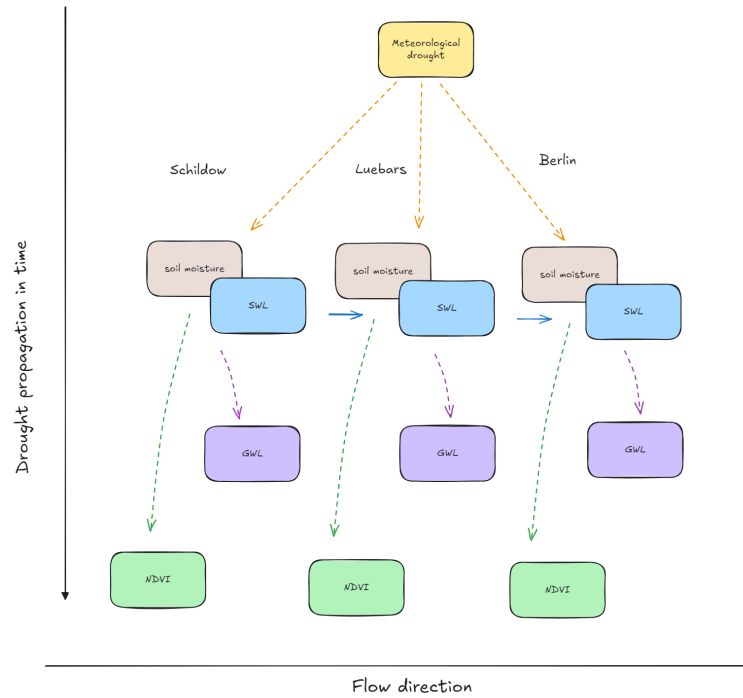


Figure 3. Conceptual model of drought propagation along the Tegeler Fließ.

Fig. 3 presents the conceptual model of drought propagation within the catchment: across different domains and along the river as well. A meteorological drought could trigger droughts at the surface level, via the reduction of soil moisture content and streamflow (hydrological drought). Hydrological drought also propagates downstream along the river. Later in time, reduction in recharge can lead to drought in the groundwater, and the reduced available soil moisture (and in the case of deep rooted plants reduced groundwater table) can also lead to a drought in vegetation. In the following, we will present how we analyze the drought propagation over the different domains based on the available datasets. We use the conceptual model as a roadmap to try to infer the relations of the different drought types at the different sites.

2.4 Drought and Vegetation^{PF} Indices Calculation

As outlined in the introduction, various indices exist for assessing different drought types. The relationship among the various types of drought is complex. It is important to note that there is no standardised way to assess drought (Heim Jr, 2002; Heim Jr, 2019). Numerous drought indices exist, and even the same index can be calculated using slightly different methods, depending on the characteristics of the region and the type of drought being studied.^{PF} In this study, we define drought as a period of at least one month during which water availability is significantly below average, resulting in a deficit in its respective domain: precipitation deficit (meteorological drought), reduced surface water levels (hydrological drought) or reduced groundwater levels (hydrogeological drought). To capture these aspects, we applied the SPI for meteorological drought, the Standardized Surface Water Level

Index (SSWLI) as a proxy for hydrological drought, and the Standardized Groundwater Level Index (SGLI) for groundwater drought. Each of these indices was selected to provide a consistent, standardised assessment of drought conditions, facilitating direct comparison and enabling a comprehensive analysis of drought propagation.^{PF} The following subsections describe the calculation procedure and application of methods used to calculate^{PF} the indices used in this study.

2.4.1 Standardised Precipitation Index (SPI)

~~The SPI is one of the most widely used drought indices for assessing meteorological drought and provides a standardised approach to analysing precipitation anomalies. Developed by McKee et al. (1993), the~~^{PF}~~The SPI standardises precipitation anomalies by fitting a gamma distribution to the precipitation data and then transforming it to a normal distribution. The gamma distribution is chosen for its ability to model the typically skewed nature of precipitation data, especially in semi-arid regions (McKee et al., 1993)(ibid). We aggregated~~~~In this study,~~ daily precipitation data ~~were aggregated~~ into monthly totals to calculate SPI over a three-month period (SPI3). The three-month timescale is particularly relevant for short-term droughts that affect water supplies, ecosystems and agriculture (Stagge et al., 2015). The 'SPEI' R package (Beguería and Vicente-Serrano, 2023) ~~was~~ used to calculate SPI3. In the 'SPEI' R package, the gamma distribution fitting and transformation process is automated, ensuring consistent calculation across datasets and allowing SPI values to be easily compared between different time periods and regions.

2.4.2 Standardised Surface Water Level Index (SSWLI) ~~and Standardized Groundwater Level Index (SGLI)~~^{PF}

The SSWLI is calculated by standardizing deviations of observed surface water levels from their long-term mean, following the same statistical approach as the SPI using the SPEI R package, replacing the input with river levels. A three-month accumulation period (SSWLI3) was used to capture short-term hydrological droughts relevant for water resource management and ecosystem response.~~While the SPI is specifically designed for precipitation (McKee et al., 1993), it is also applicable to streamflow and groundwater data because the same principles of standardising deviations from long-term means can be applied to assess anomalies in hydrological and hydrogeological data (Vicente-Serrano et al., 2012; Vicente-Serrano et al., 2013). By standardising surface and groundwater levels, the resulting two indices allow us to assess the intensity of hydrological and groundwater droughts in a way that is directly comparable to meteorological droughts.~~^{PF}

Due to the unavailability of discharge data at two of the three monitoring stations along the Tegeler Fliess, we employed the SSWLI as a proxy for hydrological drought.~~The commonly used drought indices used for surface water monitoring rely on streamflow data, but this was not available at the stations on the Tegeler Fliess. Hence we are using an index calculated from the river levels, the Standardized Surface Water Level Index (SSWLI).~~^{PF} A similar approach has been used by Zhong et al. (2022) for ungauged rivers with satellite data, that was able to monitor drought propagation in river systems. By standardizing surface water levels, the resulting index allowed us to assess the intensity of hydrological drought in a way that is directly comparable to meteorological drought (Vicente-Serrano et al., 2012; Bloomfield and Marchant, 2013). Note however, that this approach can affect the accuracy of hydrological drought characterization, as river levels (especially in smaller streams) are more susceptible to nonlinear behavior.~~that this approach has a lower accuracy than traditional discharge-based indices, as river~~

255 levels (especially in smaller streams) are more susceptible to nonlinear behavior due to the river profile. SSWLI is calculated similarly to SPI using the SPEI R package, replacing the input with river levels.

2.4.3 Standardised Groundwater Level Index (SGLI)

The Standardised Groundwater Level Index (SGLI) extends the SPI methodology to groundwater level data, allowing for the assessment of hydrogeological drought. The SGLI, as applied in this study, is based on the index introduced by Bloomfield
260 and Marchant (2013), which standardizes groundwater level time series to characterize groundwater droughts. This approach aligns with SPI and SSWLI. Standardising deviations from the historical mean allows the SGLI to provide a consistent metric for assessing periods of groundwater scarcity. Similarly to SPI3 and SSWLI3, SGLI, SGLI and SGLI was also calculated over a three-month period (SGLI3).

Drought classes were used to categorise the severity of drought conditions based on standard thresholds of different
265 drought indices (see Table 2). For this study, we classified drought events according to the standardised values of SPI3, SSWLI3 and SGLI3, following common classification systems in the drought literature (McKee et al., 1993; Nalbantis and Tsakiris, 2009). A drought index value of ≤ -1 indicates at least moderate drought. This is when conditions are at least one standard deviation below the historical mean and significantly dryer than usual. Values between -1.5 and -2 classified as severe, while values below -2 as an extreme drought.

270 2.4.4 Normalised Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a remotely sensed proxy for plant productivity (Nemani et al., 2003) and is thus a widely used metric for assessing vegetation health and its response to drought (Bachmair et al., 2018; Kloos et al., 2021). It is a standardized value based on the inverse relationship of red and near-infrared reflectance and thus provides continuous monitoring of the 'greenness' of the photosynthetically active biomass of the plant canopy cover (Tucker, 1979;
275 Jensen, 2013, p. 384). We also classified NDVI values into different classes based on the range of the index to assess vegetation health and its response to drought. NDVI values range from -1 to +1, with higher values indicating denser and healthier vegetation and lower values indicating non-vegetated surfaces. The NDVI classification lacks a universally accepted standard, so the vegetation classes were adapted based on De La Iglesia Martinez and Labib (2023). This approach stems from the observation that the relationship between NDVI and vegetation density is non-linear, with changes in the lower NDVI range
280 (e.g. 0.2 to 0.3) reflecting more significant increases in green cover and vegetation types than equivalent changes in the higher NDVI range (e.g. 0.6 to 0.7) (ibid.). This finding justifies the uneven distribution of our vegetation classes, as the sensitivity of NDVI varies across its range. The thresholds capture meaningful vegetation transitions while reflecting how changes in NDVI affect green cover. This uneven distribution is further supported by the NDVI distribution per station, as shown in Supplementary Fig. S3.

285 2.5 Statistical Tests and Measures Analysis Process

Table 2. Drought Indices and Vegetation Classes.

Drought Class	Value Range	NDVI Class	Value Range
No Drought	> -1	Water, Snow, Clouds	$-1 \leq x < 0$
Moderate Drought	$-1 \geq x > -1.5$	Bare Soil, Rock, Build Up	$0 \leq x < 0.2$
Severe Drought	$-1.5 \geq x > -2$	Sparse Vegetation	$0.2 \leq x < 0.3$
Extreme Drought	$x \leq -2$	Moderate Vegetation	$0.3 \leq x < 0.5$
-	-	Dense Vegetation	$0.5 \leq x < 1$

The overview of the analysis process is shown in Fig. ??.

After calculating the different drought indices, different statistical tests were applied to compare them with each other. A Spearman correlation test was performed to assess potential relationships between drought indices (SPI3, SSWLI3, SGLI3) and NDVI across all stations. Spearman’s rank correlation is a non-parametric measure used to determine the strength and direction of association between two variables. It is particularly useful in this context as it does not assume a normal distribution and can detect monotonic relationships. This test was chosen to investigate whether lower Drought Index values correspond to lower NDVI values and vice versa.

For trend analysis, the Mann-Kendall test was applied to each time series to identify statistically significant trends in SPI3, SSWLI3 and SGLI3 over the 13-year study period. This non-parametric test was chosen due to its robustness in detecting monotonic trends (either increasing or decreasing) in time series data that are not normally distributed. The test was performed using the ‘Kendall’ R package (McLeod, 2022).

Additionally, drought occurrences were counted for each index and station. To assess how drought conditions propagate between compartments, propagation rates and conditional probabilities were calculated between meteorological (SPI3), hydrological (SSWLI3), and hydrogeological (SGLI3) droughts. Here, “upstream” and “downstream” refer to the sequence of compartments (compare Fig. 3) and not the geographic location.^{PF}

The Granger causality test was used to assess the time-lagged relationships between drought indices and vegetation stress. Granger (1969) introduced the Granger causality test originally within the field of economics as a statistical method for determining whether one time series can predict another. Since then, the test has gained widespread application across various disciplines, including ecosystem science and hydrology, due to its computational simplicity (Papagiannopoulou et al., 2017; Kong et al., 2018; Singh and Borrok, 2019; Li et al., 2024). The test checks whether information from one time series (e.g. SPI) improves the prediction of another time series (e.g. NDVI) beyond what could be predicted from past values of the latter alone (Shojaie and Fox, 2022). The ‘lmtest’ package (Zeileis and Hothorn, 2002) and the ‘vars’ package (Pfaff, 2008) were used, with lag periods ranging from 1 to 6 months to allow for delayed vegetation responses to drought conditions. We initially explored time-lag analysis, but inconclusive results prompted the use of ^{PF}Granger causality was used to determine whether different drought indices predict each other or influence future NDVI values, providing insight into the interaction between drought propagation and ecosystem response.

3 Results

3.1 Precipitation and Water Level Dynamics

In Fig. 4 the general statistics of the input data: precipitation, surface water and groundwater levels are shown. ~~At a glance over Fig. 4, the~~ ^{PF} precipitation patterns at the Tegel-DWD station averaged 45 mm per month, with ~~some outlier months exceeding 100 mm, as the result of heavy rainfall events. occasional heavy rainfall events exceeding 100 mm.~~ ^{PF} These heavy rainfall events are likely to contribute to localized water level surges ~~as can be seen in Fig. 4~~ ^{PF}. However, both the linear and non-parametric trend analyses indicate no significant long-term change in precipitation ($R^2 = 0.001$, $p = 0.67$, MK $p = 0.51$), ~~confirming overall stable rainfall conditions over the study period.~~ ^{PF}

Comparing surface and groundwater levels, however, reveals the variation across sites. Surface water levels at Luebars fluctuated between ~~0.35 m35-cm~~ ^{PF} and ~~0.55 m55-cm~~, visually showing the greatest variability between stations. ~~Despite these fluctuations, Luebars exhibits only a weak and statistically not significant decline in surface water levels~~ ($R^2 = 0.02$, $p = 0.08$). ^{PF} In contrast, Schildow ~~displayed~~ more stable surface water levels, averaging around ~~0.23 m23-cm~~, but shows a significant decreasing trend ($R^2 = 0.21$, $p < 0.001$, MK $\tau = -0.32$) ^{PF} throughout the study period. The Tegel station had a similar mean surface water level, but greater variability, indicating possible site-specific differences in hydrological behavior. ~~At Tegel, no consistent trend was detected~~ ($R^2 = 0.006$, $p = 0.36$). ^{PF} Tegel and Luebars displayed the highest surface water level variability with Coefficient of Variation (CV) of 30.9 percent and 33.9 percent respectively, with Schildow being the lowest at 20.4 percent. Higher CV values may indicate less stability in water-level conditions, potentially due to factors like localized hydro-climatic influences, different water management practices, etc.

Groundwater levels showed further variability between stations. Schildow recorded the highest median groundwater level at about 40 m above sea level (mNHN), while Tegel recorded the lowest, with a difference of 8 m along the river. These observations underline the variability of water availability in the study region, which is likely to be influenced by local environmental conditions and hydrological patterns specific to each station. ~~The trend analyses confirm a consistent and significant groundwater decline across all stations~~ (Schildow: $R^2 = 0.28$, MK $\tau = -0.38$; Luebars: $R^2 = 0.29$, MK $\tau = -0.35$; Tegel: $R^2 = 0.47$, MK $\tau = -0.48$; all $p < 0.05$), indicating a depletion of subsurface storage ~~which is not explained by precipitation trends.~~ ^{PF} A full statistical summary is presented in Table S1 in the Supplementary Material.

3.2 Drought Variability ~~and Long-Term Trends~~

3.2.1 Drought Propagation and Station-Specific Drought Responses

~~Drought propagation to precipitation patterns vary by site. In Fig. 5, the~~ The stations show ~~differences distinct trends~~ in meteorological, surface water and groundwater drought indices, ~~which translate to varying drought propagation patterns and highlighting~~ localised hydrological stress.

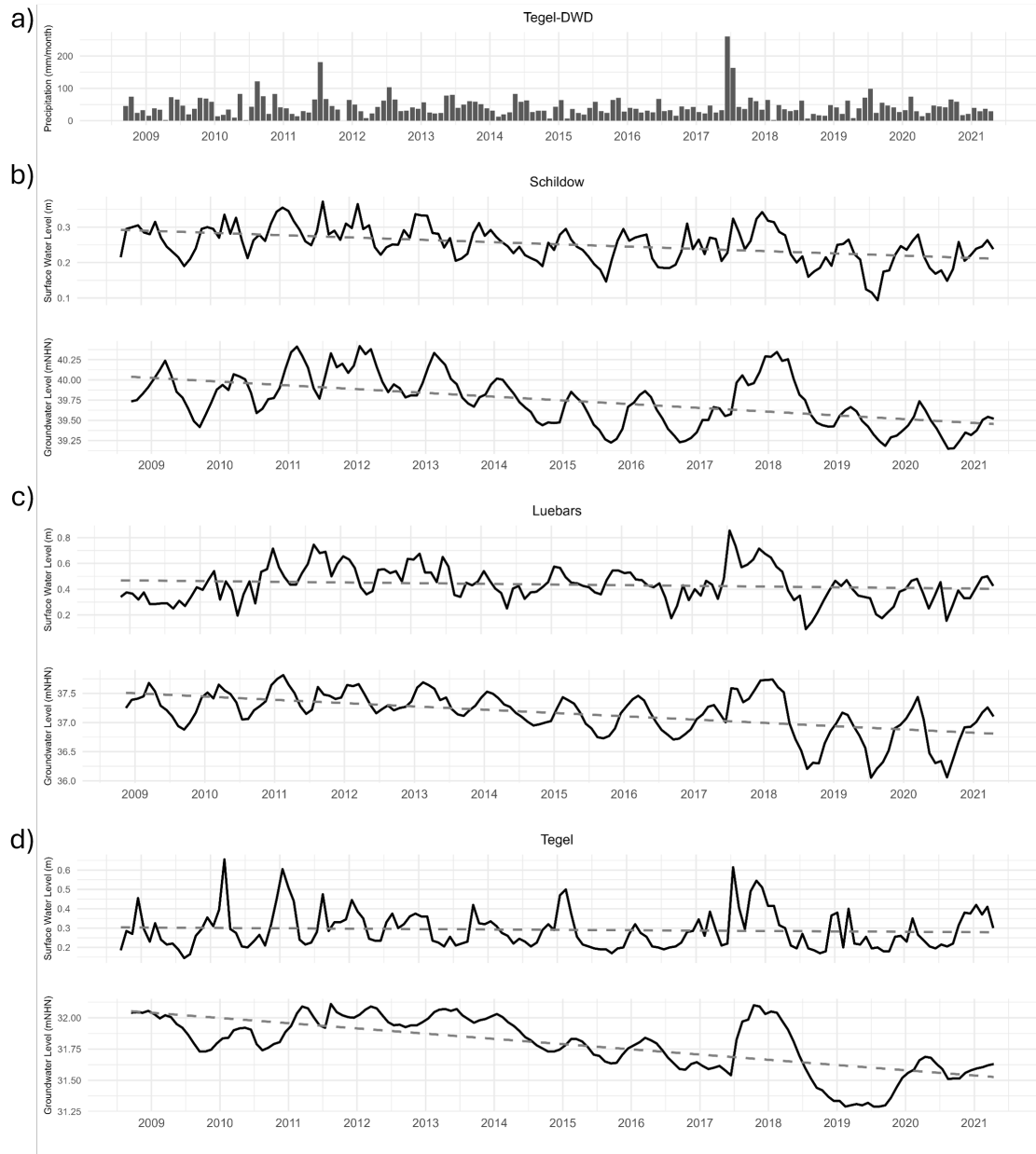


Figure 4. Observation time series used in the analysis: a) monthly precipitation sums at Tegel-DWD (black bars), and monthly mean surface water and groundwater levels (solid black lines) at Schildow (b), Luebars (c) and Tegel (d). Dashed gray lines indicate long-term linear trends. Statistics of precipitation, surface water level and groundwater level at the different stations: ^{PF}

At Tegel-DWD, the SPI3 plot in Fig. 5, shows relatively stable meteorological conditions between 2009 and 2017 with a moderate-severe drought returning almost every year. The precipitation-rich period between mid-2017 and mid-2018 is re-

flected in high SPI3 values, ~~consistent with precipitation peaks which can also be seen in high precipitation values~~ in Fig. 4.

345 However, a significant shift occurs in 2018, when SPI3 drops below -2, marking an extreme meteorological drought spanning several months, before meteorological conditions get back close to how they were before the drought event of 2018/2019. The absence of a significant trend in SPI3 ($R^2 = 0$, $p = 0.92$; MK $p = 0.90$) confirms that water availability through precipitation remained stable over the study period. This suggests, that subsequent hydrological changes are not directly linked to declining precipitation.^{PF}

350 ~~The hydrological and groundwater drought indices show different pictures at all stations:~~ At Schildow, hydrological and groundwater drought intensify over the course of the study period as is revealed by the indices. Surface water levels remained ~~most upstream water levels are~~ stable between 2008 and 2013. However, from 2014 onwards, drought periods became more frequent and severe, reaching a peak after 2018 ~~periods of water stress and occasional droughts start to appear, and they become more severe after 2018 from when severe and extreme surface water droughts were recorded,~~ with SSWLI3 values falling

355 below -2. This pattern is supported by a significant negative trend ($R^2 = 0.5$, MK $\tau = -0.50$, $p < 0.001$).

In terms of groundwater, Schildow experienced moderate droughts from around 2015, after a period of no droughts from 2008 to 2014, based on SGLI3 data. Between 2014 and 2016, mild but consistent groundwater droughts were observed, with SGLI3 values hovering around -1, indicating dry periods. From 2018 onwards, Schildow experienced prolonged groundwater stress, with SGLI3 values consistently below -1 until 2020. ~~The SGLI3 trend confirms this decline ($R^2 = 0.39$, MK $\tau = -0.47$, $p <$~~

360 ~~0.001).~~ Although no extreme groundwater droughts were recorded, the frequent moderate droughts suggest a lasting impact on the region's groundwater resources. ~~Out of 150 months, Schildow recorded 26 hydrological and 31 groundwater drought months. More than 70 percent of the hydrological droughts were followed by a groundwater drought within one month, while meteorological droughts propagated to hydrological droughts only in about 23 percent of the cases. This finding is supported by the conditional probability of a downstream drought occurring given that there was an upstream drought, compared to the~~

365 ~~probability of a downstream drought occurring even if there was no upstream drought: $P(SSWLI3 \mid SPI3) = 23$ percent vs $P(SSWLI3 \mid \text{no } SPI3) = 15$ percent, whereas $P(SGLI3 \mid SSWLI3) = 74$ percent vs $P(SGLI3 \mid \text{no } SSWLI3) = 11$ percent. This indicates a limited meteorological influence, but a strong downward propagation. Comparing the different drought indices, surface water systems were more affected by the 2018-2019 SPI3 drought event than groundwater systems in Schildow.~~

370 SSWLI3 data in Luebars shows different extremes. Between 2008 and 2010 there was a prolonged drought, with several months characterised by severe dry conditions (SSWLI3 values between -1.5 and -2). After 2010, there was an improvement in surface water conditions, as indicated by positive SSWLI3 values, reflecting the absence of drought, which lasted until around 2014 (similarly to Schildow). From 2014 onwards, ~~shorter but recurring drought periods appear of moderate to severe intensity between 2018 and 2021. SSWLI3 values show a significant drop, with shorter drought periods but the severity of these is much lower than at Schildow. Severe droughts only appear between 2018 and 2020 when there were instances of moderate to severe drought with a sustained period of SSWLI3 values persistently below -1.5.~~ These observations align with the trend results showing only a weak and statistically not significant decline ($R^2 = 0.02$, $p = 0.06$; MK $\tau = -0.12$).

The SGLI3 timeseries in Luebars shows a lot of similarities with the SSWLI3 curve in Schildow. Between 2008 and 2010,

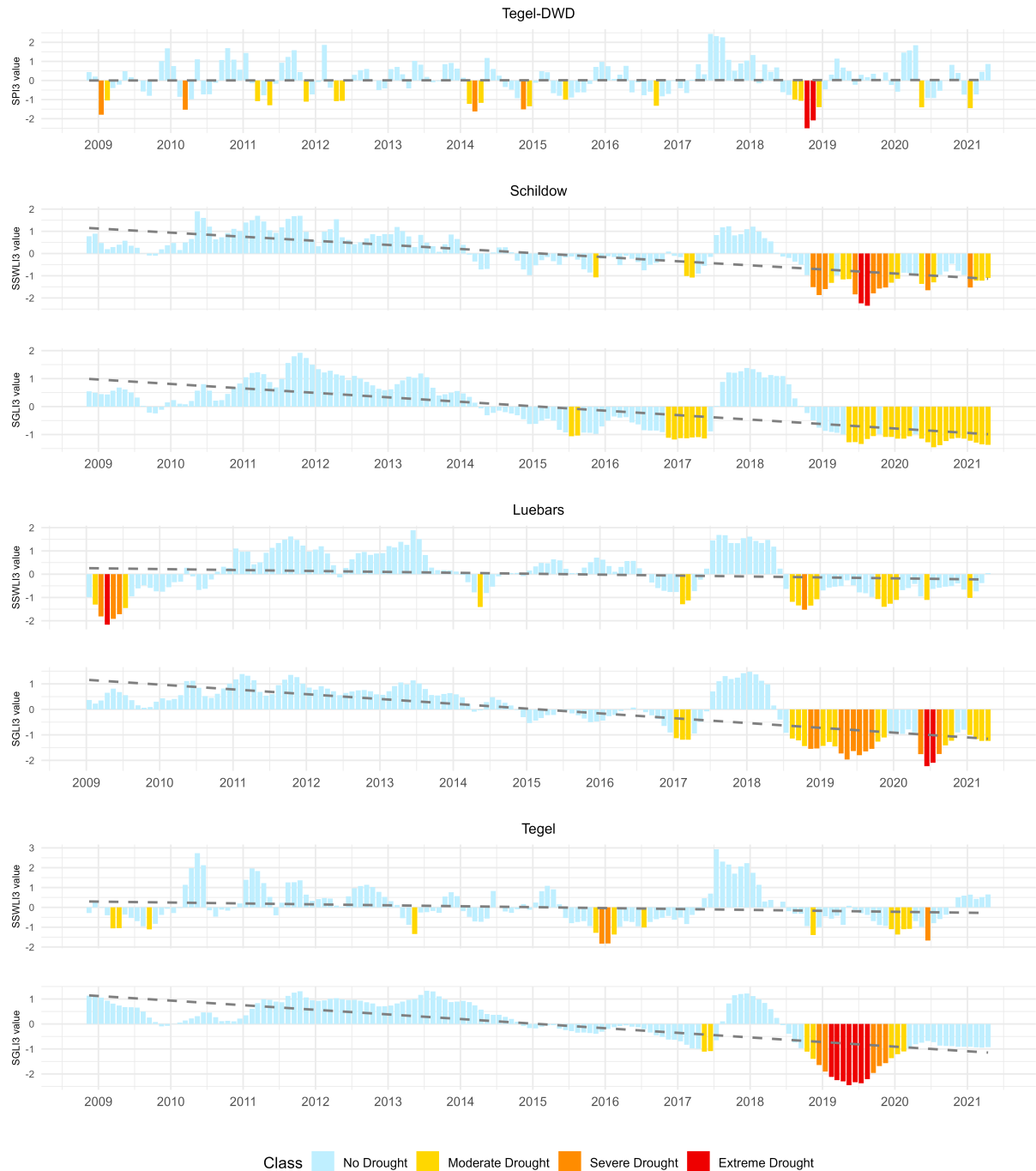


Figure 5. Time series of standardized drought indices across the study sites. The top panel shows the Standardized Precipitation Index (SPI3) at Tegel-DWD and the remaining panels display the Standardized Surface Water Level Index (SSWLI3) and Standardized Groundwater Level Index (SGLI3) for Schildow, Luebars, and Tegel. Bars are color-coded by drought class (no, moderate, severe, extreme), and dashed gray lines indicate long-term linear trends. **Drought Index Classes and long-term Trends across all Study Sites.**^{PF}

SGLI3 values remained positive, indicating the absence of groundwater drought. However, after 2015 there was a shift towards lower SGLI3 values signaling the onset of drought conditions. While groundwater drought persisted, its intensity was relatively lower compared to surface water scarcity. Between mid-2018 and 2020, there was a period of drought where groundwater scarcity worsened, with SGLI3 values below 1.5 or lower on several occasions from late 2019 to 2020. This period also saw several consecutive months of drought, signaling a considerable impact on local groundwater resources. This decline is statistically significant ($R^2 = 0.52$, $MK \tau = -0.49$, $p < 0.001$). In total, Luebars experienced 20 surface water and 29 groundwater drought months. Propagation analysis shows that 36 percent of meteorological droughts resulted in hydrological drought within one month, while 45 percent of hydrological droughts were followed by groundwater drought within the same time frame. Conditional probabilities confirm this pattern: $P(SSWLI3 | SPI3) = 36$ percent, $P(SSWLI3 | \text{no } SPI3) = 10$ percent and $P(SGLI3 | SSWLI3) = 45$ percent, $P(SGLI3 | \text{no } SSWLI3) = 16$ percent. This demonstrates that, at Luebars, hydrological droughts often emerge independently of immediate meteorological influences, but can quickly propagate to groundwater.

At Tegel, hydrological droughtsSSWLI3 values are generally less persistent, but highly variable.lower, and show higher variability. Interestingly, droughts here are much shorter, and less severe than the previous two sites. Initially, between 2008 and 2011, the SSWLI3 fluctuated between negative and positive^{PF} values, indicating periods of drought alternating with periods of recovery. However, after 2013 the drought periods became more frequent and more severe.there was a noticeable transition to prolonged and severe drought conditions. From mid-2015 to 2016, Tegel experienced surface water shortages, with SSWLI3 values falling below -1.5, indicating severe drought conditions during this period, with consistently negative SSWLI3 values over a prolonged period. One interesting anomaly at this site is the SSWLI3 drought in 2016 which is not visible in any other locations, and cannot be linked to a meteorological drought directly. Based on our available information we can only speculate on the reason behind this event, but a targeted study would be required for a better understanding. The long-term trend in hydrological drought is weak but significant ($R^2 = 0.03$, $p = 0.03$; $MK \tau = -0.14$, $p = 0.01$). Despite some improvement in surface water levels towards the end of 2020 and early 2021, the persistent drought from 2016 to 2020 highlights the vulnerability of Tegel's surface water systems to prolonged periods. This is the only site out of the three, that was strongly impacted by the severe meteorological drought period in 2015-2016. The Tegel site shows resilience in the sense of having the fastest recovery times of the three sites, but the severity within the shorter times could be equal, or higher.^{PF}

The SGLI3 data for Tegel show a sustained period of groundwater depletion, which contrasts with surface water resources. From 2008 to mid-2014, the SGLI3 remained mostly positive, indicating normal groundwater levels. However, from 2015 onwards, a prolonged period of groundwater scarcity appeared, with SGLI3 values dipping into negative values, indicating the onset of drought conditions. In 2019 and 2020, Tegel experienced an extended period of drought, with the SGLI3 falling below -2. The prolonged dry spell led to a depletion of groundwater reserves and an imbalance of conditions due to reduced rainfall, as indicated by the SPI3. At this site this period was shorter than at the previous two, but with more severe index values. Overall, 15 hydrological and 19 groundwater drought months were recorded, indicating a shorter drought persistence compared to Schildow and Luebars. The long-term trend for SGLI3 is statistically strong ($R^2 = 0.50$, $MK \tau = -0.50$, $p < 0.001$) and confirms ongoing groundwater decline. Propagation rates are the lowest among the stations, with only 14 percent

of meteorological droughts translating into hydrological droughts, and 20 percent of hydrological droughts further leading to groundwater droughts within the time frame of one month. Conditional probabilities confirm these findings, with $P(SSWLI3 | SPI3) = 14$ percent and $P(SGLI3 | SSWLI3) = 20$ percent, being both close to their no-drought baselines with $P(SSWLI3 | \text{no } SPI3) = 9.5$ percent and $P(SGLI3 | \text{no } SSWLI3) = 12$ percent. This indicates a weak connection between drought stages.

Drought propagation differs clearly between stations. Schildow shows strong downward propagation from surface water to groundwater, Luebars shows moderate coupling, and Tegel weak linkage with rapid recovery. These patterns indicate that despite stable meteorological conditions, there is increasing hydrological and groundwater drought intensity over time.

3.2.2 Comparative Drought Dynamics across Stations

Comparing the different sites, we see different responses to meteorological and hydrological stress. Between 2018 and 2020, SSWLI3 values often fell below -1 at all three sites. However, the groundwater systems at Luebars and Tegel responded more strongly to drought conditions, with SGLI3 values falling below -1.5 during the same period. This suggests a higher vulnerability of the groundwater to drought stress than surface water systems, which were more resilient to such short-term fluctuations. In contrast, Schildow showed more resilience in its groundwater systems compared to Luebars or Tegel. Schildow's surface water systems suffered severely during the drought between 2018 and 2020. Its groundwater systems did not experience any extreme events and only experienced moderate drought stress. This suggests that Schildow's groundwater systems are less vulnerable to drought impacts, even though surface water systems experienced higher levels of stress. The Mann-Kendall test for Schildow's SSWLI3 confirmed a significant downward trend ($MK \tau = -0.5, p < 0.001$), reflecting a long-term decline in surface water availability that was less pronounced in groundwater systems. Tegel showed the highest degree of both intensity and duration of groundwater droughts. Groundwater droughts at Tegel lasted the longest, with 17 consecutive months in 2019 and 2020. In contrast to Luebars and Schildow systems at Tegel were more susceptible to prolonged droughts, showing slower recovery and greater stress. Granger causality tests at Tegel also revealed a strong relationship between meteorological drought (SPI3) and both surface and groundwater systems, with an $p \ll 0.05$, highlighting the sensitivity of Tegel's hydrological systems to meteorological conditions. In summary, Tegel experienced the most severe and prolonged groundwater droughts, while Schildow showed more resilience in its groundwater systems despite severe surface water droughts. Luebars displayed the greatest variability in both surface and groundwater responses, with surface water systems being more resilient compared to their groundwater systems. These observations underline the varying vulnerability of stations along the Tegeler Fließ to drought, likely influenced by different local environmental conditions and/or water system uses.

3.3 Vegetation Response over Time

To investigate the impact of droughts on the vegetation, satellite-based NDVI data is used. The NDVI timeseries for the three sites are shown in Fig. 6. The seasonal variation of the vegetation in a cool temperate climate is evident from the NDVI values at all stations, with pronounced peaks in the summer months and dips in the winter months. Throughout the study period, NDVI values predominantly fall within the moderate to dense vegetation classes, indicating generally healthy vegetation. This

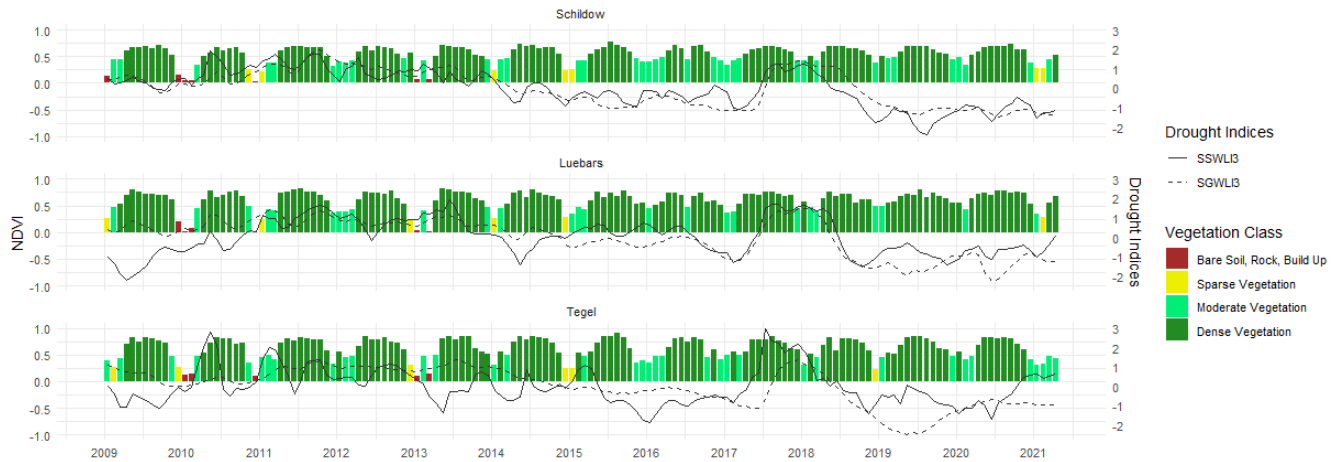


Figure 6. NDVI Classes with SSWLI3 and SGLI3 Time Series at the Stations Schildow, Luebars and Tegel.

resilience is consistent across Schildow, Luebars and Tegel, with Luebars and Tegel showing a slight advantage in vegetation health with 110 and 101 months of dense vegetation respectively. Schildow showed 96 months of dense vegetation, still within a healthy range but slightly lower than the other stations. Despite occasional fluctuations, NDVI values show a slight greening trend over time, although statistical tests did not yield significant results. For example, the Mann-Kendall test for NDVI at Schildow showed a MK $\tau = 0.066$ and $p = 0.23$, suggesting that the greening trend, while present, is weak and not statistically significant.

In particular, the early years of the study (2009-2011) show instances where vegetation fell into the Bare Soil or Rock/Build-Up classes, especially during the winter months. However, from 2014 these classes no longer occurred. This could indicate an increase in vegetation cover or an improvement in overall stability. Studies demonstrating higher growth rates in high-density regions with increasing air temperatures and decreasing precipitation provide evidence in favor of this, indicating that vegetation may profit from these circumstances in specific urban environments (Dahlhausen et al., 2018). Furthermore, the Deutscher Wetterdienst (n.d.) shows a rising trend in Berlin's winter air temperatures during the same time period, which highlights the possibility of more resilient and stable vegetation in milder winters. An even more plausible explanation however is the presence of long-lasting snow cover in the winter months. German weather service data shows snow cover in the winters of 2010 and 2011 at the Tegel station. While there are no direct DWD snow measurements at the stations Schildow and Luebars, the regional climate and landscape characteristics suggest that similar snow conditions likely prevailed at these sites as well. The proximity of the stations and the absence of significant topographic differences support this assumption. Luebars and Tegel were particularly affected by an SSWLI3 drought between 2009 and 2010, which seemed to coincide with reduced vegetation health in the following winter months. However, this relationship was not consistently observed, as winter months with lower NDVI values sometimes occurred without preceding drought events. After 2018, all stations experienced significant periods of drought, as reflected in the SSWLI3 and SGLI3 indices. SSWLI3 and SGLI3 values frequently fell below -1, indicating

moderate to severe drought conditions. Despite these persistent droughts, NDVI values remained in the moderate to dense vegetation classes, suggesting a degree of vegetation resilience in these ecosystems. However, Schildow and Tegel showed prolonged periods of stress where the vegetation took a little longer to recover, as indicated by longer periods in the sparse or moderate vegetation classes.

The NDVI data point to overall stable vegetation conditions and a weak evidence of long-term greening, despite recurring drought periods. These observations are further supported by statistical analyses.

Spearman correlation tests between NDVI and the drought indices (SSWLI3, SGLI3 and SPI3) showed no significant results, with correlation coefficients close to zero at all stations. This lack of strong correlation suggests that vegetation health, as represented by NDVI, may not directly reflect drought conditions in these ecosystems. However, Granger causality tests revealed more nuanced relationships. At Schildow, the combination of SPI3 and SSWLI3 was a significant predictor of NDVI with a lag of 1 month, with $p \ll 0.05$. SPI3 alone was also a significant predictor of NDVI at this station, although the combination of SPI3 and SSWLI3 performed better. At Luebars, SPI3 alone was found to be a significant predictor of NDVI with a lag of 1 month, while at Tegel, the combination of SPI3 and SSWLI3 also gave the best results, with $p \ll 0.05$.

While these data suggest some predictive relationships, it is important to note that satellite-based NDVI may be too coarse to adequately capture localized vegetation responses to drought. In-situ measures of vegetation health could provide more precise insights and supplement satellite-derived indices in these analyses.

In summary, while meteorological drought events, particularly after 2018, are clearly reflected in the SSWLI3 and SGLI3 indices, they do not appear to have a direct and immediate impact on vegetation health as measured by NDVI. Instead, ecosystems at these stations show a degree of resilience: vegetation is either not affected by or quickly recovers after periods of drought. The statistical tests reinforce the idea that while SPI3 and SSWLI3 may influence vegetation health, the overall relationship between drought indices and NDVI remains complex and non-linear across stations.

4 Discussion

4.1 Drought Dynamics and Interconnections of Drought Types

The stations along the Tegeler Fliess - Schildow, Luebars and Tegel - showed unique responses to drought stress over the study period, despite their geographical proximity. While the Tegel surface water system also experienced moderate to severe droughts from 2015 to 2020, the groundwater system faced more sustained stress. Schildow experienced more severe surface water droughts but had relatively stable groundwater levels. Luebars showed the greatest variability, with severe groundwater drought but more resilient surface water conditions.

At all stations, surface water droughts manifested and receded more quickly than groundwater droughts, which showed a delayed but longer-lasting response. For example, during the 2008-2010 and 2018-2020 droughts in Luebars, there was a decline in surface water levels followed by a lasting strain on groundwater resources, suggesting that it takes time for groundwater levels to recover once they have been depleted. Similarly, in Schildow, surface water droughts occurred rapidly with declining

precipitation, but groundwater droughts developed more gradually, suggesting that these systems absorb cumulative meteorological impacts over time. The main differences between these sites are primarily driven by their unique local environments, with the Tegel station situated in a peri-urban landscape that is influenced by a nearby densely developed urban area. In such an environment, the great amount of sealed surfaces put a lot of stress on groundwater resources via disturbed recharge processes (Zink et al., 2017). ~~Visual assessment of historical satellite imagery confirmed that no large-scale urban expansion or significant changes in surface sealing occurred directly near the wells during the study period (2008-2021). This increases confidence that the most severe groundwater drought impacts observed at Tegel are predominantly a response to hydrological stress, which in this case resulted in the most severe groundwater drought impacts.~~^{AG} While Tegel experienced the most severe groundwater stress, Schildow was more vulnerable to surface water droughts. Note that this could be an artefact from the methodology, as at the most upstream station river levels are the most sensitive to external influences. However the first half of the timeseries show similar drought dynamics, which indicates consistency in the methodology across the stations. Schildow is located in an open agricultural area, which implies a more direct connection with the atmospheric conditions. This resulted in a much faster hydrological drought dynamics, with droughts setting in and recovering faster than at the other sites. These fast recoveries however are not reflected in the groundwater: here, this site suffers the longest drought periods, with slightly mitigated impacts. These findings imply that drought monitoring programs should be tailored to the specific vulnerability of each site to ensure that both surface and groundwater resources are properly managed.

These results align with those of Van Loon (2015), who observed that groundwater droughts often persist after meteorological droughts and surface water droughts have ended. ~~The propagation of drought, from meteorological to hydrological drought via soil moisture was shown in Berlin on a catchment level by Pohle et al. (2025). Our results show that this propagation is observable on a smaller scale, but emphasizes the importance of local factors in relation to drought resilience.~~ Furthermore, the prolonged period of groundwater depletion in Tegel is comparable to the patterns observed by Nalbantis and Tsakiris (2009) in Spain, where groundwater systems were highly vulnerable to prolonged drought conditions. The downward trend in SPI3 observed in Grillakis (2019) highlights the increasing vulnerability to meteorological droughts across Europe due to changing precipitation patterns under climate change ~~and could become relevant for our study site in the future, even though no significant trend in SPI3 was observed during our study period.~~ . It is also important to note, that the three sites are located in hydrogeologically very different settings. Most notably, the aquifer at the Luebars site is an isolated local aquifer body, with limited recharge connections to the atmosphere. The Schildow site also features a thick isolating layer above the aquifer, which contributes to the observed higher resilience. This emphasizes the importance of recharge processes on groundwater resources of the region, and shows the importance to further investigate these processes in the region.

4.2 Impact of Drought on Vegetation

Despite the occurrence of severe and prolonged droughts, particularly from 2018 to 2020, vegetation along the Tegeler Fliess showed notable resilience. NDVI values generally remained within the moderate to dense vegetation classes, indicating that vegetation was not strongly impacted during periods of hydrological and hydrogeological drought. ~~Applying a remotely sensed index like MODIS NDVI to a catchment as small and heterogenous as the Tegeler Fliess immediately brings up the question of~~

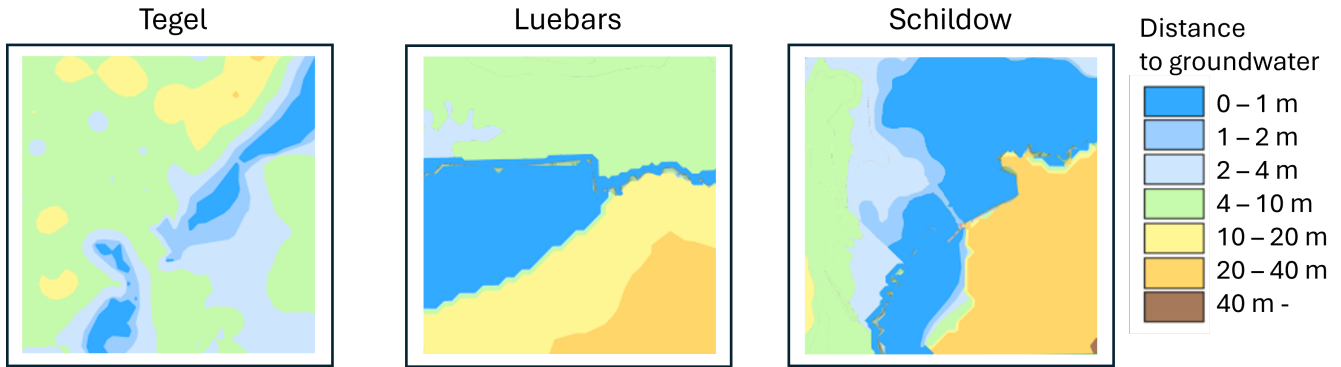


Figure 7. Average groundwater distances at Tegel, Luebars and Schildow.

scale. We are aware of the solid precedent for using MODIS at this level. For instance, Buras et al. (2021) effectively tracked forest drought stress across Germany by pairing NDVI with drought indices, and Liu et al. (2024) used similar indicators to investigate vegetation lag times across broad climate areas. The key difference, however, appears to be the uniformity of those study areas. In these kinds of transitional, peri-urban landscapes, the 250 m resolution feels like a particularly rudimentary tool. One averaged MODIS pixel value could easily be blending the signature of a dense patch of forest, the irrigated green of a few suburban lawns, and the asphalt of a parking lot. This is the classic 'mixed-pixel' problem. It seems to be a fundamental limitation of the data in this context, suggesting that any findings should probably be interpreted with a healthy dose of skepticism.^{AG} To validate the MODIS-based NDVI results, we also analysed NDVI based on Landsat data, which offer higher spatial resolution (30 m) compared to MODIS (250 m). However, the Landsat record contained many temporal gaps due to cloud cover and limited revisit frequency, while MODIS provided more consistent temporal coverage. For the most part, the two datasets aligned well (see Fig. S4 in the Supplementary Material), except for a systematic discrepancy during winter months, which is interesting but not relevant to this study's objectives.^{PF}

~~Still~~, Granger causality tests showed that SPI3 and SSWLI3 influenced NDVI at several stations, particularly at Schildow and Tegel. However, SGLI3 did not show a significant relationship with NDVI. These results suggest that surface water and precipitation play a more critical role in maintaining vegetation than groundwater.

Not having a strong correlation between the drought indices and NDVI indicates a resilience within the ecosystem, likely to be influenced by different factors. These could include vegetation type, soil moisture [groundwater depth](#), and land management practices ~~such as irrigation~~. In the regions around Schildow and Luebars, the NDVI remained stable, despite hydrological and groundwater drought conditions. The small distance to the groundwater table near the river allows for deep rooted plants to use groundwater resources directly, as a buffer for drought periods with low soil moisture content (see Fig. 7). While this connection could be severed due to groundwater level decrease, we did not see it happen during the study time frame. Regional scale studies however warn about a general decreasing trend in groundwater levels (Heudorfer et al. , 2023; Somogyvári et al. , 2024), therefore the investigation of the groundwater-vegetation relationship stays relevant for the future. Irrigation practices,

and water infrastructure could also provide resilience. For example at the fields near Luebars there is a trench network that could help a more efficient distribution of water in the area after stronger rainfall events than natural runoff. We would also like to note that monitoring of vegetation health should go beyond the use of NDVI, as this index alone may not capture the extent of water stress, especially in areas of agriculture. Adaptive management strategies should focus on balancing the needs of both natural ecosystems and agricultural activities, which can further exacerbate water depletion in times of drought. Take Luebars, for example. The NDVI signal there is likely dominated by seasonal agriculture, such as cereals and fodder grasses. While these crops are known to show sharp declines in NDVI during a drought, the use of irrigation could be propping up these values, potentially masking the full impact of water scarcity. Schildow, in contrast, tells a different story. Its diverse mix of deep-rooted trees and fen meadows may contribute to the more buffered NDVI response we observed, suggesting a landscape with greater natural resilience. Then there is the peri-urban environment of Tegel, where the vegetation is almost certainly managed through irrigation or municipal landscaping. This would help explain why its NDVI values stay high even as local groundwater levels decline. What this all seems to suggest is that in agricultural or managed areas, we should be cautious about relying on NDVI alone. The index might not fully capture the extent of water stress, especially when human intervention obscures the natural signal. To get the real story, we probably need to look beyond a single satellite indice.^{AG}

Furthermore, the resilience observed in the vegetation across the stations suggests that the natural ecosystems in the Tegeler Fliess area are relatively robust even during periods of water scarcity. ~~It is also^{AG} possible that the shallow-rooted plants typical of these areas are more dependent on short-term precipitation and surface water sources than on deeper groundwater (Jackson et al., 1996), and thus show limited effects of groundwater drought.~~ In addition, the study period ending in April 2021 may not have been long enough to capture the delayed effects of the prolonged drought conditions of 2018-2020 on vegetation. The time frame of our study was limited by the availability of complete data sets. Even though some measurements date as far back as 1945, the surface water level station at Luebars only started in 2008 and precipitation measurements were discontinued at the site in 2021. Furthermore, while a visual inspection of historical satellite imagery suggested that localized land use changes did not considerably influence the observed dynamics, the analysis lacks precise local data on specific anthropogenic activities, such as subsurface pumping rates, development permits, or changes in stormwater infrastructure. The absence of such data represents a restriction in fully quantifying all potential human impacts on water level dynamics.^{AG} The divergence between drought indices and NDVI observed in this study is consistent with findings from similar regions where vegetation resilience or human intervention (e.g. irrigation) mitigated the effects of drought (Gessner et al., 2023). This suggests that in peri-urban catchments such as the Tegeler Fliess, the response of vegetation to drought is more complex and may require more detailed, long-term studies that consider both natural and anthropogenic factors.

5 Conclusions

This study examined drought patterns in the Tegeler Fliess area by analyzing meteorological droughts and their impact on surface water and groundwater systems from 2008 to 2021. Several significant droughts were observed during this period. The

most severe droughts occurred between 2018 and 2020. The results showed that surface water systems responded quickly to changes in precipitation (SPI3), with rapid onset and recovery phases. At the same time, groundwater systems experienced prolonged droughts and slower recovery times. In particular, Tegel groundwater experienced a severe 17-month drought from 2019 to 2020, while Schildow showed more resilience in groundwater levels but showed stress in surface water systems.

595 Luebars showed variability in surface water responses, but its groundwater systems appeared more vulnerable in recent years. The interpolation of groundwater data, particularly for Schildow, and the study time frame introduced some uncertainty. This is a key limitation, as the study period of 13 years may not fully capture longer-term climate cycles that influence drought patterns. Vegetation health, as measured by NDVI values, remained relatively stable throughout the study, with moderate to dense vegetation classes persisting throughout the study period. The lack of significant correlation between drought indices and NDVI

600 suggests a complex, non-linear relationship between water availability and vegetation response, with some ecosystems showing resilience, particularly during shorter droughts. However, this finding should be interpreted with caution due to limitations in data resolution and ~~the complex land cover structure across the study sites~~^{classification methods}^{AG}. The MODIS NDVI data with a spatial resolution of 250 m ~~may be too coarse to adequately~~^{may not}^{AG} capture finer scale vegetation responses, especially in areas with heterogeneous land use such as Schildow's diverse patches or Luebar's distinct agricultural fields. This

605 ~~heterogeneity may partially explain the inconsistent response of vegetation to drought conditions in our results. Furthermore, while~~^{AG} the subjective classification of NDVI values into vegetation classes based on De La Iglesia Martinez and Labib (2023) may not fully capture the complexity of vegetation dynamics. While the SPI is a robust and widely used metric for drought assessment, its simplicity does not account for other critical factors, such as temperature or soil moisture, which could improve the understanding of drought impacts. Future research should extend this work by using more long-term datasets

610 or incorporating additional drought indicators, such as soil moisture or temperature-based indices. ~~The investigation of soil moisture is especially important, as its dynamic is a key element to understand the vegetation response to drought conditions and to understand how ecosystems could recover from prolonged drought. Investigating the lag between drought onset and vegetation response for different plant species could provide insights into how ecosystems recover from prolonged drought.~~ In addition, higher resolution data or a vegetation index that better accounts for different vegetation types and conditions would

615 improve the accuracy of monitoring vegetation health. Integrating human factors such as land use and irrigation practices could also improve our understanding of how anthropogenic activities affect water availability and vegetation resilience in peri-urban environments such as the Tegeler Fließ.

Code and data availability. The used surface water and groundwater data can be accessed at the water portal of the Berlin Senate https://wasserportal.berlin.de/stationen_start.php (SenUVK, 2023) and at the water portal of Brandenburg: <https://apw.brandenburg.de/> (Landesamt für Umwelt Brandenburg, 2023). Precipitation data is openly accessible from the German Weather Service (DWD) https://opendata.dwd.de/climate_environment/CDC/. Code is available upon request from the corresponding author.

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Author contributions. PF and AG carried out the data collection and the analysis. All authors contributed to the writing and editing of the manuscript.

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

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References

- Abu Arra, A., and Şişman, E. (2024). A comprehensive analysis and comparison of SPI and SPEI for spatiotemporal drought evaluation. *Environmental Monitoring and Assessment*, 196(10), 980. <https://doi.org/10.1007/s10661-024-13127-7>
- 630 Bachmair, S., Tanguy, M., Hannaford, J., and Stahl, K. (2018). How well do meteorological indicators represent agricultural and forest drought across Europe? *Environmental Research Letters*, 13(3), 034042. <https://doi.org/10.1088/1748-9326/aaafda>
- Baugenossenschaft Freie Scholle zu Berlin eG. (2024). Tegeler Fliess. Retrieved from <https://www.freiescholle.de/siedlungen/tegeler-flieess/>. Last accessed 26 September 2024.
- Berliner Senatsverwaltung für Stadtentwicklung (Eds.): Natura 2000-Gebiet Tegeler Fließtal. Retrieved from <https://www.berlin.de/sen/uvk/natur-und-gruen/naturschutz/natura-2000/natura-gebiete/tegeler-fliesstal/>. Last accessed 11 July 2025.
- 635 Bloch, R., Wechsung, F., Heß, J., et al. (2015). Climate change impacts of legume-grass swards: implications for organic farming in the Federal State of Brandenburg, Germany. *Regional Environmental Change*, 15, 405–414. <https://doi.org/10.1007/s10113-014-0656-2>
- Bloomfield, J. P., and Marchant, B. P. (2013). Analysis of groundwater drought building on the standardised precipitation index approach. *Hydrology and Earth System Sciences*, 17(12), 4769–4787. <https://doi.org/10.5194/hess-17-4769-2013>
- 640 Blöschl, G., Ardoin-Bardin, S., Bonell, M., Dörninger, M., Goodrich, D., Gutknecht, D., Matamoros, D., Merz, B., Shand, P., and Szolgay, J. (2007). At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes*, 21(9), 1241–1247. <https://doi.org/10.1002/hyp.6669>
- Beguería, S., and Vicente-Serrano, S. M. (2023). *SPEI: Calculation of the Standardized Precipitation-Evapotranspiration Index* (R package version 1.8.1). Retrieved from <https://CRAN.R-project.org/package=SPEI>. Last accessed 28 September 2024.
- 645 Boessenkool, B. (2023). *rdwd: Select and Download Climate Data from 'DWD' (German Weather Service)* (R package version 1.8.0). Retrieved from <https://CRAN.R-project.org/package=rdwd>. Last accessed 26 September 2024.
- Buras, A., Rammig, A., and Zang, C. S. (2021). The European Forest Condition Monitor: Using remotely sensed NDVI to track forest stress across Europe. *Frontiers in Plant Science*, 12, 689220. <https://doi.org/10.3389/fpls.2021.689220>
- Chen, X., et al. (2018). The mixed pixel effect in land surface phenology: A simulation study. *Remote Sensing of Environment*, 211, 338–344. <https://doi.org/10.1016/j.rse.2018.04.030>
- 650 Crausbay, S. D., Ramirez, A. R., Carter, S. L., Cross, M. S., Hall, K. R., Bathke, D. J., Betancourt, J. L., Colt, S., Cravens, A. E., Dalton, M. S., Dunham, J. B., Hay, L. E., Hayes, M. J., McEvoy, J., McNutt, C. A., Moritz, M. A., Nislow, K. H., Raheem, N., and Sanford, T. (2017). Defining ecological drought for the twenty-first century. *Bulletin of the American Meteorological Society*, 98(12), 2543–2550. <https://doi.org/10.1175/BAMS-D-16-0292.1>
- 655 Cullmann, A., Sundermann, G., Wäagner, N., von Hirschhausen, C. R., and Kemfert, C. (2022). Water resources in Germany: Increasingly polluted and regionally overused. *DIW Weekly Report*, 12(49/50), 307–315. https://doi.org/10.18723/diw_dwr:2022-49-1
- Dahlhausen, J., Rötzer, T., Biber, P., et al. (2018). Urban climate modifies tree growth in Berlin. *International Journal of Biometeorology*, 62, 795–808. <https://doi.org/10.1007/s00484-017-1481-3>
- De La Iglesia Martinez, A., and Labib, S. M. (2023). Demystifying normalized difference vegetation index (NDVI) for greenness exposure assessments and policy interventions in urban greening. *Environmental Research*, 220, 115155. <https://doi.org/10.1016/j.envres.2022.115155>
- 660 Deutscher Wetterdienst. (2024). Daily station observations (temperature, pressure, precipitation, sunshine duration, etc.) for Germany, Version v24.3.

- Deutscher Wetterdienst (DWD). (n.d.). German Climate Atlas. Retrieved from https://www.dwd.de/EN/climate_environment/climateatlas/climateatlas_node.html. Last accessed 28 January 2024.
- 665 European Environment Agency (EEA). (2021). CLCplus Backbone 2021 (10 m raster) – Europe. *Copernicus Land Monitoring Service*. Retrieved from <https://land.copernicus.eu/en/products/clc-backbone>. Last accessed 20 October 2025.
- Germer, S., Kaiser, K., Bens, O., and Hüttl, R. F. (2011). Water balance changes and responses of ecosystems and society in the Berlin-Brandenburg region – a review. *DIE ERDE – Journal of the Geographical Society of Berlin*, 142(1-2), 65–95. Retrieved from <https://www.die-erde.org/index.php/die-erde/article/view/43>.
- 670 Gessner, U., Reinermann, S., Asam, S., and Kuenzer, C. (2023). Vegetation Stress Monitor—Assessment of drought and temperature-related effects on vegetation in Germany analyzing MODIS time series over 23 years. *Remote Sensing*, 15(22), 5428. <https://doi.org/10.3390/rs15225428>
- Granger, C. W. (1969). Investigating causal relations by econometric models and cross-spectral methods. *Econometrica: Journal of the Econometric Society*, 424–438. <https://doi.org/10.2307/1912791>
- 675 Grillakis, M. G. (2019). Increase in severe and extreme soil moisture droughts for Europe under climate change. *Science of The Total Environment*, 660, 1245–1255. <https://doi.org/10.1016/j.scitotenv.2019.01.001>
- Heim Jr, R. R. (2002). A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society*, 83(8), 1149–1166. <https://doi.org/10.1175/1520-0477-83.8.1149>
- Helmholtz Centre for Environmental Research (2023). Drought Monitor Germany. Retrieved from <https://www.ufz.de/index.php?en=37937>.
- 680 Last accessed 25 September 2024.
- Heudorfer, B., Liesch, T., Broda, S. (2023). On the challenges of global entity-aware deep learning models for groundwater level prediction. *Hydrology and Earth System Sciences Discussions*, 2023, 1-28. <https://doi.org/10.5194/hess-28-525-2024>
- Hufkens, K. (2023). The MODISTools package: an interface to the MODIS Land Products Subsets Web Services. *Zenodo*. <https://doi.org/10.5281/zenodo.7551165>
- 685 Ihinegbu, C., and Ogunwumi, T. (2022). Multi-criteria modelling of drought: a study of Brandenburg Federal State, Germany. *Modeling Earth Systems and Environment*, 8, 2035–2049. <https://doi.org/10.1007/s40808-021-01197-2>
- Jackson, R. B., Canadell, J., Ehleringer, J. R., et al. (1996). A global analysis of root distributions for terrestrial biomes. *Oecologia*, 108, 389–411. <https://doi.org/10.1007/BF00333714>
- Jensen, J. (2013). *Remote sensing of the environment: An Earth resource perspective*. Pearson Education, Limited. Retrieved from <https://ebookcentral.proquest.com/lib/kbdk/detail.action?docID=5173657>. Last accessed 7 November 2024.
- 690 Jimenez, R. B., Lane, K. J., Hutyra, L. R., and Fabian, M. P. (2022). Spatial resolution of Normalized Difference Vegetation Index and greenness exposure misclassification in an urban cohort. *Journal of Exposure Science and Environmental Epidemiology*, 32, 213–222. <https://doi.org/10.1038/s41370-022-00409-w>
- Kahlenborn, W., Porst, L., Voss, M., Fritsch, U., Renner, K., Zebisch, M., Wolf, M., Schönthaler, K., and Schauser, I.
- 695 (2021). *Climate Impact and Risk Assessment 2021 for Germany – Summary*. Umweltbundesamt, Dessau-Roßlau. Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/cc_27-2021_climate_impact_and_risk_assessment_2021_for_germany_english_summary_bf.pdf. Last accessed 29 December 2024.
- Kuhlemann, L. M., Dubbert, M., Pätzold, S., and Cuntz, M. (2022). The imprint of hydroclimate, urbanization and catchment connectivity on the stable isotope dynamics of a large river in Berlin. *Journal of Hydrology*, 613, 128335. <https://doi.org/10.1016/j.jhydrol.2022.128335>

- Kloos, S., Yuan, Y., Castelli, M., and Menzel, A. (2021). Agricultural drought detection with MODIS-based vegetation health indices in Southeast Germany. *Remote Sensing*, 13(19), 3907. <https://doi.org/10.3390/rs13193907>
- Kong, D., Miao, C., Duan, Q., Lei, X., and Li, H. (2018). Vegetation-climate interactions on the Loess Plateau: A nonlinear Granger causality analysis. *Journal of Geophysical Research: Atmospheres*, 123, 11,068–11,079. <https://doi.org/10.1029/2018JD029036>
- Köstner, B., Surke, M., and Bernhofer, C. (2007). Klimadiagnose der Region Berlin / Barnim / Uckermark / Uecker-Randow für den Zeitraum 1951-2006. Materialien der Interdisziplinären Arbeitsgruppe Zukunftsorientierte Nutzung ländlicher Räume LandInnovation. Berlin-Brandenburgische Akademie der Wissenschaften, Nr. 18. Berlin.
- Li, Z., Sun, F., Wang, H., Wang, T., and Feng, Y. (2024). Detecting the interactions between vegetation greenness and drought globally. *Atmospheric Research*, 304, 107409. <https://doi.org/10.1016/j.atmosres.2024.107409>
- Liu, M., Zhang, X., Liao, J., and Zhu, Y. (2024). Time-lag and accumulation responses of vegetation growth to climate extremes in China. *Science of the Total Environment*, 945, 174084. <https://doi.org/10.1016/j.scitotenv.2024.174084>
- McKee, T. B., Doesken, N. J., and Kleist, J. (1993). The relationship of drought frequency and duration to time scales. In *Proceedings of the 8th Conference on Applied Climatology* (Vol. 17, No. 22, pp. 179–183).
- McLeod, A. (2022). *Kendall: Kendall Rank Correlation and Mann-Kendall Trend Test* (R package version 2.2.1). Retrieved from <https://CRAN.R-project.org/package=Kendall>.
- NABU Berlin. (n.d.). Das Tegeler Fließtal, Naturschatz im Norden Berlins. Retrieved from <https://berlin.nabu.de/stadt-und-natur/naturschutz-berlin/18942.html>. Last accessed 9 December 2024.
- Nalbantis, I., and Tsakiris, G. (2009). Assessment of hydrological drought revisited. *Water Resources Management*, 23, 881–897. <https://doi.org/10.1007/s11269-008-9305-1>
- Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B., and Running, S. W. (2003). Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, 300(5625), 1560–1563. <https://doi.org/10.1126/science.1082750>
- Ojha, S. S., Singh, V., and Roshni, T. (2021). Comparison of meteorological drought using SPI and SPEI. *Civil Engineering Journal*, 7(12), 2130–2149. <https://doi.org/10.28991/cej-2021-03091783>
- Papagiannopoulou, C., Miralles, D. G., Dorigo, W. A., Verhoest, N. E. C., Depoorter, M., and Waegeman, W. (2017). Vegetation anomalies caused by antecedent precipitation in most of the world. *Environmental Research Letters*, 12(7), 074016. <https://doi.org/10.1088/1748-9326/aa7145>
- Pei, Z., Fang, S., Wang, L., and Yang, W. (2020). Comparative analysis of drought indicated by the SPI and SPEI at various timescales in Inner Mongolia, China. *Water*, 12(7), 1925. <https://doi.org/10.3390/w12071925>
- Pfaff, B. (2008). VAR, SVAR and SVEC models: Implementation within R package vars. *Journal of Statistical Software*, 27(4). Retrieved from <https://www.jstatsoft.org/v27/i04/>.
- Pohle, I., Zeilfelder, S., Birner, J. and Creutzfeldt, B. (2025). The 2018–2023 drought in Berlin: impacts and analysis of the perspective of water resources management. *Natural Hazards and Earth System Sciences*, <https://doi.org/10.5194/nhess-25-1293-2025>
- R Core Team. (2024). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from <https://www.R-project.org/>.
- Reyer, C., Bachinger, J., Bloch, R., et al. (2012). Climate change adaptation and sustainable regional development: A case study for the Federal State of Brandenburg, Germany. *Regional Environmental Change*, 12, 523–542. <https://doi.org/10.1007/s10113-011-0269-y>

- Schindler, U., Steidl, J., Müller, L., Eulenstein, F., and Thiere, J. (2007). Drought risk to agricultural land in Northeast and Central Germany. *Journal of Plant Nutrition and Soil Science*, 170(3), 357–362. <https://doi.org/10.1002/jpln.200622045>
- Shojaie, A., and Fox, E. B. (2022). Granger causality: A review and recent advances. *Annual Review of Statistics and Its Application*, 9(1), 289–319. <https://doi.org/10.1146/annurev-statistics-040120-010930>
- Singh, N. K., and Borrok, D. M. (2019). A Granger causality analysis of groundwater patterns over a half-century. *Scientific Reports*, 9, 12828. <https://doi.org/10.1038/s41598-019-49278-8>
- Smakhtin, V. U., and Schipper, E. L. F. (2008). Droughts: The impact of semantics and perceptions. *Water Policy*, 10(2), 131–143. <https://doi.org/10.2166/wp.2008.036>
- Somogyvári, M., Scherer, D., Bart, F., Fehrenbach, U., Okujeni, A., Krueger, T. (2024). A hybrid data-driven approach to analyze the drivers of lake level dynamics. *Hydrology and Earth System Sciences*, 28(18), 4331–4348. <https://doi.org/10.5194/hess-28-4331-2024>
- Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P., and Dosio, A. (2018). Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, 38(4), 1718–1736. <https://doi.org/10.1002/joc.5291>
- Stagge, J. H., Kohn, I., Tallaksen, L. M., and Stahl, K. (2015). Modeling drought impact occurrence based on meteorological drought indices in Europe. *Journal of Hydrology*, 530, 37–50. <https://doi.org/10.1016/j.jhydrol.2015.09.039>
- Svoboda, M. D., and Fuchs, B. A. (2016). *Handbook of drought indicators and indices* (Vol. 2). World Meteorological Organization, Geneva, Switzerland.
- Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8(2), 127–150.
- Van Loon, A. F. (2015). Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water*, 2(4), 359–392. <https://doi.org/10.1002/wat2.1085>
- Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, 23(7), 1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>
- Vicente-Serrano, S. M., López-Moreno, J. I., Beguería, S., Lorenzo-Lacruz, J., Azorin-Molina, C., and Morán-Tejada, E. (2012). Accurate computation of a streamflow drought index. *Journal of Hydrologic Engineering*, 17(2), 318–332. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000433](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000433)
- Xiao, L., Guo, C., Zheng, C., Lu, Z., Khan, M. A., Zhou, J., and Wu, X. (2025). Dense vegetation as a natural buffer: Mitigating and decelerating drought propagation. *Journal of Environmental Management*, 389, 126027. <https://doi.org/10.1016/j.jenvman.2025.126027>
- Yihdego, Y., Vaheddoost, B., and Al-Weshah, R. A. (2019). Drought indices and indicators revisited. *Arabian Journal of Geosciences*, 12, 1–12. <https://doi.org/10.1007/s12517-019-4237-z>
- Zeileis, A., and Hothorn, T. (2002). lmtest: Diagnostic checking in regression relationships. *R News*, 2(3), 7–10. Retrieved from <https://CRAN.R-project.org/doc/Rnews/>.
- Zhong, R., Zhao, T., Chen, X., and Jin, H. (2022). Monitoring drought in ungauged areas using satellite altimetry: The Standardized River Stage Index. *Journal of Hydrology*, 612, 128308. <https://doi.org/10.1016/j.jhydrol.2022.128308>
- Zink, M., Kumar, R., Cuntz, M., and Samaniego, L. (2017). A high-resolution dataset of water fluxes and states for Germany accounting for parametric uncertainty. *Hydrol. Earth Syst. Sci.*, 21(3), 1769–1790. doi: 10.5194/hess-21-1769-2017
- Zolghadr-Asli, B., Enayati, M., Pourghasemi, H. R., Naghdizadegan Jahromi, M., and Tiefenbacher, J. P. (2021). Application of Granger-causality to study the climate change impacts on depletion patterns of inland water bodies. *Hydrological Sciences Journal*, 66(12), 1767–1776. <https://doi.org/10.1080/02626667.2021.1944633>