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

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Abstract. 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 severe and prolonged groundwater droughts, while the groundwater in the nature reserve and fen meadow area (Schildow) 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 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, and it is evident that the Berlin/Brandenburg region will not be spared from the consequences of climate change. Studies show that extreme heat waves and dry spells will become increasingly frequent and intense 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

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droughts become longer and more spatially 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 areas, 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). 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 empirical 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 Institut, 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, water stress, increased fire 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 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 (SenMVKU, n.d.). There are several surface and groundwater monitoring stations along the stream, so data availability is good, but 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 Institut, 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.

Given its multifaceted nature, a universal drought definition does not exist; rather, it depends on the perspective and objective of a study. 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; Yihdego et al., 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

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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., 2010). 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). However, the complexity and additional data requirements limit the use of SPEI.

In this study a three-month accumulation period was used to evaluate drought conditions, based on the studies of McKee et al. (1993) and Bloomfield and Marchant (2013). By using this approach, we were able to analyse short-term drought patterns in the area, making the indices comparable with one another and across study sites, while also gaining valuable insights into various aspects of drought dynamics such as meteorological influences and how they affect surface and groundwater systems. By combining these drought indices with an examination of long-term trends and conducting Granger Causality tests the research seeks to uncover trends in how droughts propagate and impact vegetation health.

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 uncover persistent drought-vegetation dynamics that have emerged over the study period. 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?
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

2.1 Study Area

The Tegeler Fließ is an approximately 30 km long stream that crosses the northern border between Berlin and Brandenburg. Its catchment area spans 126 square kilometers. 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

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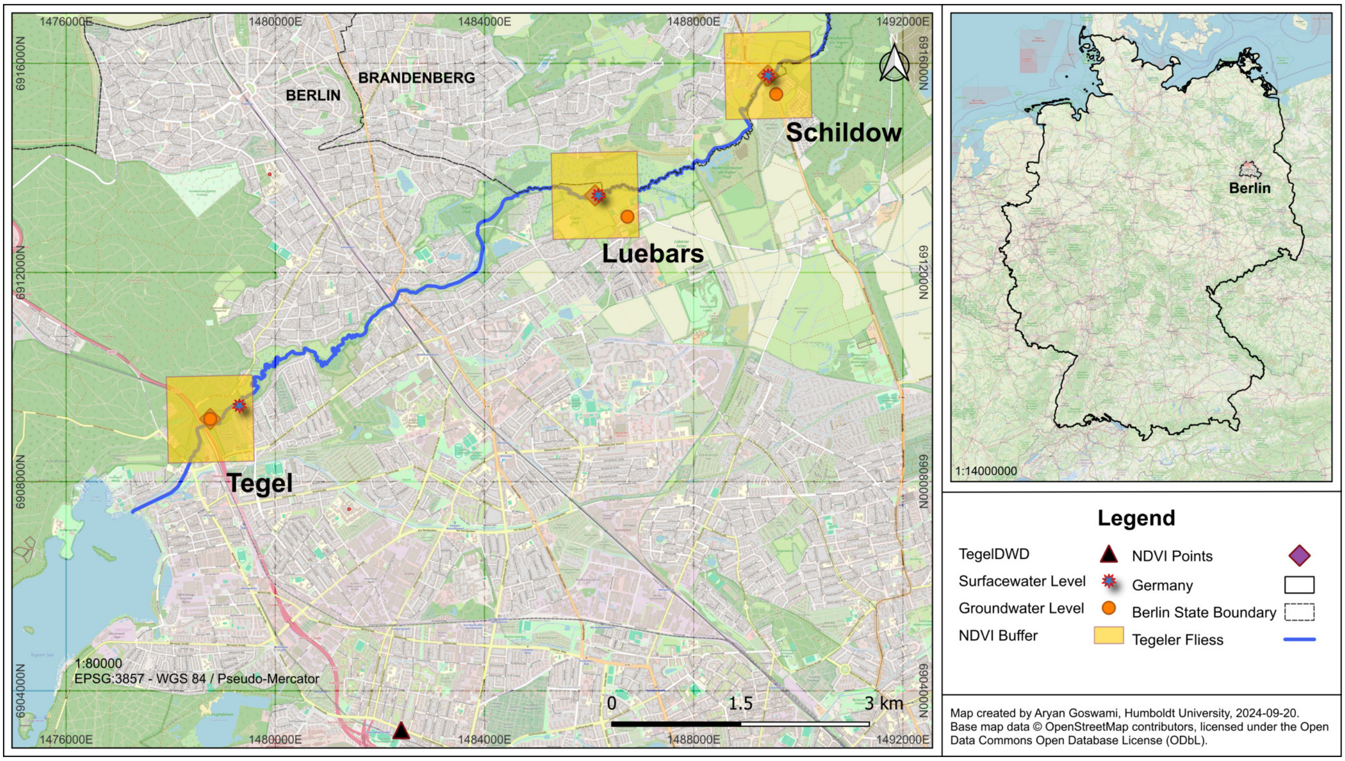

Figure 1. Map of Study Area.

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; SenMVKU, n.d.). The selected sites - Schildow, Luebars and Tegel - represent key points along the Tegeler Fließ. 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. 1).

2.2 Data Collection and Processing Tools

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, indicating that while it is complete, some parameters may still require correction. Given the short distances between stations within the Tegeler Fließ

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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	

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 (R Core Team, 2024) was used for data pre-processing and all analysis steps (see 2.4). Daily surface water and groundwater level measurements were obtained from 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 measurements, while groundwater data at Tegel and Luebars showed minor gaps with no measurements. 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 metres and a temporal resolution of 16 days, accessed using the R package ’MODISTools’ (Hufkens, 2023). A point was selected near each site, the coordinates of which are given in Table 1, and the mean NDVI value within a 500 metre buffer (see Fig. 1) was calculated to represent vegetation health.

2.3 Drought Indices Calculation

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; Yihdego et al., 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. 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). The following subsections describe the methods used to calculate the indices used in this study.

2.3.1 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 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 (ibid). 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) is 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.

2.3.2 Standardized Surface Water Level Index (SSWLI) and Standarized Groundwater Level Index (SGLI)

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; Bloomfield and Marchant, 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.

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). 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. Note however that this approach has a lower accuracy than traditional discharge based indices, as river 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.

The Standarised 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 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 SPI, SWLI and SGLI was also calculated over a three-month period.

Drought classes are used to categorise the severity of drought conditions based on standard thresholds of different drought indices (see Table 2). For this study, we classified drought events according to the standardised values of SPI, SSWLI and SGLI, following common classification systems in the drought literature (McKee et al., 1993; Nalbantis and Tsakiris, 2009). A drought index value of $\leq$ -1 indicates at least moderate drought. This is when conditions are at least one standard deviation

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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.

2.3.3 Normalized 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; 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 (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.

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	$0.5 \leq x < 1$

2.4 Analysis Process

The overview of the analysis process is shown in Fig. 2. 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

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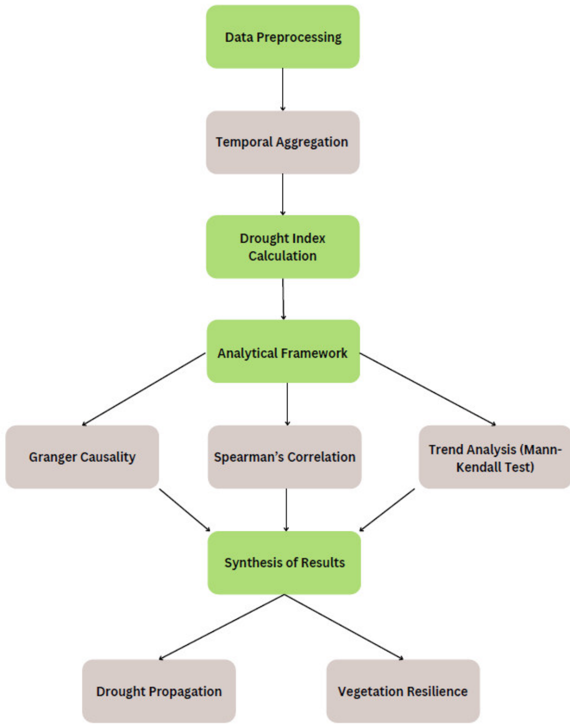

Figure 2. Overview of the data analysis process.

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). 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 Granger causality 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.

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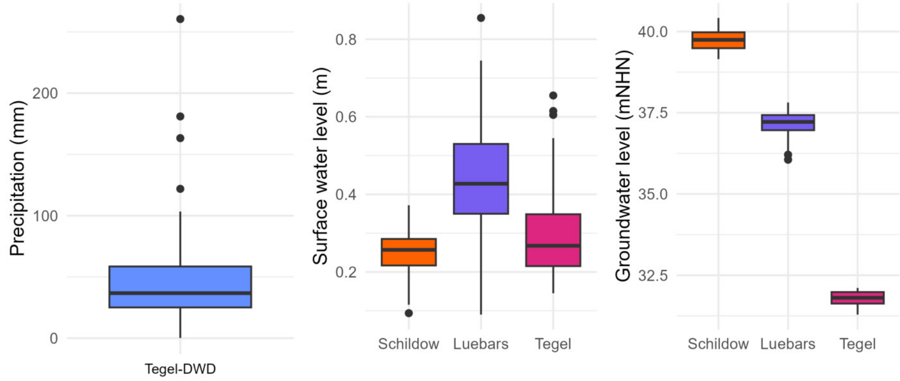

Figure 3. Statistics of precipitation, surface water level and groundwater level at the different stations.

3 Results

3.1 Precipitation and Water Level Dynamics

In Fig. 3 the general statistics of the input data: precipitation, surface water and groundwater levels are shown. At glance over Fig. 3, the precipitation patterns at the Tegel-DWD station averaged 45 mm per month, with occasional heavy rainfall events exceeding 100 mm. These heavy rainfall events are likely to contribute to localised water level surges. Comparing surface and groundwater levels, however, reveals the variation across sites. Surface water levels at Luebars fluctuated between 35 cm and 55 cm, visually showing the greatest variability between stations. In contrast, Schildow had more stable surface water levels, averaging around 23 cm throughout the study period. The Tegel station had a similar mean surface water level, but greater variability, indicating possible site-specific differences in hydrological behaviour. 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 metres above sea level (mNHN), while Tegel recorded the lowest, with a difference of 8 meter 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. 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. 4, the stations show distinct trends in meteorological, surface water and groundwater drought indices, highlighting localised hydrological stress.

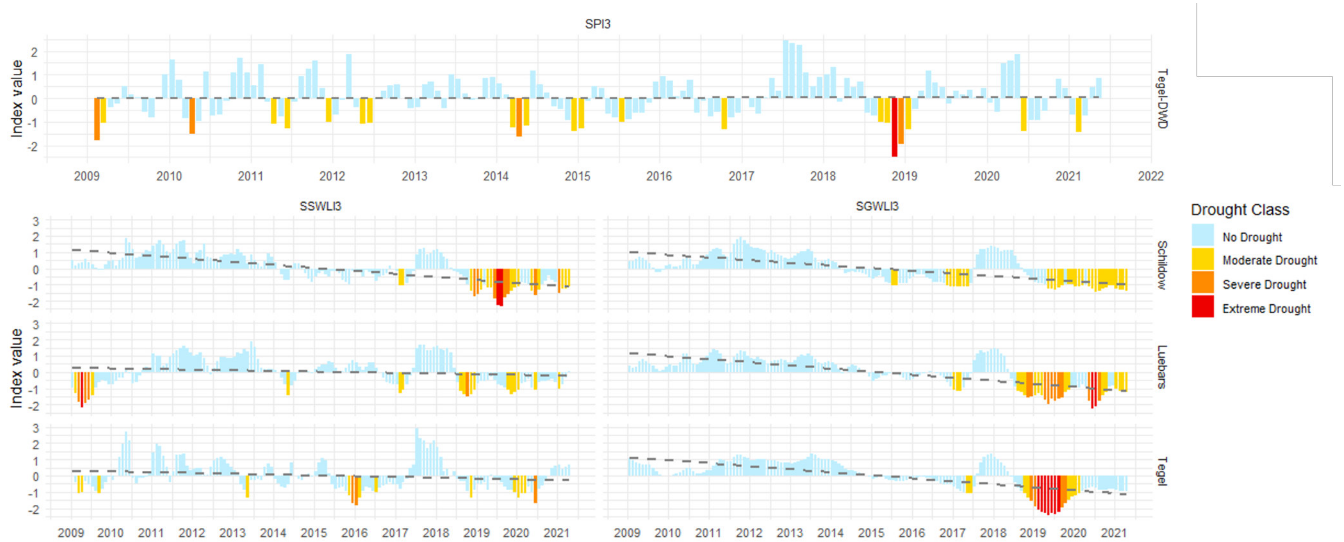

Figure 4. Drought Index Classes and long-term Trends across all Study Sites.

At Tegel-DWD, the SPI3 plot in Fig. 4, show 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 reflected in high SPI3 values, which can also be seen in high precipitation values in Fig. S2 in the Supplementary Material. 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 hydrological and groundwater drought indices show different pictures at all stations. At Schildow, most upstream water levels are stable between 2008 and 2013. However, from 2014 onwards, 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 below -2. 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. Although no extreme groundwater droughts were recorded, the frequent moderate droughts suggest a lasting impact on the region's groundwater resources. Comparing the different drought indices, surface water systems were more affected by the 2018-2019 SPI3 drought event than groundwater systems in Schildow.

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

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2014 (similarly to Schildow). From 2014 onwards, 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. The SGLI3 timeseries in Luebars shows a lot of similarities with the SSWLI3 curve in Schildow. Between 2008 and 2010, SGLI3 values remained positive, indicating the absence of groundwater drought. However, after 2015 there was a shift towards 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.

At Tegel, SSWLI3 values are generally 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 values, indicating periods of drought alternating with periods of recovery; however, after 2013 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. 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 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.

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 (tau = -0.501, $p < 2.22e-16$), reflecting a long-term decline in surface water availability that was less pronounced in groundwater systems. Tegel showed the highest degree of both intensity

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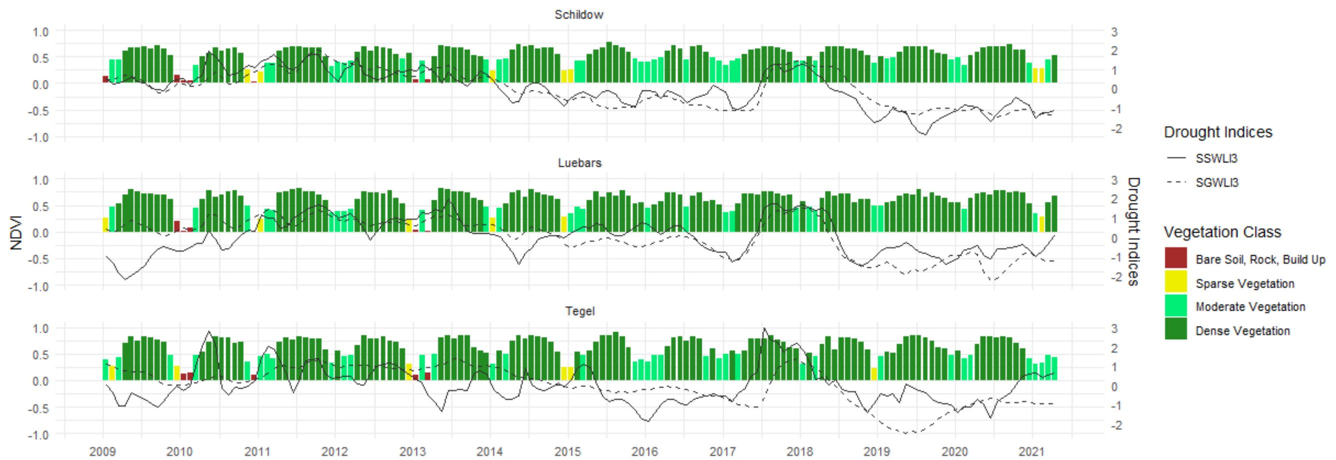

Figure 5. NDVI Classes with SSWLI3 and SGWLI3 Time Series at the Stations Schildow, Luebars and Tegel.

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 $p << 0.05$, 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. 5. 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 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 tau value of 0.0575 and a p-value of 0.30011, suggesting that the greening trend, while present, is weak and not statistically significant.

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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. 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 SGWLI3 indices. SSWLI3 and SGWLI3 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. These observations are further supported by statistical analyses. Spearman correlation tests between NDVI and the drought indices (SSWLI3, SGWLI3 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-values well below 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-values much lower than 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 SGWLI3 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.

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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), which in this case resulted in the most severe groundwater drought impacts. 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. 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 both our study and Grillakis (2019) highlights the increasing vulnerability to meteorological droughts across Europe due to changing precipitation patterns under climate change.

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

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vegetation was not strongly impacted during periods of hydrological and hydrogeological drought. 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 and land management practices such as irrigation. In the regions around Schildow and Luebars, where there is agricultural activity, irrigation practices may have maintained vegetation health despite declining water levels. This could explain why NDVI remained stable, masking the potential impact of drought on vegetation. These results suggest that monitoring of vegetation health should go beyond the use of NDVI, as this index alone may not fully capture the extent of water stress, especially in areas with active land management or irrigation. 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.

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's 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 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. 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 timeframe 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

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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 classification methods. The MODIS NDVI data with a spatial resolution of 250 meters may not capture finer scale vegetation responses, while 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 or incorporating additional drought indicators, such as soil moisture or temperature-based indices. 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 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.

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

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