Link to paper discussion:
https://egusphere.copernicus.org/preprints/2025/egusphere-2025-471/#discussion

Comments by Referee #1

1.1.-RC: I find the toolchain and approach presented in this study to be highly practical for large-scale investigations of drought and vegetation resilience. However, the current methodology is not well-suited for a localized study. The authors have overlooked significant opportunities provided by the specific site, such as ground-truth monitoring, which could have enhanced the robustness of their findings. Given these limitations, I recommend rejection but encourage resubmission following a substantial revision that incorporates site-specific data and methodologies

AC: Thank you for your constructive feedback regarding the methodological scope of our study. We appreciate your recognition of the practicality of our approach and toolchain for large-scale drought analysis, and we acknowledge your concerns about its suitability for a localized context.

Our study was designed to examine drought propagation dynamics across multiple hydrological compartments at three distinct locations along a single stream. With this our goal was to bridge the gap between large-scale drought assessment tools in the form of standardized indices and their application at the local scale. This approach was chosen to ensure comparability across sites while enabling integration with broader regional studies.

However, we fully recognize that our methodology has inherent limitations for a highly localized study, particularly regarding the lack of ground-truth monitoring of vegetation and soil moisture. As stated in the manuscript, the use of MODIS NDVI at 250 m resolution may not capture fine-scale vegetation responses, and the lack of field validation constrains the ecological interpretation of our findings.

The analysis is based on data from three monitoring stations along the Tegeler Fließ, with the focus on local variability and drought propagation within this specific catchment. The time frame (restrained by data availability, compare later comment) and retrospective nature of our study did not allow for in-situ measurements or ground-truth monitoring. Our study's findings highlight significant differences between sites, underlining the importance of local context and limiting direct extrapolation to larger regions without additional data.

We agree that the lack of ground-truthing represents a key limitation, and we discuss this in the manuscript while emphasizing the need for future research to incorporate higher resolution and field-based data to improve the accuracy of drought assessment.

In response to your recommendation, we plan to revise the manuscript to:

- *incorporate higher resolution remote sensing data (e.g., Landsat) where applicable,*
- *include additional land cover information,*
- *expand the discussion on methodological limitations and more explicitly justify the applicability of our approach in a localized setting.*

While our methodology is scalable and well-suited to regional analysis, its current application is indeed localized through the use of site-specific hydrological and hydrogeological data. We will clarify this conceptual distinction in the revised version to avoid confusion and better contextualize the strengths and constraints of our approach.

We thank you again for your thoughtful suggestions and the encouragement to resubmission.

1.2.-RC: My primary concern is that the authors did not take advantage of the opportunity to visit the field site and use field data to better understand and support the observed differences between the chosen indices and locations. Instead, the manuscript offers speculative explanations without providing the depth of analysis that could have been achieved through direct field observations and data.

AC:

One of the main motivations behind the paper was a series of visits to the field site, when we visited multiple locations in the catchment (as part of a walk along the whole stream). These visits were the inception of the general methodology framework, after experiencing the stark differences between the different landscapes within the catchment.

More visits to the field site probably could have provided opportunities for additional measurements and observations, however we would argue whether they could significantly improve our understanding of the catchment.

The presented methodology is based on the analysis of a multi-year time series. Such a data analysis approach cannot directly improve just by additional field visits, as it would just extend the time series by a single data-point (also out of the investigated timeframe).

Field measurements could have helped to reveal some of the hydrological characteristics of the stream, most notably by measuring the river profile to estimate the stage-discharge relations. In the case of the Tegeler Fliess, this however was not possible at 2 of the 3 existing stations (please see our comments later regarding this issue specifically). We will acknowledge this limitation in the revised version of our manuscript.

To increase our understanding of droughts in the soil, vegetation and groundwater, the installation of additional observation infrastructure would have been necessary. This however was beyond the scope of our study. Additionally, the operation of such instruments over a longer time period would have been necessary to incorporate their results to our workflow.

1.3.-RC: l375: “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”. How are the aquifer properties in the different areas which may lead to this resilience? For instance, If the porosity is larger, water level declines are less for the same amount of water extracted.

AC: Thank you for this comment! This was indeed an aspect which we overlooked in our interpretation.

The borehole profiles from the three different areas indeed show a very diverse geological picture, especially the profile in Luebars. The monitoring station in Luebars is filtering a local isolated groundwater body, which is formed by local geological processes. This aquifer is located under more than 10 meter thick shale, suggesting a much weaker coupling with recharge processes as the other two sites.

In Schildow, a similar thick sand layer with some silt is present, that could have a similar, although much lesser isolation effect - which could lead to better resilience. The aquifer at Tegel has no confining, or semi-confining layer above, it is just a sequence of different sand layers. This should indicate a more direct connection to atmospheric processes - which can be a reason behind the weaker resilience.

The most likely explanation for the extended groundwater drought in Tegel after 2019, is that after the initial phase of the drought, any further incoming precipitation was already used up at the soil level. This peri-urban site has a lot of sealed surfaces that obstruct any rain percolation, and also the vegetation in this area is well developed, which could have caused high evapotranspiration.

Unfortunately no porosity logs were available for the three investigated locations, hence we cannot surely say whether it impacts the droughts index calculations, however the main aquifer material is a similar middle sand at each location, which suggests similar porosities. We can still note that the aquifer at Tegel has the most sand, which could have higher storage than at the other sites. This could explain the smaller observed yearly oscillation in the groundwater values.

In the revised manuscript, we will include a detailed hydrogeological description of the three sites, highlighting the differences in their geologies. We will also revise our discussions regarding the groundwater drought results (section 4.1), including the geological diversities as potential explanations for the observed differences.

Added to section 2.1:

“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 meters of shale, in an isolated by a local aquifer formed by regional geological processes. 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."*

And added to section 4.1:

"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."

1.4.-RC: "In-situ measures of vegetation health could provide more precise insights and supplement satellite-derived indices in these analyses." While this is a valid suggestion, the study would benefit from a more comprehensive inclusion of land cover distribution for each MODIS pixel analyzed. The variation in NDVI changes is highly dependent on vegetation type. For instance, if the NDVI signal predominantly reflects trees with deep root systems, a summer drought may have little impact on leaf greenness. In contrast, grasslands are likely to show more noticeable NDVI changes under similar drought conditions. Additionally, although the manuscript briefly mentions the influence of agriculture, it lacks specific and quantitative details. It would be beneficial to clarify the proportion of agricultural land within the MODIS pixels and to specify which types of crops are present in these areas. For a study focused on local conditions, this information should be readily obtainable and incorporated into the analysis. For the reader, at least one picture of each study site would be helpful

AC: We thank the reviewer for his thoughtful and constructive suggestion. We completely agree that the interpretation of NDVI signals—particularly in terms of drought impacts—is heavily influenced by vegetation type and land cover structure. Your feedback helped us improve our spatial interpretation of NDVI responses across our research locations.

To address this, we have made two significant revisions to the updated manuscript:

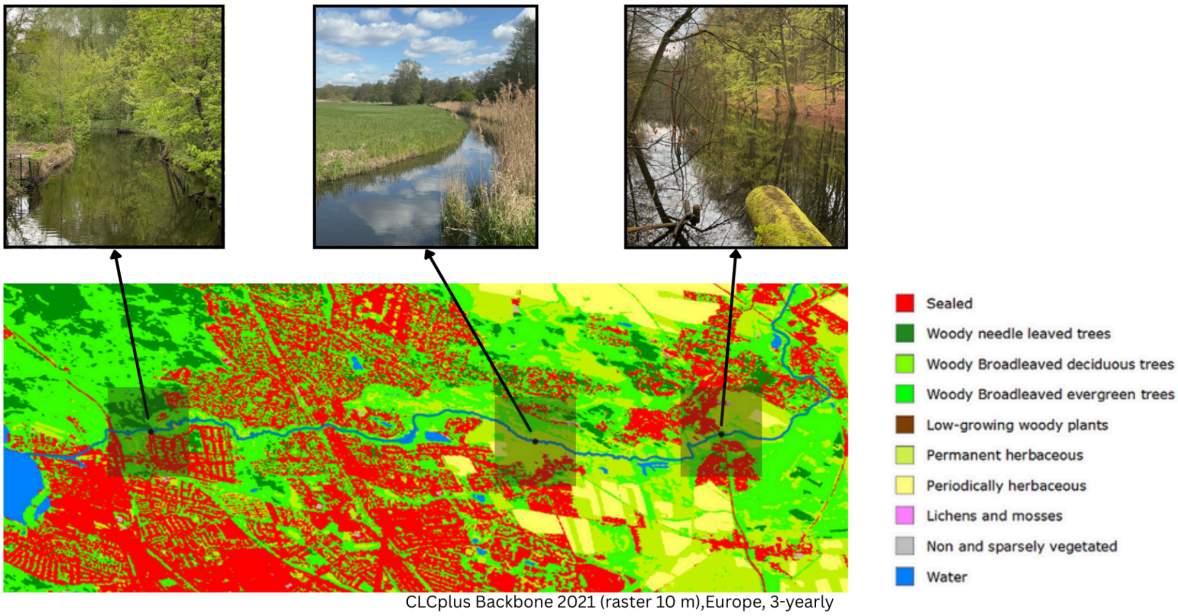
- *Figure below displays a representative ground-level photograph from each study location (Schildow, Luebars, and Tegel). These give readers a better understanding of the topography, dominating vegetation, and land use at each place.*
- *Land Cover Characterization in MODIS Pixels: We assessed land cover within the 500 m buffers for NDVI extraction at each station. This was accomplished using the CLCplus Backbone 2021 dataset (10 m resolution, published by the European Environment Agency), which contains high-resolution raster classifications of land cover across Europe.*

We also used the HCMGIS plugin in QGIS to visually assess high-resolution satellite imagery that was retrieved through the Google Satellite layer in order to support and validate these classifications. We were able to visually evaluate field structures, plant patterns, and built-up regions at each location thanks to this imagery, which is undated and without metadata but provides detailed, cloud-free mosaics assembled from several sources.

Our combined analyses indicated the following:

- *Luebars is mostly characterized by open agricultural fields and shrubland, with little tree cover. Based on visual assessment of field geometry and local land use patterns, these regions are most likely planted with seasonal crops, particularly cereals and fodder grasses, which are widely grown in the Berlin-Brandenburg area. However, as our sources do not contain crop-type metadata, we have treated this as a cautious interpretation and clarified this limitation in the revised text.*
- *Schildow has a more diverse landscape, with small-scale agriculture, tree cover, and patches of fen meadow and semi-natural flora. This structural variety could explain the somewhat buffered NDVI response seen here.*
- *Tegel, being a peri-urban environment, has a mix of vegetation, including managed green spaces, tree-lined urban infrastructure, and proximity to developed regions. Irrigation or municipal landscaping measures are most likely used to manage the plants in this area.*

These findings have been integrated into the revised manuscript, and the discussion has been updated to reflect how land cover variation across MODIS pixels can influence the strength and timing of NDVI responses to drought. We have also emphasized that, while NDVI can be a valuable proxy for vegetation state, it has limits, particularly when not combined with more precise ground-based or high-resolution vegetation structure data.



1.5.-RC: Another critique is the usage of the SSWLI index. As the authors state mention by themselves, that "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", but they did not provide any estimate of how less accurate the chosen approach is. Considering that all gauges are along the same river, different resilience to drought can only be estimated by comparing discharges due to the impact of cross-section and streambed roughnesses variability at each station (see Manning-Strickler Formula). I suggest conducting a number of discharge measurements at each station and deriving a rating curve (https://en.wikipedia.org/wiki/Rating_curve) to convert the water level estimates to discharges.

AC: Thank you for this comment and constructive feedback regarding the use of SSWLI and the challenge of discharge measurements in our study. We appreciate the opportunity to clarify our methodological choices and provide additional context, including relevant literature and practical considerations.

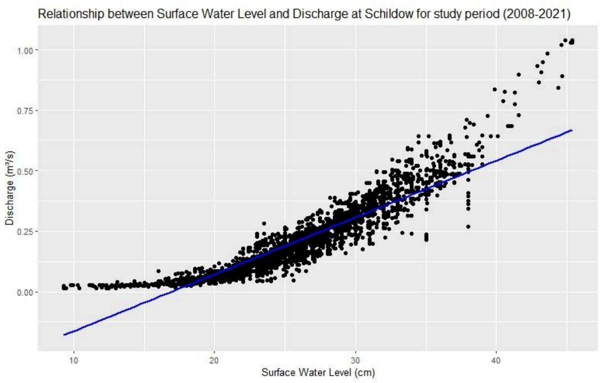
We fully recognize the importance of discharge-based indices for hydrological drought assessment and agree that, in principle, comparing discharges across stations would offer a more direct evaluation of drought resilience. We have considered performing a series of discharge measurements along the stream, but this was technically not feasible. The streambed is very wide near the level measurement stations, creating a very shallow profile and making it impossible to use standard flow measurement equipment. The installation of a weir or other permanent hydraulic structures is also not possible due to the stream's width and local regulations. Furthermore, continuous water level records, as used in our study, provide more robust insights into drought dynamics than isolated, punctual discharge measurements (Tetzlaff et al., 2017).

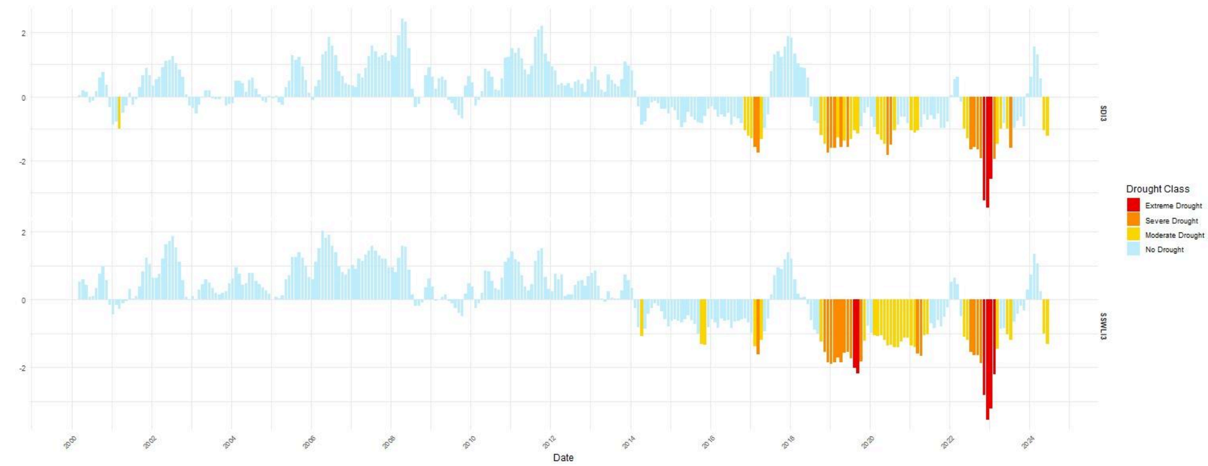
In catchments where discharge data is unreliable or unavailable, studies have used surface water proxies, such as water level, river width or surface water extent (often derived from remote sensing), to estimate flow dynamics, calibrate models or validate model output (Karamuz et al., 2016; Hulsman et al., 2018; de Vitry and Leitão, 2020; Mao et al., 2025). The use of surface water proxies is becoming increasingly common, particularly in ungauged or data-scarce regions. The growing adoption of satellite-based river monitoring further supports the use of level data as a practical alternative (Schwatke et al., 2015).

At the Schildow station, an artificial narrowing (called the Tegeler Fließ waterfall) of the otherwise largely natural course of the Tegeler Fluss was created to enable flow measurements. In addition to the water level, the discharge is also recorded close to this station. We compared the level and discharge data with each other and found that *linearity between surface water level and discharge for levels above 20 cm (compare scatterplot below), supporting the use of water level as a reliable proxy in this range. Very low surface water levels correspond to negligible discharge, which is consistent with hydrological expectations. The SSWLI index is more sensitive to low water levels than the discharge based index SDI. This makes it better suited for detecting drought conditions, especially during periods of minimal flow. Comparing SSWLI and SDI, the SSWLI often indicated more severe droughts, suggesting it is less likely to overlook critical low-water events (compare figure below).*

Our method is designed to be applicable in other catchments and regions where only water level data are available, which is the case for many rivers globally. There are far more stations equipped with water level sensors than with discharge measurement devices. Moreover, observation infrastructure for field measurements is declining over time, both in Germany and internationally (Vörösmarty et al., 2006; DFG, 2013; Rhodes et al., 2015). This trend underscores the need for methodologies that utilize existing data sources, as it is unlikely that new discharge stations will be widely installed in the future. As a result, there is a global shift towards satellite-derived data, which is becoming increasingly available, while in-situ discharge data are stagnating or decreasing.

We acknowledge the limitations of using water level as a proxy and have now provided an empirical comparison at Schildow to estimate the degree of correspondence between water level and discharge. We will include the scatterplot (rating curve) and comparative drought index classifications in the supplements of the revised manuscript to enhance transparency. We will also expand the discussion of methodological limitations and the implications for drought assessment in similar settings.





1.6.-RC: Based on your map, there appear to be surface tributaries (e.g., Kindelfließ) and a lake (Hermsdorfer Lake) within the study area, which could influence the SSWLI index at the downstream gauges. How might these features impact the observed values? This could help explain the variations in drought conditions observed at each station (Figure 3).

AC:

We would expect a smoothing effect over the observed river level values from these tributaries. This however would be mostly apparent on a higher temporal resolution than our analysis. On this monthly scale we don't expect a strong impact.

For transparency we will mention these factors when discussing the SSWLI in the revised manuscript.

1.7.-RC: One assumption of your approach is that the dynamics of groundwater and surface water levels can be directly attributed to drought conditions. However, groundwater levels, for example, may also be influenced by anthropogenic factors, such as the lowering of local groundwater levels due to construction activities or changes in the extent of sealed surfaces. Did you consider these potential impacts in your analysis?

AC:

We thank the reviewer for highlighting this important point. We agree that anthropogenic influences such as construction activities or increasing surface sealing can have a significant impact on groundwater dynamics, particularly in urban or peri-urban environments.

To assess this possibility, we used Google Earth to visually inspect high-resolution historical satellite imagery during the whole study period (2008-2021). This enabled us to evaluate potential land use changes and urban growth around the groundwater wells in Schildow, Luebars, and Tegel.

Our observations indicate that:

- *Despite being located in or near urban areas, Luebars and Schildow showed no significant construction activity in the immediate vicinity of the groundwater wells during the study period.*
- *Tegel, located in a more semi-urban region, also revealed no evident indicators of large-scale urban expansion, new infrastructure construction, or extensive surface sealing over the 13-year period.*

Based on this assessment, we concluded that the groundwater dynamics observed at the three sites are unlikely to be considerably influenced by anthropogenic land use changes throughout the research period. This gives us more confidence in interpreting the observed patterns as responses to climatic and hydrological drought stress.

However, we accept that more precise local data (such as subsurface pumping, development permits, or changes in stormwater infrastructure) would provide an additional layer of confidence. As such data were not available for this analysis, we have included a brief statement of this restriction in the revised manuscript to ensure full transparency.

We appreciate the reviewer's attention to this nuance and have included it in our revised discussion of uncertainty and site-specific variability.

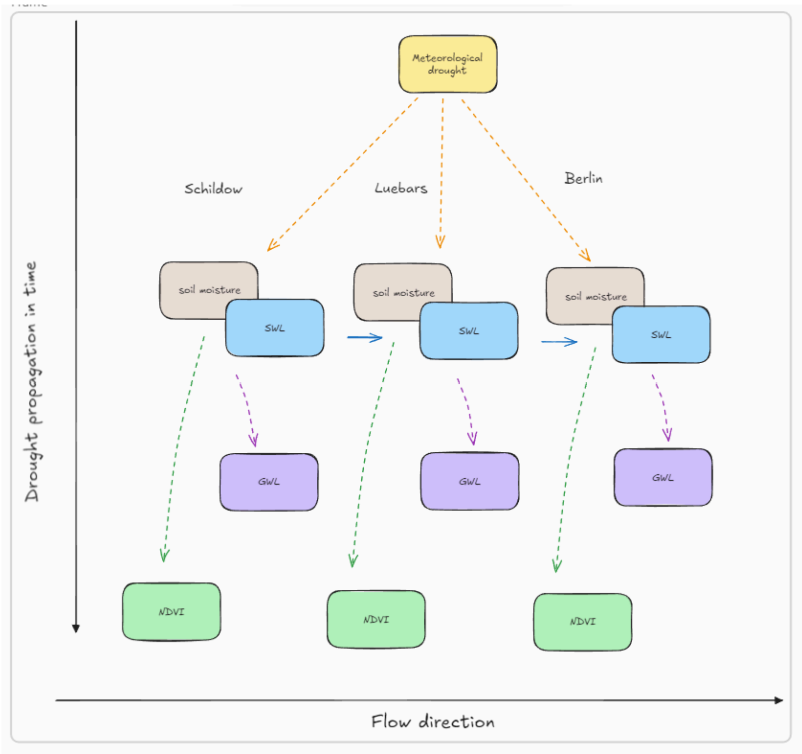
1.8.-RC: Although the authors reference the drought index from the Helmholtz Centre, they did not analyze soil drought conditions, which are conceptually the link between meteorological drought and groundwater drought. If the authors choose not to include this analysis, they should provide a clear justification for this decision.

AC:

We have based our analysis on data that was available from the catchment, which was limited to surface water and groundwater observations. Soil moisture measurements in Berlin exist, but the available timeseries started after our investigation timeframe, and data only available from other catchments. Drought information for the site from the drought monitor would be based on model outputs and not observations.

Without this data we had to rely on surface water levels as a near-surface drought indicator. This of course impose a limitation on our analysis, which limitation we will acknowledge in the revised manuscript. A comparison of the surface water time series with available soil moisture data nearby (although outside from the catchment) show a similar temporal behavior in general (https://wasserportal.berlin.de).

We introduce a new concept figure in the revised manuscript to clarify the multi-domain drought propagation:



"2.3 Conceptual model of drought propagation

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."

In the revised manuscript we will also extend the conclusions to emphasize the need for soil moisture observations to fully assess the multi-domain drought dynamics within the catchment.

1.9.-RC: The study would benefit from a discussion on the applicable scale of your analysis and I feel there is a lack of mentioned studies which did similar works, please provide some more references. Are there limitations to using individual MODIS cells for the indices, considering the sensitivity of values to neighboring cells? Addressing this potential issue could be valuable and could be incorporated into the introduction section.

AC: We thank the reviewer for this thoughtful observation. We agree that a discussion of scale is critical when working with remotely sensed indices-especially in a relatively small and heterogeneous catchment like the Tegeler Fließ.

Regarding MODIS NDVI, we acknowledge that working with 250m resolution data has certain limitations at the sub-catchment level. Particularly in transitional peri-urban settings, each pixel may represent a variety of vegetation types, surfaces, or land use. This creates "mixed-pixel" problems, where signals from developed infrastructure, tree cover, and agricultural fields may be combined in a single cell. Due to this heterogeneity, studies like Chen et al. (2018) and Jimenez et al. (2022) have demonstrated how coarser resolutions might weaken the NDVI's spectral response in urban and semi-urban areas. Similarly, Ordoyne and Freidl (2008) showed that NDVI varied significantly between plant groups that were only a few meters away, even in small wetlands.

In our case, the three NDVI points selected were deliberately placed in areas where vegetation was dominant within the 500m buffer to reduce this problem. Nevertheless, we now more clearly acknowledge in the manuscript that neighbouring land cover and sub-pixel variation may influence NDVI values and may partially explain the inconsistent response of vegetation to drought conditions in our results.

We also updated the introduction to incorporate citations to pertinent research that has employed MODIS NDVI in catchment-scale drought studies in order to bolster this argument. These include seminal studies (e.g. Tucker 1979; Huete et al. 2002) and more recent research Buras et al. (2021), which assessed forest drought stress in Germany by combining MODIS NDVI with drought indices like scPDSI and NDWI. We also cite research by Liu et al.(2024) , who used MODIS indicators to investigate vegetation lag and drought timing in several climate areas.

1.10.-RC: L18. The second part of the sentence is an empty phrase, as the planet naturally includes the Berlin/Brandenburg region.

AC: Thank you for pointing it out. We rephrased the sentence as follows to be more specific:

The phenomenon of global warming is having a significant impact on our planet, with observable consequences already affecting the Berlin/Brandenburg region.

1.11.-RC: L44. SenMVKU reference (and some others) have no year, please update

AC: Thank you for pointing that out. The SenMVKU reference refers to a website that unfortunately does not contain any information about the year in which the information was made available. Following the NHESS submission guidelines examples for reference types for websites, we have therefore added the date at which the information was accessed and written out the abbreviation to make it easier for the reader to understand.

(Berliner Senatsverwaltung für Stadtentwicklung, 2025)

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.

1.12.-RC: L46. It is called Helmholtz Centre for Environmental Research and not Helmholtz Institut

AC: Thank you for the important note. We have adjusted the reference accordingly:

Helmholtz Centre for Environmental Research (2023). Drought Monitor Germany. Retrieved from https://www.ufz.de/index.php?en=37937. Last accessed 25 September 2024.

1.13.-RC: L50 – L 68. I believe there is an overlap with Section 2.3. In the introduction, you should list different indices for precipitation, hydrometry, and groundwater resources, discussing their advantages and disadvantages one by one. The specific details of the technique used in this study can be covered in Section 2.3."

AC: Thank you for this valuable suggestion. We have adapted the paragraph in the introduction along with parts of section 2.3 as follows.

Introduction L50 - L68:

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). 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). 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 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; Ohja et al., 2021; Abu Arra and Si¸sman, 2024).
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 water level measurements can be influenced by local channel morphology and may not always accurately reflect actual flow conditions.
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.
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.

Methods Section:

2.3 Drought and Vegetation Indices Calculation

As outlined in the introduction, various indices exist for assessing different drought types. 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. The following subsections describe the calculation procedure and application of the indices used in this study.

2.3.1 Standardised Precipitation Index (SPI)

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). We aggregated daily precipitation data into monthly totals to calculate SPI over a three-month period (SPI3).
[rest of the paragraph unchanged]

2.3.2 Standardized Surface Water Level Index (SSWLI)

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.
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. 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 can affect the accuracy of hydrological drought characterization, as river levels (especially in smaller streams) are more susceptible to nonlinear behavior.

2.3.3 Standarised Groundwater Level Index (SGLI)

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 SPI3 and SWLI3, 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 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.

2.3.4 Normalized Difference Vegetation Index (NDVI)
[rest of the paragraph unchanged]

1.14.-RC: L73. Provide reference to Granger Causility test

AC: The original work by Granger (1969), which introduced the Granger Causality test (GC), is introduced in greater detail in Section 2.4. However, since the first mention occurs in L 73, we have included the reference there and also provided additional citations to studies that apply GC in drought research within hydrology and environmental sciences:

By combining these drought indices with an examination of long-term trends and conducting Granger Causality tests (Granger, 1969), 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).

1.15.-RC: Figure1: Surface Water instead of Surfacewater

AC: Thank you for pointing it out. We will adjust the figure accordingly in the revised manuscript.

1.16.-RC: Section 2.2. Here you mentioned the Software “R” first. So here you should reference R and mention, which version did you use

AC: Thank you for pointing that out. We moved the sentence mentioning the software “R” to the beginning of the paragraph and added the version we used, so it is referenced before specific R packages are mentioned further on.

1.17.-RC: L190: Why did time lag analysis fail? Perhaps you should not mention it here but using it in the discussion section

AC: That's a very good question! An earlier version of the manuscript was meant to include a time lag analysis. With the development of the script, however, we have deviated from this and should adapt that accordingly. Thank you for the important observation. We will remove the mention here in a revised version and address it in the discussion section instead.

1.18.-RC: Figure3: The plot of absolute surface water levels and groundwater levels for comparing different stations provides limited insight. In Surface Water Hydrology, with a focus on water budgets rather than water levels, it is more informative to compare changes in discharge rather than stage, as stage is dependent on discharge and cross-sectional area. Since discharge data is not available, I recommend normalizing the stages and presenting them in a boxplot or histogram to visualize the distribution across all stations. For groundwater levels, the absolute values provide limited context for the reader. Instead, it is more meaningful to assess the distance from the surface, as this helps evaluate how accessible the groundwater is for vegetation, which is a central aspect of your study.Therefore, I suggest revising Section 3.1 to reflect these points, too.

AC: Thank you very much for your thoughtful and detailed feedback regarding Figure 3. We fully agree with your assessment that presenting normalized surface water levels and visualizing their distributions across stations with boxplots will provide more meaningful insights. We also appreciate your suggestion to present groundwater levels relative to the ground surface, as this will better contextualize groundwater accessibility for vegetation. We will revise Figure 3 and Section 3.1 accordingly in the revised manuscript, implementing your recommendations to improve the clarity and interpretability of our results.

Please note, as a response to multiple other comments, we will also move supplementary figure S2 into the main text, as it provides more detailed insight into the observed surface and groundwater dynamics.

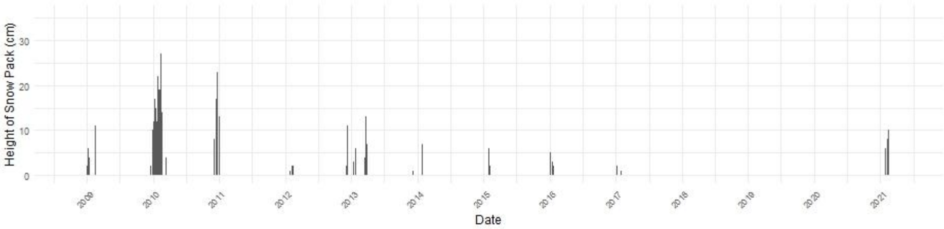
1.19.-RC: Fig4: All plots should share the X Axis to make temporal comparison more easy.

AC: Thank you for your suggestion. This point was also raised by your fellow referee. We appreciate your feedback and will rearrange the plots in Figure 4 to make it easier to compare the different plots in the revised version of the manuscript.

1.20.-RC: L285-295: The authors provide several potential explanations for the low NDVI values during the winter months between 2009 and 2011, such as reduced vegetation cover and lower growth rates. I believe the answer is very simple: There was a long lasting snow layer during this years. I recommend checking the DWD snow data to verify this and rephrasing the discussion to provide a more explicit and clear explanation, avoiding any ambiguity.

AC: Thank you for your helpful suggestion regarding the interpretation of low NDVI values during the winter months of 2009 to 2011. Following your recommendation, we examined the DWD snow data for Tegel station. The analysis (see figure below) confirms your observation. There was indeed substantial and long-lasting snow cover at Tegel, particularly in the winters of 2010 and 2011. 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.

We agree that the persistent snow cover is the most plausible and straightforward explanation for the observed low NDVI values during these winters. We will revise the discussion in the manuscript to explicitly state this finding and remove any ambiguity, making it clear that snow cover was the primary driver of the low winter NDVI values during this period.



We have added to the section:

"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."

1.21.-RC: L313: ":. v", improve language

AC: Thank you for pointing out the typo. We have corrected it accordingly.

1.22.-RC: L379: If you say 13 years is not enough to capture longer-term climate cycles, why did you start in 2008 and end in 2021?

AC: The timeframe of our study was defined by the availability of complete datasets. 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.

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Comments by Referee #2

2.1.-RC: While the research question is relevant, the study lacks a comprehensive conceptual framework for the field settings. This absence leaves the connection between groundwater and surface water droughts and vegetation responses vague, despite the application of various statistical methods. A more robust conceptual model is necessary to illustrate the relationships among the land surface, groundwater, and surface water at the study sites. Understanding these hydrological connections is critical to understand or verify how drought propagates through this system and affects vegetation.

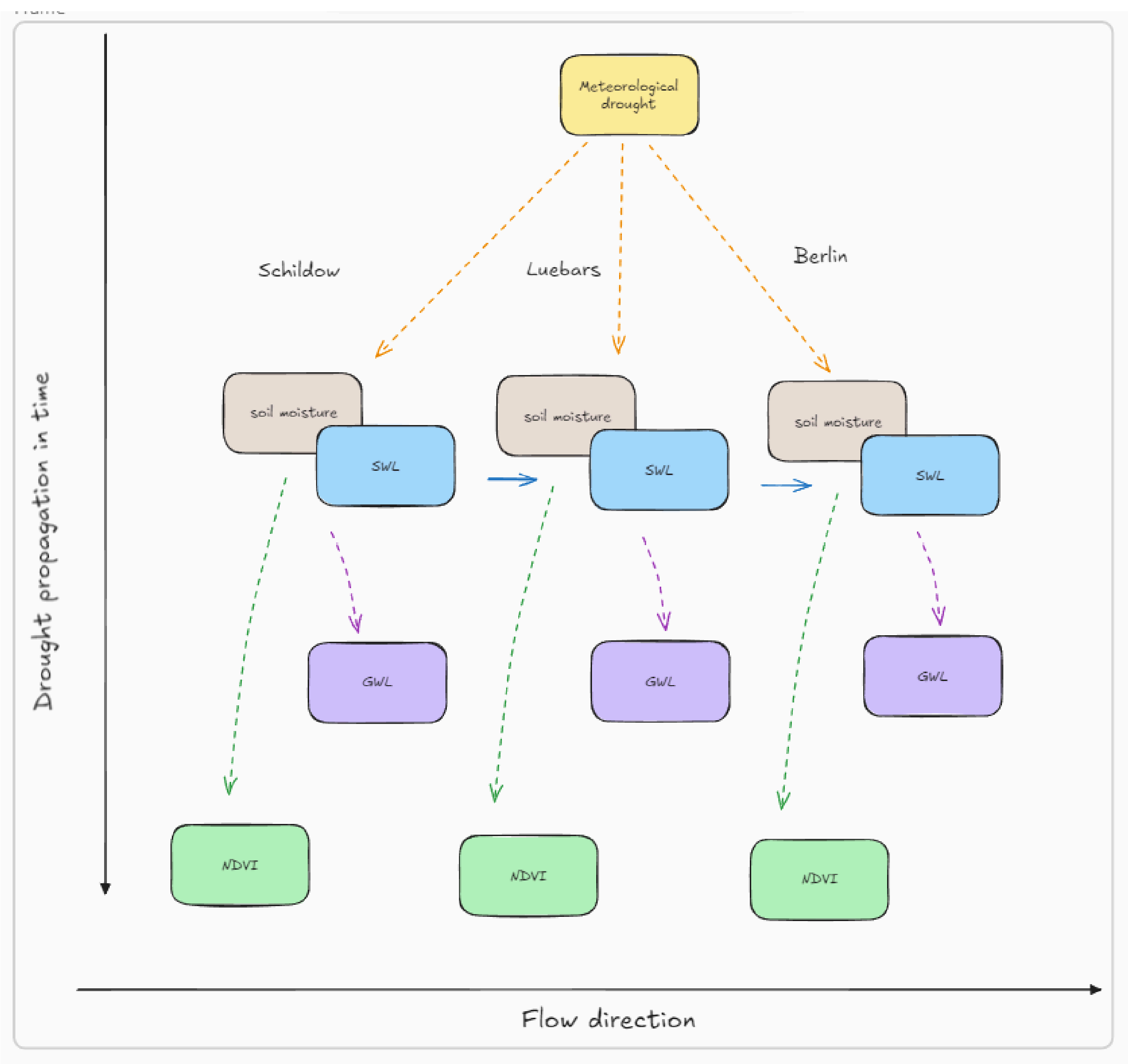
AC:

Thank you very much for your detailed comments. Please find our answers and proposed modifications below the specific comments.

2.2.-RC: **Conceptual Model:** The paper lacks a conceptual model for each of the study sites, detailing how drought propagates through the system. It's crucial to establish the distances between land surface, groundwater, and surface water. How does the groundwater well relate to stream measurements? Are groundwater flow directions understood? Moreover, soil water storage and its direct impact on vegetation should be discussed early on—a critical missing link in the observations of the system, more directly affecting drought propagation to vegetation than surface water or groundwater levels alone.

AC:

Thank you for this comment. We have created a conceptual model for the catchment which we summarize on the new figure below:



"2.3 Conceptual model of drought propagation

Fig. # 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."

In the catchment of the Tegeler fliess unfortunately no soil moisture measurements were available, hence to characterize the drought conditions near the surface we had to rely on the hydrological drought indices. We will acknowledge this limitation in the conclusions of the revised manuscript.

Regarding the groundwater drought, we have to note two additional details: first, not all of the available wells are filtering the same groundwater body. The area near Luebars is defined as a separate groundwater body, due to the special geological conditions near this site. While this groundwater unit is not completely isolated from the aquifers at the other two sites (which is the same aquifer unit GWL 1.3 and GWL 2 citation) we cannot assume a *direct groundwater connection between the 3 sites. We will emphasize this in the revised manuscript and put more focus on the cross-domain drought propagation (related to the recharge processes).*

Second, there is an overall decreasing trend in groundwater levels. This is a regional phenomenon observed across multiple wells that can be related to long term climate change impacts (Somogyvari et al., 2024).

2.3.-RC: **Drought Index and Data Trends:** The data itself, as seen in Figure S2, already depicts long-term trends that should be discussed more thoroughly. While indices offer clearer comparisons, understanding the data and its trend provides a lot of discussion material. Moving Figure S2 to the manuscript's main section would enhance this discussion, please consider this suggestion. Relate the findings to other regional studies. The indices primarily reflect the underlying data trends, not necessarily drought propagation effects in the system. The interpretation and discussion of the drought indices time series seems to be mainly based on visual inspection, including mainly qualitative and somewhat subjective descriptions. Thus the findings remain rather vague.

AC: Thank you for your thoughtful comment. After careful consideration, we have decided to move Figure S2 into the main manuscript, as you suggested. In the revised version, we will also provide a more thorough discussion of the long-term trends to enhance the context of the figure and interpretation of our results. However, we believe it is important to retain the drought indices as central elements of our analysis, as they provide essential high-level information for understanding drought dynamics across the different domains studied.

We appreciate your observation regarding the interpretation of drought indices time series being mainly based on visual inspection. Our intent was to provide an initial exploration of drought propagation dynamics across compartments, but we acknowledge and agree that a stronger quantitative basis is needed to support and clarify the findings. We will address this oversight in the revised manuscript by including a quantitative assessment of drought occurrence and propagation. Specifically, we propose to

- *count the number of drought events detected per index and site, disaggregated by drought severity class,*
- *quantify the frequency of drought propagation by tracking whether a drought identified in one compartment (e.g., meteorological) is followed by drought conditions in downstream compartments (e.g. surface or groundwater),*
- *calculate drought transition rates (e.g., how often an SPI drought is followed by an SDI or GDI drought in subsequent months),*
- *where feasible, evaluate how often certain types of drought propagate and to what extent this varies across sites.*

We believe this addition will make the discussion more robust and transparent.

Another referee comment also addressed the importance of relating our findings to other studies. Please refer to our response to that comment for a detailed answer.

2.4.-RC: **Groundwater Drought and Vegetation (NDVI):** The study posits that groundwater drought impacts NDVI but does not convincingly explain this relationship. If NDVI shows minimal effects, why emphasize the need for improved vegetation monitoring over groundwater or water management strategies?

AC:

In the city of Berlin there is a very active discord on water management to mitigate the impact of drought periods, with a special dedicated focus on green areas. Multiple studies are focusing on the sponge city concept, to retain water after rainfall and not to lead it straight out from the city. This is an integrated water management concept that needs to consider both the available groundwater, surface water and also rainwater resources - and also the water demand by the vegetation.

The minimal effects seen in the NDVI values show that there is still enough buffer in the system to not develop serious stress responses in the vegetation itself. Groundwater resources could be behind this resilience, as the distance to the groundwater table is within reach for trees in the near vicinity of the river (3-4 meters, Hackmann et al., 2025). Decrease in groundwater levels however could easily disable this connection, putting more stress on the vegetation in drought conditions.

Our study showed several limitations in the existing observation infrastructure: most notably the lack of soil moisture data did not allow us to investigate in detail drought stress development in the vegetation.

Please see our detailed modifications regarding this question at comment 2.32

2.5.-RC: L28 Please rephrase this. It sounds now, as if the country would be a wet region. While Brandenburg does have many surface waters, it is overall a water limited region, which is not a contradiction but I guess needs more than this single reference and a better explanation (the tight water balance with very low precipitation for a temperate humid climate and the high atmospheric demand (evapotranspiration)).

AC: Thank you for pointing out the misleading phrasing. We have adjusted the paragraph as follows, taking your comments into account, and added additional references:

Although often associated with abundant surface water bodies, Berlin/Brandenburg is characterized by a tight water budget, with low annual precipitation relative to its temperate humid climate 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, particularly vulnerable to droughts (Cullmann et al., 2022), presenting a compelling case for an empirical study.

2.6.-RC: L34 As you describe a cascade, maybe put the declining groundwater table as the last argument in the list

AC: We rearranged the cascade to a logically causal order reflecting how one phenomenon leads to the next, starting with the deficit in available water and progressing to typical hydrological and ecological impacts:

Droughts in the region have cascading effects, including water stress, declining groundwater tables, increased fire risk, and significant reductions in agricultural productivity (Reyer et al., 2021).

2.7.-RC: L45 – if there are a few studies, you should cite them here and summarize what they found

AC: In the Introduction, we have referenced and summed up these research as follows:

"there are only a few studies that have investigated drought in this particular region. For instance, Kuhlemann et al. (2021) used stable isotope analysis to trace changes in urban water balances during the 2018–2019 drought, revealing strong evaporative losses and altered groundwater-surface water interactions across Berlin. Using remote sensing indices, Ihinegbu and Ogunwumi (2022) examined the geographical extent of the 2018 drought in Brandenburg and discovered that more than 90% of the territory was hit by high to extreme drought conditions, with agricultural regions being among the most severely affected. These results demonstrate that the Tegeler Fließ landscape and the surrounding area have been more severely affected by recent drought occurrences. 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."

2.8.-RC: L46 –also be precise here – what significant effects did they find?

AC: Please see our previous answer.

2.9.-RC: L50ff merge the two paragraphs, shorten (or move parts to the methods section, there is some overlap)

AC: We revised this section after your and R#1's recommendations as:

"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). 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).

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 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; Ohja et al., 2021; Abu Arra and Si¸sman, 2024). "*

2.10.-RC: L77, not sure, if "persistent" is already an appropriate word, considering the rather short time frame of the analysis overall

AC: Revised as:

"The objectives of this study is 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 the drought-vegetation dynamics over the study period."

2.11.-RC: L87 Add information, to which larger river the Tegeler Fließ is a tributary of.

AC: We will add:

"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."

2.12.-RC: Section 2.3.1 and 2.3.2 – why does one index gets its own section, while the others are combined in one?

AC: After your and Reviewer #1's recommendation, we will change this in the revised manuscript:

"2.3 Drought and Vegetation Indices Calculation

(...)

2.3.1 Standardised Precipitation Index (SPI)

(...)

2.3.2 Standardised Surface Water Level Index (SSWLI)

(...)

2.3.3 Standardised Groundwater Level Index (SGLI)

(...)

2.3.4 Normalised Difference Vegetation Index (NDVI)"

2.13.-RC: Section 2.4 and Figure 2, consider to rename the section heading to "statistical tests and measures"

AC: We will revise the heading and the caption accordingly.

2.14.-RC: Your analysis process is not very difficult, so I think in such a linear process also Figure 2 is not required. Instead, structure the section with line breaks/paragraphs between the different statistical tests and measures you describe.

AC: We agree, and we also think the new conceptual model figure is more important to be in the main text. Therefore we will move Fig. 2 to the supplements in the revised manuscript.

2.15.-RC: Figure 3: Precipitation over what time frame? I don't think the graph in its current form is very useful. The groundwater level plot show just the groundwater gradient the landscape along the Tegeler Fließ and the water level in the river actually doesn't say a lot at all (as you also correctly mention its limitations). However, with only this data available – the critical thing to show is the relation between the groundwater level and the surface water level, as well as the distance of the groundwater level to the land surface. So either include surface water level statistics in absolute heights, or think of a better way also to include the important land surface to groundwater level information.

AC:

Based on the recommendations, we have decided to replace this figure with the full timeseries of the observations.

2.16.-RC: L196 You seem to show monthly cumulative precipitation amounts in Figure 3. Even if there is outliers in your distribution (extreme precipitation for the time frame you consider) – this is by no means to be determined as heavy rainfall from this graph! Heavy rainfall is actually large amounts over very short time frames (<day).

AC:

Based on multiple comments, we decided to move figure S2 into the main text of the manuscript (here referred as Fig. #). This should help with the clarification here.

We also rephrased the sentence in question:

"At glance over Fig. 3, the 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. These heavy rainfall events are likely to contribute to localised water level surges as it is shown in Fig. #."

2.17.-RC: L197 Either you have data to support your guess, or leave it out, or discuss in more detail why you guess this (related to the missing conceptual model I) – doesn't the Figure S2 support this claim?

AC: Revised as (with reference to Fig. S2 that will be moved to the main text):

These heavy rainfall events are behind the localised water level surges, as it is shown in Fig. #.

2.18.-RC: L204 how much "water management" is there for the Tegeler Fließ and the surrounding groundwater? If there is a lot of influence of water management on the field sites and observed water levels, then they would not be suited to assess the study goal of observing a drought propagation from precipitation to the surface and groundwater levels.

AC: There is minimal amount of water management within the catchment. The most notable installation is a water quality improvement system, where some of the river water is diverted to a phosphate-removal plant, then returned cleaned. This installation however is downstream from all three sites, hence could not affect our observations.

2.19.-RC: L204ff The groundwater levels show the slope in the groundwater along the river stretch. How much is the elevation difference for the land surface? More interesting might be to discuss the variations of the water levels themselves.

AC:

Following the groundwater levels along the three sites could be misleading, as due to local hydrogeological settings, the well at the Luebars site is screening a different groundwater body then the other two. Although these groundwater bodies are connected, we cannot assume a direct groundwater connection or flow along our groundwater site locations.

Regarding groundwater level variations, the most interesting is the dampened variation at the Tegel site compared to the other two locations. This could be caused by the higher sand content in the aquifer and hence the increased storage. The Tegel site also has the most sealed surfaces that can reduce the connection with the atmosphere.

In the revised manuscript we will include a section on introducing the hydrogeological setting of the site. Please also see our response to Reviewer #1, regarding the hydrogeological differences at the sites and the variations of water levels.

2.20.-RC: L211 Not sure, what you want to say with this sentence – what the reader will see in section 3.2? Then place before the subsection heading – or consider to remove completely.

AC: We will remove this sentence to avoid any confusion.

2.21.-RC: Figure 4: This is the main figure of your study – give it more space. Make sure the time series of SPI and other indices directly comparable by sharing the same x-axis! Either placing all the panels below each other (a one-page plot) or showing SPI twice, above each of the columns. The caption should give more information, especially also about the dashed line, that does not appear in the legend.

AC: We will revise this figure according to your recommendations, by showing the SPI plot twice.

2.22.-RC: L241 Check again – generally lower is not directly what I see from Figure 4. What is with the drought event in 2016 at the Tegel site? There is none corresponding strong event in the precipitation and none at the other sites. Is this a water management related effect? Add to the following sentence: "… fluctuating between negative *and positive* values …"

AC: The SSWLI3 index shows negative values much more at the Tegel site, especially before 2017. Although these drought events are not so severe, they are different from the observations at the two other sites.

We don't think the 2016 drought would be a management related effect, as the raw timeseries (supplementary figure S2) do not show any strong outlying behavior. It could be a local artefact of the measurement station (it is located at a very shallow part of the river), but also a result of weather patterns. WIth the available information we can only guess, and we would require a more detailed investigation to understand this phenomena.

We will add:

"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."

We will correct the next sentence accordingly.

2.23.-RC: L243 "noticeable transition…" I do not clearly see a transition.

AC: We would like to argue that here after 2013 more drought events are visible than before, and their length is also increased. We rephrased this section as:

"Initially, between 2008 and 2011, the SSWLI3 fluctuated between negative values, indicating periods of drought alternating with periods of recovery; however, after 2013 the drought periods became more frequent and more severe."

2.24.-RC: L241ff the findings drawn in this paragraph from the visual inspection of the time series of the indices remain rather vague and seemingly subjective/only qualitative description.

AC: We believe that the visual inspection of the drought index timeseries could highlight well the differences and the temporalities of the drought propagation. However to avoid being seemingly subjective, we will perform a quantitative assessment over our results where we will assess the individual drought events more in details. Specifically we propose to do in the revised manuscript to:

- *count the number of drought events detected per index and site, disaggregated by drought severity class,*
- *quantify the frequency of drought propagation by tracking whether a drought identified in one compartment (e.g., meteorological) is followed by drought conditions in downstream compartments (e.g. surface or groundwater),*
- *calculate drought transition rates (e.g., how often an SPI drought is followed by an SDI or GDI drought in subsequent months),*
- *where feasible, evaluate how often certain types of drought propagate and to what extent this varies across sites.*

2.25.-RC: L247 – but the surface water index at the end of the time series shows a faster and more pronounced recovery from the drought event, while at other sites the drought persists and index values stay below 0. Stating here, a higher vulnerability of the surface waters to drought seems far fetched, also the recovery at the end of the time series suggests resilience in my opinion. Or am I missing something?

AC: Compared to Luebars, the indices at this site show higher drought classes, but indeed they show a faster recovery. We think our original sentence "the persistent drought from 2016 to 2020 highlights the vulnerability of Tegel's surface water systems to prolonged period" is valid, but we agree that the fast recoveries are indeed showing resilience. Therefore we add the following to the end of this section:

"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."

2.26.-RC: L248 "severe meteorological drought period in 2015-2016…" there is only a moderate drought (for 1 month?).

AC: This might not be well visible, but there is a multi-month severe drought in this time period.

2.27.-RC: L249 I do not see a strong contrast between Tegel surface water and groundwater index – both in the same direction and mostly below 0 for the period, no?

AC: The strong difference is from the fact that we see no groundwater drought before 2016. Also the groundwater dynamics is different and much smoothed. We would argue that this is the site where the greatest difference is visible.

2.28.-RC: Section 3.3: Why don't you consider the NDVI as a measurement, as the other data you look at (precipitation and water levels) and calculate a trend for the time series. "Normalizing" the vegetation observation by deriving an index as you do on the other data might show better a drought propagation/impact on vegetation?

AC:

Thank you for this recommendation, we will test out this approach. We were so far cautious on introducing a new index here, as the yearly periodicity of NDVI could lead to a false understanding of the vegetation conditions. We used NDVI so far as it is used as the standard method to characterize the condition of the vegetation.

2.29.-RC: Section 4.1 stays vague as well, see my general comment on the missing conceptual model, I guess this section will require a revision. Includes quite some speculations, could be more precise of relying on additional data or relating to findings of other studies in the region (see maybe references within Altdorff et al. (2024): https://egusphere.copernicus.org/preprints/2024/egusphere-2024-3848/ (there are some studies cited, that deal with the 2018 -2020 drought period).

AC: Thank you for this comment.

We strongly revised this section. We will frame the section in line with our proposed conceptual model, with more focus on:

- *geological differences between the sites and their impact on groundwater drought*
- *include more comparison on studies on the 2018-2020 drought (Pohle et al., 2024; Warter et al., 2024)*
- *and we will note on the lack of soil moisture data*

Please see our modifications in the revised manuscript.

2.30.-RC: L343 There is no downward trend in your SPI3 data as shown in Figure 4 (or do you mean the indices related to surface water and groundwater?)

AC: We are not sure that we understand this comment exactly, we hope we answered what you meant.

There is no downward trend in SPI3 nor in NDVI data. Granger casualty test revealed that there is a relation between the different timeseries, but this does not necessarily mean that we see the exact trends, as this relation could appear on higher frequencies.

2.31.-RC: L350 Why should groundwater impact vegetation? This is only relevant if land surface – groundwater level distances are low and vegetation can directly use groundwater for evapotranspiration (tap into the capillary fringe) – is this the case at your sites? Otherwise, this would not be a relation to test at all.

AC:

Near the river this assumption is mostly true. According to the data available in the Geoportal Berlin (https://gdi.berlin.de/viewer/main/) and at the Auskunftsplattform Wasser Land Brandenburg (https://apw.brandenburg.de/), on the river floodplains the distance to the groundwater is less than 1 meter, while in within most of our vegetation assessment area it is less than 7 meters.

The access to groundwater by the larger plants could buffer the drought impacts on vegetation, and could be a reason why we don't see a strong vegetation response in the NDVI values at the investigated sites.

Please see our modification for this section in the next comment.

2.32.-RC: L355 – was there irrigation? I thought there is rather little irrigation operated, so I would not expect a big effect on NDVI. Any information to support your guess?

AC: Unfortunately we do not have any information about irrigation. We modified this section in our revised manuscript to be less speculative:

"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.

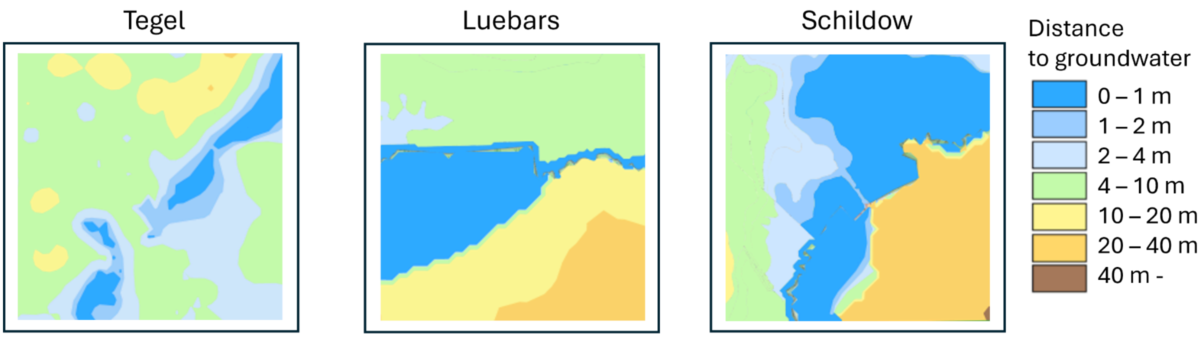


Figure 7 - Average groundwater distances near the selected stations.

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. 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 (Somogyvari et al., 2024, Heudorfer 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."

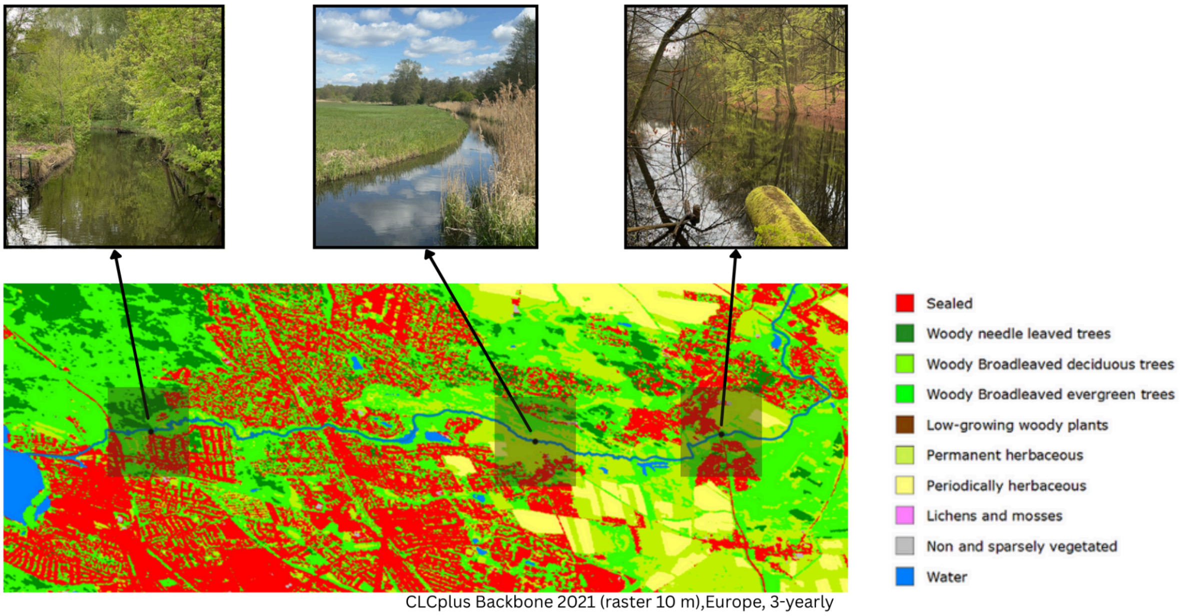
2.33.-RC: L362 – what are "shallow-rooted plants typical of these areas"?

AC: We removed this statement at the revision for the previous comment.

2.34.-RC: L363 plants rely, if at all, on shallow groundwater, never on deeper groundwater. I get what you mean though, but please stay precise and rephrase the sentence accordingly. It then again strongly depends what type of vegetation/land use you have. In this respect it would be good to show somewhere a bit more detailed what land use is covered by your NDVI data (agriculture, forest…).

AC:

In the revised manuscript we have prepared a new figure to present the land use distribution and the diverse landscapes at the three sites.



2.35.-RC: L365 – How would the decline in groundwater tables (and surface waters) affect vegetation (the long term decline in the data, Fig. S2)? This is a rather vague statement – again missing is the agricultural or soil moisture drought that would be actually relevant for vegetation (see general comments).

AC: During our timeframe we did not see an impact. For the long term however, we expect this to be an issue as the decreasing groundwater levels could lead to a disconnection between the deep rooted plants and the groundwater table. Please see our previous responses.

2.36.-RC: L378 – I would like to see this point mentioned earlier in the manuscript (describing the data itself, potentially including Fig. S2 in the main manuscript). Looking at your interpolation (the Figure is good to keep in the appendix) – I do not think the interpolation introduces a lot of uncertainty here. So definitely not the interpolation/gap filling a key limitation of your study.

AC: We will include fig. S2 in the main manuscript.

As the region is getting more and more extreme rainfall events due to climate change, we think it is important to emphasize this limitation. Such data gaps could easily miss peak river levels, and could lead to incorrect conclusions.

2.37.-RC: L382 first: all your ecosystems seem to show resilience, as you define it. Second, I think again the missing link here is the soil water storage (as you discuss just then a couple of lines below) – I would like to see this as part of the discussion chapter and not within the conclusions.

AC: We will add a sentence on the importance of soil moisture in relation to the vegetation health, and commenting on the lack of this information in the revised section 4.2.

2.38.-RC: L390 I do not think assessing single plant species would make sense here – as you are interested in the effect on the ecosystem. Rather including additional data on temperature, evapotranspiration or atmospheric demand or soil moisture might close the missing gap you have so far.

AC: Thank you, we revised this sentence as:

"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.

The investigation of soil moisture is especially important, as its dynamics is a key element to understand the vegetation response to drought conditions and to understand how ecosystems could 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."

2.39.-RC: For all the manuscript: The figure and table captions should contain more information, to make the graph/table self-explanatory without the need for the reader to go into detail in the text, also including the explanation again for abbreviations.

AC: We will revise the captions according to your comment.

2.40.-RC: Please go through the manuscript to check the units of precipitation, it should be clearly stated, over which time interval cumulative amounts are given, so not only mm but mm/day or mm/week.

AC: We will revise them accordingly.

2.41.-RC: L11 Rephrase the sentence for NDVI. To a reader it is not clear, what "moderate to dense classes" are. Either add "vegetation" or rather just say, that there was no, or only a moderate effect to be observed in the NDVI

AC: Thank you for drawing our attention to this lack of clarity in the abstract. We will revise the sentence as suggested to ensure it is clear to readers, specifying that the NDVI analysis showed little to no observable effect or only moderate changes in vegetation. Additionally, as part of the methodological improvements planned for the revised manuscript (e.g. use of higher-resolution NDVI data), we will further clarify this point. Please also refer to our earlier comments regarding planned methodological adjustments.

2.42.-RC: L19 These studies are projections, so include "likely" or similar

AC: Thank you for pointing this out. We revised the sentence to include "likely", as you recommended, to reflect the nature of projections.

2.43.-RC: L44 Not in references list, no date, please fix. I guess it is some authorities? So spelling out the abbreviation would be helpful.

AC: Thank you for pointing that out. The SenMVKU reference refers to a website that unfortunately does not contain any information about the year in which the information was made available. Following the NHESS submission guidelines examples for reference types for websites, we have therefore added the date at which the information was accessed and written out the abbreviation to make it easier for the reader to understand.

(Berliner Senatsverwaltung für Stadtentwicklung, 2025)

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.

2.44.-RC: Figure 1: I found the legend hard to read, usually it is first the symbol then the legend entry (left aligned close to its according symbol). As it is, the first symbol and the second column of the legend are best aligned. Additionally: is it possible, to zoom in a little on each of the sites to better see the landuse for the NDVI area? (there is a lot of blank space in the lower right of the map)

AC: Thank you for the valuable suggestion. We have revised the legend such that the symbols are now aligned to the left, followed by the corresponding legend entries, ensuring improved readability. Unfortunately, further zooming is not feasible without excluding the Tegel DWD station, represented by a black triangle near the southern boundary of the map. However, to enhance the reader's understanding of the study sites, we have included a land cover graphic featuring representative images for each class.

2.45.-RC: L107 Two different authorities is not “various”

AC: We replaced “various” with “two” to be more precise.

2.46.-RC: L108 I know that data integration is a challenge – this is always the case, I would delete the sentence

AC: We will delete this sentence in the revised version of the manuscript.

2.47.-RC: L109 Awkward sentence, rephrase

AC: We propose the following rephrasing:

The groundwater measurement station at Schildow provided only weekly data, whereas groundwater records at Tegel and Luebars were more complete but contained some minor gaps.

2.48.-RC: L300 line break and new paragraph following “analyses.”

AC: Thank you for your suggestion. We agree that splitting the text into more paragraphs would improve its readability, and we will implement this change in the revised version.

References #2

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