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Global-scale drought propagation and the drivers and patterns of multi-year groundwater drought

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Abstract. Groundwater stores a third of all global freshwater and supports water supply, irrigation and ecosystems across the world. As such, groundwater drought can have wide-reaching financial, social and environmental impacts, particularly when drought events are prolonged or multi-year. Although recent work has made significant progress in understanding the drivers and patterns of multi-year meteorological droughts, we do not know how this signal translates into multi-year groundwater drought, where subsurface processes, anthropogenic influences and abstractions can alter the meteorological signal. This is particularly true at the global-scale, where a major barrier to understanding large-scale groundwater drought dynamics is the difficulty of obtaining consistent and comprehensive groundwater data. In this research, we use a new global hyper-resolution ($\sim$1 km) groundwater dataset to investigate the global patterns and drivers of groundwater drought from 1960-2019, with a specific focus on multi-year events. We start by characterizing the propagation of meteorological (represented by SPEI-12) to groundwater drought, evaluating how and to what extent the sub-surface plays a role in modulating the meteorological drought signal. Subsequently, we define three global groundwater response types that provide a framework for understanding the processes and geo-physical drivers of normal versus multi-year groundwater droughts. We find that 35% of the world has an average groundwater drought duration which is multi-year. In 83% of these locations, the subsurface extends the meteorological drought signal, whereas in the remaining 17%, groundwater drought duration appears to be primarily driven by meteorological anomalies. Our analysis offers new insights into global-scale drought exposure by identifying regions which have been most vulnerable to multi-year groundwater drought in the past, as well as those which might be more vulnerable in the future. Importantly, our typology also highlights areas where multi-year groundwater droughts can be anticipated based on meteorological drought anomalies and can therefore inform strategies for managing and mitigating future water scarcity risks.

1 Introduction

Groundwater stores a third of all global freshwater and supports water supply, irrigation and ecosystems across the world (Mena Benavides et al., 2023). It is estimated that 2 billion people rely on groundwater as their primary source of water and that groundwater-dependent ecosystems cover millions of square kilometres (Rohde et al., 2024). As such below normal levels of groundwater can have wide-reaching financial, societal and environmental impacts (Huggins et al., 2023; Saccò et al., 2024).

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Below normal levels of groundwater may result from unsustainable groundwater extraction or may indicate the occurrence of a groundwater drought (Leijnse et al., 2024; Wada et al., 2013; Taylor et al., 2013; Ashraf et al., 2021; Scanlon et al., 2023). Groundwater drought arises primarily from a decrease in groundwater recharge, which is typically attributed to deficits in precipitation or increased evaporative demand (Han et al., 2019), but can be exacerbated by human pressures such as groundwater abstractions. A groundwater drought is preceded by a meteorological drought, which propagates via the unsaturated zone to the groundwater (or saturated zone) at varying rates depending on the local geo-physical properties, antecedent conditions and the characteristics of the meteorological drought (Han et al., 2019; Liu et al., 2023; Hellwig et al., 2022; Van Lanen et al., 2013). The severity of the groundwater drought impacts will depend on a number of factors, one of which is the drought duration (Athukoralalage et al., 2024; Pauloo et al., 2020). Since groundwater is usually the most resilient component of the hydrological cycle, it is crucial for supporting river flow in dry conditions and is often used as a buffer to mitigate the impacts of meteorological drought e.g. by maintaining irrigation or supporting water supply (Jasechko et al., 2024; Liu et al., 2022; Apurv and Cai, 2020). Consequently, the impacts of prolonged groundwater drought can be particularly severe, threatening water and food supplies, as well as socio-economic security (Castle et al., 2014; Taylor et al., 2013; Schreiner-McGraw and Ajami, 2021; Bierkens and Wada, 2019).

In recent decades, some of the most impactful drought events have spanned multiple years, for example the Millennium Drought in Australia or South Africa's 'Day Zero' drought. Unlike prior droughts which were too short for significant groundwater decline, the prolonged nature of Australia's Millennium Drought severely depleted groundwater stores which led to wide-spread financial and environmental problems (Fowler et al., 2022; Xie et al., 2016; Heberger, 2012). The groundwater drought intensified the decline in streamflow across some of Australia's most important river basins, such as the Murray-Darling Basin, where groundwater dependent baseflow contributes 48% of streamflow (Van Dijk et al., 2013; Leblanc et al., 2012). Here, groundwater depletion was particularly problematic, since the catchment supports half of Australia's total water extraction (84% of extracted water is used for agriculture, 13% for the water supply industry and 2% for household use). To make matters worse, observations from the Murray- Darling Basin revealed that almost a decade after the Millennium drought event, 70% of groundwater wells had still not fully recovered or had continued to decline (Chen et al., 2024; Le Brocque et al., 2018). Past events have taught us that the impacts of multi-year groundwater droughts can be much harder to mitigate than shorter drought events, and consequently, understanding what drives a multi-year groundwater drought event is essential for planning and preparedness.

In the future, we expect climate change to increase the frequency, duration, and magnitude of groundwater drought (Pascale et al., 2020; Rakovec et al., 2022; Mishra et al., 2024). Not only will changes in weather patterns exacerbate drought from a meteorological perspective (Cook et al., 2020; Pokhrel et al., 2021), but at the same time, the overall vulnerability to groundwater drought will be enhanced by increasing groundwater abstractions (Belleza et al., 2023; Leijnse et al., 2024). It is estimated that 71% of global groundwater aquifers are already declining, with approximately 30% demonstrating an acceleration in decline over recent decades. This trend is only projected to intensify under continued climate change and the resultant increases in human water demands (Jasechko et al., 2024; Wunsch et al., 2022; Nazari et al., 2025). Future groundwater droughts are likely to be more frequent, but might also last longer, leading to an increase in multi-year droughts (Wunsch et al., 2022).

Although recent work has made significant progress in understanding the drivers and patterns of multi-year meteorological droughts (van Mourik et al., 2025; Van der Wiel et al., 2023; Pascale and Ragone, 2025), we do not know how this signal translates into multi-year groundwater droughts, where subsurface processes and anthropogenic pumping or abstractions can alter the meteorological signal (Chen et al., 2024; Schreiner-McGraw and Ajami, 2021). This is particularly true at the global-scale, where a major barrier to understanding large-scale groundwater drought dynamics is the difficulty of obtaining consistent and comprehensive groundwater data. Observational data are often sparse or incomplete, and although initiatives like the International Groundwater Resources Assessment Center (IGRAC) (IGRAC, 2024), the global-scale integrated GROundWater package (GROW) (Bäthge et al., 2026), or the European Groundwater Drought Initiative (Brauns et al., 2020) collate groundwater timeseries on continental to global scales, they are still limited in their spatial coverage and representativeness (Condon et al., 2021). Comparatively, whilst satellite datasets such as GRACE have made large-scale groundwater analysis possible (Rodell et al., 2018; Richey et al., 2015; Famiglietti et al., 2011), this data is limited in its temporal coverage and remains at coarse spatial resolutions, meaning that it cannot resolve patterns and trends on smaller, more regional or local scales. Furthermore, when analysis focuses on multi-year drought, there are fewer events in the observational records, mandating long-term temporal and spatial coverage. In the absence of observational data, groundwater models can provide valuable insights. These models can simulate groundwater levels over large spatial domains at high temporal resolutions. Historically, groundwater models have had to balance spatial resolution with spatial coverage and therefore operate at scales too coarse for actionable use (Condon et al., 2021; van Jaarsveld et al., 2026). However, recent advances in computational power have shown us that hyper-resolution groundwater modelling is now possible at the global scale (Verkaik et al., 2024; Ebeling et al., 2025).

In this paper, we use a new global hyper-resolution ($\sim$1 km) groundwater dataset (van Jaarsveld et al., 2026) produced by the global groundwater model GLOBGM to investigate the global patterns and drivers of groundwater drought from 1960-2019, with a specific focus on multi-year events. We start by exploring the propagation from meteorological to groundwater drought, evaluating how and to what extent the subsurface plays a role in modulating the meteorological drought signal. Subsequently, we define three global groundwater response types based on the relationship between meteorological and groundwater drought, providing a framework for understanding the processes and geo-physical drivers of normal versus multi-year groundwater drought events within each type. By disentangling this relationship at the global scale, we identify regions that are most prone to multi-year groundwater drought under present-day conditions, as well as those that may be more vulnerable in the future. Our analysis offers new insights into the spatial patterns of global drought propagation and can help inform strategies for managing, mitigating, and predicting future water scarcity risks.

2 Materials and Methods

2.1 GLOBGM modelled groundwater data

The groundwater dataset used in this paper was produced by GLOBGM v1.1, a two-layer transient MODFLOW-based groundwater model which represents confined, confining and unconfined aquifers (Verkaik et al., 2024; van Jaarsveld et al., 2026). The model simulates monthly groundwater heads and water table depths at $\sim$1 km spatial resolution for the time period 1960

- 2019. The model distributes independent unstructured grids over three continental-scale groundwater models (Afro-Eurasia, America, Australia) and one representing the remaining islands. GLOBGM employs an offline coupling approach whereby local runoff, groundwater abstraction and groundwater recharge outputs at the 5 arc-minutes resolution ($\sim$10 km at the equator) are derived from the PCR-GLOBWB2 global hydrological model (Sutanudjaja et al., 2018). These inputs are then used as boundary conditions and forcing to simulate groundwater dynamics.

The validation of global groundwater models is notoriously difficult due to mismatches in spatial resolution and representation between observed groundwater data and model simulations of groundwater. Nonetheless, the outputs from GLOBGM have been validated in previous work (Verkaik et al., 2024; van Jaarsveld et al., 2026). These studies showed that approximately 85% of the evaluated points had a positive correlation when compared to local observations. They observed that there is a tendency of GLOBGM to show reduced variability in monthly water table depths and there is a bias in simulated mean water depths (van Jaarsveld et al., 2026). The model performance is best where water table depths are between 5 and 60m. Since this study focuses on drought, an extra validation was performed to assess how effectively GLOBGM simulates patterns of groundwater drought against two sources of observed groundwater data which are introduced below.

2.1.1 Observed groundwater data

To validate the simulations produced by GLOBGM from a drought perspective we use two observational datasets. Initially, we use the observed data to validate the GLOBGM outputs by calculating the anomaly correlation and comparing the duration and timing of observed drought events to those simulated by the model. The anomaly correlation measures the drought synchronisation, whilst calculating the average drought duration assesses the simulation of key drought characteristics. These metrics are introduced in more detail below (see section 2.3).

The first observational dataset is obtained from remotely sensed groundwater estimates from NASA's Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions. Specifically, we use the GRACE(-FO) mascon gridded data with a JPL solution (release 06.1 v3) (Wiese Grace-Fo, 2024; Watkins et al., 2015). These observations represent gridded, monthly, global, terrestrial water storage anomalies (relative to a time-mean) and the data is available from April 2002 to 2023. For our validation, we used the period April-2002 to December-2019 to coincide with the simulated groundwater data. Gaps smaller than 6 months are filled by linearly interpolating across the existing observational data.

The second observational dataset uses observations from the IGRAC database (IGRAC, 2024). We subset the database to ensure that points are only included where there are more than 10 years of continuous data between 1960 and 2019, this leaves 16639 locations. The majority of the locations are distributed across North America, Europe and Australia (96.5% of data points are located in these regions) and the average water table depth is 17.9m.

2.2 Drought definitions

Throughout this study we refer to two types of drought: Normal Droughts (ND) and Multi-Year Droughts (MYD). A MYD event is defined as any event that lasts for at least 12 consecutive months (Van der Wiel et al., 2023; van Mourik et al., 2025;

Ruijsch et al., 2025). Comparatively, a ND is defined as any event which lasts for less than 12 months. The onset and termination of a drought event is defined using run-theory, where a drought is defined as a continuous period below a threshold.

2.2.1 Groundwater drought

Groundwater drought thresholds are calculated based on the monthly standardized anomaly, where a drought is initiated when the water table depth (or water storage) falls more than one standard deviation below the long-term monthly mean. By definition, this assumes that (when the data is normally distributed) there will be a drought in 16% of the record.

Monthly standardized anomaly, $Z(t)$, is calculated as:

$$Z(t) = \frac{X(t) - \mu_m}{\sigma_m} \tag{1}$$

where $X(t)$ represents the water table depth at a given timestep, μ_m and σ_m are the long-term mean and standard deviation for month m, respectively. $Z(t)$ is the resulting monthly standardized anomaly used to identify drought conditions. A drought is initiated when this value falls below -1. This approach is comparable to the quantification of droughts using normalized meteorological drought indicators (e.g. SPI and SPEI).

2.2.2 Recharge drought

To understand whether multi-year groundwater droughts are driven by processes in the saturated (groundwater) or unsaturated (recharge) zone, we also calculate the average recharge drought duration globally. Groundwater recharge is generated by PCR-GLOBWB2 and is used as an input to the groundwater model (GLOBGM). Unlike the groundwater data (which is at ∼1 km resolution), recharge data is only available at 5 arcmin (∼10 km at the equator). To identify drought events, we calculate the monthly standardized anomaly from the recharge timeseries using the same formula as in equation 1 and use the same threshold approach where a drought is initiated when the monthly standardized anomaly falls below -1 (more than one standard deviation below the mean).

2.2.3 Meteorological drought

To define a meteorological drought we use the 12-month averaged Standardized Precipitation-Evapotranspiration Index (SPEI-12) which consists of the standardized difference between precipitation and potential evapotranspiration (Vicente-Serrano et al., 2010). By choosing a 12-month accumulation period, we inherently account for the accumulated precipitation and evapotranspiration over the preceding 12 months, which provides a stronger connection between the meteorological drought and the potential groundwater response. This is done because often groundwater droughts are the composite of multiple shorter meteorological droughts (Van Lanen et al., 2013). We use the same threshold approach as for groundwater and recharge, assuming that when SPEI-12 falls below -1, a meteorological drought begins. Each meteorological drought can be considered a function of the combined effects of the meteorological anomalies of the last year. This is not the case for a groundwater drought, which is defined only based on the current month assuming that the current groundwater state is already an accumulation of the incoming groundwater recharge over the last 12 months.

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We chose this measure since it encompasses a wide range of meteorological data and does not rely solely on precipitation and thus is closer related to the groundwater recharge. SPEI-12 has been calculated from the W5E5 reanalysis data (Lange et al., 2022) and the python package xclim (Bourgault et al., 2023). SPEI-12 is calculated at the 0.5°spatial resolution, and the temporal resolution has been coarsened from a daily to monthly timestep to match the GLOBGM monthly outputs.

2.3 Quantifying the propagation of meteorological to groundwater drought

To understand the global vulnerability to groundwater droughts, we first aim to understand the role of the subsurface properties in the propagation of meteorological drought into groundwater drought. The following section introduces the metrics used in this manuscript to characterize the relationship between meteorological and groundwater drought. These metrics are also used to evaluate the model against observed groundwater data.

2.3.1 Drought Duration Ratio (DDR)

To quantify differences in the average length of groundwater and meteorological droughts, we calculate the Drought Duration Ratio (DDR). This metric characterizes the responsiveness of the groundwater system to the meteorology with the following equation:

$$\mathrm{DDR} = \frac{\overline{Dur_{GW}}}{\overline{Dur_{meteo}}} \tag{2}$$

The mean groundwater drought duration ($\overline{Dur_{GW}}$) and mean meteorological drought duration ($\overline{Dur_{meteo}}$) are calculated globally in each grid cell using a database of drought events which were calculated using the methods introduced in sections 2.2.1 and 2.2.3. Droughts which have already begun at the start of the simulation period or that have not ended on the final timestep are excluded from the calculation of the average drought duration. The DDR can vary between 0 and ∞ where values $<$1 represent areas with on average longer meteorological droughts than groundwater droughts, values $>$1 represent places where the average groundwater drought is longer than the average meteorological drought and a value of 1 means the average length of a meteorological drought is equal to the average length of a groundwater drought.

To check whether the average drought duration could be skewed towards long or short drought events, we also calculate the ND/ MYD ratio which compares the number of total months spent in ND versus MYD.

2.3.2 Groundwater response types

Based on the DRR concept, we define three groundwater response types that describe the relationship between meteorological and groundwater drought duration. To account for uncertainty in the distribution and number of simulated meteorological and groundwater drought events, and to establish whether the length of an average groundwater drought is significantly different from the length of an average meteorological drought, the typology is not based on the raw DDR alone. Instead, for each grid cell with more than one groundwater and meteorological drought event, we first calculate uncertainty bounds for the mean groundwater and meteorological drought duration. These bounds are defined for groundwater (GW) and meteorological

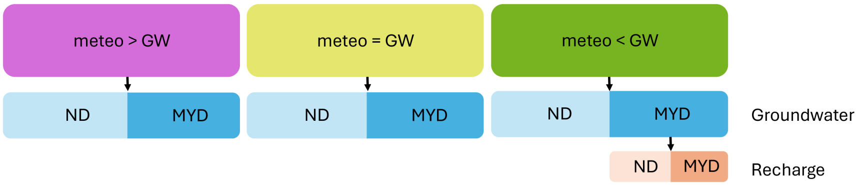


Figure 1. Schematic introducing the global groundwater response types (top row) and the subsequent division of data into multi-year and normal droughts in groundwater (second row) and recharge (bottom row).

(meteo) droughts as:

$$\left[\mu^{\mathrm{GW}}_{-\max}, \mu^{\mathrm{GW}}_{-\min}\right] \quad \text{and} \quad \left[\mu^{\mathrm{meteo}}_{-\max}, \mu^{\mathrm{meteo}}_{-\min}\right].$$

where ($\mu_{-\max}$) represents the mean drought duration excluding the longest drought event and ($\mu_{-\min}$) represents the mean drought duration excluding the shortest drought event. We then use these upper and lower bounds to identify the limits of the DDR and classify grid cells as:

$$\text{Type} = \begin{cases} \text{meteo} < \text{GW}, & \text{if } (\mu^{\mathrm{meteo}}_{-\min} < \mu^{\mathrm{GW}}_{-\max}),\ \text{DDR always} > 1 \\ \text{meteo} = \text{GW}, & \text{if } (\mu^{\mathrm{meteo}}_{-\min} \geq \mu^{\mathrm{GW}}_{-\max} \ \wedge\ \mu^{\mathrm{meteo}}_{-\max} \leq \mu^{\mathrm{GW}}_{-\min}),\ \text{DDR above and below 1} \\ \text{meteo} > \text{GW}, & \text{if } (\mu^{\mathrm{meteo}}_{-\max} > \mu^{\mathrm{GW}}_{-\min}),\ \text{DDR always} < 1 \end{cases}$$

Where a location only has one groundwater or meteorological drought event, we cannot compute the confidence bounds and thus directly compare the raw means.

The three response types represent locations where (1) groundwater drought events are on average longer than meteorological drought events (meteo<GW), (2) the average length of a groundwater drought cannot be distinguished from the average length of a meteorological drought (meteo=GW) and (3) groundwater drought events are on average shorter than meteorological drought events (meteo>GW). For each type, we then separate the data based on whether the average groundwater drought event is multi-year or normal across the simulation period (Figure 1). For those locations in the meteo<GW type where groundwater droughts are multi-year, we also look at the average length of a recharge drought to establish whether the multi-year drought is driven by processes in the saturated or unsaturated zone. Our assumption is that if a recharge drought is also multi-year, then it is processes in the unsaturated zone that drive the modulation from meteorological ND to groundwater MYD, rather than the local groundwater properties. However, it is also possible that the recharge signal is further amplified by the saturated zone to extend the MYD further.

2.3.3 Anomaly Correlation (drought synchronicity)

To explore the synchronicity of meteorological and groundwater drought, we calculate the anomaly correlation between the simulated timeseries of standardized monthly groundwater table depth and SPEI-12. As part of our model evaluation, we also calculate the anomaly correlation between the simulated timeseries of standardized monthly groundwater table depth and timeseries of monthly standardized observed groundwater data. Since seasonality has been removed from these data, the anomaly correlation reflects how well the temporal variability in anomalous conditions aligns between two datasets and thus how directly the anomalies in the meteorological signal are translated to the groundwater anomalies.

To assess whether there is a lag between the meteorology and the groundwater, we also calculate the anomaly correlation between SPEI-12 and several lagged iterations of the simulated standardized monthly groundwater table depth. To identify the dominant lag, we shift the groundwater timeseries back by 1-12 months and find the dataset with the highest anomaly correlation at a given lag. For a lag to be considered dominant it must have an anomaly correlation of at least 0.073 (threshold calculated using the standard t-test for Pearson correlation) which confirms that the correlation is statistically significant at the 5% level. It must also be at least 0.03 higher than the anomaly correlation associated with the timeseries without shifts (lag 0). Conceptually, the lag represents a delay in the groundwater response, usually related to subsurface properties and processes.

2.3.4 Groundwater drought predictability

To complement the anomaly correlation, we also calculate the ROC AUC score (Receiver Operating Characteristic Area Under the Curve), which quantifies the extent to which the SPEI-12 metric can predict groundwater drought events. The ROC AUC score can vary between 0 and 1 where a value of 1 implies that SPEI-12 can perfectly predict groundwater droughts simulated by GLOBGM. A ROC AUC score of 0.5 or less implies that the model does no better than random chance. The ROC AUC score was computed using the non-parametric definition implemented in `scikit-learn`. Formally, the ROC AUC can be expressed as:

$$\mathrm{AUC} = \frac{1}{N_{\mathrm{pos}} N_{\mathrm{neg}}} \sum_{i:\, y_i=1} \sum_{j:\, y_j=0} \mathbf{1}(s_i > s_j),$$

where N_{pos} and N_{neg} are the number of drought and non-drought months in the groundwater timeseries; s_i and s_j are the SPEI values at time steps classified as groundwater drought ($y_i = 1$, where the standardized groundwater anomaly is below the drought threshold) and non-drought ($y_j = 0$) months, respectively; and $\mathbf{1}$ is the indicator function.

3 Results

We first validate the GLOBGM outputs against observed data to assess their ability to simulate groundwater droughts. We then distribute the global data into three groundwater response types based on the relationship between average groundwater and meteorological drought duration. Next, we disentangle the processes that contribute to each response type and examine the characteristics associated with locations within each type.

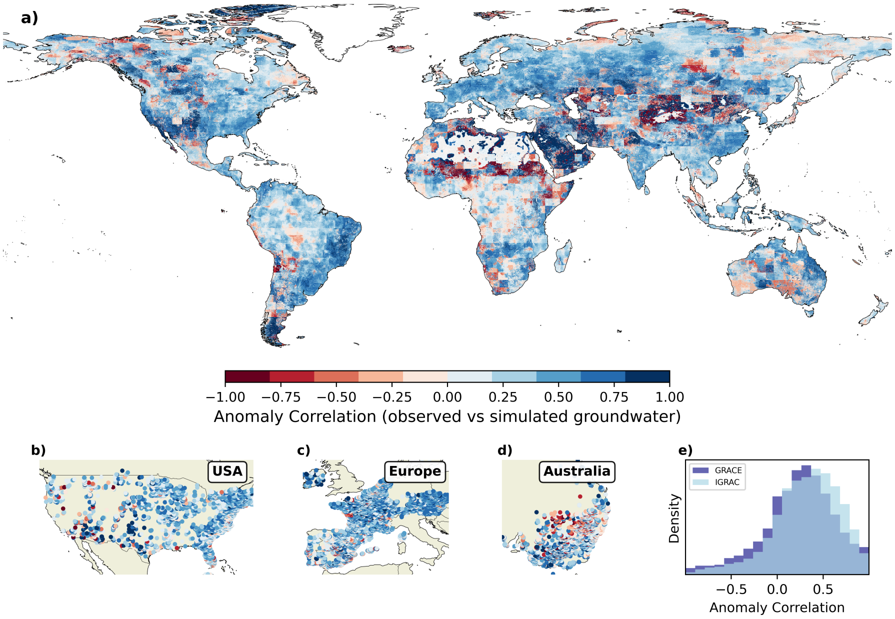


Figure 2. Anomaly correlation between a) observed GRACE and simulated groundwater data and b,c,d) point observations from the IGRAC data base and simulated groundwater data. 90% of all point observations in the IGRAC database (with sufficient data) are displayed in sub figures b, c, and d. e) compares the distribution of anomaly correlation coefficients computed with GRACE and IGRAC datasets.

3.1 Drought based groundwater model validation

Figure 2 plots the anomaly correlation between the observed and simulated groundwater data. The mean anomaly correlation between observed GRACE and simulated groundwater data (Figure 2a) is 0.23 (median 0.27), whilst the mean anomaly correlation between the point IGRAC observed data and simulated groundwater data (Figure 2b,c,d) is 0.32 (median 0.35). The distribution of anomaly correlation coefficients is similar across the two observational datasets (Figure 2e). Positive correlations dominate across most of the world, with consistently strong correlations observed across Europe and southern USA. The correlation is weakest south of the Sahara desert and strongest in the Arabian desert, both areas which are relatively dry.

The groundwater model simulates drought events of a similar average duration to those recorded in the observational record (see supplementary material Figure S1). The mean drought duration across the IGRAC observational data is 5.4 months and the median drought duration is 3.4 months. At the same locations, the simulated groundwater data has drought events with a mean duration of 6.4 months and a median duration of 2.9 months suggesting that the model records a greater number of long groundwater droughts at these locations which are not seen in the observational record. When comparing the global GRACE observational data to the simulated groundwater droughts, we see that GRACE records a mean drought duration of 5.5 months and a median of 4.3. Comparatively, in the regions which overlap with the GRACE coverage, the model simulates a mean drought duration of 9.9 months and a median of 5.4 months (note that this value differs from above because of only including data which overlaps with the observed GRACE data) suggesting that again the model simulates a greater number of long groundwater droughts. This is likely because of slower model response times and a higher degree of auto-correlation.

3.2 The propagation of meteorological to groundwater drought

3.2.1 Drought Duration

Figure 3a displays the global pattern of the Drought Duration Ratio. Roughly half of groundwater cells (49%) have average drought durations shorter than the corresponding meteorological drought (ratio less than one, purple), with the remaining half (51%) exhibiting longer groundwater droughts (ratio more than one, green). 17% of points have an average groundwater drought duration ±25% the length of the associated meteorological drought (yellow).

This pattern is predominantly driven by the spatial variation in the average length of a groundwater drought (Figure 3b,c), since this is much more variable than the average length of a meteorological drought (see supplementary material Figure S2). Regions where the DRR is less than 1 tend to be regions where the average groundwater drought is less than 6 months. The pattern of groundwater drought is broadly in line with the global climate zones and precipitation regimes, where regions with low seasonal variation but high precipitation and generally high water availability coincide with regions with on average shorter groundwater droughts (Konapala et al., 2020; Beck et al., 2018). The longer groundwater droughts and regions with higher DDR tend to be those with deeper water tables and higher aridity (Ruijsch et al., 2025; van Jaarsveld et al., 2026). The mean groundwater drought duration is 20.4 months whilst the median is 6.8 months (comparatively the mean length of an SPEI-12 drought is 6.7 months and the median is 6.3 months). The global mean groundwater drought duration is heavily skewed toward longer drought. Meaning that the average drought duration is heavily affected by a number of particularly long drought events. 35% of the world has an average drought duration of more than 12 months (multi-year).

In approximately 12% of groundwater cells, more time is spent in multi-year drought than normal drought (ND/ MYD ratio < 1) despite the average drought duration being below 12 months (these points fall in the bottom left quadrant in Figure 3d). In these locations, the average drought duration is skewed lower by a number of short drought events which mask the presence of at least one dominant multi-year groundwater drought. These tend to be locations where average water table depth is close to the surface water level (see supplementary material section S3). The opposite to this is rarely true, with less than 1% of points having a ND/MYD ratio of more than 1 and an average drought duration of more than 12 months, meaning that the average drought duration is rarely multi-year unless there is also more time spent in MYD than ND.

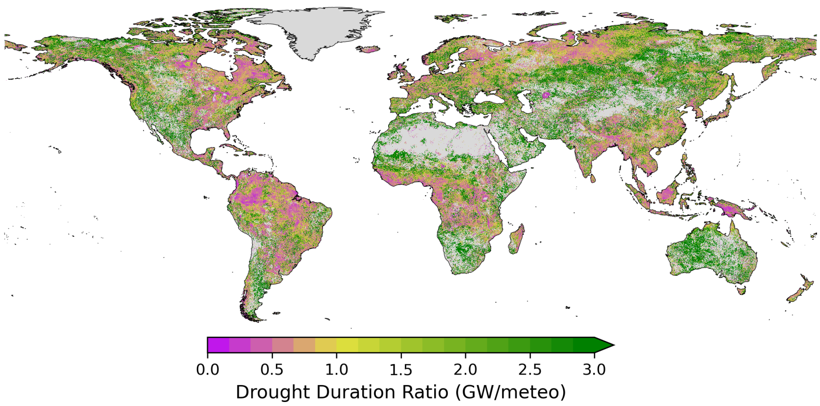
3.2.2 Groundwater response types

Based on the Drought Duration Ratio, Figure 4 shows the separation of global groundwater data into the three response types introduced in Section 2.3.2. These types describe the relationship between meteorological and groundwater drought duration. Within each type, the data are further divided according to whether the average groundwater drought is normal or multi-year.

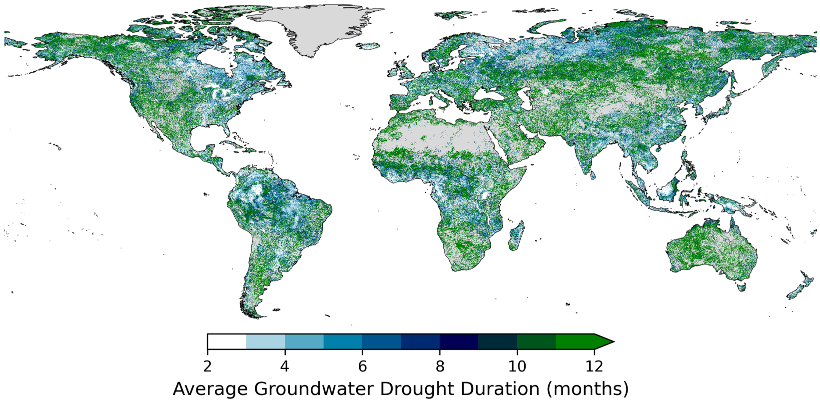
In 19% of the world, groundwater drought appears to be primarily driven by meteorology (meteo = GW). Within this type, 32% of the data (6% of global data) has a multi-year average groundwater drought duration, while the remaining 68% (13%

https://doi.org/10.5194/egusphere-2026-2335
Preprint. Discussion started: 29 April 2026

a) Drought Duration Ratio (DRR)



b) Average Groundwater Drought Duration



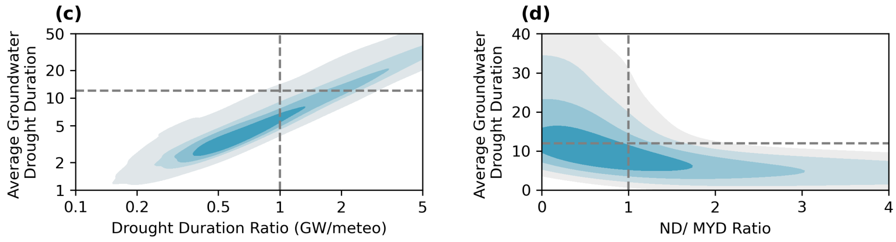


Figure 3. (a) Global distribution of the Drought Duration Ratio. (b) Global distribution of Mean Groundwater Drought Duration. (c) Relationship between average Groundwater Drought Duration and the Drought Duration Ratio. The horizontal line denotes the threshold used to classify multi-year droughts, while the vertical line indicates where groundwater drought duration exceeds meteorological drought duration. (d) Relationship between Average Groundwater Drought Duration and the ratio of months spent in normal versus multi-year drought. The bottom left quadrant highlights locations where the average groundwater drought duration is less than 12 months, yet a greater proportion of time is spent in multi-year drought than in normal drought (ND/ MYD $<$1).

https://doi.org/10.5194/egusphere-2026-2335
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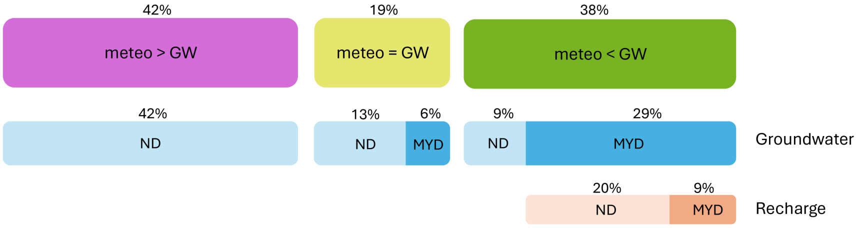

Figure 4. Global groundwater response types (top row) with data assigned. In the second row (blue) the data associated with each type is divided based on whether the average groundwater drought is a MYD or ND, and in the third row, the data which has a multi-year average drought duration is further sub-divided based on whether the average duration of a recharge drought is multi-year or normal.

of global data) has an average duration of less than one year. Consequently, in regions where meteorology is classified as the main driver of groundwater drought, we can expect mostly normal droughts.

The meteo $<$ GW type contains 38% of global groundwater data. Of this, 76% (29% of global data) has a multi-year average groundwater drought duration, while 24% (9% of global data) has a normal average duration. However, 90% of the data in this type (34.2% of global data) spends more months in multi-year drought (MYD) than in normal drought (ND). This suggests that, in 57% of cases where the average indicates a normal drought, the mean is biased downward by a series of short events. In these locations, significant multi-year droughts are common but interspersed with short events, making the average duration potentially unrepresentative.

For locations in the meteo $<$ GW type with an average groundwater drought duration which is multi-year, we also examine recharge drought duration. 69% of data in this category (20% of the world) has an average recharge drought duration of less than 12 months which is subsequently extended into a multi-year groundwater drought. This indicates that processes within the saturated zone are primarily responsible for amplifying the meteorological drought signal. In the remaining 31%, multi-year groundwater droughts are instead driven by processes in the unsaturated zone (where recharge drought durations are on average multi-year).

A large amount of data still falls into the meteo$>$GW type (42%), but almost all of these locations have a normal groundwater drought duration. For these regions we see that anomalies in the groundwater system typically have a faster response time than 12 months. Although these fast responsing systems make up a large portion of the meteo$>$GW type, there are also locations with very shallow groundwater or strong connectivity to the surface water that exhibit similar behaviour. We will discuss this in more detail in the Discussion.

3.2.3 Groundwater processes

To demonstrate some of the key processes driving the drought classification in Figure 4, Figure 5 plots three representative pairs of groundwater and SPEI-12 time series. In Figure 5a we observe the groundwater system extending the meteorological

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signal by pooling multiple meteorological droughts into one prolonged groundwater drought. To define pooling we calculate the mean number of meteorological droughts that overlap with each groundwater drought. In this timeseries we can also see the groundwater lagging behind the meteorology. Although these processes do not always co-exist, in practise, points with significant pooling (mean meteo overlap $>$ 2) tend to be associated with a lagged or delayed groundwater response. Amongst the points where a statistically significant correlation could be established between the groundwater timeseries and SPEI-12, those which also have significant pooling have an average lag of 5.8 months, compared to 1.1 months where there is no pooling of meteorological drought events. Places with a lag also tend to have deeper groundwater, where the mean water table depth at locations with lag 12 is $\sim 97.8m$ vs $\sim 40.4m$ for the data with no lag. Both of these processes are associated with data predominantly in the meteo<GW category, where 76% of data with a lag more than 1 falls into this category.

Figure 5b demonstrates an example of a location where the average groundwater drought duration is skewed lower by a series of short groundwater drought events, meaning that despite the presence of multiple intense multi-year droughts the average drought duration remains less than 12 months. This behaviour appears to be associated with points which have water table depths close to the surface level. By definition this behaviour falls into the meteo>GW category, despite spending more time in MYD than ND (purple in Figure 5e with ND/MYD below 1).

Finally, Figure 5c demonstrates the mismatch between fast responding groundwater time series (top) and SPEI-12 (bottom). Places which demonstrate this behaviour almost always fall into the meteo>GW category where we almost never observe multi-year groundwater droughts and groundwater has a much higher variability. This is quantified in Figure 5f where the standard deviation of first differences is much higher amongst the points in the meteo>GW category (purple).

3.2.4 Drought synchronicity and predictability (anomaly correlation and ROC-AUC score)

The anomaly correlation between the monthly standardized groundwater table depth and the SPEI-12 is displayed in Figure 6a. The correlations are highest across Europe, eastern USA, central Africa and large parts of South America and lowest in Australia, Argentina, western USA and across central Asia. The global mean anomaly correlation achieved between SPEI-12 and simulated groundwater is 0.36 and the median is 0.42. 81.3% of the world has a statistically significant anomaly correlation (p=0.05) at lag 0. Visually, places with a long average groundwater drought duration also have a lower anomaly correlation (Figure 6a versus Figure 2b). Comparatively, places with a DDR close to 1 tend to have a higher anomaly correlation (Figure 6d), implying that the systems are closely connected. The lowest correlations are most common in the meteo<GW type where there is more of a disconnect between the meteorology and groundwater which is dictated by the geo-physical properties of the saturated and unsaturated zones (Figure 6a,d).

Figure 6c plots the distribution of statistically significant anomaly correlation values (>0.073), grouped based on the groundwater lag (see supplementary material Figure S4 for global map of dominant lag). We compare data from lag 0 - lag 12 and find that places with a higher lag tend to also have lower anomaly correlations (Figure 6c). 56% of the data with a lag of one month or more is from the meteo<GW type, 15% from meteo=GW and 5% from meteo>GW suggesting that a lag is more common in areas where the groundwater anomalies are the result of pooling the meteorological drought signal.

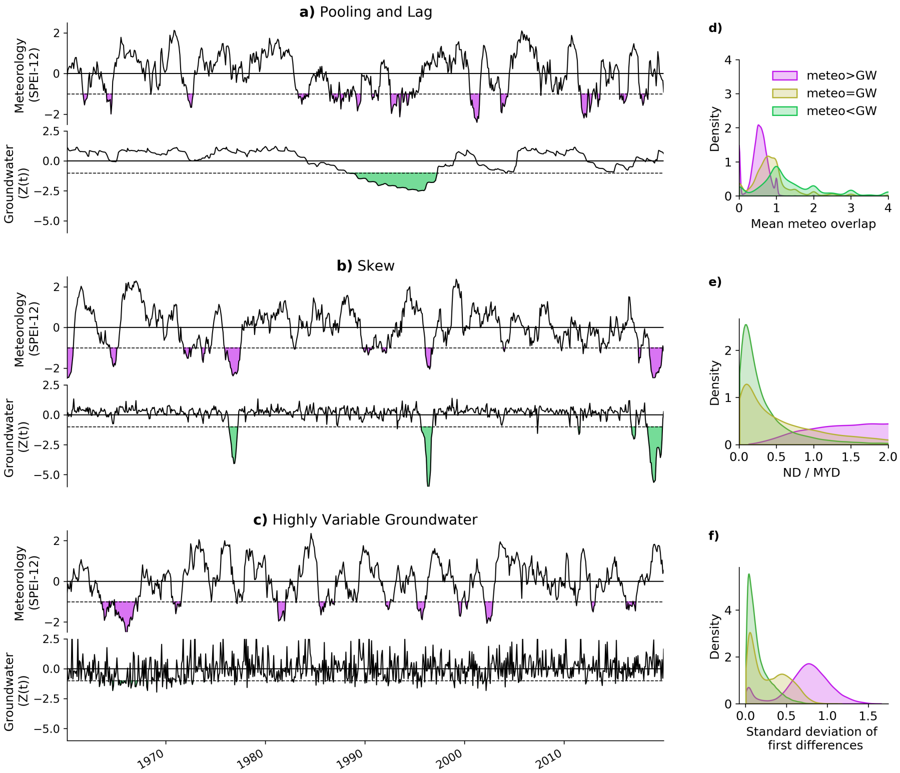

Figure 5. Time series demonstrating key groundwater processes where a) demonstrates a lag between meteorology and GW timeseries and the pooling of meteorological drought events, b) visualises the process which leads to a skew in average groundwater drought duration, and c) shows a mismatch in groundwater and meteorological accumulation periods. Each of these processes is associated with a histogram which characterises the types in which these behaviours are typically observed. Subplot d) compares the distribution of points in each groundwater type to the mean meteo overlap, a metric which calculates the average number of meteorological droughts which overlap with each groundwater drought and indicates pooling. Subplot e) compares the distribution of points in each groundwater type to the number of months in ND/ number of months in MYD ratio, and subplot f) compares the distribution of points in each groundwater type to the standard deviation of first differences which characterises the variability of the groundwater timeseries.

335 In Figure 6b we visualise the global ROC AUC score, a measure of groundwater drought predictability. A value of more than 0.5 indicates a groundwater drought is more likely to coincide with a meteorological drought than if it were left to random chance. 84% of global ROC values exceed 0.5. The spatial pattern is very similar to the anomaly correlation. Similarly, areas with a high ROC score tend to be those where the Drought Duration Ratio is close to 1 (supplementary material Figure S5b). Regions with a long lag also tend to have a lower ROC score (supplementary material Figure S5a).

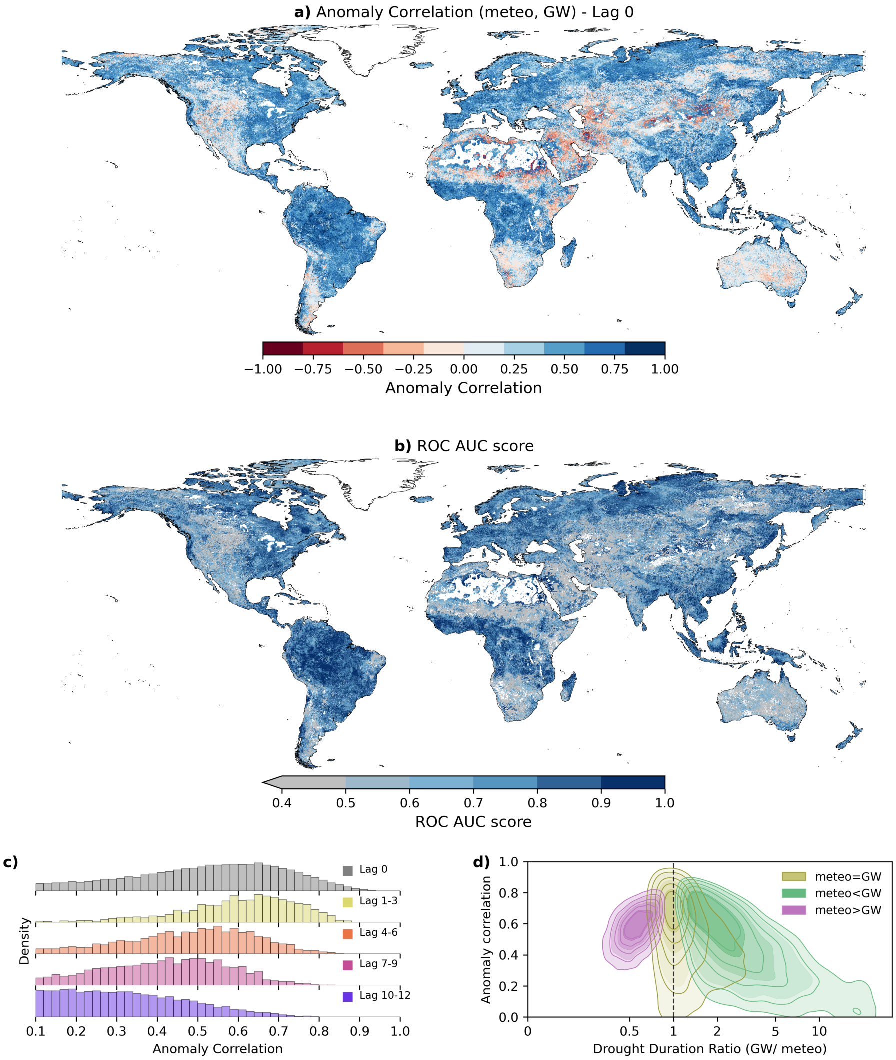

Figure 6. a) Anomaly Correlation between standardized groundwater table depth and SPEI-12, b) global distribution of ROC-AUC score, c) histogram displaying the distribution of anomaly correlation scores for groundwater data with lags between 1 and 12 months. d) density plot representing the relationship between the anomaly correlation and the Drought Duration Ratio, plots are coloured based on their groundwater response type.

4 Discussion

4.1 Main findings and implications

The lack of comprehensive global groundwater data has in the past meant that groundwater has been excluded from global drought propagation analysis (Fuentes et al., 2022; Wang et al., 2025; Han et al., 2019), or has been represented by coarse and

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temporally limited data (Akl et al., 2025). Although drought propagation has received significant attention at local, regional and national scales, the variability in the global patterns and drivers of groundwater drought mean that these findings cannot be easily extrapolated for actionable use. To the authors knowledge, this global analysis is the first to use hyper-resolution data to focus specifically on the drivers and patterns of multi-year groundwater drought.

Our results suggest that subsurface geo-physical properties are the primary drivers that modulate meteorological droughts into multi-year groundwater droughts. Although drought propagation begins with the meteorology, we find that in much of the world groundwater resources are substantially disconnected from the meteorological input and that the sub-surface significantly amplifies and modifies the drought signal (meteo<GW). Less than 2% of the world has an average meteorological drought duration of more than one year, but by comparison, 35% of the world has an average groundwater drought duration which is multi-year.

Disentangling the relationship between meteorology and groundwater exposes areas which are vulnerable to multi-year drought in the present day, but also identifies those which will be more vulnerable in the future. At present, the regions where meteorology and groundwater are connected to one another do not frequently experience multi-year drought (only 6% of global data has a multi-year average groundwater drought duration and also falls into the meteo=GW category). However, in the future, we expect an increase in the frequency and magnitude of multi-year meteorological droughts (Van der Wiel et al., 2023; Pascale et al., 2021; Rakovec et al., 2022), and thus regions in this category will be increasingly at risk from multi-year groundwater drought. An increase in the frequency or duration of meteorological droughts might also push more points into the meteo<GW category. If meteorological droughts are lengthened, or more frequent, then there will be less time for recovery between drought events, which might encourage increased pooling of meteorological droughts into groundwater droughts (Ebeling et al., 2025). This process may also amplify the relationship between meteorology and groundwater for points already in the meteo<GW category (increasing the DDR), since increased pooling would extend the meteorological signal in a non-linear way. It is also likely that increases in groundwater abstractions or pumping might push data from the meteo=GW category to the meteo<GW category (Rusli et al., 2024). Although we have not considered the impacts of abstractions on the typology we have presented in this paper, in many regions this is likely to have a significant impact on groundwater trends and should thus be considered in future work. However, strong trends in groundwater levels also have impacts on the proper characterisation of drought anomalies and thus require methodological advances in drought studies (Wanders et al., 2015).

Understanding the dynamics of multi-year drought propagation can inform local drought mitigation and help to predict and prepare for drought impacts (Minea and Albulescu, 2025; Parry et al., 2018). This is particularly important in the context of multi-year groundwater drought, since groundwater is often used to supplement surface water and sustain vegetation (Mu et al., 2021), so a prolonged absence of this resource can have wide-reaching implications. The typology that we implement in this study provides a simple baseline for understanding global patterns of groundwater responsiveness, which in turn can inform drought mitigation. For example, in regions where the meteorology and the groundwater are connected (which in our analysis makes up 19% of the world), the magnitude and timing of a drought can be anticipated based on the observed anomalies in the meteorological conditions. If we know the systems to be closely connected, then the end of a meteorological drought (which is much easier to measure and observe) is likely to also signal the end of a groundwater drought. It is also beneficial to understand whether or not a location falls into the meteo<GW type, since in these cases even a short meteorological drought might signal the start of a multi-year groundwater drought for which society needs to prepare. Contrastingly, in places where the meteorological droughts tend to be longer than the groundwater droughts, a multi-year groundwater drought is extremely unlikely since multi-year meteorological droughts are rare.

4.2 Processes and properties which extend the meteorological drought signal

Consistent with findings from other studies (Ebeling et al., 2025; Minea and Albulescu, 2025), our analysis confirms that even regions which are subject to similar meteorological forcing may exhibit a very different groundwater response. The modulation of meteorological drought is controlled by the presence (or absence) of several key groundwater processes which are tied to local catchment characteristics and aquifer properties.

Lag, attenuation, pooling and lengthening are all well-established mechanisms of drought propagation which we observe in this study (Van Loon, 2015; Brauns et al., 2020). The existence of a multi-year groundwater drought is often facilitated by the lengthening of the meteorological signal, and we find that the most extreme examples of this are usually accompanied by pooling of several meteorological drought events. In these cases, the clustering of meteorological droughts could be made more likely by persistent weather patterns and decadal climate variability (Rust et al., 2019).

In general, the places where groundwater lags behind SPEI-12 also tend to be locations which substantially amplify the meteorological signal and are more likely to encounter a multi-year groundwater drought. In agreement with other studies, we find that longer lags tend to be associated with deeper groundwater and have longer average drought durations and lower anomaly correlations (Schreiner-McGraw and Ajami, 2021; Ebeling et al., 2025). Understanding the groundwater lag also has significant benefits for drought forecasting, where the characteristics of a meteorological drought can be used to anticipate the upcoming groundwater response.

Outside of the more well-established drought propagation processes, our analysis also identified a cluster of points which have a notably bimodal distribution of drought events. In these locations more time is spent in multi-year drought than normal drought, but the average drought duration is skewed down (to less than 12 months) by frequent short drought events. Groundwater here is typically shallow, and close to surface and potentially connected to surface water. We hypothesise that these regimes have tipping points where the groundwater system can buffer shorter, or less intense meteorological droughts, but when recharge is reduced beyond a certain threshold the groundwater becomes disconnected from the surface water, descending into an intense, multi-year drought event. Since small changes in groundwater management could prevent or trigger this mechanism, it is important that we can predict where and when this process might occur.

4.3 Difficulties associated with drought definition

Throughout this analysis we encountered several difficulties associated with the definition of groundwater and meteorological drought. Firstly, variability in the response time of groundwater to meteorological anomalies meant that it was hard to characterise groundwater droughts with one uniform meteorological drought index. Although this was made more difficult by the diversity inherent in global data, other studies have also found this to be a challenge on smaller, more regional scales (Minea

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and Albulescu, 2025; Ebeling et al., 2025; Hellwig et al., 2022; Kumar et al., 2016). For this study we chose to use SPEI with a 12 month accumulation which was consistent with multi-year drought literature (Ruijsch et al., 2025; van Mourik et al., 2025), but also aligned with other global studies which found the average groundwater accumulation period to be close to 12 months (Liu et al., 2023; Ndehedehe et al., 2023). However, mismatches in SPEI-12 and groundwater accumulation still result in a portion of data falling into the meteo>GW type. In these locations the groundwater responds to the meteorology faster than the 12 month accumulation inherent in SPEI-12 and this results in shorter groundwater drought events. Since the main focus of this study was to identify the drivers of multi-year groundwater droughts, and they are not common in these fast responding regions, this has not hindered our analysis, but should be considered if this analysis was to focus on the drivers of shorter events.

Another challenge for groundwater drought definition was the presence of trends. Globally, many groundwater aquifers are experiencing significant decline both from unsustainable abstractions and from climate change (Jasechko et al., 2024; Nazari et al., 2025; Berghuijs et al., 2024). These trends remove the stationarity assumption that is often used in drought characterisation and can artificially inflate or deflate drought length. Solutions such as de-trending the data have not been successful in other global groundwater drought studies (e.g. Herbert and Döll, 2025; Wanders et al., 2015), so instead, here we suggest that global maps are considered in combination with masks quantifying the magnitude of groundwater trends (van Jaarsveld et al., 2026).

Finally, we also had difficulty defining droughts in regions with very little variability. In these locations, the monthly standardized anomaly was very small and thus sensitive to small changes in groundwater table depth.

4.4 Avenues for future work

This study has identified several new research avenues which could further enhance our understanding of multi-year groundwater drought. Firstly, although GLOBGM includes groundwater abstractions, this study has not attempted to disentangle their influence on groundwater drought. Future work could leverage the modelling framework introduced here to test how varying levels of groundwater abstractions impact multi-year groundwater drought development and evaluate whether changes to groundwater pumping could be an effective strategy for drought mitigation. Secondly, it would be beneficial to perform a similar analysis using model simulations which are forced with future climate data. Understanding how the drivers and patterns of multi-year drought might change in the future under climate change is important for preparedness and could inform long-term policy and planning. Finally, it would also be interesting to perform a similar analysis on the event-scale. Our work considers only the average relationship between groundwater and meteorological drought events, but this many vary on an event-to-event basis.

5 Conclusions

This study presents the first hyper-resolution, global scale analysis of the drivers and patterns of multi-year groundwater drought. We find that in many parts of the world the subsurface significantly modulates the meteorological drought signal resulting in frequent multi-year groundwater drought. By categorising the global groundwater data into types which describe the responsiveness of the groundwater to the meteorology, we provide a simple framework for understanding the vulnerability to multi-year drought. Our findings can inform drought planning and mitigation whilst emphasising the differences in groundwater response across the world.

Data availability. GLOBGMv1.1 simulations based on (van Jaarsveld et al., 2026) can be accessed via:
https://public.yoda.uu.nl/geo/UU01/AKSHOX.html

Author contributions. The conceptualisation of this research was carried out by SS and NW. The data was provided by BvJ who also assisted SS with the data processing. SS, NW, JvM, DR and SH developed the framework for drought definition. All analysis was carried out by SS. All authors helped to write and edit the manuscript.

Competing interests. The authors declare that no competing interests are present.

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