PROPAGATION FROM ATMOSPHERIC TO HYDROLOGICAL DROUGHTS IN BRAZILIAN CATCHMENTS

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INTRODUCTION

Drought propagation is generally understood as the transformation of atmospheric water deficits into deficits in hydrological compartments, such as streamflow and groundwater. During this transfer, drought signals may be delayed, attenuated, intensified or interrupted by catchment storage, evapotranspiration, recharge pathways, aquifer properties and human regulation (Van Loon, 2015; Zhang et al., 2022). As a result, precipitation deficits do not always develop into hydrological droughts, and those that propagate often become fewer, longer and later events (Sattar et al., 2019; Brunner and Chartier-Rescan, 2024; Teutschbein et al., 2025).

Groundwater drought is commonly interpreted as the slowest stage of drought propagation. However, groundwater responses are controlled by subsurface storage, recharge mechanisms, aquifer connectivity and regional flow systems, which can make groundwater drought weakly synchronized with meteorological or streamflow droughts (Bloomfield and Marchant, 2013; Brunner and Chartier-Rescan, 2024). Therefore, groundwater drought cannot be reliably inferred from precipitation or streamflow deficits alone. This limitation is especially relevant in tropical regions, where groundwater observations remain sparse and large-sample studies integrating meteorological, streamflow and groundwater records are still limited.

In Brazil, recent advances in large-sample hydrological datasets and groundwater monitoring databases provide an opportunity to assess how drought events propagate from the atmosphere to groundwater across contrasting hydroclimatic conditions. Previous studies have investigated meteorological-to-hydrological drought propagation in Brazil and other regions (Bevacqua et al., 2021; Hellwig et al., 2022), but observed groundwater drought propagation remains poorly quantified at the catchment scale. Here, we address this gap by combining precipitation, climatic water balance, streamflow and groundwater records from Brazilian catchments to evaluate whether drought propagation to groundwater is frequent, how long it takes, and which hydrological pathways most strongly connect atmospheric and subsurface droughts.

METHODOLOGY

We selected Brazilian catchments with daily information available for precipitation, potential evapotranspiration, streamflow and groundwater level. Streamflow and meteorological data were obtained from the latest version of the Catchment Attributes and Meteorology for Large-sample Studies for Brazil, CAMELS-BR (Chagas et al., 2020), while groundwater data were obtained from GWDBrazil (Uchôa et al., 2025). Only unconfined aquifers were retained to reduce the influence of

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confined systems with longer and more complex hydraulic responses. This filtering resulted in 51 catchments and 181 groundwater wells distributed across Brazilian biomes.

Drought events were identified separately for precipitation (P), climatic water balance (P−ET), streamflow (Q) and groundwater level (GW) using a variable threshold approach commonly applied in hydrological drought studies (Van Loon and Laaha, 2015; Brunner and Chartier-Rescan, 2024). For each variable and catchment, daily records were smoothed using a 30-day moving average. A seasonally varying drought threshold was then computed as the 20th percentile of the smoothed variable for each day of the year, using a ±15-day window. Days below this threshold were classified as drought days, and consecutive drought days were merged into events. Events lasting fewer than 30 days or presenting zero cumulative deficit were excluded. Drought propagation was assessed using an event-based matching approach. Events in consecutive compartments were linked when the target event started during the source event or within 30 days after its end, allowing temporal overlap between droughts in different hydrological compartments. When multiple target events satisfied this condition, the pair with the greatest temporal overlap was retained.

RESULTS AND DISCUSSIONS

Drought propagation to groundwater was selective and delayed across the analyzed Brazilian catchments (Figure 1). Only 15% of precipitation droughts and 14% of climatic water-balance droughts propagated to groundwater, whereas 37% of streamflow droughts reached groundwater, indicating that streamflow droughts represent the strongest hydrological connection with groundwater droughts. Among precipitation droughts, 42% remained restricted to precipitation, while 26% propagated to streamflow and only 15% reached groundwater. For climatic water-balance droughts, 52% did not propagate to other compartments, whereas 34% propagated to streamflow. Propagation lags also increased along the hydrological continuum: the transition from precipitation to climatic water balance was rapid, with a median lag of 8 days, while transitions to streamflow occurred over intermediate timescales, with median lags of 75 days from P−ET to Q and 109 days from P to Q. In contrast, groundwater responses were much slower, with median lags of 197 days from P−ET to GW, 277 days from Q to GW and 352 days from P to GW. Maximum lags reached 1,032 days for the Q–GW pathway, showing that groundwater drought may occur several months or even years after atmospheric or streamflow drought onset.

These results show that groundwater drought is not simply the final stage of a linear drought-propagation sequence. Instead, drought propagation acts as a filtering process, in which meteorological deficits may be delayed, attenuated or interrupted by catchment storage, recharge pathways and hydrological connectivity (Van Loon, 2015; Zhang et al., 2022). The low propagation fractions from P and P−ET to GW, only 15% and 14%, respectively, indicate that most atmospheric droughts are not sufficient to generate groundwater droughts, reinforcing that groundwater cannot be inferred directly from precipitation deficits alone. This interpretation agrees with previous evidence from Brazil, where Bevacqua et al. (2021), analyzing 457 catchments, showed that hydrological droughts are generally longer-lasting, more severe and slower to recover than meteorological droughts, with recovery times in dry regions reaching up to four times those of meteorological droughts. Our results extend this interpretation to groundwater by showing that propagated groundwater droughts occur with median lags of 197 to 352 days and maximum lags exceeding 1,000 days. These long delays reflect the role of aquifer storage, recharge timing and subsurface connectivity, which can decouple groundwater drought from short-term atmospheric variability (Bloomfield and Marchant, 2013; Hellwig et al., 2022; Brunner and Chartier-Rescan, 2024).

Therefore, monitoring only precipitation or streamflow may underestimate delayed groundwater drought risk, especially in basins where groundwater supports baseflow and water supply.

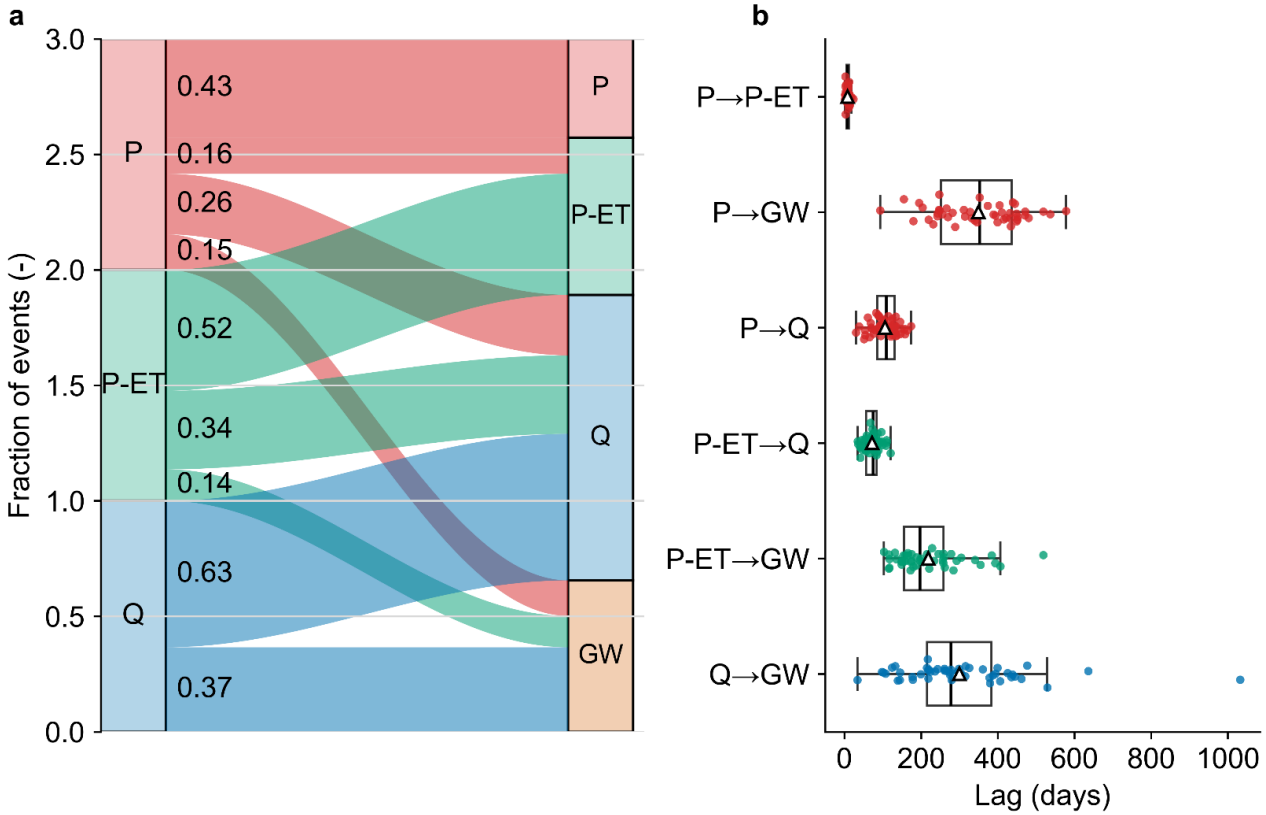


Figure 1. Event-based drought propagation across climatic and hydrological variables. (a) Alluvial representation of drought-event propagation from precipitation (P), climatic water balance (P−ET) and streamflow (Q) toward subsequent states, including groundwater droughts (GW). Flow widths indicate mean propagation fractions. (b) Start-to-start lag distributions for the main propagation pathways. Boxplots summarize basin-level lag times; horizontal lines indicate medians, triangles indicate means and points represent individual catchments.

CONCLUSIONS

This study shows that drought propagation to groundwater across Brazilian catchments is both selective and delayed. Only 15% of precipitation droughts and 14% of climatic water-balance droughts reached groundwater, whereas 37% of streamflow droughts propagated to groundwater. The propagation lags further demonstrate the slow response of groundwater systems. While atmospheric-to-surface transitions occurred within days to a few months, groundwater responses typically required several months, with median lags ranging from 197 to 352 days and maximum delays exceeding 1,000 days. These findings reinforce the importance of integrated drought monitoring that combines atmospheric, streamflow and groundwater observations. In water-resources management, relying only on precipitation or streamflow indicators may underestimate delayed subsurface drought risks.

Groundwater observations are essential for identifying persistent drought impacts, especially in regions where aquifers support baseflow, water supply and drought resilience.

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