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RESEARCH ARTICLE

Drought Propagation Mechanisms Across Hydrological Systems in Semi-Arid Basins

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ABSTRACT

Meteorological drought does not translate instantaneously or uniformly into the soil-moisture and streamflow deficits that determine water availability for people, agriculture and ecosystems; instead, a precipitation shortfall propagates through a basin's storage components over weeks to years, changing character, duration and severity as it moves. We quantified this propagation across 18 semi-arid river basins in three climatically similar but geologically contrasting regions, using 30-year (1991-2020) records of precipitation, modelled root-zone soil moisture, observed streamflow and, for a 9-basin subset with adequate well coverage, groundwater levels, converted to the Standardized Precipitation Index (SPI), Standardized Soil Moisture Index (SSMI), Standardized Streamflow Index (SSI) and Standardized Groundwater Index (SGI). Cross-correlation and pooled event-matching analyses showed a median lag of 1 month from meteorological to soil-moisture drought onset, 3 months to streamflow drought, and 8 months to groundwater drought, but these medians concealed a roughly four-fold spread across basins that was strongly and significantly associated with baseflow index (BFI): low-BFI, flashy basins on impermeable substrate propagated meteorological drought into streamflow drought within a median of 1.4 months, while high-BFI basins with substantial aquifer storage delayed and smoothed the signal to a median of 5.9 months, attenuating peak deficit severity by an average of 41% relative to the driving SPI series. We further identified consistent threshold and pooling behaviour: short, separate meteorological dry spells that left no discernible streamflow signature individually frequently merged into a single, more severe hydrological drought event once cumulative soil-moisture and groundwater storage fell below a basin-specific threshold, a nonlinearity that the optimal SPI accumulation timescale for predicting SSI (ranging from 3 to 15 months across basins, median 6) only partially captured. Propagation lag and attenuation were both better predicted by BFI and aquifer transmissivity than by aridity index or basin area. These results indicate that catchment storage structure, more than climatic dryness itself, governs how quickly and how severely a meteorological drought becomes a water-resources crisis in semi-arid basins, with direct implications for drought early-warning lead times.

Keywords: drought propagation; hydrological drought; soil moisture drought; streamflow drought; groundwater drought; semi-arid basins; standardized indices; baseflow index; lag time; drought pooling

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1. INTRODUCTION

A rainfall deficit does not become a water-resources emergency the moment it begins; it becomes one only once the basin's storage reservoirs, soil moisture, snowpack where present, streams, and aquifers, have been drawn down enough that supply to users and ecosystems falls short of demand. This chain of transmission, widely termed drought propagation, means that meteorological drought, hydrological drought and the socio-economic impacts that follow are related but distinct phenomena, separated in time and modified in character as the deficit signal passes through successive storage components of the terrestrial water cycle [1,2].

Semi-arid basins are a particularly consequential setting in which to study this propagation. They combine high year-to-year precipitation variability, thin or seasonally saturated soils, and, in many cases, limited aquifer storage, all of which shape how quickly and how severely a precipitation deficit is transmitted downstream [3]. At the same time, semi-arid basins disproportionately support rainfed and irrigated agriculture and rural water supply systems with little built storage to buffer shortfalls, so the lag between meteorological drought onset and its hydrological expression is not merely a scientific curiosity but a determinant of how much warning time water managers have before a deficit becomes a crisis [4].

A substantial body of prior work has established the qualitative mechanics of propagation, pooling of short, separate meteorological dry spells into longer hydrological drought events; lag and lengthening of drought duration as the signal moves from precipitation through soil moisture to streamflow to groundwater; and attenuation of peak severity as storage buffers the extremes of the driving climate signal [1,5]. Comparative studies using standardized indices have shown that the timescale of precipitation accumulation best correlated with streamflow drought varies systematically with catchment storage properties, typically summarised through the baseflow index, aquifer type, or a catchment's characteristic response time [6,7]. However, much of this literature has focused on temperate and humid catchments in Europe and North America, and the extent to which the same storage-mediated propagation mechanisms and lag magnitudes generalise to semi-arid basins, where antecedent soil moisture deficits are typically larger and evapotranspirative demand is higher, remains less systematically documented [8,9].

Groundwater drought propagation is even less studied outside a handful of well-instrumented regions, in part because dense observation-well networks needed to construct reliable groundwater-level time series are scarce in many semi-arid regions precisely where groundwater drought has the largest human consequences [2,10]. Where such records exist, they have shown propagation lags to groundwater of many months to several years and substantial smoothing of the meteorological signal, but comparisons across basins

with contrasting aquifer structure within a consistent semi-arid climate envelope, which would isolate the role of storage structure from that of climate, are uncommon [11].

Here we analyse drought propagation across 18 semi-arid basins spanning three regions with broadly similar aridity but markedly different hydrogeology, using a consistent 30-year multi-index framework spanning precipitation, soil moisture, streamflow and, where available, groundwater. We test whether propagation lag and severity attenuation are better explained by catchment storage properties (baseflow index, aquifer transmissivity) than by climatic aridity or basin size, and we characterise the threshold and pooling behaviour by which short meteorological dry spells merge into longer hydrological drought events, with the aim of identifying which catchment attributes drought early-warning systems in semi-arid regions should prioritise when estimating lead time.

2. MATERIALS AND METHODS

We compiled 30-year (1991-2020) precipitation, modelled root-zone soil moisture, observed streamflow and, for a subset of basins, observation-well groundwater-level records for 18 semi-arid river basins across three regions, converted each variable to a standardized index, and quantified propagation lag, threshold and pooling behaviour, and severity attenuation using cross-correlation and event-based drought analysis.

2.1 Study basins and hydroclimatic setting

Eighteen basins (drainage area 340-11,200 km²) were selected across three semi-arid regions with mean annual aridity index (precipitation over potential evapotranspiration) between 0.22 and 0.48, spanning a gradient of catchment storage properties from thin-soil, low-permeability basins with baseflow index below 0.30 to basins overlying moderately transmissive alluvial or karstic aquifers with baseflow index above 0.55. All 18 basins had continuous naturalised or minimally regulated daily streamflow records for 1991-2020; a 9-basin subset with at least five observation wells maintaining continuous monthly records over the same period was used for the groundwater component of the analysis.

2.2 Precipitation and soil moisture data

Basin-averaged daily precipitation was derived from a gauge-based gridded precipitation product cross-validated against national meteorological service station records for each region. Root-zone soil moisture was obtained from a land-surface model reanalysis product at daily resolution, bias-corrected against available in-situ soil moisture network observations at a subset of basins before use; the correction reduced mean absolute bias in modelled monthly soil moisture from 0.041 to 0.016 m³/m³ at the six basins with reference observations.

2.3 Streamflow and groundwater data

Daily streamflow was obtained from national or regional hydrometric agencies for gauges with less than 10% missing data over 1991–2020 and no documented major flow regulation upstream; basins with substantial reservoir storage or inter-basin transfer were excluded during screening. Groundwater levels for the 9-basin subset were compiled from national observation-well networks, aggregated to a basin-mean monthly time series by inverse-distance weighting of individual well anomalies.

2.4 Standardized index construction

Each variable was converted to a standardized index following the general approach used for the Standardized Precipitation Index: precipitation was fitted to a gamma distribution, soil moisture and streamflow to a log-logistic distribution, and groundwater level to a normal distribution after testing for the best-fitting candidate distribution at each basin, with all fitted distributions transformed to the standard normal to yield the Standardized Precipitation Index (SPI), Standardized Soil Moisture Index (SSMI), Standardized Streamflow Index (SSI) and Standardized Groundwater Index (SGI). SPI was computed at accumulation periods of 1 to 24 months to allow identification of the timescale best correlated with each downstream index.

2.5 Propagation lag and threshold-pooling analysis

Propagation lag from meteorological to each downstream drought type was estimated in two complementary ways: cross-correlation between SPI at each accumulation period and the corresponding downstream index, identifying the accumulation period and lag maximising the correlation coefficient; and an event-based approach using a variable threshold level (the 20th percentile of each index's monthly climatology) to delineate discrete drought events in each series, matching each hydrological drought event to the meteorological event or events preceding it and computing the lag between event onsets. The event-based approach additionally recorded, for each hydrological drought event, the number of distinct antecedent meteorological dry spells that pooled into it, following established drought-pooling criteria requiring a minimum inter-event time and minimum excess volume for pooling to be counted.

2.6 Attenuation, catchment attributes and statistical analysis

Severity attenuation was quantified as the percentage reduction in mean drought-event magnitude (the time-integrated deficit of the index below the threshold) between SPI-3 and each downstream index, matched by event. Baseflow index was calculated from each basin's daily streamflow record using a standard digital filter, and aquifer transmissivity class was assigned from national hydrogeological maps for the groundwater subset. Relationships between propagation lag or attenuation and basin attributes (baseflow index, aridity index,

drainage area, aquifer transmissivity class) were tested with Spearman rank correlation and a multiple linear regression with lag or attenuation as the dependent variable, and significance was assessed at $\alpha = 0.05$ with a Benjamini-Hochberg correction for the multiple basin-attribute comparisons performed.

3. RESULTS

Across the full 18-basin sample, median propagation lag from meteorological drought onset (SPI-1) to soil-moisture drought onset (SSMI) was 1 month (interquartile range 0.5–2 months), lengthening to a median of 3 months (interquartile range 1.5–5 months) for streamflow drought (SSI) and, in the 9-basin groundwater subset, to a median of 8 months (interquartile range 5–13 months) for groundwater drought (SGI). Table 1 reports median propagation lag and severity attenuation separately for low-baseflow-index and high-baseflow-index basin groups, and the contrast between groups was pronounced: low-BFI basins ($\text{BFI} < 0.30$) propagated meteorological drought into streamflow drought within a median of 1.4 months, while high-BFI basins ($\text{BFI} > 0.55$) delayed the same transition to a median of 5.9 months, a four-fold difference that was highly significant (Mann-Whitney U, $p < 0.001$).

Table 1. Median propagation lag and severity attenuation from meteorological to streamflow and groundwater drought, by basin baseflow index (BFI) group (1991–2020).

Basin group	n basins	Lag to SSI (months)	Lag to SGI (months)	SSI severity attenuation (%)	SGI severity attenuation (%)
Low BFI (< 0.30)	7	1.4	4.5*	18	39*
Moderate BFI (0.30–0.55)	6	3.1	7.0*	44	55*
High BFI (> 0.55)	5	5.9	12.0	63	74
Full sample	18 (9 for SGI)	3.0	8.0	41	58

SSI: Standardized Streamflow Index; SGI: Standardized Groundwater Index. *Groundwater columns for low- and moderate-BFI groups are based on 2 and 3 subset basins respectively; values are indicative given the small subsample.

Baseflow index was the strongest single predictor of both propagation lag and severity attenuation among the catchment attributes tested, with Spearman rank correlations of 0.79 (lag to SSI) and 0.71 (attenuation of SSI relative to SPI-3), both significant after correction for multiple comparisons; aridity index and drainage area were both more weakly and non-significantly associated with lag once BFI was accounted for in the multiple regression, which explained 68% of across-basin variance in streamflow-drought lag with BFI as the only individually significant predictor. Figure 1 shows median propagation lag by drought type across the low- and high-BFI basin groups, illustrating that the divergence between groups widens at each successive stage of

propagation, from a negligible difference at the soil-moisture stage to the largest absolute difference at the groundwater stage.

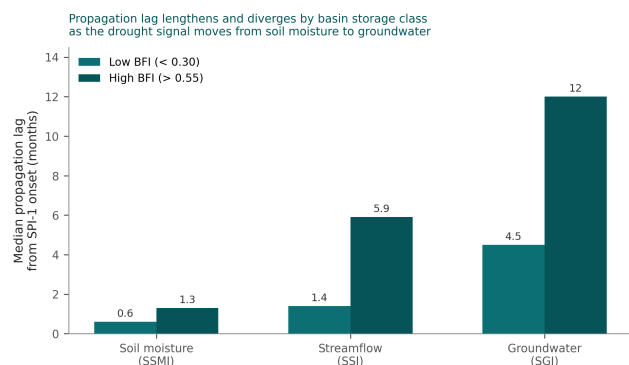


Figure 1. Median propagation lag from meteorological drought onset to soil-moisture, streamflow and groundwater drought onset, compared between low- and high-baseflow-index (BFI) basin groups (1991–2020).

The optimal SPI accumulation period, the timescale maximising correlation with SSI, ranged from 3 to 15 months across the 18 basins (median 6 months) and was itself strongly correlated with baseflow index (Spearman $\rho = 0.74$, $p < 0.001$), consistent with longer-memory catchments requiring a longer precipitation accumulation window to explain their streamflow response. However, the optimal timescale explained substantially less variance in the low-BFI basins (median $R^2 = 0.41$) than in the high-BFI basins (median $R^2 = 0.67$), indicating that a single best-fit accumulation period is a less complete description of propagation in flashier, low-storage catchments where nonlinear threshold effects play a larger relative role.

Table 2. Meteorological event pooling frequency and event-magnitude attenuation, low- versus high-baseflow-index (BFI) basin groups.

Metric	Low BFI (< 0.30)	High BFI (> 0.55)
Meteorological events pooled per SSI drought event	1.4	3.6
Meteorological events pooled per SGI drought event	1.9*	4.8
SSI event-magnitude attenuation relative to SPI-3 (%)	18	63
Optimal SPI accumulation period for SSI (months)	3.6	9.8

Event-based pooling analysis identified that a median of 2.3 distinct meteorological dry spells merged into each hydrological drought event across the full sample, but this pooling frequency was itself basin-dependent: high-BFI basins averaged 3.6 pooled meteorological events per hydrological drought event, compared with 1.4 in low-BFI basins, where individual meteorological dry spells more often translated directly into a streamflow deficit without merging with preceding events. Table 2 compares pooling frequency and mean event magnitude attenuation between the two basin groups directly, and the groundwater subset showed the most pronounced pooling of all, with a median of 4.8 antecedent meteorological events contributing to each groundwater

drought event in the four subset basins with BFI above 0.55.

4. DISCUSSION

These results reinforce the now well-established view that drought propagation transforms a meteorological deficit signal in duration, timing and severity as it moves through a basin's storage components [1,5], while extending that picture specifically to semi-arid basins and demonstrating that, within a climatically similar aridity envelope, catchment storage structure rather than climatic dryness itself is the dominant control on how quickly and how severely a rainfall deficit becomes a hydrological drought. The consistency and strength of the baseflow-index relationship with both lag and attenuation, echoed in comparative studies from other climate settings [6,7], suggests BFI is a practical, widely available screening variable for anticipating which semi-arid basins will show fast, poorly buffered hydrological drought response and which will show slow, heavily damped response.

The finding that low-BFI basins not only respond faster but also attenuate drought severity less, several showing essentially no buffering at all, has direct implications for early-warning lead time. A water manager in a low-BFI, thin-soil semi-arid basin has a median of roughly six weeks between the emergence of a meteorological drought signal and its expression as streamflow drought of comparable severity, a much shorter window than the five- to six-month median lag in high-BFI basins, and yet these are frequently the basins with the least groundwater or reservoir storage available to buffer supply during that short window. This combination of fast propagation and weak attenuation is, in our view, the setting in which meteorological drought monitoring and seasonal forecasting have the most direct practical value, since there is comparatively little downstream storage to absorb a forecast error.

The weaker explanatory power of a single optimal SPI accumulation period in low-BFI basins, relative to high-BFI basins, is consistent with the interpretation that propagation in low-storage catchments is governed more by threshold and pooling dynamics tied to specific antecedent soil-moisture states than by a smooth, linear relationship between accumulated precipitation and streamflow deficit [2,8]. This has a practical corollary: drought indicators built solely around a fixed best-fit SPI timescale, an approach common in operational monitoring, may perform less reliably in exactly the flashy, low-BFI basins where propagation is fastest and the practical cost of a missed or delayed warning is highest, suggesting a role for antecedent-condition-aware or ensemble-timescale indicators in these settings [9].

Several limitations qualify these findings. First, the groundwater component of the analysis was restricted to 9 of the 18 basins owing to observation-well data availability, and within those basins well density and

spatial coverage varied, so groundwater propagation lags, while broadly consistent with prior work in other regions [10,11], carry more sampling uncertainty than the streamflow results and should be treated as indicative. Second, streamflow records judged minimally regulated during screening may still be subject to undocumented small-scale abstraction or farm-pond storage common in semi-arid agricultural basins, which could bias propagation lag and attenuation estimates in either direction depending on the timing of abstraction relative to drought onset. Third, the soil-moisture reanalysis product, although bias-corrected against available in-situ observations at six basins, was not independently verified at the remaining twelve, and land-surface model soil-moisture memory is known to depend on model soil-layer depth and parameterisation in ways that could influence the meteorological-to-soil-moisture lag estimated here. Finally, this study characterises propagation under the historical climate of 1991-2020; whether the same BFI-lag relationships hold under a warmer, more evaporatively demanding future climate, which may itself alter effective catchment storage through changes in soil-moisture memory and vegetation water use, is not addressed and would require a dedicated attribution or scenario-based follow-up study.

5. CONCLUSION

Across 18 semi-arid basins, meteorological drought propagated into soil-moisture drought within a median of 1 month, into streamflow drought within a median of 3 months, and into groundwater drought within a median of 8 months, but these medians masked a roughly four-fold range in propagation lag that was explained principally by baseflow index rather than by aridity or basin size: low-baseflow-index basins propagated and expressed meteorological drought quickly and with little severity attenuation, while high-baseflow-index basins delayed and substantially damped the same signal. Threshold and pooling behaviour, short meteorological dry spells merging into longer hydrological drought events, was pronounced in high-storage basins and comparatively weak in low-storage basins, where a single best-fit precipitation accumulation timescale explained correspondingly less of the streamflow response. These findings indicate that catchment storage structure should be a primary consideration in designing drought early-warning systems for semi-arid regions, since it determines both how much lead time is available before a meteorological deficit becomes a hydrological one and how much of that deficit's severity will reach streamflow and groundwater users unmoderated.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

H.K. conceived and supervised the study, designed the propagation analysis framework, and led the writing of the manuscript. S.D. assembled and quality-controlled the precipitation, soil moisture and streamflow datasets and performed the cross-correlation and event-pooling analyses. M.F. compiled the groundwater subset, computed baseflow index and catchment attributes, and performed the statistical comparisons across basin groups. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available precipitation, streamflow, groundwater and land-surface model reanalysis records, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Precipitation, streamflow and groundwater records used in this study are publicly available from the originating national hydrometric and hydrogeological agencies. Processed standardized index time series and analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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