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A Multi-Scale Framework for Assessing Long-Term Drought Persistence and Spatial Synchronization: Application to the Urmia Lake Basin

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Abstract

The endorheic Urmia Lake Basin faces growing water-security challenges from persistent drought, intensive water demand, and ecological vulnerability. This study presents a station to basin assessment of meteorological drought during 1981-2024 using seven synoptic stations completed with locally bias-corrected CHIRPS precipitation. The Standardized Precipitation Index (SPI) was calculated at 3, 6, 12, 18, 24, and 48-month accumulation periods, and drought characteristics, spatial synchronization, trends, and abrupt changes were quantified. Bias correction increased the network-mean CHIRPS-station correlation from 0.78 to 0.88 and reduced MAE and RMSE by approximately 37% and 34%, respectively. Drought frequency declined from 6.71 events per station per decade at SPI-3 to 0.64 at SPI-48, while mean duration increased from 6.5 to 80.2 months. This pattern reflects a shift toward fewer but more persistent events. Widespread drought affected 5.0-8.5% of valid months and was most frequent at SPI-12. The 1999-2002 drought dominated persistent basin-wide conditions, whereas 2008 showed rapid synchronization and strong seasonal intensity. Basin-wide drought frequency showed no significant trend, but several stations exhibited significant local deterioration. This contrast shows that regional aggregation can mask important spatial changes. The results support multi-timescale monitoring for short-term preparedness, annual water-allocation planning, and persistent multi-year drought risk.

Keywords: Standardized Precipitation Index; meteorological drought; CHIRPS; bias correction; drought persistence; Urmia Lake Basin;

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1. Introduction

Drought is a recurrent but structurally complex hydroclimatic hazard whose gradual onset, uncertain termination, and cumulative impacts distinguish it from rapidly developing extremes. A precipitation deficit may initially appear as an atmospheric anomaly, but its persistence subsequently reduces soil moisture, crop productivity, streamflow, reservoir inflows, groundwater recharge, and ecosystem functioning¹. These non-linear propagation processes are especially consequential in climate-sensitive basins, where long-term hydroclimatic variability can substantially alter the magnitude, frequency, and temporal organization of hydrological extremes². Such changes are particularly important in arid and semi-arid regions, where water consumption is high relative to renewable supply. The Lake Urmia Basin provides a critical setting for examining these dynamics. Historically the second-largest hypersaline lake in the world, Lake Urmia has undergone severe desiccation over the past three decades. The exposed lakebed has also become a source of saline dust, with consequences for regional air quality, agriculture, and human health³.

The desiccation of Lake Urmia reflects a complex interaction between anthropogenic pressures and natural climatic variability. More broadly, hydrological responses in water-stressed basins reflect the combined influence of climate variability and human interventions, including water regulation, land-use change, and intensive water use⁴. Within the Urmia Lake Basin, agricultural expansion, groundwater abstraction, and flow regulation have reduced the system's tolerance to dry periods⁵. Meteorological drought and climatic variability therefore act as important stress multipliers. The basin's pronounced elevation range creates substantial spatial differences in water availability and orographic precipitation⁶, while rising temperatures increase atmospheric water demand and can intensify agricultural and ecological stress. Major drought periods, including 1999–2001 and 2008, further reduced river inflows through severe climatic and snow-drought conditions⁷. Climate projections also suggest increasing risks from persistent drought and compound dry-hot conditions^{8,9}. Accurate characterization of drought onset, severity, persistence, and spatial development is therefore essential for water allocation, early warning, and environmental rehabilitation.

The Standardized Precipitation Index (SPI) remains one of the most widely used indicators of meteorological drought. It requires only precipitation data, expresses anomalies relative to a fitted probability distribution, and permits comparison among locations with different climatological regimes¹⁰. Its multi-timescale structure is particularly useful because short accumulation periods respond rapidly to recent anomalies and are relevant to seasonal moisture conditions and agricultural planning, whereas long accumulation periods suppress short-term fluctuations and reveal persistent precipitation deficits that influence deep aquifers, reservoirs, and terminal lakes^{11,12}. Robust SPI assessment nevertheless depends on the length, homogeneity, and representativeness of precipitation records. In data-scarce regions, discontinuous gauge observations often require integration with satellite-gauge products. CHIRPS provides a high-resolution quasi-global precipitation record that was developed partly for drought monitoring, but its grid-scale estimates may contain systematic retrieval and topographic biases. Local bias correction, including quantile mapping, can therefore improve agreement with point observations before gridded precipitation is used for drought indexing¹³.

77 Previous work in the Urmia Lake Basin has examined drought with multiple indices, remote
78 sensing, climate projections, and forecasting methods. SPEI-based studies have reported spatial
79 variability in drought deterioration and severity-area-frequency relationships¹⁴, while reservoir
80 analyses have identified a seven- to nine-month lag between meteorological and storage
81 drought¹⁵. Machine-learning studies have also used GLDAS outputs and satellite-derived
82 climatic predictors for short-lead drought prediction^{16,17}.

83 Despite these advances, important aspects of historical drought architecture remain
84 insufficiently integrated. Many studies emphasize individual stations, selected timescales,
85 basin-averaged conditions, or raw gridded products. These approaches can obscure
86 microclimatic contrasts in the basin's complex topography and can mask local deterioration
87 when spatial aggregation is applied. Uncorrected satellite and reanalysis products may also
88 distort the probability distributions used to estimate drought severity, duration, and frequency
89¹³. More fundamentally, station-level analyses do not by themselves describe how drought
90 becomes synchronized across the basin, while basin-average indices cannot show whether
91 persistent deterioration is concentrated at particular locations. Conventional trend analyses also
92 provide limited insight into whether change arises through frequency, duration, cumulative
93 severity, or spatial organization. Assessments restricted to short accumulation periods may
94 further miss the legacy of multi-year precipitation deficits that influence groundwater,
95 baseflow, and lake inflows.

96 This study addresses these gaps through a 44-year, station-to-basin assessment of precipitation-
97 driven meteorological drought across seven synoptic stations in the Urmia Lake Basin. Station
98 records were reconstructed and extended with locally bias-corrected CHIRPS precipitation,
99 and SPI was calculated at six accumulation periods from 3 to 48 months. Run theory was used
100 to quantify event frequency, duration, severity, and intensity, while a station-network coverage
101 framework distinguished localized, regional, and synchronized basin-wide drought. Modified
102 trend and change-point tests were then used to identify long-term changes at both station and
103 network scales. The framework therefore links drought event structure, spatial coordination,
104 and long-term change within a common observational basis. By distinguishing acute seasonal
105 anomalies from persistent multi-year deficits and by retaining station-level information
106 alongside basin-scale summaries, the study provides a reproducible basis for drought
107 monitoring, water-allocation planning, and long-term environmental management in the Urmia
108 Lake Basin.

2. Materials and Methods

2.1. Study area and precipitation records

As shown in **Figure 1a**, the Urmia Lake Basin (ULB) is an endorheic drainage basin in northwestern Iran, located approximately between 35°40'-38°30' N and 44°07'-47°54' E. It covers about 51,876 km² across parts of West Azerbaijan, East Azerbaijan, and Kurdistan provinces⁶. Lake Urmia occupies the low-lying central part of the basin and forms its terminal sink. The mapped elevation ranges from approximately 1,231 to 3,755 m above sea level, with lower terrain around the lake and mountainous areas along the basin margins (**Figure 1b**). A dense network of permanent and seasonal rivers drains the surrounding highlands toward the lake; the principal tributaries include the Zarrineh-Rud, Simineh-Rud, Mahabad River, and Aji Chay. The basin has a predominantly semi-arid climate, and most precipitation occurs during the cool season. The combined effects of topography and seasonal precipitation contribute to substantial spatial variability in precipitation and drought conditions. These hydroclimatic characteristics support the use of a distributed station network and multiple SPI accumulation periods to characterize drought variability and persistence. The geographical setting, drainage network, topography, and locations of the seven selected synoptic stations are shown in **Figure 1**.

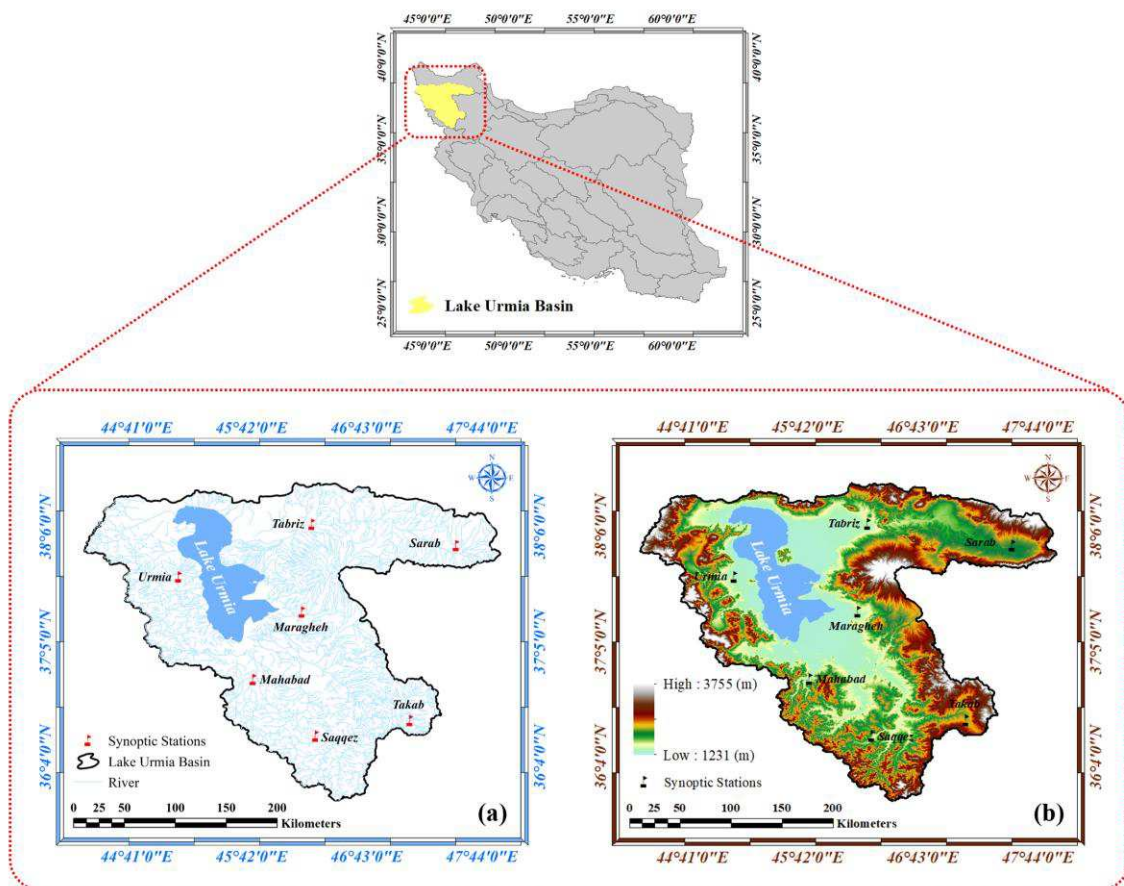


Figure 1- Study area and monitoring network of the Urmia Lake Basin: (a) location of the basin within Iran, basin boundary, Lake Urmia, drainage network, and seven selected synoptic stations; (b) topographic setting and elevation distribution derived from the SRTM 1 Arc-Second Global Digital Elevation Model (~30 m resolution). Source: U.S. Geological Survey¹⁸.

Monthly precipitation records were assembled for Mahabad, Maragheh, Saqqez, Sarab, Tabriz, Takab, and Urmia. The network represents the western, eastern, northern, and southern sectors of the basin and captures substantial elevation and precipitation contrasts. According to **Table 1**, the available station records covered January 1993-December 2022. They were completed to a common January 1981-December 2024 period with bias-corrected CHIRPS precipitation. The final series contained 528 monthly values per station. Available station observations were retained unchanged; corrected CHIRPS values were used only where station observations were unavailable or outside the original station period.

Table 1- Characteristics of the synoptic stations used for meteorological drought assessment.

Station	Station ID	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Original synoptic period	Final completed period
Mahabad	40726	36.753	45.715	1385	1993-2022	1981-2024
Maragheh	40713	37.348	46.146	1477	1993-2022	1981-2024
Saqqez	40729	36.253	46.266	1523	1993-2022	1981-2024
Sarab	40710	37.935	47.508	1682	1993-2022	1981-2024
Tabriz	40706	38.122	46.234	1361	1993-2022	1981-2024
Takab	40728	36.39	47.1	1765	1993-2022	1981-2024
Urmia	40712	37.658	45.056	1315.9	1993-2022	1981-2024

2.2. CHIRPS bias correction and record extension

CHIRPS precipitation was adjusted separately for each station and calendar month over the 1993-2022 overlap period. Positive precipitation was represented with a gamma distribution and zero precipitation was treated as a discrete probability.

Equation (1) defines the station and month-specific gamma quantile mapping procedure used to bias-correct the CHIRPS estimates. Each CHIRPS value was adjusted to match the station-observation distribution at the equivalent cumulative probability:

$$P_{s,m,t}^{BC} = F_{O,s,m}^{-1}[F_{C,s,m}(P_{s,m,t}^C)] \quad (1)$$

where $P_{s,m,t}^{BC}$ is bias-corrected CHIRPS precipitation, $F_{C,s,m}$ is the CHIRPS cumulative distribution, and $F_{O,s,m}^{-1}$ is the inverse cumulative distribution of station precipitation for station s and calendar month m .

By fitting separate gamma distributions to each calendar month, the bias correction preserved the seasonal precipitation regime of the basin¹³. Bias correction performance was then evaluated within the overlap period through temporally blocked cross validation, which separated the periods used to estimate the mapping from those used to evaluate it. For each withheld time block, month-specific mappings were fitted with the remaining overlap data and applied to the withheld observations. Performance was summarized by the Pearson correlation coefficient (r), mean absolute error (MAE), root mean square error (RMSE), and percentage bias (PBIAS). The network PBIAS summary was the mean of station-level absolute PBIAS values.

2.3. SPI calculation

Meteorological drought was evaluated using the SPI at accumulation periods of 3, 6, 12, 18, 24, and 48 months. These timescales represent progressively longer precipitation memory, from seasonal anomalies to persistent multi-year deficits. SPI-3 and SPI-6 indicate short-term and seasonal anomalies, SPI-12 represents annual-scale conditions, and SPI-18 and SPI-24 describe longer and more persistent precipitation deficits. SPI-48 was included to examine broad multi-year drought persistence. For station s , ending month t , and accumulation period k , accumulated precipitation was calculated using Equation (2):

$$X_{s,t}^{(k)} = \sum_{j=0}^{k-1} P_{s,t-j} \quad (2)$$

where $P_{s,t-j}$ is monthly precipitation and $X_{s,t}^{(k)}$ is the accumulated precipitation over the preceding k months. Accumulated precipitation was fitted separately for each ending calendar month to a two-parameter gamma distribution expressed in Equation (3). This monthly fitting procedure prevented precipitation totals from different seasons from being compared within the same probability distribution.

$$g(x) = \frac{x^{\alpha-1} \exp(-x/\beta)}{\beta^{\alpha} \Gamma(\alpha)}, \quad x > 0 \quad (3)$$

where α and β are the shape and scale parameters, respectively, and $\Gamma(\alpha)$ is the gamma function. The parameters were estimated over the 1981-2024 reference period. Since the gamma distribution is defined only for positive values, the probability of zero precipitation, q , was incorporated using Equation (4).

$$H(x) = q + (1 - q)G(x) \quad (4)$$

where $G(x)$ is the cumulative gamma probability for positive precipitation. The cumulative probability was transformed to the standard normal distribution according to Equation (5):

$$SPI_{s,t}^{(k)} = \Phi^{-1} \left[H(X_{s,t}^{(k)}) \right] \quad (5)$$

where Φ^{-1} is the inverse standard normal cumulative distribution function^{11,19} Finally, the calculated SPI values were classified using the conventional thresholds presented in **Table 2**.

Table 2- Classification of wet and dry conditions based on SPI values.

SPI range	Classification
$SPI \geq 2$	Extremely wet
$1.5 \leq SPI < 2$	Severely wet
$1 \leq SPI < 1.5$	Moderately wet
$-1 \leq SPI < 1$	Near normal
$-1.5 \leq SPI < -1$	Moderate drought
$-2 \leq SPI < -1.5$	Severe drought
$SPI \leq -2$	Extreme drought

2.4. Drought-run characterization

Drought runs were identified separately for each station and SPI timescale with run theory²⁰. A run began when SPI became negative, qualified as a drought event if at least one month reached $SPI \leq -1$, and ended when SPI returned to a nonnegative value. Negative runs that never reached the drought threshold were excluded. This definition means that event duration and severity include mildly negative months within a qualifying run; drought-month percentages, by contrast, include only months with $SPI \leq -1$. According to Equation (6), for event e , cumulative severity was defined as the absolute sum of negative SPI values:

$$S_e = - \sum_{t=1}^{D_e} SPI_t \quad (6)$$

where S_e and D_e denote the severity and duration of event, respectively. D_e was defined as the number of consecutive months between drought onset and termination. Larger values of S_e indicate longer or more intense precipitation deficits. Mean drought intensity was calculated by dividing event severity by its duration, as expressed in Equation 7:

$$I_e = \frac{S_e}{D_e} \quad (7)$$

where I_e is the average deficit per month of the qualifying run. The event catalogue recorded onset, termination, duration, minimum SPI, cumulative severity, and mean intensity. Summaries included total event count, events per station per decade, mean and maximum duration, mean and maximum severity, mean intensity, and the proportion of station-months with $SPI \leq -1$.

2.5. Spatial extent and drought synchronization

Monthly drought extent was measured as the proportion of stations simultaneously experiencing at least moderate drought. For each month t and SPI timescale k , the drought-coverage ratio was calculated as:

$$C_t^{(k)} = \frac{1}{N} \sum_{s=1}^N \mathbb{I}(SPI_{s,t}^{(k)} \leq -1), \quad N = 7 \quad (8)$$

where $\mathbb{I}$ equals one when the threshold is met and zero otherwise. Conditions affecting one or two stations were classified as localized, those affecting three or four as regional, and those affecting five to seven as widespread. A synchronized basin-wide event comprised one or more consecutive widespread months. Each event was summarized by duration, maximum and mean station coverage, mean SPI among affected stations, and the spread between the earliest and latest onset dates of the overlapping station-level drought runs. Because long-timescale runs can begin many years before basin-wide overlap, onset spread was treated as a measure of antecedent asynchrony rather than the duration of basin-wide drought.

2.6. Temporal trend and change point analysis

Long-term changes during 1981-2024 were assessed for annual precipitation, annual drought-month count, annual minimum SPI, annual cumulative drought severity, annual maximum station coverage, and annual basin-wide drought-month count. The variance-corrected Mann-Kendall test was used to reduce the effect of serial correlation²¹, and Sen's estimator quantified slope magnitude²². Pettitt's test identified a single potential abrupt change in each annual series²³. The Benjamini-Hochberg procedure controlled the false discovery rate within families of related tests²⁴. Statistical significance was assessed at an adjusted probability of $q < 0.05$. Trend and change point results describe statistical behavior in precipitation-driven meteorological drought; they do not establish climatic or anthropogenic causation. Long-timescale results, especially SPI-48, were interpreted as supporting evidence because of serial dependence and the limited number of effectively independent fluctuations.

3. Results

3.1. Bias-correction performance and precipitation-record reconstruction

Figure 2 represents the monthly precipitation records used to reconstruct the seven station series, including available observations, raw and bias-corrected CHIRPS estimates during the 1993-2022 overlap period, and bias-corrected CHIRPS values used outside the observational record. The reconstruction produced continuous monthly precipitation series for all seven stations from January 1981 to December 2024, with 528 values per station.

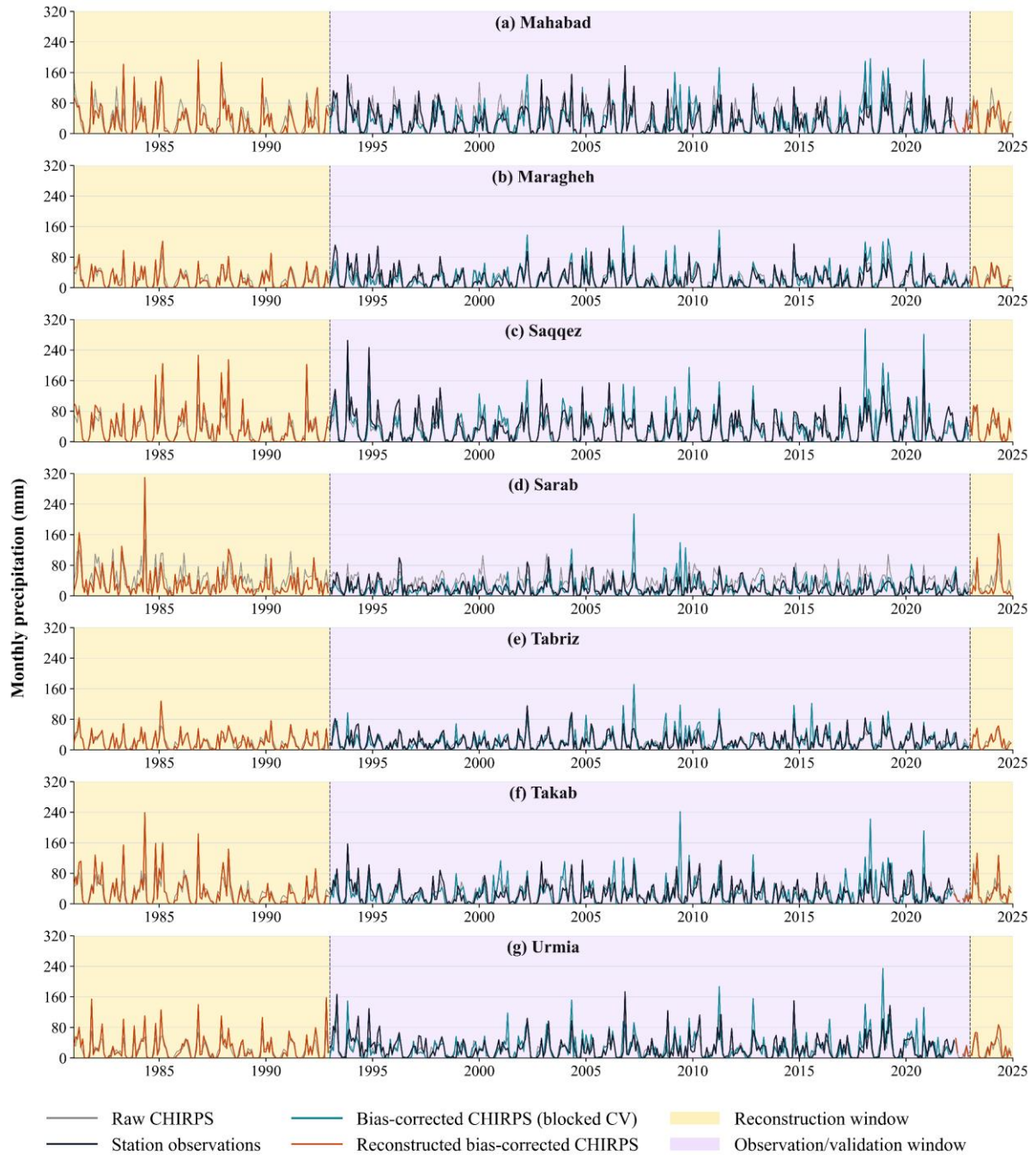


Figure 2- Monthly precipitation series at the (a) Mahabad, (b) Maragheh, (c) Saqqez, (d) Sarab, (e) Tabriz, (f) Takab, and (g) Urmia synoptic stations during January 1981-December 2024.

Table 3 summarizes the validation performance of raw and bias-corrected CHIRPS precipitation during the 1993-2022 overlap period. The calendar-month-specific gamma quantile mapping improved all four evaluation metrics across the station network. At the network level, mean absolute PBIAS decreased from 10.7% for raw CHIRPS to 2.4% after correction, which corresponds to a 77.6% reduction in systematic bias. Mean MAE decreased from 13.0 to 8.2 mm month⁻¹, while mean RMSE declined from 18.9 to 12.5 mm month⁻¹. These changes represent reductions of approximately 37% and 34%, respectively. At the same time, the network-mean Pearson correlation coefficient increased from 0.78 to 0.88. The combined reduction in bias and error, together with the increase in temporal correlation, indicates substantially improved agreement between CHIRPS estimates and station observations after correction.

Table 3- Performance of raw and bias-corrected CHIRPS monthly precipitation against synoptic-station observations during 1993-2022, evaluated using five contiguous six-year temporal validation blocks. *r* is the Pearson correlation coefficient; MAE is mean absolute error; RMSE is root mean square error; and PBIAS is percentage bias. Positive and negative PBIAS values indicate overestimation and underestimation, respectively.

Station	Dataset	<i>r</i>	MAE (mm month ⁻¹)	RMSE (mm month ⁻¹)	Mean PBIAS (%)
Mahabad	Raw CHIRPS	0.79	12.8	18.6	+11.4
	Bias-corrected CHIRPS	0.89	8.1	12.3	+2.6
Maragheh	Raw CHIRPS	0.76	13.5	19.7	-9.8
	Bias-corrected CHIRPS	0.87	8.7	13.1	-2.1
Saqqez	Raw CHIRPS	0.83	10.9	16.2	+8.7
	Bias-corrected CHIRPS	0.91	6.9	10.7	+1.8
Sarab	Raw CHIRPS	0.72	15.4	22.1	-13.6
	Bias-corrected CHIRPS	0.85	9.8	14.5	-3.0
Tabriz	Raw CHIRPS	0.78	12.1	17.8	+10.2
	Bias-corrected CHIRPS	0.88	7.6	11.8	+2.3
Takab	Raw CHIRPS	0.74	14.7	21.0	-11.9
	Bias-corrected CHIRPS	0.86	9.2	13.8	-2.7
Urmia	Raw CHIRPS	0.81	11.6	17.0	+9.5
	Bias-corrected CHIRPS	0.90	7.3	11.2	+2.0
Network mean	Raw CHIRPS	0.78	13.0	18.9	10.7
	Bias-corrected CHIRPS	0.88	8.2	12.5	2.4

The improvement was also evident at individual stations. Raw CHIRPS performance was weakest at Sarab, where the initial correlation was 0.72 and the MAE reached 15.4 mm month⁻¹. After bias correction, the correlation increased to 0.85 and the MAE decreased to 9.8 mm month⁻¹. Similar improvements occurred at the remaining stations; corrected correlations ranged from 0.85 to 0.91, while station-level absolute PBIAS values were reduced to approximately 1.8-3.0%. The validation was conducted using five contiguous temporal blocks, which reduced dependence on a single calibration period and provided a temporally structured assessment of correction performance. The corrected CHIRPS values were subsequently used only where station observations were unavailable, while the original observations were retained unchanged. This procedure produced the seven continuous monthly precipitation records used in the subsequent SPI analysis.

3.2. Multi-timescale SPI dynamics and spatial heterogeneity

The multi-timescale SPI analysis revealed pronounced temporal variability and spatial contrasts among the seven stations during 1981-2024 (**Figure 3**). Short accumulation periods, particularly SPI-3 and SPI-6, alternated rapidly between dry and wet conditions, whereas SPI-12 to SPI-48 produced broader and more persistent periods of anomalous wetness and dryness. The network-mean SPI shown at the bottom of each panel further illustrates the transition from high-frequency seasonal variability to longer-term precipitation anomalies as the accumulation period increased. **Table 4** summarizes the corresponding interstation agreement, spatial dispersion, drought occurrence, and observed extremes across the six accumulation periods.

Several episodes illustrate the contrasting information provided by short and long accumulation periods. In October 2014, SPI-3 ranged from 1.33 at Takab to 3.19 at Mahabad, and all seven stations were at least moderately wet, while the network-mean SPI-48 remained slightly negative at -0.23. In contrast, June 2008 represented an exceptionally coherent short-term drought. The network-mean SPI-3 reached -3.04, with station values ranging from -2.30 at Sarab to -3.70 at Mahabad. The drought also extended to the seasonal and annual scales. Then network-mean SPI-6 and SPI-12 reached -1.94 and -2.15, respectively, and Tabriz recorded an SPI-12 value of -3.46. The magnitude of the anomaly weakened at SPI-24 and SPI-48. A different temporal pattern characterized the 1999-2003 drought. Short-term SPI fluctuated during this period, whereas persistent negative conditions developed at SPI-12, SPI-18, SPI-24, and SPI-48 across most stations. In August 2000, the network-mean SPI became progressively more negative from -0.37 at SPI-3 to -1.85 at SPI-24, while negative SPI-48 conditions persisted broadly until approximately 2003. The strongest coherent wet period occurred during the mid-1990s. Positive conditions affected most stations between 1993 and 1997 and became increasingly persistent at longer accumulation periods. In February 1994, the network-mean SPI-12 reached 2.25, with Saqqez recording 3.33, while the network-mean SPI-48 peaked at 1.83 in September 1995. The highest individual SPI-48 value, 2.86, occurred at Maragheh in January 1997.

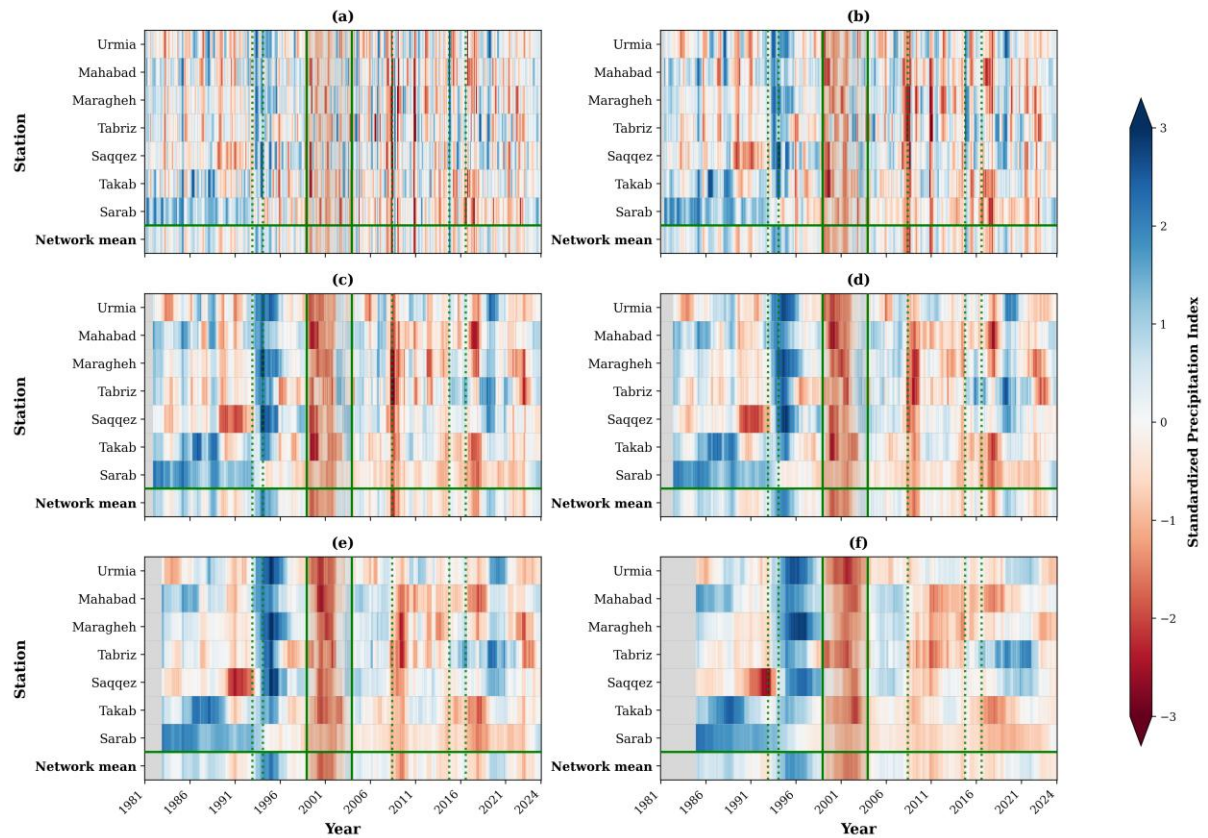


Figure 3- Spatiotemporal variability of the Standardized Precipitation Index at accumulation periods of (a) 3, (b) 6, (c) 12, (d) 18, (e) 24, and (f) 48 months across the seven synoptic stations during 1981-2024. Red and blue shades indicate dry and wet conditions, respectively. Green dotted vertical lines mark, from left to right, December 1992, February 1994, June 2008, October 2014, and August 2016. The green solid vertical lines and the shaded band highlight the 1999-2003 multi-year drought episode. Stations are ordered from west to east according to longitude.

The statistics in **Table 4** demonstrate that spatial heterogeneity remained substantial and generally increased at longer accumulation periods. Mean interstation correlation was 0.55 at SPI-3 and SPI-6 and declined gradually to 0.46 at SPI-48. The range of pairwise correlations widened from 0.25-0.71 at SPI-3 to -0.29-0.82 at SPI-48, which shows that some station pairs exhibited contrasting multi-year precipitation behavior. Mean monthly spatial standard deviation also increased from 0.63 at SPI-3 to 0.68 at SPI-48, while its interquartile range expanded from 0.49-0.75 to 0.44-0.92. The strongest short-term spatial contrast occurred in August 2016, when the SPI-3 range reached 4.38. Sarab recorded -2.59, whereas Maragheh recorded 1.79. At longer timescales, the greatest contrast occurred in December 1992, when SPI-48 ranged from -2.85 at Saqqez to 1.31 at Sarab. The percentage of months with network-mean $SPI \leq -1$ was highest at intermediate accumulation periods, reaching 11.9% at SPI-6 and 11.0% at SPI-12, before decreasing to 7.9% at SPI-48.

Table 4- Summary of the temporal and spatial variability of SPI across the seven synoptic stations at different accumulation periods during 1981-2024. Mean interstation correlation represents the average Pearson correlation among all station pairs. Mean monthly spatial SD represents the average cross-station standard deviation of SPI. Spatial range is the monthly difference between the highest and lowest station SPI. Network mean SPI ≤ -1 (%) is the percentage of common months in which the network-average SPI was at or below -1.

SPI timescale	Valid period	Mean interstation correlation	Pairwise correlation range	Mean monthly spatial SD (IQR)	Network mean SPI ≤ -1 (%)	Maximum spatial range (date)	Lowest SPI (station; date)	Highest SPI (station; date)
SPI-3	Mar. 1981-Dec. 2024	0.55	0.25 to 0.71	0.63 (0.49-0.75)	7.8	4.38 (Aug. 2016)	-3.70 (Mahabad; Jun. 2008)	3.19 (Mahabad; Oct. 2014)
SPI-6	Jun. 1981-Dec. 2024	0.55	0.13 to 0.75	0.64 (0.50-0.78)	11.9	3.53 (Apr. 1983)	-3.47 (Maragheh; Dec. 2010)	3.05 (Saqqez; Feb. 1994)
SPI-12	Dec. 1981-Dec. 2024	0.52	-0.10 to 0.77	0.66 (0.51-0.83)	11	3.36 (Apr. 1983)	-3.46 (Tabriz; Jun. 2008)	3.33 (Saqqez; Feb. 1994)
SPI-18	Jun. 1982-Dec. 2024	0.51	-0.16 to 0.77	0.67 (0.51-0.86)	10.4	3.51 (May 1991)	-2.67 (Tabriz; Feb. 2009)	3.06 (Saqqez; Nov. 1994)
SPI-24	Dec. 1982-Dec. 2024	0.50	-0.21 to 0.78	0.67 (0.50-0.87)	8.5	3.69 (Nov. 1991)	-2.62 (Saqqez; Dec. 1990)	3.19 (Saqqez; Dec. 1994)
SPI-48	Dec. 1984-Dec. 2024	0.46	-0.29 to 0.82	0.68 (0.44-0.92)	7.9	4.15 (Dec. 1992)	-2.85 (Saqqez; Dec. 1992)	2.86 (Maragheh; Jan. 1997)

Spatial divergence was also evident during the final decade of the record. Tabriz and, to a lesser extent, Saqqez experienced extended positive SPI intervals during parts of the late 2010s and early 2020s, whereas Sarab, Takab, Mahabad, and Maragheh showed more persistent negative conditions at longer accumulation periods. By December 2024, short- to medium-term conditions were generally near normal, but SPI-48 remained negative at most stations and reached -1.01 at Urmia. Thus, the end of the record was characterized by relatively weak short-term anomalies alongside persistent long-term precipitation deficits at several stations.

3.3. Drought-event characteristics across SPI accumulation periods

The event-based analysis showed a clear transition from frequent, short-lived droughts at shorter accumulation periods to fewer but substantially longer events with greater cumulative severity at longer SPI timescales. **Figure 4** presents the station-level patterns in event frequency, mean duration, maximum severity, and mean intensity, while **Table 5** summarizes the corresponding across-station event statistics.

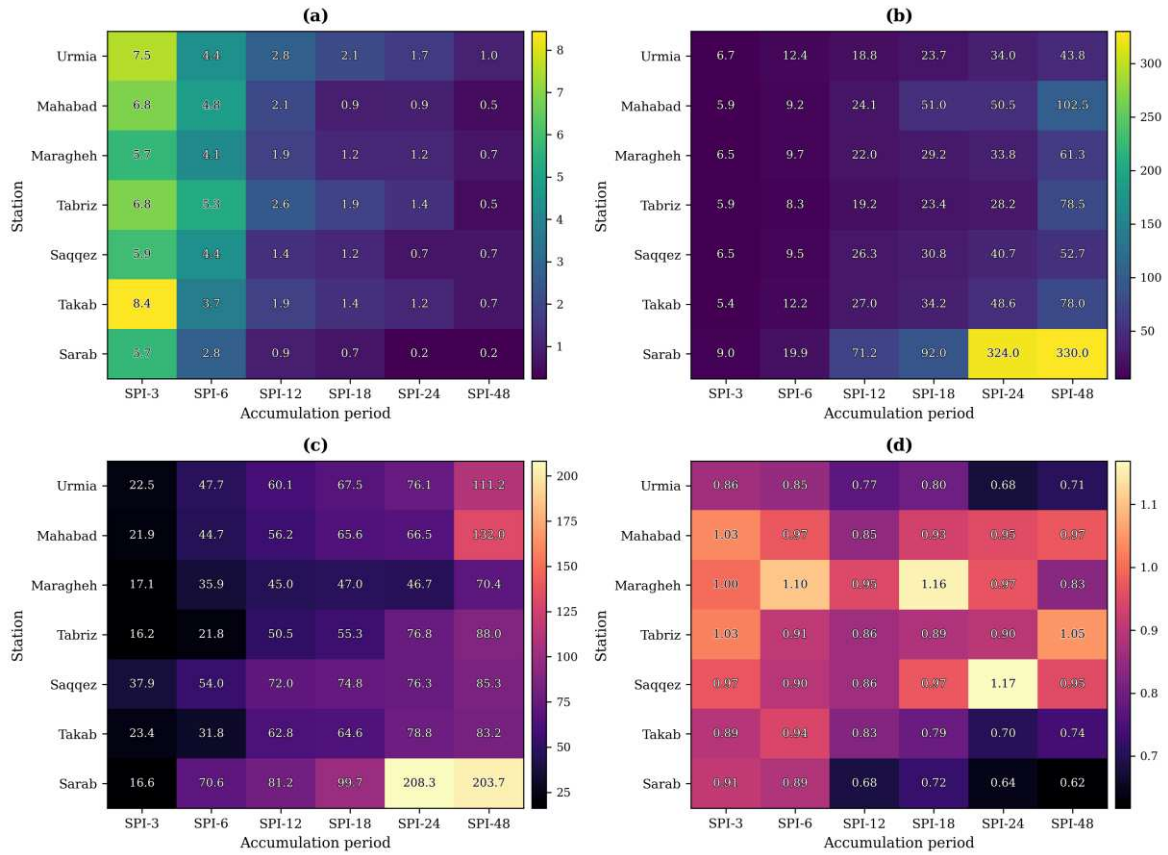


Figure 4- Station-level characteristics of meteorological drought events at SPI accumulation periods of 3, 6, 12, 18, 24, and 48 months during 1981-2024: (a) event frequency, expressed as events per decade; (b) mean event duration in months; (c) maximum cumulative drought severity; and (d) mean event intensity. A drought event was defined as a continuous negative SPI sequence that reached $SPI \leq -1$ and ended when SPI returned to a nonnegative value.

Drought-event frequency declined markedly as the accumulation period increased (**Figure 4a**). At the network level, mean frequency decreased from 6.71 events per station per decade at SPI-3 to 4.20 at SPI-6, 1.92 at SPI-12, 1.34 at SPI-18, 1.05 at SPI-24, and 0.64 at SPI-48 (**Table 5**). Short-term recurrence also varied among stations. Takab recorded the highest SPI-3 frequency at 8.4 events per decade, followed by Urmia at 7.5, whereas Maragheh and Sarab had the lowest frequencies at 5.7 events per decade. At SPI-6, Tabriz recorded the highest frequency at 5.3 events per decade, while Sarab had only 2.8. At longer accumulation periods, Urmia consistently showed the highest recurrence, with 2.8, 2.1, 1.7, and 1.0 events per decade at SPI-12, SPI-18, SPI-24, and SPI-48, respectively. In contrast, Sarab experienced relatively few distinct long-term events because its negative SPI sequences persisted with limited interruption. Despite the decline in event frequency, the proportion of station-months classified as at least moderately dry varied within a relatively narrow range. Drought months represented 14.6% of valid station-months at SPI-3, increased to a maximum of 17.2% at SPI-6, and ranged from 13.6% to 15.4% between SPI-12 and SPI-48. Increasing the accumulation period therefore mainly reorganized drought conditions from numerous separate episodes into fewer continuous events rather than substantially reducing the overall proportion of drought months. According to **Figure 4b**, this transformation was particularly evident in event duration. Across-

station mean duration increased from 6.5 months at SPI-3 to 11.0 months at SPI-6, 25.7 months at SPI-12, 34.6 months at SPI-18, 47.3 months at SPI-24, and 80.2 months at SPI-48.

Table 5- Across-station summary of drought-event frequency, duration, cumulative severity, and mean intensity across the seven synoptic stations at different SPI accumulation periods during 1981-2024. Drought-month percentage represents the proportion of valid station-month observations with $SPI \leq -1$. Severity is the absolute sum of negative SPI values during each event.

SPI timescale	Total events	Events station ⁻¹ decade ⁻¹	Drought months (%)	Mean duration (months)	Maximum duration (station; period)	Mean severity	Maximum severity (station; period)	Mean intensity
SPI-3	206	6.71	14.6	6.5	43 (Saqqez; Nov. 1988-May 1992)	5.99	37.94 (Saqqez; Nov. 1988-May 1992)	0.95
SPI-6	128	4.20	17.2	11.0	86 (Sarab; Jan. 2016-Feb. 2023)	10.47	70.63 (Sarab; Jan. 2016-Feb. 2023)	0.94
SPI-12	58	1.92	15.4	25.7	98 (Sarab; Apr. 2015-May 2023)	22.73	81.24 (Sarab; Apr. 2015-May 2023)	0.84
SPI-18	40	1.34	14.6	34.6	129 (Sarab; Jan. 2013-Sep. 2023)	31.61	99.73 (Sarab; Jan. 2013-Sep. 2023)	0.89
SPI-24	31	1.05	14.6	47.3	324 (Sarab; Mar. 1997-Feb. 2024)	40.77	208.27 (Sarab; Mar. 1997-Feb. 2024)	0.85
SPI-48	18	0.64	13.6	80.2	330 (Sarab; Dec. 1996-May 2024)	66.80	203.68 (Sarab; Dec. 1996-May 2024)	0.84

At the station level, Sarab showed the greatest long-term persistence. Its mean event duration reached 71.2 months at SPI-12, 92.0 months at SPI-18, 324.0 months at SPI-24, and 330.0 months at SPI-48. Because only one uninterrupted event occurred at Sarab at SPI-24 and SPI-48, the mean durations at these two timescales were identical to the corresponding maximum durations in **Table 5**. The SPI-24 event extended from March 1997 to February 2024, while the SPI-48 event lasted from December 1996 to May 2024. These exceptionally long Sarab events require careful interpretation under the adopted event definition. Once a continuous negative SPI sequence reached $SPI \leq -1$, the entire negative sequence was treated as a single drought event until SPI returned to a nonnegative value. The reported 324- and 330-month durations therefore do not imply that every month experienced moderate or more severe drought. Rather, they represent persistent below-normal accumulated precipitation that included mildly negative months as well as months reaching the drought threshold. This interpretation is supported by Sarab's relatively low drought-month proportions of 10.3% at SPI-24 and 5.4% at SPI-48 despite the exceptionally long negative sequences.

Cumulative drought severity increased strongly with accumulation period (**Figure 4c**). Across-station mean severity rose from 5.99 at SPI-3 to 10.47 at SPI-6, 22.73 at SPI-12, 31.61 at SPI-18, 40.77 at SPI-24, and 66.80 at SPI-48. The largest maximum severities occurred at Sarab, reaching 208.27 at SPI-24 and 203.68 at SPI-48. For comparison, Mahabad recorded the second-highest SPI-48 maximum severity of 132.04 during December 2008-January 2021, while Urmia experienced an SPI-48 drought from November 1998 to October 2006 with a cumulative severity of 111.16. Saqqez displayed a contrasting long-term drought pattern, characterized by shorter but more intense events. Its SPI-48 drought from February 1989 to December 1993 lasted 59 months and had a cumulative severity of 85.31, a mean intensity of 1.45, and a minimum SPI of -2.85. The corresponding SPI-24 event lasted 51 months and had a mean intensity of 1.50. Thus, although Sarab accumulated much greater total severity through persistence, the principal long-term drought at Saqqez produced a considerably stronger average monthly deficit.

Unlike event duration and cumulative severity, mean event intensity did not increase systematically with accumulation period (**Figure 4d**). Across-station mean intensity remained within a relatively narrow range of 0.84-0.95 across the six timescales. At the station level, the highest mean intensities occurred at Saqqez for SPI-24 (1.17) and Maragheh for SPI-18 (1.16), whereas Sarab recorded the lowest long-term values at SPI-24 (0.64) and SPI-48 (0.62). The strongest individual event intensity occurred at Maragheh during the SPI-6 drought from November 2010 to March 2011, when a five-month event reached a mean intensity of 2.41 and SPI fell to -3.47 in December 2010.

3.4. Spatial coverage and synchronization across the station network

The spatial-coverage analysis showed that meteorological drought occurred more often as a localized phenomenon, although several episodes expanded rapidly and affected most or all stations (**Figure 5**). According to **Table 6**, localized drought was the dominant spatial category at every accumulation period, accounting for 23.3-31.8% of valid months, while regional drought occurred during 5.5-12.0% and widespread drought during 5.0-8.5%. The proportion of months with no station reaching $SPI \leq -1$ remained relatively stable at 55.7-57.5%. Widespread drought was most frequent at SPI-12 (8.5%), followed by SPI-6 (8.0%) and SPI-18 (7.8%), but was less common at SPI-3 (5.3%) and SPI-48 (5.0%). Thus, synchronization was most prominent at seasonal to interannual accumulation periods rather than at the shortest or longest timescales. The number of synchronized events decreased markedly with accumulation period. Eighteen events were identified at both SPI-3 and SPI-6, compared with six at SPI-12, seven at SPI-18, three at SPI-24, and four at SPI-48. Mean synchronized-event duration increased from 1.6 months at SPI-3 and 2.3 months at SPI-6 to 7.3 months at SPI-12 and 11.0 months at SPI-24. The longest synchronized episodes lasted 13 months at SPI-12, 11 months at SPI-18, 24 months at SPI-24, and 21 months at SPI-48. At SPI-48, the mean duration was only 6.0 months because three isolated one-month events occurred alongside one dominant event from March 2001 to November 2002. That event reached all seven stations, affected an average of 6.10 stations, and had a mean affected-station SPI of -1.54. The progression from shorter-scale deficits in 1998-1999 to persistent SPI-24 and SPI-48 drought during 2000-2002 shows how seasonal deficits accumulated into a multi-year synchronized event.

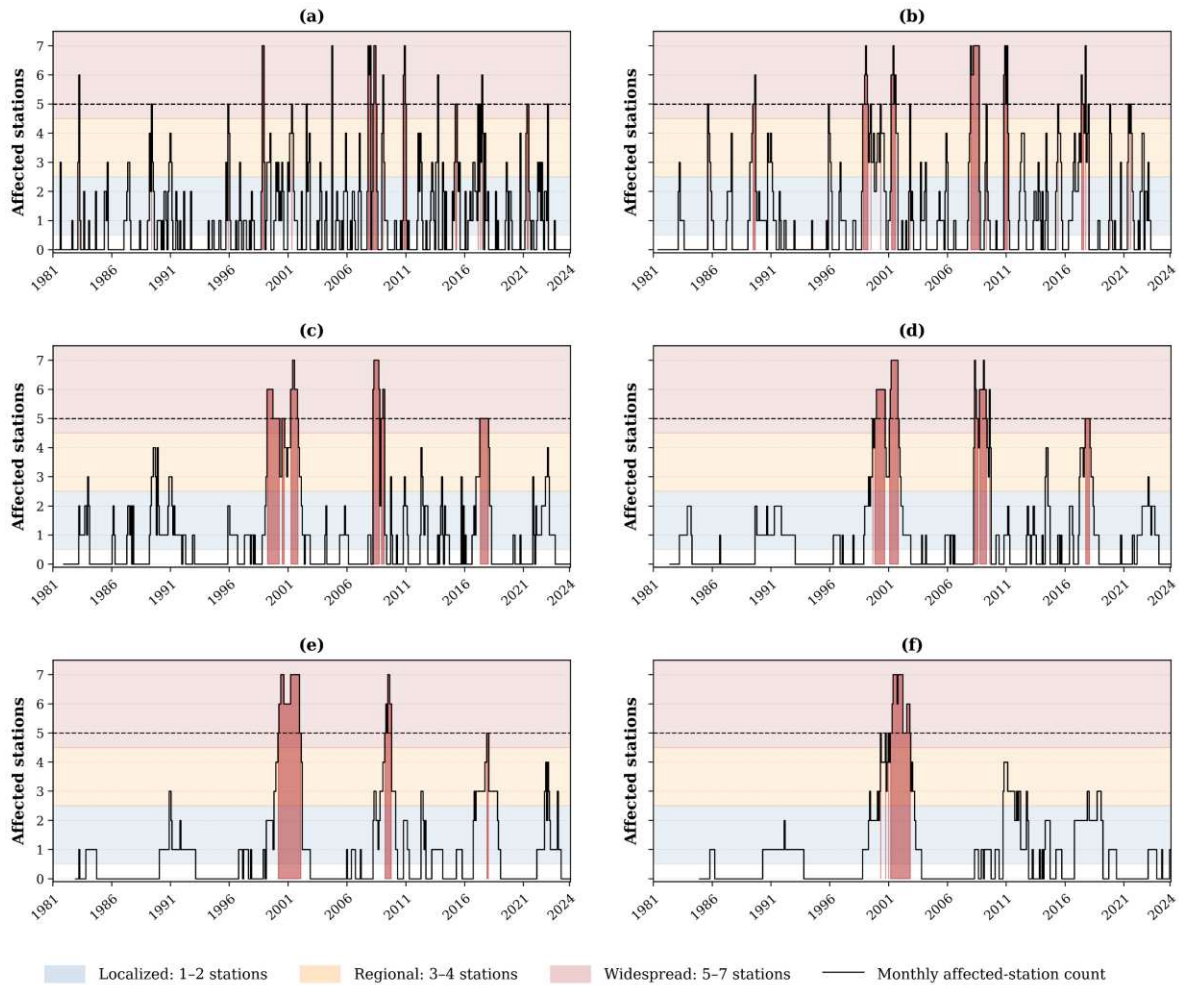


Figure 5- Monthly spatial coverage of meteorological drought at SPI accumulation periods of (a) 3, (b) 6, (c) 12, (d) 18, (e) 24, and (f) 48 months during 1981-2024. The black line represents the number of stations simultaneously experiencing at least moderate drought ($SPI \leq -1$). Conditions affecting one or two stations were classified as localized, those affecting three or four stations as regional, and those affecting five to seven stations as widespread or basin-wide. Red shading highlights synchronized basin-wide drought months, and the dashed horizontal line indicates the five-station synchronization threshold.

The 2008 drought showed a different pattern, with rapid spatial synchronization and much stronger short-term intensity. At SPI-3, widespread drought persisted from April to July 2008, reached all seven stations, and produced a mean affected-station SPI of -2.31; the network-mean SPI-3 fell to -3.04 in June. At SPI-6, synchronized drought lasted nine months from January to September, with an average spatial coverage of 96.8%, and all seven stations were affected during seven months. The event also persisted from April to October at SPI-12, with a mean coverage of 95.9% and a mean affected-station SPI of -1.96. Its influence subsequently appeared at SPI-18 and SPI-24, but not prominently at SPI-48, showing that the 2008 deficit was intense and widespread without becoming the dominant four-year precipitation anomaly. Other synchronized episodes were shorter or more spatially heterogeneous. The November 2010-January 2011 SPI-3 event lasted only three months but produced the lowest event-mean affected-station SPI of all identified synchronized events (-2.39), with all seven stations under drought in December 2010. Its limited expression at SPI-12 and longer periods shows that an acute basin-wide drought did not necessarily persist across longer accumulation windows. In

2017-2018, all seven stations experienced SPI-6 drought in October 2017, whereas generally only five remained affected at longer scales. Widespread conditions persisted from May 2017 to January 2018 at SPI-12, from October 2017 to February 2018 at SPI-18, and during December 2017-January 2018 at SPI-24. This episode therefore remained widespread but showed greater spatial contrast than the nearly uniform 2008 drought.

Table 6- Spatial coverage and synchronization characteristics of meteorological drought across the seven synoptic stations at different SPI accumulation periods during 1981-2024. A synchronized event consisted of one or more consecutive months during which at least five stations recorded $SPI \leq -1$. Onset spread represents the difference between the earliest and latest onset dates of the overlapping station-level drought events.

SPI timescale	Localized months (%)	Regional months (%)	Widespread months (%)	Synchronized events	Mean duration (months)	Longest event (months; period)	Maximum coverage (stations)	Mean onset spread (months)	Lowest event-mean affected SPI (period)
SPI-3	27.2	10.1	5.3	18	1.6	4 (Apr. 2008-Jul. 2008)	7	5.7	-2.39 (Nov. 2010-Jan. 2011)
SPI-6	23.3	12.0	8.0	18	2.3	9 (Jan. 2008-Sep. 2008)	7	17.7	-2.19 (Oct. 2017)
SPI-12	28.0	7.4	8.5	6	7.3	13 (Apr. 1999-Apr. 2000)	7	37.8	-1.96 (Apr. 2008-Oct. 2008)
SPI-18	29.2	5.5	7.8	7	5.7	11 (Nov. 1999-Sep. 2000)	7	29.0	-1.83 (Oct. 2017-Feb. 2018)
SPI-24	27.5	9.1	6.5	3	11.0	24 (Mar. 2000-Feb. 2002)	7	135.7	-1.65 (Dec. 2017-Jan. 2018)
SPI-48	31.8	7.5	5.0	4	6.0	21 (Mar. 2001-Nov. 2002)	7	23.8	-1.54 (Mar. 2001-Nov. 2002)

Synchronization also did not begin simultaneously across stations. Mean onset spread increased from 5.7 months at SPI-3 and 17.7 months at SPI-6 to 37.8 months at SPI-12, while SPI-24 reached 135.7 months. Sarab most frequently recorded the earliest onset across short and intermediate timescales. The exceptionally large SPI-24 onset spread should not be interpreted as the duration of basin-wide drought; it reflects station-level negative sequences that began years before the five-station synchronization threshold was reached. For the principal 2000-2002 SPI-24 event, the onset spread was 38 months, whereas some later synchronized periods overlapped with much earlier station-level negative sequences and produced much larger spreads.

3.5. Long-term trends and change points in drought conditions

The trend analysis revealed a clear contrast between basin-wide drought occurrence and station-level drought evolution. As shown in **Figure 6**, at the basin scale, annual synchronized drought months were strongly episodic but showed no statistically significant monotonic trend or abrupt change during 1981-2024. Short-timescale synchronization at SPI-3 and SPI-6 occurred intermittently throughout the record, with maximum annual values of five and nine months, respectively. In contrast, SPI-12 to SPI-48 emphasized the prolonged 1999-2002 drought, with secondary clusters around 2008-2010 and 2017-2018. Despite these prominent episodes, the Sen slope for annual basin-wide drought months was 0.0 months year⁻¹ at every timescale, with FDR-adjusted q values of 0.631 at SPI-3 and SPI-6 and 0.755 at SPI-12 to SPI-48. No Pettitt change point remained significant after correction. Annual maximum spatial coverage also showed no significant trend; the strongest nominal increase occurred at SPI-24 (0.026 affected stations year⁻¹, q = 0.109). Thus, basin-wide synchronization occurred as irregular drought clusters rather than increasing or decreasing systematically through time.

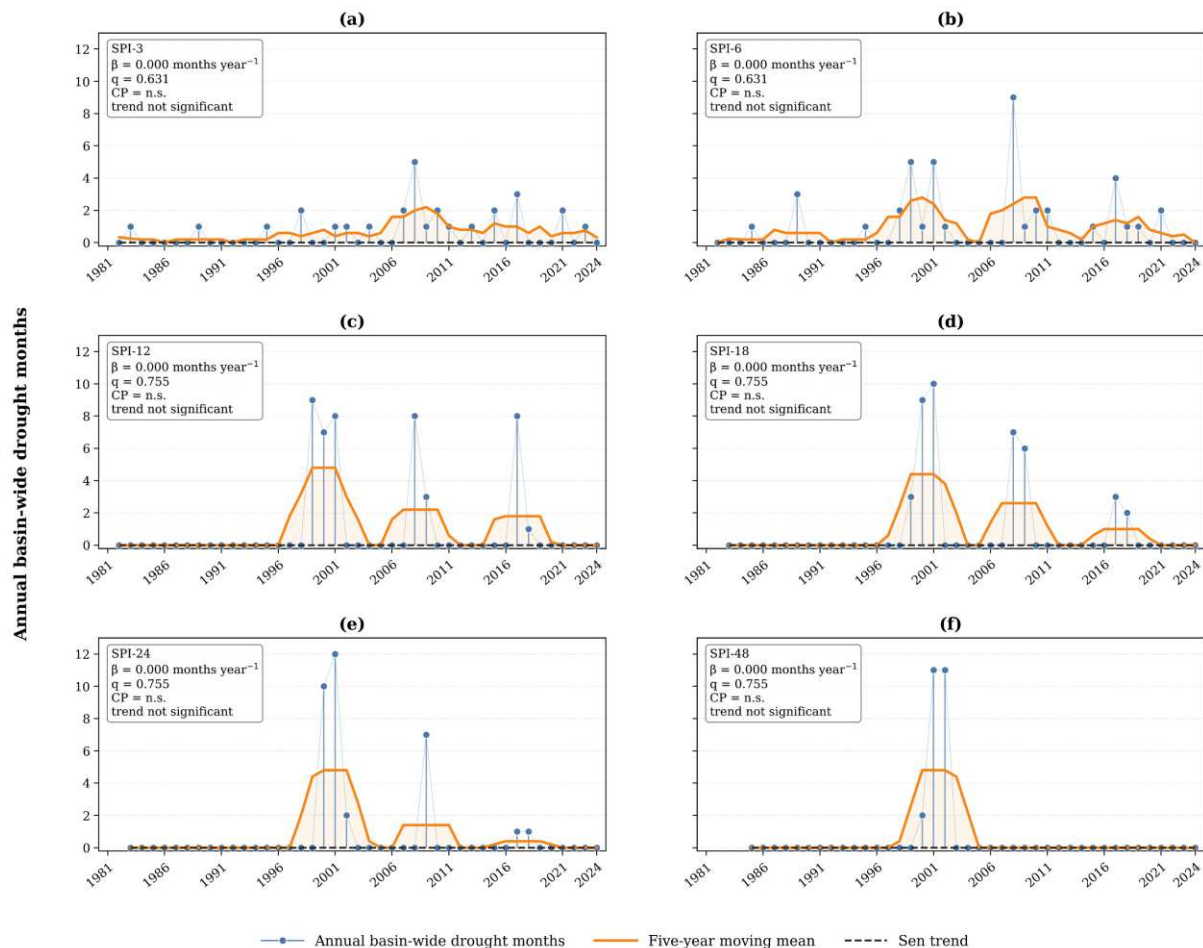


Figure 6- Annual number of synchronized basin-wide meteorological drought months at SPI accumulation periods of (a) 3, (b) 6, (c) 12, (d) 18, (e) 24, and (f) 48 months during 1981-2024. Blue markers and vertical lines represent annual values, orange lines show the centered five-year moving mean, and dashed black lines represent Sen's trend estimates. A basin-wide drought month was defined as a month during which at least five of the seven stations recorded $SPI \leq -1$. The notation "CP = n.s." indicates that no Pettitt change point remained significant after false-discovery-rate correction.

Station-level trends were more heterogeneous and were stronger for drought magnitude than for drought-month frequency (**Table 7; Figure 7a**). Significant increases in annual drought-month frequency were limited to Maragheh at SPI-3 and SPI-6 and Sarab at SPI-3. No station showed a significant frequency trend at SPI-12 or longer accumulation periods. At Maragheh, SPI-3 and SPI-6 increased by approximately 0.04 drought months year⁻¹, while Sarab increased by 0.07 months year⁻¹ at SPI-3. These rates correspond to roughly 1.6-3.1 additional drought months over the 44-year record, whereas the remaining stations had zero or near-zero frequency slopes.

Table 7- Summary of modified Mann-Kendall trends, Sen slopes, and Pettitt change points for station-scale and basin-scale meteorological drought indicators during 1981-2024. β is the median station-level Sen slope or the basin-level Sen slope; W and I denote the numbers of stations with significant worsening and improving trends, respectively; CP denotes the number of stations with significant Pettitt change points, followed by their median change year; and q is the Benjamini-Hochberg-adjusted probability.

SPI timescale	Annual drought months	Annual minimum SPI	Annual cumulative severity	Annual maximum coverage	Annual basin-wide drought months
SPI-3	($\beta = 0.000$); W=2/7; I=0/7; CP=2/7 (1995)	($\beta = -0.012$); W=2/7; I=0/7; CP=3/7 (1994)	($\beta = 0.052$); W=2/7; I=0/7; CP=2/7 (1996)	($\beta = 0.042$); (q=0.271);	($\beta = 0.000$); (q=0.631);
SPI-6	($\beta = 0.000$); W=1/7; I=0/7; CP=1/7 (1995)	($\beta = -0.014$); W=1/7; I=0/7; CP=3/7 (1994)	($\beta = 0.047$); W=2/7; I=0/7; CP=2/7 (1996)	($\beta = 0.036$); (q=0.164);	($\beta = 0.000$); (q=0.631);
SPI-12	($\beta = 0.000$); W=0/7; I=0/7; CP=0/7	($\beta = -0.023$); W=2/7; I=0/7; CP=2/7 (1995)	($\beta = 0.000$); W=1/7; I=0/7; CP=1/7 (1996)	($\beta = 0.000$); (q=0.271);	($\beta = 0.000$); (q=0.755);
SPI-18	($\beta = 0.000$); W=0/7; I=0/7; CP=0/7	($\beta = -0.023$); W=1/7; I=0/7; CP=3/7 (1997)	($\beta = 0.000$); W=1/7; I=0/7; CP=2/7 (1998)	($\beta = 0.000$); (q=0.381);	($\beta = 0.000$); (q=0.755);
SPI-24	($\beta = 0.000$); W=0/7; I=0/7; CP=0/7	($\beta = -0.035$); W=1/7; I=0/7; CP=4/7 (1998)	($\beta = 0.000$); W=3/7; I=0/7; CP=3/7 (1997)	($\beta = 0.026$); (q=0.109);	($\beta = 0.000$); (q=0.755);
SPI-48	($\beta = 0.000$); W=0/7; I=0/7; CP=0/7	($\beta = -0.026$); W=3/7; I=0/7; CP=4/7 (1998)	($\beta = 0.000$); W=1/7; I=0/7; CP=5/7 (1998)	($\beta = 0.000$); (q=0.271);	($\beta = 0.000$); (q=0.755);

Annual minimum SPI showed more widespread deterioration (**Figure 7b**). Maragheh had significant negative trends at SPI-3, SPI-6, SPI-12, SPI-18, and SPI-48, with slopes of approximately -0.023 to -0.036 SPI units year⁻¹. Sarab declined significantly at SPI-3, SPI-12, SPI-24, and SPI-48, including the strongest trend of -0.069 SPI units year⁻¹ at SPI-48. Mahabad also showed a significant SPI-48 decline of -0.049 SPI units year⁻¹. Cumulative drought severity displayed a similar but localized worsening pattern (**Figure 7c**). Sarab showed significant increases at all six accumulation periods, with Sen slopes from 0.185 severity units year⁻¹ at SPI-3 to 0.261 at SPI-48. Maragheh increased significantly at SPI-3, SPI-6, and SPI-24, while Takab showed a significant increase at SPI-24. No significant improving trend was detected for any drought indicator at any station or timescale. Overall, Sarab and Maragheh showed the most consistent deterioration, with additional long-timescale worsening at Mahabad and Takab.

Pettitt change-point analysis further showed that many station-level shifts clustered in the mid-to late 1990s. For annual minimum SPI, significant change points occurred at three stations at SPI-3 and SPI-6 and at four stations at SPI-24 and SPI-48, while the median change year shifted from about 1994 at shorter accumulation periods to 1998 at longer ones. Sarab showed the clearest sequence, with annual minimum SPI change points progressing from 1993 at SPI-3 to 1998 at SPI-48. Its post-change median annual minimum SPI decreased by approximately 1.59-2.14 units. Cumulative severity at Sarab also shifted between 1995 and 1998, with post-change medians increasing by approximately 6.1-8.3 severity units. Takab showed significant annual-minimum-SPI change points between 1994 and 1997 across all six accumulation periods, while Mahabad exhibited long-timescale shifts around 1998. Thus, station-level changes were concentrated in the 1990s even though no basin-wide change point was detected.

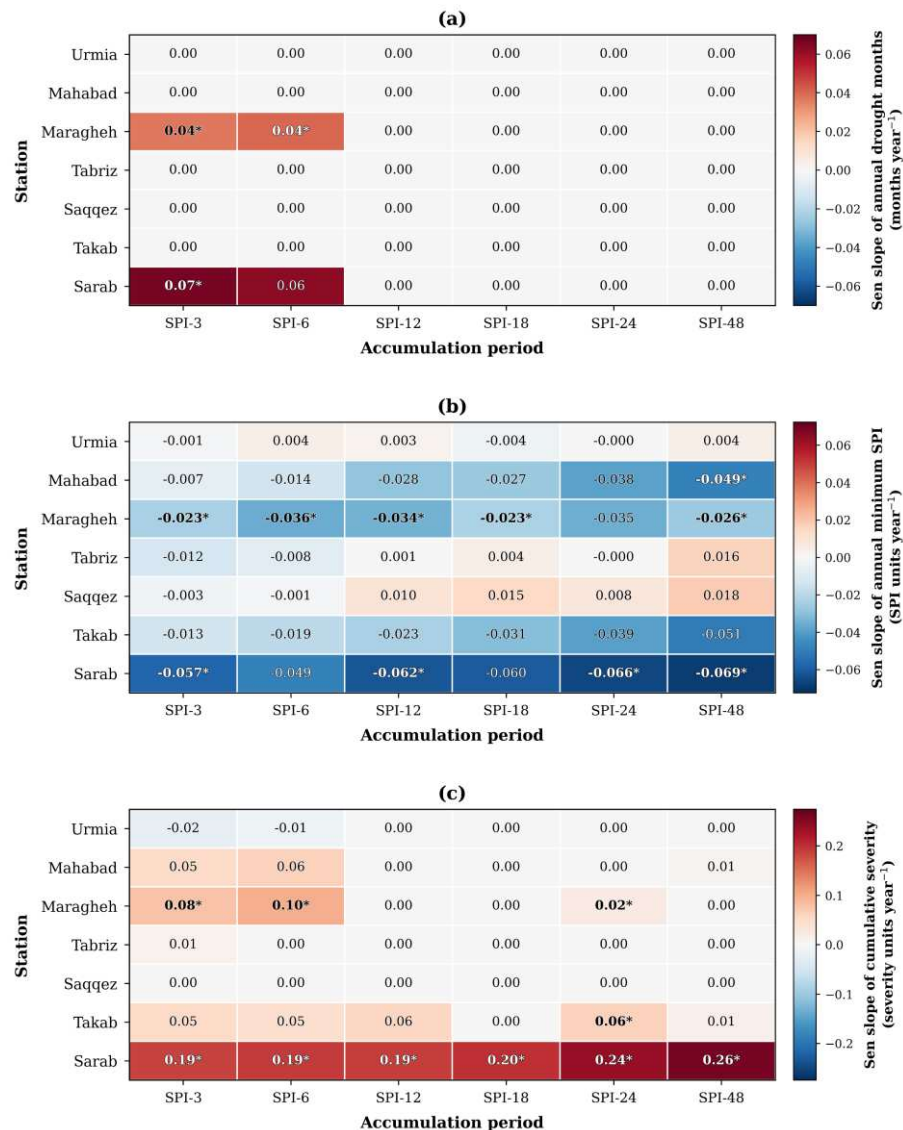


Figure 7- Station-level Sen slopes for (a) the annual number of drought months, (b) annual minimum SPI, and (c) annual cumulative drought severity at 3-, 6-, 12-, 18-, 24-, and 48-month accumulation periods during 1981-2024. Positive slopes in panels (a) and (c) indicate increasing drought frequency and cumulative severity, respectively, whereas negative slopes in panel (b) indicate increasingly severe annual minimum SPI conditions. Asterisks (*) denote statistically significant worsening trends and daggers (†) denote statistically significant improving trends after Benjamini-Hochberg false-discovery-rate correction.

Annual precipitation trends were consistent with several of these local drought changes (**Table 8**). Significant precipitation decreases occurred at Sarab, Mahabad, and Takab. Sarab showed the strongest decline at $-7.38 \text{ mm year}^{-1}$, accompanied by a significant 1996 change point and a 250.1 mm reduction in median annual precipitation after the change. Mahabad and Takab declined by 2.84 and 2.50 mm year^{-1} , with significant change points in 1997 and 1994, respectively. Maragheh also had a negative slope of $-1.48 \text{ mm year}^{-1}$, although it was not significant after FDR correction ($q = 0.069$). No significant precipitation trend was detected at Urmia, Tabriz, or Saqqez. The trend and change-point results show that the absence of a systematic basin-wide increase in drought synchronization coexisted with marked deterioration at several individual stations.

Table 8- Modified Mann-Kendall trends, Sen's slopes, and Pettitt change points in annual precipitation at the seven synoptic stations during 1981-2024.

Station	Sen slope (mm year^{-1})	Trend FDR (q)	Trend interpretation	Pettitt change year	Pettitt FDR (q)	Median change (mm)
Urmia	-0.33	0.842	No significant trend	—	0.767	-53.1
Mahabad	-2.84	0.049	Significant decrease	1997	0.046	-145.5
Maragheh	-1.48	0.069	No significant trend	—	0.478	-40.0
Tabriz	+0.05	0.879	No significant trend	—	0.767	+35.5
Saqqez	+0.92	0.778	No significant trend	—	0.671	+32.2
Takab	-2.50	0.049	Significant decrease	1994	0.025	-120.7
Sarab	-7.38	0.049	Significant decrease	1996	<0.001	-250.1

4. Discussion

4.1. Timescale-dependent drought architecture and event anatomy

The results showed that increasing the SPI accumulation period reorganizes drought rather than simply reducing its occurrence. Months with $SPI \leq -1$ represented 13.6-17.2% of the record across the six timescales, yet event frequency declined from 6.71 events per station per decade at SPI-3 to 0.64 at SPI-48, while mean duration increased from 6.5 to 80.2 months. Mean event intensity remained comparatively stable at 0.84-0.95. Thus, the increasing cumulative severity at long accumulation periods primarily reflects persistence rather than systematically stronger monthly deficits. This distinction is important because SPI event statistics depend on the selected accumulation period, event definition, fitted distribution, and uncertainty in the tails^{25,26}. The exceptionally long SPI-24 and SPI-48 runs at Sarab should therefore be interpreted as persistent below-normal accumulated precipitation under the adopted run definition rather than uninterrupted moderate-to-extreme drought. The analysis also distinguished two contrasting drought archetypes. The late-1990s to early-2000s drought developed gradually and retained a pronounced SPI-24 and SPI-48 signature, whereas the 2008 event intensified rapidly and became highly synchronized at short and annual timescales. Previous studies likewise identify the late 1990s-early 2000s and the 2007-2008 period as major drought intervals in the Urmia Lake Basin and Iran^{14,27,28}. The persistence of the former episode is also consistent with reported snow-drought and long-memory behavior in the basin⁷, while climate projections suggest that persistent drought may become increasingly important under future warming⁸. These contrasting events demonstrated why drought severity should be interpreted jointly with duration and intensity. Sarab accumulated very large long-term severity through persistent but relatively moderate deficits, whereas Saqqez experienced shorter but more intense multi-year events. Similarly, the coexistence of positive SPI-3 and slightly negative SPI-48 in October 2014 shows that short-term rainfall recovery can occur while a multi-year precipitation deficit remains unresolved. A single SPI timescale can therefore provide an incomplete, and occasionally misleading, assessment of drought recovery.

4.2. Spatial synchronization and the limits of basin-scale assessment

Spatial drought behavior was also strongly timescale-dependent. Mean interstation correlation decreased from 0.55 at SPI-3 and SPI-6 to 0.46 at SPI-48, while some station pairs became negatively correlated. Longer accumulation periods therefore reduced short-term temporal variability without producing greater spatial uniformity. This pattern likely reflects the increasing influence of persistent local precipitation regimes, topography, and moisture pathways as anomalies accumulate over time. Synchronization exhibited a similar non-monotonic pattern, with widespread drought being most frequent at SPI-12 (8.5%) but less common at SPI-3 (5.3%) and SPI-48 (5.0%). The 1999-2002 episode produced the clearest synchronization at intermediate and long accumulation periods, consistent with previous assessments of severe basin-wide drought around 1998-2001¹⁴. In contrast, the 2008 event was characterized by rapid spatial expansion at shorter timescales. Previous assessments also identify 2008 as an important drought year in Iran and the Lake Urmia Basin^{27,29}. These events demonstrate that similar spatial coverage can arise through different pathways, either via rapid seasonal synchronization or through the gradual accumulation of persistent deficits. The results

also illustrate the limitations of basin-average drought indicators. The synchronization metric used here represents the fraction of monitoring stations crossing the drought threshold rather than continuous areal drought coverage. Consequently, deterioration at one or several locations can remain hidden when other stations follow different trajectories. This issue is particularly important in the later years of the record, when short-term conditions approached normal at several stations while SPI-48 remained negative across much of the network. Long-term meteorological drought in the Urmia Lake Basin should therefore not be assumed to be spatially uniform, and station-level information should be retained alongside basin-scale summaries.

4.3. Local drought deterioration beneath basin-scale stability

The trend analysis highlighted an important scale-dependent contrast. Annual synchronized drought-month counts showed no significant monotonic trend, whereas precipitation deficits and drought conditions worsened significantly at several individual stations. This discrepancy partly stems from the aggregation criteria, as a synchronized drought month required at least five of the seven stations to reach an SPI of -1 or lower. Consequently, substantial intensification at one or more locations can occur without producing a detectable network-wide trend. Conversely, the absence of a local trend does not imply low drought risk, as evidenced by Saqqez, which experienced several of the most intense multi-year events despite showing no significant monotonic decline. Sarab provides the clearest evidence of persistent local change. Annual precipitation declined by approximately 7.38 mm yr^{-1} , with a 250.1 mm decline in median precipitation after the 1996 change point, while annual minimum SPI and cumulative severity also shifted during the 1990s. Later change points at SPI-24 and SPI-48 should be interpreted cautiously because overlapping accumulation windows propagate anomalies forward and reduce the number of independent observations. The absence of a significant network-wide SPI trend is consistent with studies reporting weak or spatially heterogeneous basin-wide precipitation changes, alongside severe late-1990s droughts and declining snow storage⁷. Furthermore, this finding aligns with SPEI-based evidence of drought deterioration in parts of the basin¹⁴, as the SPEI also incorporates atmospheric evaporative demand. Consequently, regional warming can intensify SPEI-based droughts even where precipitation trends are weak or spatially variable³⁰. Moreover, the lack of a meteorological drought trend does not imply stable water-resource stress, because irrigation expansion, water withdrawals, and reservoir operations can amplify precipitation deficits and alter lake inflows^{5,31,32}.

4.4. Operational implications, limitations, and future research

The multi-timescale results support the tiered screening framework summarized in **Table 9**. Short accumulation periods provide rapid information on emerging seasonal deficits, intermediate periods indicate whether anomalies are persisting across seasons, and longer periods characterize accumulated multi-year precipitation memory. These timescales should be interpreted as complementary indicators rather than interchangeable drought measures. Research on drought propagation likewise demonstrates that a single meteorological timescale may fail to represent hydrological responses that occur with different lags^{33,34}. The station-coverage metric provided an additional spatial dimension by distinguishing localized from synchronized conditions. A recent Lake Urmia study reported a 7-9 month lag between

meteorological and reservoir drought¹⁵, while multi-index frameworks recommend combining precipitation with soil moisture, runoff, storage, vegetation, and water-demand information^{35,36}. Such integration is particularly important in the Urmia Lake Basin, where agricultural water use and reservoir operation modify the translation of precipitation deficits into inflow and ecological stress^{5,31}. The station-level deterioration identified here further suggests that monitoring and adaptation strategies should retain spatial differentiation rather than relying exclusively on basin-average conditions.

Table 9- Proposed interpretation of SPI accumulation periods for drought screening in the Urmia Lake Basin.

SPI timescale	Primary signal	Evidence from this study	Potential decision relevance
SPI-3	Rapid short-term and seasonal precipitation deficits	Produced the highest drought-event frequency, averaging 6.71 events per station per decade. Takab and Urmia showed particularly high short-term recurrence, while the 2008 and 2010-2011 droughts developed rapidly across the station network.	Crop-condition monitoring, irrigation scheduling, and initial drought alerts
SPI-6	Persistent seasonal-to-medium-term precipitation deficits	Recorded the largest proportion of drought months, at 17.2%, and identified strongly synchronized episodes, including the nine-month basin-wide drought during January-September 2008 and the widespread drought in October 2017.	Seasonal allocation review, reservoir preparedness, and groundwater-demand control
SPI-12	Annual-scale precipitation stress	Showed the highest proportion of widespread drought months, at 8.5%, and clearly represented the basin-wide episodes of 1999-2000, 2008, and 2017-2018.	Annual water allocation, coordinated reservoir operation, and regional drought planning
SPI-18	Sustained interannual precipitation deficits	Identified fewer but considerably longer events, with a mean duration of 34.6 months, and emphasized persistent synchronized drought during 1999-2000, 2008-2009, and 2017-2018.	Multi-season restrictions, contingency planning, and preparedness for prolonged supply pressure
SPI-24	Persistent multi-year meteorological drought	Produced a mean event duration of 47.3 months and identified the longest synchronized drought, which persisted for 24 months from March 2000 to February 2002. Sarab showed exceptionally persistent and severe conditions at this scale.	Strategic allocation, groundwater recovery, cropping-pattern adjustment, and long-term reservoir planning
SPI-48	Long-memory multi-year precipitation conditions	Revealed persistent spatial contrasts and the long-term legacy of the 1999-2002 drought. It also showed significant deterioration in annual minimum SPI at Mahabad, Maragheh, and Sarab, although interpretation is less certain because of the limited number of independent 48-month periods.	Long-term vulnerability assessment, drought-legacy evaluation, and strategic demand management

The limitations of this study highlight critical priorities for future research. Additional gauges and spatially and temporally adaptive bias correction would improve transferability to ungauged locations, and the integration of gauge observations, satellite precipitation, topography, and geostatistical interpolation could support gridded SPI fields that permit area-weighted coverage, hotspot persistence, and drought-centroid analysis. Uncertainty from precipitation reconstruction, bias correction, SPI distribution fitting, reference-period selection, and drought thresholds should be propagated into event and synchronization metrics.

638 Ensemble, Monte Carlo, Bayesian, or temporally dependent bootstrap approaches could
639 provide uncertainty intervals for these quantities. Such approaches follow uncertainty-aware
640 practices already applied to environmental indicators³⁷. Finally, future analyses should validate
641 SPI timescales and synchronization thresholds against independent streamflow, reservoir-
642 storage, groundwater, snowpack, vegetation, agricultural-impact, and water-demand records.
643 Comparison with temperature-sensitive and hydrological drought indices would also help
644 distinguish precipitation deficits from drought conditions intensified by evaporative demand
645 and water-system processes.

5. Conclusions

This study combined temporally blocked CHIRPS bias correction, multi-timescale SPI, run theory, station-network coverage, modified trend tests, and change-point analysis to characterize meteorological drought across seven stations in the Urmia Lake Basin during 1981-2024. Bias correction increased the mean CHIRPS-station correlation from 0.78 to 0.88 and reduced MAE from 13.0 to 8.2 mm month⁻¹. The resulting 528-month precipitation series provided a consistent basis for evaluating drought behavior from seasonal to multidecadal timescales.

The principal finding was a clear scale-dependent transformation in drought structure. Although months with $SPI \leq -1$ accounted for a relatively stable 13.6-17.2% of the record, mean event frequency declined from 6.71 events per station per decade at SPI-3 to 0.64 at SPI-48. In contrast, mean duration increased from 6.5 to 80.2 months, while mean event intensity remained within 0.84-0.95. Thus, the greater cumulative severity of long-timescale droughts resulted mainly from persistence rather than stronger monthly deficits. The analysis also distinguished two drought archetypes. The 1999-2002 drought developed gradually and produced synchronized episodes lasting 24 months at SPI-24 and 21 months at SPI-48. The 2008 drought intensified rapidly: network-mean SPI-3 reached -3.04 in June, and widespread SPI-6 drought persisted for nine months. These events illustrate the difference between slow-developing multiyear drought and acute, spatially synchronized precipitation failure.

Drought was more commonly localized than widespread. One or two stations were affected during 23.3-31.8% of valid months, whereas at least five stations were affected during only 5.0-8.5%. Widespread drought was most frequent at SPI-12, where it occurred during 8.5% of the record. Longer accumulation periods did not eliminate spatial differences because mean interstation correlation declined from 0.55 at SPI-3 and SPI-6 to 0.46 at SPI-48. Sarab was distinguished by exceptional drought persistence and cumulative severity, whereas Saqqez experienced shorter but more intense multiyear events. At the network scale, annual synchronized drought-month counts had a Sen slope of zero at all six timescales and showed no significant change point. However, annual precipitation decreased significantly by 7.38, 2.84, and 2.50 mm year⁻¹ at Sarab, Mahabad, and Takab, respectively. Sarab also showed worsening cumulative drought severity at all six timescales, while annual minimum SPI deteriorated at five timescales at Maragheh. Therefore, the absence of a across-station trend does not imply spatially uniform stability because aggregation can conceal substantial local deterioration.

These findings support a tiered drought-monitoring framework. SPI-3 and SPI-6 can identify emerging seasonal stress, SPI-12 and SPI-18 can support annual and multi-season planning, and SPI-24 and SPI-48 can characterize multiyear precipitation memory. SPI magnitude should be interpreted together with persistence and station coverage to distinguish localized anomalies from events that require coordinated action. Future studies should extend this framework through denser observations, spatially continuous drought mapping, probabilistic uncertainty assessment, and integration with streamflow, reservoir storage, groundwater, snowpack, vegetation stress, and water demand.

Data availability

The CHIRPS precipitation data used in this study are publicly available from the Climate Hazards Center at the University of California, Santa Barbara, and were accessed through Google Earth Engine. The synoptic precipitation records were obtained from the Iran Meteorological Organization (IRIMO). The processed datasets and derived data generated during the current study are available from the corresponding author upon reasonable request.

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Mozhgan Rezazadeh: Methodology, Software, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Farshad Jahangiri:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Hossein Rezaei:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision. **Keyvan Khalili:** Conceptualization, Resources, Writing – review & editing, Supervision.

Competing interests

The authors declare no competing interests.