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DETECTING EMERGING DROUGHT PATTERNS THROUGH LONG-TERM RAINFALL VARIABILITY ANALYSIS

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Abstract

Long-term rainfall records are crucial for drought detection to understand temporal variability and to detect emerging hydroclimatic risks. In this study, multi-decadal duration of meteorological data obtained from 50 stations across the state of Sinaloa, Mexico, was analyzed to capture the rainfall variability, drought events, and longer-term trends in rainfall occurring across the state. Precipitation records for the annual and monthly cycles were analyzed through descriptive statistics, standardized precipitation anomalies, comparisons for the periods and Mann–Kendall trend analysis. The average annual precipitation was 707.64 mm and was very variable from year to year. A total of 13 large drought periods were identified, one from 1987 with significant drought and another from 2024, indicating a recent significant dry event. The regional rainfall showed no significant monotonic change ($p=0.869$) but station level analysis indicated significant decreasing trends at some stations, showing spatial heterogeneity. The frequency of droughts did not continuously increase over time. Emerging drought conditions were dominated overall by recurring rainfall deficits, pockets of rainfall decreases, and significant rainfall variability over time, rather than regional drying. The results are useful for local drought monitoring and adaptive management of water resources.

Keywords: drought detection, rainfall variability, precipitation trends, meteorological drought, climate variability

1. Introduction

Drought is one of the longest lasting hydroclimatic hazards due to its slow onset, the long time periods for droughts, and its ability to cascade through water resources, agriculture, ecosystems, and socioeconomic systems. Drought is a hazard that often occurs as a result of long-term precipitation deficits and does not typically become obvious until after the precipitation deficit has been felt through soil moisture, streamflow, reservoir storage, or crop water availability. So rainfall is a critical variable to understand meteorological drought, especially in areas where the availability of water resources and agricultural production is largely influenced by seasonal rainfall. Long meteorological records are critical in differentiating between short-term variability in rainfall and a long-term change in climatic behavior, and they help identify periods of climatic moisture deficits (Meskelu et al., 2024).

Rainfall variability happens at several time scales and can include changes in the amount of rainfall, in the way it is distributed during the season, in the frequency of rain events, and in the duration of the dry period. This variability can significantly influence the frequency and intensity of drought, even if there is little change in the mean rainfall over the longer term. A rainfall analysis must therefore go beyond the average precipitation and include anomalies, variability and temporal trends which indicate deviations from the known climatic conditions. Long-term statistical characterization may reveal unusually dry years, periodic rainfall deficiency and oscillations, which may not be noticed in the aggregated climatic summaries (Das & Das, 2025). The assessments are particularly significant in terms of identifying the presence of dry conditions as isolated events or as part of longer term patterns.

Standardized indicators are often used to convert precipitation departures into comparable measures of moisture deficiency, and are therefore widely used in drought assessment. The Standardized Precipitation Index (SPI), for instance, allows for the assessment of drought conditions to be done for various accumulation periods and permits the detection of short-, medium, and longer-term rainfall deficits. Multi-timescale drought assessment is crucial since the response of agricultural, hydrological and ecological systems to precipitation shortages of varying durations are not the same (Moazzam et al., 2022). Further investigations of both short and long-term meteorological drought have also shown that drought characteristics could differ significantly depending on the time scale chosen, highlighting the importance of exploring both long-term and relatively short-term rainfall deficits (Muthiah et al., 2024).

An additional approach for finding systematic changes in rainfall and drought characteristics is to use long-term trend analysis. The Mann–Kendall test is a non-parametric test that is especially appropriate for hydroclimatic time series for which observations are not normally distributed (Tibangayuka et al., 2025). The intensity of the trend can also be assessed to provide a clearer distinction between a trend with statistical significance and small interannual variations. These methods have shown great spatial variability in precipitation patterns, such as a decrease, increase, and statistically steady pattern in the same larger climate zone (Rahman et al., 2022). The regional average variations can also mask the important local climate signals, and abrupt changes and shifts between the wet and dry periods can also happen at different temporal scales (Berhail, & Katipoğlu, 2023).

Topography and elevation, distance from the coast, atmospheric circulation, and local climate can affect rainfall distribution and are especially important for drought monitoring applications. This

can lead to different trends and drought characteristics at stations in the same geographic area. Spatially resolved analysis can help to identify regions in which drought conditions are likely to occur and separate out regional scale droughts from the occurrence of droughts in specific areas (Tefera et al., 2025). Studies conducted over long periods of time have shown that the addition of temporal trend detection and spatial rainfall assessment gives greater confidence than examining the regional average alone for water-resource planning (Nath et al., 2024). Likewise, basin-level assessments show that rainfall variability and drought frequency vary significantly between stations, underscoring the need for station-level assessment (Abubakar et al., 2025).

Emerging drought patterns are not confined to just reporting on past dry years. It needs to examine changes in drought frequency, intensity, length or spatial location over successive periods. To get a fuller picture of changes in drought conditions, recent methodological advances have also introduced drought-class frequencies along with trend analyses (Abu Arra et al., 2025). Historical records are particularly useful for this purpose, and longer records can be used to better illustrate multi-decadal variations when they are not evident in short records. An analysis of long-term climatic records shows that drought hotspot areas and temporal changes can occur in an uneven pattern and thus should be taken into account based on long-term climatic variability and recent climate conditions (Tall et al., 2023).

To assess this in the context of Sinaloa, Mexico, the following conditions can be met: Long-term meteorological records are available at stations located in coastal, valley, mountainous, and urbanized areas. These records can be used to understand a decades-long record of rainfall variability, and identify if recent dry conditions are different from past trends (Ashraf et al., 2023). Importantly, drought detection using a long rainfall record must not presume that all the recent deficits signal a long-term climatic deterioration. Rather, new behaviours should be defined by quantitative comparisons of anomalies, drought occurrences, and statistically-convincing trends. This method offers a defensible way of distinguishing between recurrent climatic variability and potential drought signals and can support regional drought monitoring, preparedness, and sustainable water-resource management.

Thus, this study examines precipitation observations over a long period of time to quantify precipitation variability, determine drought conditions, and assess changes in the drought behavior over time. The specific objectives are:

- 1.To quantify long-term rainfall variability, temporal anomalies, and precipitation extremes across the available meteorological record.
- 2.To identify drought frequency, severity, and persistence using standardized rainfall-based indicators across multiple temporal periods.
- 3.To evaluate long-term rainfall trends and determine whether recent observations indicate emerging drought patterns.

2. Materials and Methods

2.1 Study Area and Meteorological Dataset

The study relied on long-term meteorological observations that were taken throughout Sinaloa, Mexico from 1933 to 2025, as compiled by Mora et al. (2025). The database consisted of observations taken at 50 meteorological stations located in 17 municipalities and comprised data related to precipitation, evaporation, maximum temperature, minimum temperature, latitude,

longitude and altitude. Rainfall was chosen as the key variable for drought monitoring. The daily, monthly, and yearly rainfall data was analysed to provide a characterization of the rainfall behaviour at various temporal scales. To avoid the impact of incomplete measurements in 2025 on the annual trend analyses, only results for complete observations to 2024 were considered.

2.2 Data Preprocessing and Quality Assessment

Temporal fields of meteorological data were standardized and data from meteorological files were integrated based on station identification numbers. Prior to statistical analysis precipitation data were screened for missing data, temporal consistency and station coverage. Observations were made monthly and the totals by the year and month; and annual precipitation totals were grouped by station and year. Stations that had sufficient long-term coverage (30 or more annual observations) were used for station-specific trend assessment. Longitudinal comparisons were not made of the incomplete 2025 annual period. The annual rainfall was only computed if at least 5 rain gauges were available in the region.

2.3 Long-Term Rainfall Variability and Anomaly Analysis

Mean, standard deviation, coefficient of variation, absolute anomaly, and percentage departure from the long-term regional mean were used to quantify long-term rainfall variability. Rainfall for the region for each year was calculated by taking the average of the available precipitation data at each station for that year. Standardized rainfall anomalies were computed as follows, where long-term mean rainfall is subtracted from annual rainfall and the resulting difference is divided by the standard deviation of the long-term mean rainfall. Years with negative standardized values were below average rainfall years. Driest and wettest years were then ranked to define interannual extremes and quantify the intensity of historical variations of rainfall for the observation period.

2.4 Drought Identification and Characterization Challenges

Standardized annual precipitation anomalies were used to identify rainfall-based drought conditions, offering a consistent measurement of precipitation deficit in relation to the long-term climatic conditions. Standardized anomaly values of -1.0 or below were taken as a sign of significant drought, and more negative values as more droughts. Drought years were compared using the annual precipitation, standardized anomaly magnitude and percentage departure from the long term mean. Monthly standardized precipitation departures were also analyzed to better understand short-term precipitation deficiencies, and to help distinguish long-term periods of dryness over various time scales in the dataset.

2.5 Temporal Trend and Emerging Drought Pattern Analysis

Annual precipitation data were analysed for temporal trends using non-parametric Mann-Kendall test for trend and linear Sen type trend analysis to determine the statistical significance at $p < 0.05$. Only those stations with 30 or more annual observations were used for station-level analyses. Positive slopes meant an increase in precipitation while negative slopes meant a decrease in precipitation. Comparable long-term periods were further split into three separate time periods, namely 1964-1984, 1985-2004 and 2005-2024, for a further examination of emerging drought behavior. A comparison of differences in mean precipitation and drought-year frequency and

variability was made to test for intensification of precipitation deficits in recent decades.

3. Results

3.1 Characteristics and Temporal Coverage of Meteorological Records

The annual dataset had a total of 2,725 station-year observations from 50 stations spread across 17 municipalities. Records were extended from 1933 to 2025, but not used for complete-year analyses in 2025. The mean annual precipitation for all observations was 702.47 mm with a standard deviation of 343.95 mm and a median of 678.90 mm; there was strong spatial and temporal variability in annual precipitation. The most recent 72 years (1953-2024) of observations that were available at five or more stations across the region were used for regional trend calculations (Table 1).

Table 1. Numerical characteristics of the meteorological dataset

Parameter	Numeric value
Meteorological stations	50
Municipalities	17
Annual observations	2,725
Earliest record	1933
Latest record	2025
Complete-year trend endpoint	2024
Regional years analyzed	72
Mean annual precipitation (mm)	702.47
SD precipitation (mm)	343.95
Median precipitation (mm)	678.90
Minimum precipitation (mm)	0.00
Maximum precipitation (mm)	3,931.00

3.2 Long-Term Rainfall Variability and Anomalies

The amount of rainfall in the region has shown significant interannual variation from 1953 to 2024. The mean regional precipitation was 707.64 mm, the standard deviation was 122.01 mm and coefficient of variation was 17.24%. The driest year recorded was 1987, with an average of 475.44 mm of precipitation which was 32.81% below the LTM. In contrast, the highest level of

precipitation occurred in 2004 with 1066.65mm of precipitation, which is 50.73% more than the average. Multi-decadal rainfall deficits are evident in other extreme dry years, such as 1979, 2002, 2024, and 1973 (Figure 1) (Table 2).

Table 2. Major long-term rainfall extremes and anomalies

Year	Rainfall (mm)	Anomaly (mm)	Departure (%)	Rank/type
1987	475.44	−232.20	−32.81	1 – Driest
1979	510.70	−196.94	−27.83	2 – Driest
2002	519.64	−188.00	−26.57	3 – Driest
2024	524.26	−183.38	−25.91	4 – Driest
1973	544.80	−162.84	−23.01	5 – Driest
1990	892.17	+184.53	+26.08	5 – Wettest
1958	934.99	+227.35	+32.13	4 – Wettest
1984	994.67	+287.03	+40.56	3 – Wettest
2015	1,027.03	+319.38	+45.13	2 – Wettest
2004	1,066.65	+359.01	+50.73	1 – Wettest

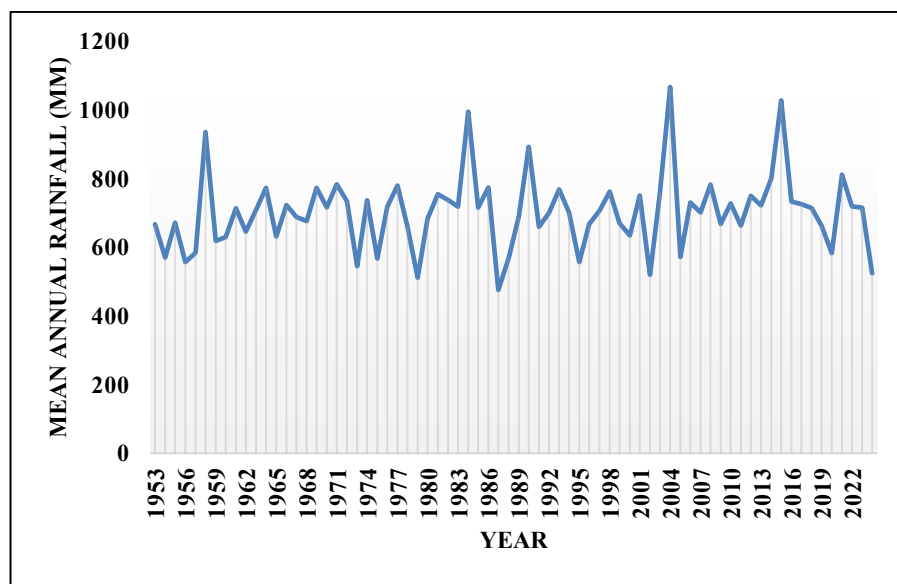


Figure 1. Long-Term Annual Rainfall Pattern

3.3 Drought Frequency, Duration, and Severity

The 13 years with standardized annual rainfall anomalies at or below -1.0 were considered as having experienced significant reductions in precipitation compared to long-term averages. The strongest drought signal occurred in 1987, with a standardized anomaly of -1.90 and regional rainfall of only 475.44 mm. Other pronounced events occurred in 1979 (-1.61), 2002 (-1.54), and 2024 (-1.50). The recurrent drought signals are spread out over decades (Figure 2), indicating that droughts were not confined to a specific time, but rather were recurrent over time, with a fair amount of variability (Table 3).

Table 3. Years identified with substantial rainfall-deficit conditions

Year	Rainfall (mm)	Standardized anomaly	Rainfall deficit (%)
1954	569.42	-1.13	-19.53
1956	557.08	-1.23	-21.28
1957	584.26	-1.01	-17.44
1973	544.80	-1.33	-23.01
1975	567.11	-1.15	-19.86
1979	510.70	-1.61	-27.83
1987	475.44	-1.90	-32.81
1988	567.39	-1.15	-19.82
1995	556.80	-1.24	-21.31
2002	519.64	-1.54	-26.57
2005	571.85	-1.11	-19.19
2020	582.79	-1.02	-17.64
2024	524.26	-1.50	-25.91

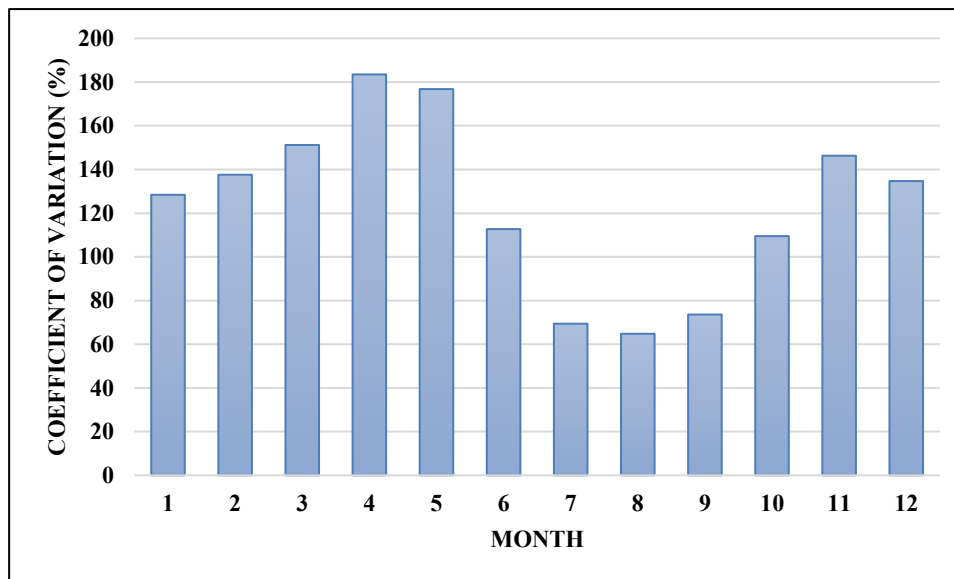


Figure 2. Monthly Standardized Rainfall Variability

3.4 Long-Term Trends in Rainfall and Drought Conditions

Regionally, there was little long-term trend in annual precipitation from 1953 to 2024. The Mann–Kendall coefficient had a value of -0.013 with $p=0.869$ and the estimated linear slope was very small ($+0.07$ mm/year). Spatial heterogeneity did exist, however, when results were looked at by station. San Joaquin, El Playon and El Fuerte were the stations with statistically significant decreasing rainfall patterns among those that had at least 30 observations. There was a strong positive trend in Guadalupe de los Reyes. So, the regional temporal signal was weaker than localized precipitation changes (Figure 3) (Table 4).

Table 4. Significant long-term precipitation trend results

Spatial unit/station	n	Kendall τ	p- value	Trend (mm/year)
Regional series	72	-0.013	0.869	$+0.07$
San Joaquin (25172)	47	-0.273	0.007	-4.93
El Playon (25030)	63	-0.229	0.008	-3.34
El Fuerte (25023)	59	-0.231	0.010	-3.17
Guadalupe de los Reyes (25036)	64	$+0.185$	0.031	$+13.30$

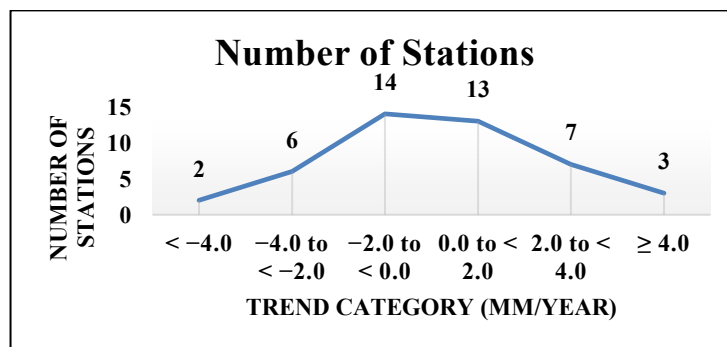


Figure 3. Distribution of Station-Level Rainfall Trend Slopes

3.5 Emerging Drought Patterns

When drought behavior was compared from one decade to the next, it was found to differ among successive decades and not to intensify consistently. Mean regional rainfall decreased from 722.68 mm during 1964–1984 to 697.63 mm during 1985–2004, before recovering slightly to 706.52 mm during 2005–2024. The frequency of drought years was highest in 1985–2004 (20.0%) than in the other two periods (14.3% in earlier and 15.0% in recent periods). However, the 2024 rainfall shortfall was extreme, indicating that there is significant drought activity in the recent climate record (Figure 4) (Table 5).

Table 5. Temporal comparison of rainfall variability and drought occurrence

Period	Years (n)	Mean rainfall (mm)	SD (mm)	CV (%)	Drought years (n)	Drought frequency (%)
1964–1984	21	722.68	124.37	17.21	3	14.3
1985–2004	20	697.63	132.66	19.02	4	20.0
2005–2024	20	706.52	116.91	16.55	3	15.0

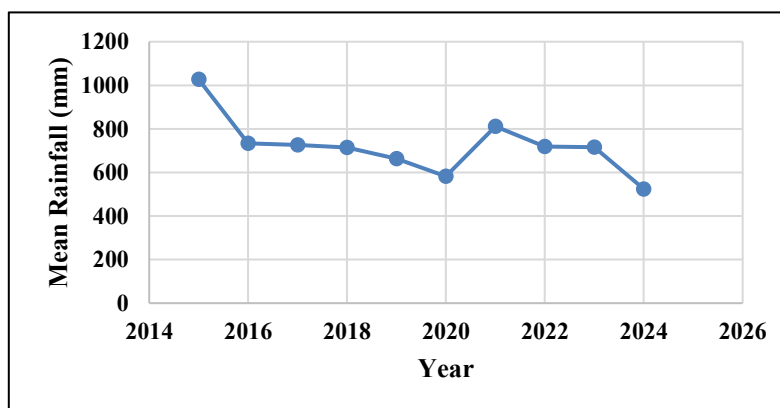


Figure 4. Recent Annual Rainfall Pattern, 2015–2024

4. Discussion

The long term meteorological analysis showed that there was a high degree of interannual rainfall variability in the study area with significant differences between the dry and wet years, but no significant trend in the region. The mean regional annual rainfall of 707.64 mm and coefficient of variation of 17.24% indicated that the rainfall was high with significant variability during the observation period. The difference between the wettest year (2004) with 1066.65 mm and the driest (1987) with 475.44 mm is further proof of temporal variability. Based on these results, the drought development in the region seems to be more related to a progressive deviation from rainfall pattern and episodic rainfall deficits than to a progressive decrease in annual precipitation. Other studies have noted that even if trends in direction remain weak or spatially variable, long-term rainfall variability may produce significant impacts on the hydrology (Fattah et al., 2024).

An interpretation of drought susceptibility is given in the context of the seasonal rainfall distribution. Several months had relatively low amounts of rainfall, while rainfall was concentrated during the main wet season months. Seasonality can make deficits during wet seasons disproportionately affect the availability of water for the year. The relative variability that is high during the drier months also suggests that there is a high amount of uncertainty in the timing and distribution of rainfall. Similar evaluations have demonstrated that the difference in precipitation timing and extremes has the potential to offer valuable information in addition to annual precipitation totals, especially when large-scale climatic processes affect seasonal precipitation patterns (Giraldo-Osorio et al., 2022). Therefore, the monitoring of droughts in Sinaloa has to take into account deficits on an annual level, as well as within-year rainfall distribution.

The regional series of rainfall analysed, shows 13 significant drought years identified by standardized rainfall anomalies. The greatest lack was in 1987 when the rainfall was about 32.81% less than the long-term average. There also has been a tendency for large droughts to happen more than once in each decade, including in 1979, 2002, and 2024. It is important to note that the distribution in time of these events does not imply that severe drought is a recent event. Instead, the record shows that there are repeated events set in the long-term context of large climatic variations. This interpretation is in line with the findings that a meaningful characterization of meteorological drought also depends on the length of the rainfall data series used, and that the rainfall deficiency is not always a persistent drought, but rather a recurring event as part of natural variability (Guo et al., 2022). It is, therefore, better to make a long-term drought analysis rather than conclusions based on recent extreme events.

Trend analysis additionally showed that the rainfall behavior in the region and local should be analyzed separately. The Mann–Kendall coefficient at the regional scale was -0.013 , with a p value of 0.869 , indicating that there is no statistical obvious trend in rainfall at the regional scale. The rate of change is also estimated to be around $+0.07$ mm/year annually, which is also a small value. The finding of this result calls into doubt the use of the study area as representing a homogeneous long-term rainfall decrease. Other studies of recent droughts around the world have also shown that contemporary droughts can be caused by an increase in drought-related variability or episodic precipitation deficits as opposed to a statistically significant decrease in precipitation (Romano et al., 2022). The benefit of trend based techniques has also been highlighted through rainfall time-series analyses, showing the ability of the techniques to separate a change in direction from a fluctuation in the very variable climatic record (Pastagia & Mehta, 2022).

Spatial heterogeneity was much greater at the station level than in the regional series, however. The precipitation trends were found to be statistically significant negative trends for San Joaquin, El Playon and El Fuerte, and statistically significant positive trend for Guadalupe de los Reyes. A regional average mask local changes in rainfall levels, as seen by the presence of both decreasing station-level rainfall, stable, and increasing station-level rainfall. This spatial variability also has implications for practice since drought exposure can vary among communities and water-management systems even within the same large-scale climatic region. The spatially heterogeneous trend is also reported when the long-term precipitation products are examined across geographically diverse environments, which further emphasizes the need for assessing them locally rather than using regional scale averages (Ramadhan et al., 2022).

There were also some indications that droughts were getting more intense over time, as shown in the period-wise comparison. Drought frequency increased from 14.3% during 1964–1984 to 20.0% during 1985–2004 but subsequently declined to 15.0% during 2005–2024. Similarly the mean rainfall showed a non-linear variation, dropping from 722.68 mm to 697.63 mm and then bouncing back to 706.52 mm for the latest period. The results show reorganization of drought periods, not a continuous shift to more arid periods. This discovery is important for drought forecasts because it is not always possible to predict the risk of drought by simple linear extrapolation of recent rainfall behavior. Drought analysis can be further strengthened by incorporating drought analysis and forecasting methods and long-term rainfall data to help assess future drought conditions (Poornima et al., 2023).

However, a significant rainfall shortfall in 2024 is significant. The region experienced a slight below-average rainfall of 524.26 mm, which falls around 25.91% below normal rainfall in the last 80 years. 2024 was one of the driest years in the available record with a slight below-average rainfall of 524.26 mm for the region. This recent event suggests that there is still a risk for severe drought even when the overall regional downward trend is minimal. Meteorological drought can also spread to hydrological systems, affecting groundwater, streamflow, and baseflow when precipitation deficits continue over a period of time (Lee & Ajami, 2023). Thus, a lack of any significant regional rainfall trend should not be assumed to be a lack of vulnerability to water resources.

In total, the results indicate that the onset of drought in Sinaloa is manifested by precipitation shortfalls, high interannual variability, recent extreme droughts, and uneven station-level drought trends as opposed to a consistent regional drying pattern. Such a separation is critical for water-resource management and drought preparedness. In future, drought assessments could incorporate meteorological drought indicators in addition to precipitation, temperature, evaporation, soil moisture, groundwater, and hydrological indicators, to assess if meteorological droughts are being translated to more extended agriculture and hydrological droughts. There is also potential for using predictive approaches to enhance early warning capability where traditional trend analysis approach is insufficient to depict non-linear drought behavior (Hameed et al., 2024).

5. Conclusion

A sound foundation for identifying the characteristics of drought and separating recurrent lack of precipitation from long-term climatic changes is provided through long-term rainfall records. The interannual variation was found to be high from the meteorological record when averaged across

the region, with an average annual precipitation of 707.64 mm and extreme wet and dry years. Thirteen major drought years were identified, with 1987 having the largest rainfall deficit, and 2024 had a severe rainfall deficit, highlighting the ongoing drought risk in recent years. The regional Mann–Kendall analysis, however, revealed no statistically significant rainfall trend, which suggests that the occurrence of droughts cannot be explained by a continuous decline in rainfall in general. There was a more complex station-level pattern, with several stations experiencing significant rainfall reductions and another station exhibiting a trend of increasing rainfall. The changes in drought frequency were also seen in the period-wise comparison, but there was no intensification of the droughts over the period 1951-2011; rather there was a peak in the frequency of droughts in 1985-2004. The results show that emerging drought characteristics are mostly bounded by high temporal variability, frequent extreme drought conditions and local variability. Ongoing station-based monitoring and combining of precipitation and temperature, evaporation, soil moisture and hydrological indicators are therefore recommended to enhance drought early warning, preparedness activities, and sustainable regional water-resource management.

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