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RESEARCH ARTICLE

CHANGING DROUGHT PATTERNS IN SIERRA LEONE UNDER A WARMING CLIMATE: A SPATIOTEMPORAL ANALYSIS OF METEOROLOGICAL AND CLIMATIC WATER DEFICITS FROM 1981 TO 2025

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Abstract

Drought is a significant climate-related hazard in Sierra Leone due to the country's reliance on seasonal rainfall, rain-fed agriculture, and climate-sensitive water resources. This study examines evidence of meteorological and climatic water deficits during 1981–2025 using the Standardized Precipitation Index (SPI) and Standardized Precipitation–Evapotranspiration Index (SPEI), with precipitation data from the Climatic Research Unit (CRU) and temperature data from ERA5, complemented by externally produced CORDEX - Africa/ CMIP projections and published assessments. The evidence indicates substantial spatial and temporal variability in drought frequency, duration, severity, and exposure, with northern areas such as Kambia and Port Loko identified in previous studies as comparatively drought-sensitive because of rainfall variability, warming, and dependence on rain-fed agriculture. Importantly, reported quantitative estimates from Amara and Ullah (2023), the Green Climate Fund (2024), Ekolu et al. (2025), Ogunrinde et al. (2026), and other sources are treated explicitly as secondary evidence rather than newly calculated results, and climate projections are interpreted within their original modelling and scenario frameworks. Overall, the evidence suggests that drought risk cannot be adequately characterized by precipitation deficits alone, as increasing temperature and atmospheric evaporative demand may intensify climatic water stress even where precipitation trends remain uncertain. Strengthening integrated drought monitoring through SPI, SPEI, soil-moisture and hydrological indicators, alongside improved early-warning systems and geographically targeted adaptation measures, is therefore essential for enhancing climate resilience, food security, and sustainable water-resource management in Sierra Leone.

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Introduction:-

Drought is one of the most important slow-onset climate hazards affecting agricultural production, water resources, ecosystems, livelihoods, and human well-being. Unlike rapid-onset hazards, drought develops over extended periods and can progress from precipitation deficits to soil-moisture stress, agricultural losses, reduced streamflow, declining groundwater availability, and wider socio-economic impacts.Sierra Leone is located on the west coast of Africa between approximately 6°N and 10°N and experiences a tropical climate characterized by a pronounced wet season and dry season. Rainfall is strongly seasonal and varies considerably across the country. The national economy and rural livelihoods remain highly dependent on agriculture, much of which is rain-fed. Consequently, variability in rainfall timing, dry-spell duration, and temperature can have important implications for agricultural production and household welfare.

Climate variability is already associated with multiple hazards in Sierra Leone. Existing assessments document exposure to flooding, drought, extreme heat, coastal hazards, and other climate-related stresses (Green Climate Fund, 2024). These hazards can also interact. Intense rainfall may increase flood risk during the wet season, while prolonged dry periods and high temperatures can increase water stress during the dry season.Climate change introduces additional complexity. Increasing temperatures can increase atmospheric evaporative demand and potential evapotranspiration (PET). Consequently, a drought assessment based only on precipitation may underestimate climatic water stress where warming increases water demand from the atmosphere, vegetation, soils, and surface-water systems.

Two complementary indices are therefore relevant. The Standardized Precipitation Index (SPI) measures precipitation anomalies over different accumulation periods, whereas the Standardized Precipitation–Evapotranspiration Index (SPEI) incorporates the climatic water balance represented ***by precipitation minus PET***.The distinction is particularly important when assessing drought under warming conditions.
Previous research has examined precipitation deficits and drought characteristics in Sierra Leone. Amara and Ullah (2023), for example, assessed precipitation deficits over multiple timescales using SPI. Other studies have examined drought persistence, hydrological drought, climate projections, and broader West African drought dynamics (Hussain et al., 2021; Ekolu et al., 2025; Ogunrinde et al., 2026).However, an important methodological issue arises when synthesizing this literature: numerical results reported in previous studies should not be presented as newly generated results unless they have been independently reproduced using the datasets and procedures described in the current study.

The present study therefore distinguishes among three forms of evidence:-
- results generated by the present analysis, where the underlying calculations are documented and reproducible;
- results obtained from external datasets or published studies, which are reported explicitly as secondary evidence; and
- climate projections and interpretations from previous modelling studies, which are discussed according to their original scenario and modelling framework.

This distinction strengthens the transparency of the study and prevents published estimates from being inadvertently presented as original calculations.

The study addresses three questions:-
1) How have meteorological and climatic water deficits in Sierra Leone changed during the period 1981–2025?
2) What evidence exists concerning the spatial and temporal distribution of drought frequency, duration, and severity across Sierra Leone?
3) How can increasing temperature and evaporative demand alter drought conditions beyond precipitation deficits alone?
4) The study also examines the implications of these changes for agriculture, water resources, food security, and climate adaptation.

Data and Methods:-

Study Area:-

Sierra Leone covers approximately 71,740 km² and can broadly be considered in terms of the Northern, Southern, Eastern, and Western areas.
The country's rainfall regime is strongly influenced by the West African monsoon and the seasonal movement of the Intertropical Convergence Zone (ITCZ). Mean annual rainfall is generally higher in southern and coastal areas than

in the north, although substantial local and interannual variability exists.The northern part of the country includes areas such as Kambia and Port Loko. Previous climate assessments have identified these areas as sensitive to changes in rainfall and temperature and to the effects of climate variability on rain-fed agricultural systems (Green Climate Fund, 2024).

Southern and coastal areas receive comparatively high rainfall but may experience different forms of drought-related exposure, including hydrological stress, agricultural impacts, and coastal and ecosystem pressures. The Western Area, including Freetown, has additional exposure associated with population concentration, urban water demand, infrastructure, and the urban heat environment.The eastern part of Sierra Leone contains extensive agricultural and forested landscapes and exhibits its own spatial variability in rainfall and drought conditions.These differences make Sierra Leone an appropriate setting for examining drought as a spatially heterogeneous climate hazard.

Data sources:-

Monthly precipitation for 1981–2025 was obtained from the CRU TS4.01 gridded precipitation dataset at 0.5° × 0.5° resolution. Temperature information was obtained from the ERA5 reanalysis for the corresponding historical period. The World Bank/CEIC Mean Drought Index series, derived from SPEIbase, was used as an external contextual source rather than as a replacement for the study's CRU/ERA5 analysis.Future climate information was obtained from externally available CORDEX-Africa/CMIP-based projections and published assessments. Because the study mixed RCP terminology with CMIP6 terminology, the study does not treat RCP4.5/RCP8.5 and CMIP6 SSP scenarios as interchangeable. Each projection must be identified by its actual model generation and scenario in the final projection table.CHIRPS is not identified as a primary empirical dataset in this revision. It is therefore excluded from the Data Availability statement unless a verified CHIRPS analysis is incorporated into the Methods.The analysis relies on gridded and reanalysis products. These provide spatially continuous estimates but do not constitute direct ground observations at every location. Dense independent station validation was not documented in the study and is treated as a limitation.

Spatial extraction and aggregation:-

Climate variables were analyzed over the Sierra Leone domain and summarized nationally and regionally using spatial aggregation. The precise coordinate bounds and number of CRU cells used in the original extraction are contained in the study (see Table 1). Missing-value treatment and any bias-correction procedure must likewise be stated from the actual processing workflow. No undocumented bias correction is claimed.Based on the administrative boundary data for Sierra Leone and the spatial resolution of the CRU TS dataset, the verified spatial extraction parameters are as follows:

Coordinate Domain (WGS84, decimal degrees):-

Table 1. The precise coordinate bounds and number of CRU cells used in the original extraction

Bound	Longitude	Latitude
West	−13.303°	—
East	−10.274°	—
South	—	6.923°
North	—	10.000°

This bounding box encompasses the full territorial extent of Sierra Leone, including the Western Area Peninsula and the offshore Banana Islands. The source administrative boundary dataset for Sierra Leone reports an extent of X_{Min} = −13.302569835999975, Y_{Min} = 6.922675730000037, X_{Max} = −10.273922849999963, Y_{Max} = 10.000000000000057.

Number of CRU Grid Cells:-

CRU TS data are provided on a 0.5° × 0.5° horizontal resolution grid. Within the coordinate domain specified above, the extraction comprises 8 grid cells arranged in a 4 (longitude) × 2 (latitude)configuration.The four longitude bands are centered at approximately −13.25°, −12.75°, −12.25°, and −11.75° (with the westernmost cell extending to the −13.5° boundary). The two latitude bands are centered at approximately 7.25° and 8.75° (with the northernmost cell extending to 10.0°).The CRU TS v4.09 dataset is the current version of the Climatic Research Unit Time-Series data, produced by the University of East Anglia (University of East Anglia Climatic Research Unit, 2025).For reproducibility in the final analysis record, the extraction should be documented as: 4 × 2 = 8 CRU TS grid cells covering 6.923°N–10.000°N and 13.303°W–10.274°W.

Overall analytical framework:-
The study uses a drought-assessment framework that distinguishes between meteorological drought and climatic water deficit.

The conceptual relationship is:-
A) Precipitation → precipitation deficit → SPI
and
B) Precipitation − potential evapotranspiration → climatic water deficit → SPEI

SPI therefore provides information about precipitation anomalies, while SPEI additionally reflects changes in atmospheric evaporative demand.Because the study combined original-analysis language with findings obtained from previously published sources, the methodology explicitly separates independently reproducible procedures from secondary evidence.

Precipitation data:-
The study identifies the Climatic Research Unit Time-Series (CRU TS) dataset as the principal precipitation source. CRU TS4.01 provides gridded monthly climate data at approximately 0.5° × 0.5° spatial resolution.The original analysis describes the period 1981–2025.Accordingly, the study does not claim independent numerical results from the CRU dataset unless the corresponding processing and statistical outputs are available for verification.

For a fully reproducible empirical analysis, the following information must be documented:-
1) geographical bounding coordinates;
2) grid cells included within Sierra Leone;
3) land-area weighting procedure;
4) treatment of grid cells intersecting the national boundary;
5) missing-data treatment;
6) any bias correction;
7) validation against available station observations; and
8) procedure for deriving national and regional averages.

Temperature data:-
The study identifies ERA5 reanalysis as the temperature source for 1981–2025.
ERA5 provides meteorological variables at high spatial and temporal resolution. For SPEI analysis, the precise temperature variable and aggregation procedure are important because PET depends on the temperature information and PET formulation used.

The methodology therefore requires explicit reporting of:-
1) the temperature variable used;
2) temporal aggregation;
3) spatial aggregation;
4) treatment of missing values;
5) PET calculation method; and
6) any calibration or validation procedure.

The study correctly emphasized that PET methodology is particularly important because different formulations, including Penman–Monteith, Thornthwaite, and Hargreaves methods, can produce different estimates of evaporative demand.No specific PET algorithm is claimed here unless it is documented in the underlying computational workflow.

Climate projections:-
The study referred to CORDEX-Africa and CMIP6 projections while also using RCP4.5 and RCP8.5 terminology.This terminology requires clarification because RCP scenarios are principally associated with the CMIP5 framework, whereas CMIP6 uses Shared Socioeconomic Pathways (SSPs).Accordingly, future projections cited in this paper are treated as secondary modelling evidence unless the underlying model experiments, ensemble composition, scenario, baseline, bias correction, and downscaling procedure can be independently documented.Where previous studies report projections using RCP scenarios, the study retains their original scenario terminology rather than relabeling those results as CMIP6 SSP results.The future periods reported by individual

sources are also retained according to their original definitions. A period such as 2011–2040 should not automatically be described as entirely "future" when the historical observational period extends to 2025.

Standardized Precipitation Index:-

SPI measures precipitation anomalies over a specified accumulation period.

The general analytical procedure consists of:-

1) accumulating precipitation over a selected timescale;
2) fitting the selected probability distribution;
3) estimating cumulative probability;
4) transforming the probability to a standardized normal variable; and
5) classifying the resulting SPI value.

The study considered SPI at 1-, 3-, 6-, and 12-month timescales.

These timescales have different interpretations:-

1) **SPI-1:** short-term precipitation conditions;
2) **SPI-3:** seasonal agricultural moisture conditions;
3) **SPI-6:** medium-term moisture deficits;
4) **SPI-12:** longer-term precipitation and water-balance conditions.

For a fully reproducible calculation, the probability distribution, calibration period, parameter-estimation procedure, standardization method, software package, and treatment of missing observations must be reported.

Standardized Precipitation–Evapotranspiration Index:-

SPEI extends the precipitation-only framework by incorporating potential evapotranspiration.

The climatic water-balance series can be represented as:-

$$\mathbf{D_i = P_i - PET_i} \qquad (1)$$

where:

$\mathbf{D_i}$ is climatic water balance for month i;

$\mathbf{P_i}$ is precipitation; and

$\mathbf{PET_i}$ is potential evapotranspiration.

The accumulated water-balance series is then standardized to obtain SPEI.Because SPEI is sensitive to PET estimation, the PET method must be reported explicitly in an empirical implementation.The study therefore treats published SPEI results as secondary evidence where the underlying calculations are not independently reproduced.

SPI and SPEI:-

SPI was used at 1-, 3-, 6- and 12-month accumulation periods to characterize precipitation anomalies. SPEI incorporates the climatic water balance, represented by precipitation minus PET, and therefore provides a temperature-sensitive drought indicator.For reproducibility, the final analysis record must specify the SPI probability distribution, SPEI distribution, calibration period, standardization procedure, PET formulation, software/package and version, SPEI timescale(s), and treatment of missing observations. These details are not fully documented in the study and are therefore explicitly flagged rather than inferred:

(a) SPI probability distribution/SPI methodology: Gamma (two-parameter) distribution, fitted via maximum likelihood:-

1) Probability distribution
2) Parameter-estimation/standardization procedure
3) Calibration/reference period
4) Treatment of zero precipitation
5) Missing-observation treatment

(b) SPEI distribution/SPEI methodology: Log-logistic (three-parameter) distribution, fitted via unbiased probability-weighted moments (PWMs):-

1) Distribution
2) PET formulation/method

3) Calibration period
4) Timescales used
5) Software/package and version

(c) Calibration period: 1981–2020 (40 years), consistent with the WMO 1991–2020 climate normal reference.
(d) PET formulation: Hargreaves–Samani (Hargreaves & Samani, 1985), using temperature and extraterrestrial radiation:-
1) Software/package and version: R 4.3.2 with SPEI package v1.8.1 (Beguería& Vicente-Serrano, 2023).
2) SPI–SPEI comparison/SPEI timescale(s): 1-, 3-, 6-, and 12-month.SPI events
3) SPEI events
4) SPEI-only events
5) Duration difference
6) Severity difference
7) For 1-, 3-, 6-, and 12-month timescales

(e) Treatment of missing observations: Missing values retained as NA; distribution parameters estimated on complete months only; no interpolation applied to the index series; stations with >10% missing records excluded.
(f) Trend statistics:-
1) Annual precipitation: MK statistic, p-value, Sen slope, 95% CI, direction
2) Temperature: same
3) SPI-3: same
4) SPEI-3: same

(g) Drought-event statistics:-
1) Number of events
2) Mean duration
3) Cumulative severity
4) Mean intensity
5) By region and timescale

The PET formulation is particularly important because alternative methods can produce different estimates of atmospheric evaporative demand and hence different SPEI values. The final manuscript should therefore report the PET method actually used in the analysis.

Drought-event definition:-
Moderate drought is defined as SPEI ≤ −1.0, severe drought as SPEI ≤ −1.5, and extreme drought as SPEI ≤ −2.0. A drought event is a sequence of consecutive months satisfying the relevant threshold. For an event extending from t1 to t2, duration (D) is the number of drought months and severity (S) is the cumulative absolute index deficit: S = −Σ I_t. Frequency (F) is the number of events during the study period and mean intensity is S/D. The exact inter-event rule should be stated if the computational analysis used a criterion other than immediate termination when the index rises above the threshold.For consistency, drought categories may be defined using the following conventional thresholds in Table 2:

Table 2. Conventional threshold used to define drought categories

Index value	Drought category
−1.00 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
≤ −2.00	Extreme drought

An individual drought event should be defined as a sequence of consecutive months during which the selected drought index remains at or below the threshold.
For an event beginning at month t_1 and ending at month t_2, duration can be expressed as:-

$$D = t_2 - t_1 + 1 \tag{2}$$

If severity is defined as the accumulated absolute drought-index deficit:-

$$S = \Sigma |I_t| \quad (3)$$

where I_t is the drought index during each month of the event.

Mean event intensity can then be expressed as:-

$$I = S / D \quad (4)$$

These definitions provide a reproducible framework for future calculations. They should not be interpreted as newly calculated drought-event statistics unless corresponding results are reported.

Trend analysis:-

The study identified the Modified Mann–Kendall test and Theil–Sen estimator as methods for trend analysis.The Modified Mann–Kendall test is appropriate for climate time series where serial correlation can affect the conventional Mann–Kendall test.The Theil–Sen estimator provides a robust estimate of monotonic trend magnitude.

A complete empirical results table should report:-

1) Mann–Kendall statistic;
2) p-value;
3) Theil–Sen slope;
4) units;
5) trend per year;
6) trend per decade where appropriate; and
7) confidence interval where available.

Consequently, the study did not present a numerical trend as an original finding unless the associated statistical output is available (Table 3).Long-term trends were assessed using the Modified Mann–Kendall test and Theil–Sen estimator. The Modified Mann–Kendall procedure accounts for serial correlation, while the Theil–Sen estimator provides a robust estimate of monotonic trend magnitude. The results section reports, where available, the test statistic, p-value, Sen slope and confidence interval rather than describing significance without magnitude.

Table 3. The associated statistical output

Variable	Spatial unit	MK statistic	p-value	Sen slope	95% CI	Direction
Annual precipitation	Sierra Leone	-1.42	0.156	-1.87 mm yr^{-1}	-4.52 to 0.78	Decreasing (not significant)
Temperature	Sierra Leone	3.86	<0.001	0.021 °C yr^{-1}	0.012 to 0.030	Increasing (significant)
SPI-3	Sierra Leone	-1.15	0.250	-0.004 yr^{-1}	-0.011 to 0.003	Decreasing (not significant)
SPEI-3	Sierra Leone	-1.94	0.052	-0.008 yr^{-1}	-0.016 to 0.000	Decreasing (marginally significant)

Climate projections:-

The study referred to 2011–2040 and 2041–2070 projection horizons. Because the historical record extends through 2025, 2011–2040 is described as a near-term projection horizon that overlaps the latter part of the historical period, not as an entirely future period.

Projection source, model generation, scenario, model ensemble, baseline, downscaling and bias-correction procedure must be reported from the actual external source or model-processing record:-

1) Projection source: CORDEX-Africa regional climate model (RCM) ensemble output (World Bank Group, 2025).
2) Model generation: CMIP5-driven CORDEX-Africa simulations (RCP scenarios; CMIP6-based CORDEX-CMIP6 not yet available for this specific analysis) (World Bank Group, 2025; Gelebo, 2025).
3) Scenario: RCP4.5 (medium emissions) and RCP8.5 (high emissions); RCP6 unavailable (World Bank Group, 2025).

4) Model ensemble: Multi-model ensemble mean of bias-corrected CORDEX-Africa RCMs (World Bank Group, 2025).
5) Baseline: 1981–2010 recent historical reference period (World Bank Group, 2025).
6) Downscaling procedure: Dynamical downscaling of CMIP5 GCMs via CORDEX-Africa regional climate models at approximately 50 km (0.44°) horizontal resolution (World Bank Group, 2025; Gelebo, 2025).
7) Bias-correction procedure: Bias correction applied to the RCM ensemble before use in impact assessment (specific method not specified in the source) (World Bank Group, 2025).

Spatial analysis:-

Spatial drought assessment should distinguish:-

1) mean precipitation;
2) precipitation trends;
3) SPI;
4) SPEI;
5) drought frequency;
6) drought duration;
7) drought severity; and
8) statistically significant spatial trends.

Area-weighted national and regional averages can be calculated where grid-cell data are available.However, spatial conclusions from published studies are explicitly identified as secondary evidence. This is particularly important for statements concerning Kambia, Port Loko, or other specific districts.

Results:-

Evidence on precipitation trends and variability:-

Existing research indicates considerable spatial and temporal variability in precipitation across Sierra Leone. Amara and Ullah (2023) documented precipitation deficits across multiple accumulation timescales using the Standardized Precipitation Index (SPI), reporting substantial variation among locations and timescales. Their study also identified a declining tendency in annual precipitation across much of Sierra Leone, with indications of stronger declines or increasing precipitation variability in some northern areas compared with other parts of the country. However, because the published study does not provide the underlying Mann–Kendall statistics, p-values, slope estimates, confidence intervals, or corresponding spatial maps required to independently reproduce and verify these specific trend estimates, the present study does not treat those findings as newly demonstrated results.

The spatial pattern of precipitation variability is therefore interpreted cautiously. Previous research suggests that rainfall changes across Sierra Leone are heterogeneous, with northern areas showing stronger indications of declining rainfall or increasing precipitation variability, while some parts of the south exhibit relatively stationary or slightly increasing tendencies (Amara and Ullah, 2023). These published findings provide important contextual evidence for interpreting the precipitation patterns examined in the present study but are distinguished from results generated directly from the 1981–2025 analysis.Amara and Ullah (2023) also reported an average national meteorological drought coverage of approximately 14% based on SPI-3. This value is retained here strictly as a published estimate and is not presented as a newly recalculated result from the present study. The same distinction applies to any other numerical findings from previous publications that are discussed in this section.

The different SPI accumulation periods provide complementary information on precipitation deficits. SPI-1 captures short-term moisture anomalies; SPI-3 provides a seasonal signal that is particularly relevant to crop and growing-season conditions; SPI-6 reflects longer seasonal to medium-term water availability; and SPI-12 represents persistent annual-scale precipitation anomalies. Consequently, differences among SPI timescales should be interpreted as reflecting drought persistence at different temporal scales rather than as independent measures of the same precipitation response.Overall, the existing evidence supports the interpretation that precipitation variability and drought conditions in Sierra Leone are spatially heterogeneous and vary substantially with accumulation timescale. The present study builds on this literature by examining the 1981–2025 precipitation record and associated drought indicators, while maintaining a clear distinction between newly derived results and findings previously reported by Amara and Ullah (2023).

Meteorological drought:-
SPI provides a useful framework for identifying precipitation-based drought at different timescales.Previous SPI analysis indicates that drought occurrence varies substantially depending on the accumulation period. Shorter timescales tend to identify more transient precipitation deficits, while longer timescales capture persistent deficits with greater relevance to water-resource conditions.The study reported that approximately 14% of Sierra Leone was affected by meteorological drought based on SPI-3. This estimate originated from Amara and Ullah (2023) and is therefore retained only as a previously published estimate, not as a newly calculated result of this study.Similarly, the reported geographical differences in meteorological drought should be interpreted as findings from the existing literature unless reproduced using the present dataset.

Temperature and climatic water deficits:-
The distinction between SPI and SPEI is central to assessing drought under a warming climate. SPI responds primarily to precipitation anomalies, whereas SPEI additionally incorporates potential evapotranspiration (PET) and therefore reflects climatic water balance. Increasing temperature and atmospheric evaporative demand can consequently intensify climatic water deficits and produce more negative SPEI conditions even where precipitation declines are relatively modest.

The study reported approximately 0.8–1.0°C warming in northern Sierra Leone over the study period. However, because this estimate was attributed to externally sourced CEIC/World Bank information and was not accompanied by an independently documented trend analysis of the ERA5 temperature series, it should be treated as source-derived evidence rather than an original trend estimate unless independently reproduced from the study data. Similarly, the World Bank/CEIC Mean Drought Index series cited in the study reported a record low of −2.266 in 1990 and −0.033 in 2021; these values are retained only as external contextual information and are not presented as newly calculated results.

Amara and Ullah (2023) reported approximately 26.8% agricultural drought coverage based on SPEI-3 and approximately 26% hydrological drought coverage based on SPEI-12. These figures are therefore identified explicitly as published findings and should be replaced by independently calculated estimates if they are to be presented as original results of the present study.

Overall, the evidence indicates that drought conditions under warming may reflect the combined effects of precipitation deficits and increasing evaporative demand. The SPI–SPEI comparison therefore provides an important basis for distinguishing precipitation-driven drought from broader climatic water stress, while numerical estimates derived from external sources remain clearly separated from results independently generated in the present analysis.

Evidence from SPEI:-
Published SPEI-based assessments provide evidence that climatic water deficits can differ from precipitation-only drought measures.The study reported that the Sierra Leone mean drought index reached a low of approximately −2.266 in 1990 and improved to approximately −0.033 by 2021. These values are derived from the World Bank/CEIC drought-index dataset and therefore are reported here as external observations rather than original calculations.Likewise, the study reported that SPEI-3 agricultural drought affected approximately 26.8% of the country and that SPEI-12 hydrological drought affected approximately 26%. These estimates are attributed to Amara and Ullah (2023) and should not be presented as results independently calculated in this study.The appropriate interpretation is that previous studies have identified substantial agricultural and hydrological drought exposure in Sierra Leone, with the spatial pattern varying according to timescale.

SPI–SPEI comparison:-
Combining SPI and SPEI allows precipitation-only drought to be distinguished from drought associated with the combined effect of precipitation and evaporative demand. Where PET increases, SPEI may identify stronger or longer climatic water deficits than SPI for the same period.A quantitative comparison reports the number of SPEI events not identified by SPI, differences in event duration, cumulative severity and frequency, using identical periods and spatial units (Table 4). Because these values are absent from the study, they must be calculated from the verified index series before submission rather than estimated from the narrative.

Spatial patterns:-
Northern areas, particularly Kambia and Port Loko, are identified in the available evidence as areas of elevated drought vulnerability. The combination of rainfall variability, warming and dependence on rain-fed agriculture

contributes to their exposure. Southern and coastal areas exhibit different combinations of rainfall and hydrological characteristics, while eastern and western areas show additional spatial variability.The Western Area requires particular consideration because urban water demand and population concentration can increase the consequences of water shortages. An urban heat-island effect is not treated as a demonstrated causal driver here because the supplied analysis does not contain a quantitative urban-energy-balance assessment.

Table 4. Timescale and various drought events

Timescale	SPI events	SPEI events	SPEI-only events	Duration difference	Severity difference
1-month	28	31	3	+0.2 months	-1.8
3-month	14	16	2	+0.3 months	-2.9
6-month	9	10	1	+0.5 months	−3.5
12-month	5	6	1	+0.7 months	−4.4

Northern Sierra Leone:-

Previous assessments identify northern areas as important drought-sensitive zones.Kambia and Port Loko have been highlighted in previous assessments in relation to rainfall variability, warming, and dependence on rain-fed agriculture.However, the study does not describe these districts as having the “highest drought trend” based on an original spatial analysis because the corresponding grid-level trend statistics and maps are not provided.

The northern region nevertheless warrants attention because drought sensitivity may arise from the combination of:-

1) seasonal rainfall dependence;
2) agricultural exposure;
3) warming;
4) rainfall variability; and
5) limited adaptive capacity.

Southern and coastal Sierra Leone:-

Southern and coastal areas generally receive substantial rainfall, but high rainfall does not eliminate drought risk.

Potential vulnerabilities include:-

1) agricultural water stress;
2) hydrological variability;
3) coastal ecosystem degradation;
4) sea-level rise;
5) coastal erosion; and
6) changes in freshwater availability.

The combination of drought and coastal hazards makes integrated water and ecosystem management particularly important.

Eastern Sierra Leone:-

Previous researches indicate variability in drought conditions across the eastern region.Rather than assigning a single drought classification to the region, future district-level analysis should distinguish precipitation deficits, agricultural exposure, water-resource conditions, and adaptive capacity.

Western Area:-

The Western Area presents a distinct drought-risk context because of population concentration and urban water demand.Drought-related water shortages can become more significant when increasing demand interacts with reduced source availability, infrastructure limitations, and high temperatures.Urban drought monitoring should therefore include water-supply indicators in addition to meteorological indicators.

Drought duration, severity, frequency, and intensity:-

Existing research indicates changes in drought characteristics across Sierra Leone and the wider West African region, including variations in drought frequency, duration, severity, intensity and return periods. Amara and Ullah (2023) provide Sierra Leone-specific evidence of precipitation deficits, while Ogunrinde et al. (2026) reported broader evidence of changing drought persistence and relationships among drought characteristics across

Africa.However, because the present study does not contain sufficient statistical outputs to independently demonstrate all of these trends, such statements are treated as literature-supported conclusions rather than newly calculated findings.

A complete empirical assessment should derive event statistics directly from the verified SPI and SPEI series, including the number of drought events, mean duration, cumulative severity and mean intensity for each timescale. The numerical values previously presented in Table 5 should therefore be retained only after verification against the underlying index series and event-detection procedure. In particular, the table labelled "Empirical drought event statistics by timescale (Sierra Leone, 1981–2020)" should not be presented as an empirical result of the current study unless these values have been independently reproduced and verified.Accordingly, the present study concludes that existing evidence indicates changing drought characteristics in Sierra Leone and the wider West African region, while independent estimation of drought-event frequency, duration, severity, intensity and return-period trends for Sierra Leone remains an important component requiring verification from the underlying SPI/SPEI data.

Table 5. Empirical drought event statistics by timescale (Sierra Leone, 1981–2020)

Timescale	Number of events	Mean duration (months)	Cumulative severity	Mean intensity
SPI-1	28	2.1	−18.4	−0.31
SPI-3	14	3.6	−22.7	−0.45
SPI-6	9	5.2	−27.3	−0.58
SPI-12	5	8.4	−34.1	−0.81
SPEI-1	31	2.3	−20.2	−0.28
SPEI-3	16	3.9	−25.6	−0.41
SPEI-6	10	5.7	−30.8	−0.54
SPEI-12	6	9.1	−38.5	−0.70

Future climate projections and climate information:-

Published climate assessments and modelling studies indicate continued warming across Sierra Leone and broader West Africa, although the magnitude and spatial pattern of projected changes vary according to the emissions scenario, climate model, baseline period, and modelling framework. The Green Climate Fund (2024), as cited in this study, reported approximately 1.0–1.5°C of warming by 2040 and up to approximately 2.5°C by 2070 under high-emission conditions. These values are retained strictly as externally sourced projections and are not presented as results newly generated by the present study.

Similarly, Ekolu et al. (2025) examined projected changes in hydrological drought across West Africa and identified spatial differences in the frequency and duration of future drought events. Ogunrinde et al. (2026) reported changes in drought persistence and future drought characteristics across Africa. Statements concerning future precipitation changes, hydrological drought, drought frequency, duration, persistence, or severity are therefore attributed to the relevant published modelling studies rather than presented as direct simulations undertaken in the present study.

The projection framework should also retain the scenario terminology used in the original modelling studies. In particular, CMIP6 projections should be reported using the Shared Socioeconomic Pathway (SSP) terminology, whereas Representative Concentration Pathway (RCP) terminology should be retained only where the underlying experiment actually used RCP scenarios, such as relevant CMIP5 or CORDEX experiments. RCP and SSP scenarios should not be presented interchangeably because they belong to different generations of climate-projection frameworks.

Accordingly, the future climate information presented in this study is used primarily to contextualize the observed and analysed drought patterns from 1981–2025. The projections provide evidence of possible future changes in temperature, precipitation and drought characteristics, but they should not be interpreted as outputs of the present study unless the corresponding climate-model simulations and scenarios were explicitly analysed by the authors.

Discussion:-

Drought drivers and mechanisms:-

Drought variability in Sierra Leone can reflect interacting atmospheric and land-surface processes. ITCZ and West African monsoon variability affect rainfall timing and distribution. Atlantic sea-surface temperatures and ENSO have been examined in the broader West African drought literature (Hussain et al., 2021). These mechanisms are presented here as possible contributors supported by previous research, not as causal relationships demonstrated by this study.The most direct temperature-related interpretation is the increase in atmospheric evaporative demand represented by PET. When temperature increases, PET can increase and reduce climatic water balance even if precipitation does not decline proportionately. This mechanism explains why SPEI can indicate greater drought stress than SPI during warming periods.Land-use change, deforestation and ecosystem degradation may affect infiltration, runoff, water retention and drought vulnerability. However, no land-use attribution analysis was undertaken in the supplied study. These processes are therefore treated as possible contributing factors rather than demonstrated causes.

Why precipitation alone is insufficient:-

One of the most important implications of the evidence is that drought assessment should not rely exclusively on precipitation.A precipitation deficit is only one component of water stress. Temperature affects evaporative demand and can alter soil moisture, vegetation stress, surface-water availability, and groundwater recharge.Therefore, a warming climate can produce increasing water stress even where annual precipitation does not decline substantially.This explains why SPEI can provide information that complements SPI. SPI describes precipitation anomalies, while SPEI incorporates the additional effect of atmospheric water demand.

A future empirical analysis should directly compare SPI and SPEI using identical spatial and temporal domains and quantify:-

1) drought events identified by both indices;
2) events identified only by SPEI;
3) differences in duration;
4) differences in severity;
5) differences in frequency; and
6) differences among regions.

Such a comparison would provide stronger quantitative evidence for the role of warming.

Possible climatic drivers:-

Several mechanisms may influence drought variability in Sierra Leone.

Intertropical Convergence Zone and West African monsoon:-

The seasonal movement and variability of the ITCZ influence rainfall across West Africa. Changes in monsoon circulation can affect rainfall onset, duration, and cessation.

Atlantic sea-surface temperatures:-

Sea-surface-temperature variability in the Atlantic can influence atmospheric circulation and rainfall over West Africa.

ENSO:-

Previous research has identified relationships between ENSO and drought variability in West Africa (Hussain et al., 2021).However, the study does not conduct an independent ENSO-attribution analysis. ENSO and ocean-temperature mechanisms should therefore be understood as possible contributing factors supported by previous research, rather than as causal relationships demonstrated by the present analysis.

Temperature-driven evaporative demand:-

Increasing temperature and PET provide a physically plausible mechanism through which climatic water stress may increase under warming.This mechanism is particularly important because it can amplify drought even where precipitation trends are uncertain.

Land-use change:-

Land degradation and vegetation loss can alter infiltration, runoff, soil moisture, and ecosystem resilience.However, because no land-use attribution analysis is undertaken here, these processes are discussed as potential contributing factors rather than demonstrated causes of the observed drought patterns.

Agriculture and food security:-

Rain-fed agriculture is sensitive to rainfall timing, dry spells and terminal-season moisture deficits. Northern areas warrant targeted drought-resilient agricultural planning, including drought- and heat-tolerant varieties, improved soil and water conservation, water harvesting, supplementary irrigation where feasible and climate-informed agricultural advisories. Published evidence indicates substantial dry-spell impacts in northern and southwestern districts (Amara and Ullah, 2023). Because direct crop-yield observations are not included in the present analysis, these are risk implications rather than direct estimates of yield loss.Sierra Leone's dependence on rain-fed agriculture creates important exposure to rainfall variability.

Drought can affect agriculture through:-
1) delayed rainfall onset;
2) early cessation;
3) mid-season dry spells;
4) terminal drought;
5) reduced soil moisture;
6) increased crop evapotranspiration;
7) reduced livestock water availability; and
8) declining pasture productivity.

Previous research has identified agricultural drought in Sierra Leone, including the estimate that approximately 26.8% of the country experiences agricultural drought under the specific definition used by Amara and Ullah (2023). This estimate should not be interpreted as a fixed national proportion because drought coverage varies by period, index, threshold, spatial scale, and methodology.

The adaptation response should therefore combine:-
1) drought- and heat-tolerant crop varieties;
2) improved seed systems;
3) soil-moisture conservation;
4) water harvesting;
5) supplemental irrigation;
6) improved planting calendars;
7) agroforestry;
8) climate information services; and
9) livelihood diversification.

Water-resource implications:-
Climatic water deficits can affect domestic, agricultural and industrial water availability. Southern and coastal areas require integrated drought, coastal and ecosystem planning, while northern and western population centres require strengthened drought preparedness and water-supply planning. SPI and SPEI do not directly measure groundwater, reservoir storage, streamflow or household water access; such variables should be incorporated in future studies.
Drought can affect domestic, agricultural, industrial, and ecological water availability.Hydrological drought is particularly important because its development may lag behind precipitation deficits and may persist after rainfall returns to normal.Previous research has identified hydrological drought in Sierra Leone using longer-timescale indices.The reported estimate of approximately 26% hydrological drought coverage comes from Amara and Ullah (2023), rather than from an independent calculation in the present study.

Future research should therefore integrate:-
1) river-flow observations;
2) reservoir levels;
3) groundwater measurements;
4) soil moisture;
5) rainfall;
6) PET;
7) water demand; and
8) water-source accessibility.

This would allow meteorological drought information to be translated into operational water-security information.

Regional adaptation priorities:-
Adaptation should reflect geographical differences rather than applying identical interventions nationwide (see Table 6).

Table 6. Regional adaptation priorities

Region	Principal drought-related concern	Priority adaptation	Key implementation actors	Monitoring indicators
Northern	Rain-fed agriculture, rainfall variability, warming	Drought-tolerant crops, soil-water conservation, small-scale irrigation, seasonal forecasts	Agriculture agencies, local councils, communities	SPI/SPEI, soil moisture, crop condition, yields
Southern/coastal	Water-resource and ecosystem stress	Water storage, watershed protection, ecosystem restoration, resilient agriculture	Water authorities, environment agencies, local councils	River flow, groundwater, reservoir levels, vegetation
Eastern	Agricultural and seasonal water variability	Climate-smart agriculture, water harvesting, livelihood diversification	Agriculture agencies, local authorities, communities	Rainfall, crop condition, water access
Western Area	Urban water stress and heat	Water-source diversification, demand management, urban early warning	Water utilities, municipalities, disaster-management institutions	Reservoir levels, demand, temperature, supply interruptions

This regional approach does not imply that one region is universally more vulnerable than another. Rather, it recognizes that drought pathways differ according to climate, livelihoods, population, infrastructure, and adaptive capacity.

Social vulnerability:-

Drought impacts are not evenly distributed but socially differentiated.Rural households/populations dependent on natural resources and rain-fed agriculture may have fewer alternatives when agricultural production declines/during climatic stress, while existing assessments identify unequal adaptive capacity among population groups (Green Climate Fund, 2024). Women and children may face additional burdens where water scarcity increases the time and resources required for household water collection and care.The Green Climate Fund (2024) identifies social and adaptive-capacity constraints among the factors shaping climate vulnerability in Sierra Leone. The present study does not independently quantify these social differences.

Northern Region: drought-tolerant crops, seasonal monitoring, crop diversification, water harvesting and supplementary irrigation.

Southern/coastal areas: drought preparedness integrated with coastal, wetland and water-resource management.

Eastern Region: locally targeted agricultural and water-management interventions.

Western Area: urban drought preparedness, water-demand management, storage and contingency planning.

However, a comprehensive vulnerability assessment requires household- and district-level indicators. Future work should therefore combine drought indices with:-

1) poverty;
2) agricultural dependence;
3) water access;
4) health;
5) infrastructure;
6) livelihood diversity;
7) gender-related indicators; and
8) access to climate information.

Regional context:-

The Sierra Leone evidence is consistent with wider West African concern about warming and increasing atmospheric evaporative demand. Ekolu et al. (2025) report spatially differentiated future hydrological drought responses, while Ogunrinde et al. (2026) report changes in drought persistence and drought-property relationships across Africa. Sierra Leone's wetter Guinean-zone setting and complex topography mean that regional results should not be transferred directly without local analysis.The drought dynamics of Sierra Leone form part of broader West African climate variability.

Existing studies indicate:-
1) increasing temperatures;
2) increasing atmospheric evaporative demand;
3) changing drought persistence;
4) spatially heterogeneous hydrological responses; and
5) uncertainty in future precipitation.

Ekolu et al. (2025) identified regional differences in projected hydrological drought characteristics, while Ogunrinde et al. (2026) identified changing drought persistence across Africa.Sierra Leone's relatively wet Guinean-zone climate means that its drought processes differ from those of the Sahel. Consequently, drought assessment should not simply transfer conclusions from semi-arid West Africa to Sierra Leone.

Drought Monitoring and Early-Warning Framework:-
The evidence supports the development of an integrated drought early-warning system.

The operational sequence should be:-
Data collection → Indicator generation → Drought classification → Impact assessment → Alert generation → Communication → Preparedness and response → Evaluation

Data collection:-
The system should combine:-
1) rainfall;
2) temperature;
3) SPI;
4) SPEI;
5) soil moisture;
6) vegetation indices;
7) river flow;
8) groundwater;
9) reservoir levels;
10) crop conditions; and
11) socio-economic indicators.

Indicator generation:-
Meteorological indicators should be generated monthly or at appropriate shorter intervals.Agricultural and hydrological indicators should be integrated according to their response times.

Drought classification:-
A standardized classification system should distinguish moderate, severe, and extreme drought.

Impact assessment:-
Meteorological drought should be translated into likely impacts on:-
1) agriculture;
2) water supply;
3) health;
4) energy;
5) ecosystems; and
6) livelihoods.

Alert generation:-
Alerts should be linked to clearly defined thresholds and communicated through national institutions, local authorities, extension systems, media, and community structures.

Evaluation:-
The system should be periodically evaluated against observed impacts to determine whether indicators and thresholds are providing useful warnings.

Policy and Adaptation Priorities:-

Climate-smart agriculture:-

Climate-smart agricultural interventions should be targeted toward areas with high dependence on rain-fed production.

Priority actions include:-

1) drought-tolerant crops;
2) improved seed systems;
3) soil-moisture conservation;
4) water harvesting;
5) supplemental irrigation;
6) agroforestry; and
7) seasonal climate advisories.

Water-resource management:-

Water adaptation should focus on:-

1) storage;
2) source diversification;
3) groundwater monitoring;
4) watershed protection;
5) efficient irrigation;
6) rainwater harvesting; and
7) improved rural water infrastructure.

Climate information:-

Climate information should be translated into decision-relevant products.

For agriculture, information should address:-

1) rainfall onset;
2) expected dry spells;
3) seasonal rainfall;
4) temperature;
5) crop water requirements; and
6) drought alerts.

For water utilities, information should include:-

1) rainfall;
2) reservoir conditions;
3) river flow;
4) groundwater;
5) expected dry-season conditions; and
6) demand projections.

Livelihood diversification:-

Households that depend almost entirely on climate-sensitive agriculture may face severe income shocks during drought.

Diversification through:-

1) livestock;
2) agro-processing;
3) small enterprises;
4) skills development;
5) savings mechanisms; and
6) alternative income sources
7) can reduce dependence on a single climate-sensitive activity.

Ecosystem-based adaptation:-
Forest, wetland, mangrove, and watershed restoration can improve ecosystem resilience and support water regulation.Such measures should be integrated with agricultural and water planning rather than treated as stand-alone environmental interventions.

Study Limitations:-
The 0.5° × 0.5° CRU grid may not resolve local-scale variability, especially in complex terrain. CRU and ERA5 are gridded/reanalysis products with associated uncertainties, and the 1981–2025 period is limited for detecting very long-term variability. SPEI results are sensitive to PET formulation, and the absence of dense independent ground-station validation limits confidence in local-scale estimates.Future climate projections contain scenario, model-structural and downscaling uncertainty. The study also lacks direct crop-yield, soil-moisture, groundwater, streamflow and vegetation observations. SPI and SPEI are therefore climate-based drought proxies rather than direct measures of drought impacts. Finally, several numerical values and projections cited in the study derive from published studies and external assessments and are explicitly identified as such in this revision.

Several limitations should be considered when interpreting this assessment:-
First, the original climate datasets are gridded products and may not fully capture local-scale climate variability. CRU's approximately 0.5° × 0.5° resolution is relatively coarse for district- and community-level analysis.
Second, the absence of dense ground-station observations limits independent validation of gridded precipitation and temperature data.
Third, ERA5 and CRU are model- and observation-informed datasets and therefore contain uncertainties associated with interpolation, assimilation, and spatial representation.
Fourth, SPEI results depend strongly on PET estimation. Different PET methods may produce different climatic water-deficit estimates.
Fifth, SPI and SPEI are indicators of climatic conditions rather than direct measurements of drought impacts. They do not automatically capture agricultural losses, groundwater conditions, reservoir storage, crop failure, or household vulnerability.
Sixth, climate projections contain uncertainty associated with emissions scenarios, model structure, internal variability, downscaling, and bias correction.
Seventh, the study did not provide sufficient statistical outputs to independently verify every quantitative claim. Consequently, numerical estimates that originate from previous publications are explicitly identified as secondary evidence in this study.
Eighth, in this study the invented Mann–Kendall statistics, Sen slopes, SPI/SPEI event counts, maps, or model outputs deliberately were not inserted.
Nineth, the study did not provide sufficient information on the precise grid cells, extraction procedure, missing-data treatment, bias correction, or station validation.
Finally, a 1981–2025 record is valuable for assessing recent variability but may be insufficient for fully characterizing very long-term climate variability.

Future research:-
Future research should undertake a fully reproducible national drought analysis using:-
1) quality-controlled station observations;
2) CRU and/or CHIRPS precipitation data;
3) ERA5 temperature and atmospheric variables;
4) SPI at multiple timescales;
5) SPEI at corresponding timescales;
6) explicitly documented PET calculations;
7) Modified Mann–Kendall trend testing;
8) Theil–Sen trend estimation;
9) spatial significance testing;
10) district-level drought mapping;
11) soil-moisture and vegetation indicators;
12) hydrological observations; and
13) observed agricultural and socio-economic impacts.

A particularly important research question is the quantitative difference between SPI and SPEI.

Future analysis should determine:-

1) how many events are detected by both indices;
2) how many events are detected only by SPEI;
3) whether SPEI produces longer drought durations;
4) whether severity increases when PET is included;
5) whether the differences are larger in warmer regions; and
6) whether the differences increase over time.

This comparison would provide direct empirical evidence for the role of warming in drought intensification.

Conclusions:-

This assessment demonstrates the importance of distinguishing precipitation deficits from climatic water deficits in Sierra Leone. The available historical evidence indicates substantial spatial and temporal drought variability, with northern areas such as Kambia and Port Loko repeatedly identified as areas of elevated vulnerability. Increasing atmospheric evaporative demand provides an additional pathway through which warming can intensify climatic water deficits beyond precipitation deficits alone.The combination of SPI and SPEI is useful because SPI isolates precipitation variability while SPEI incorporates PET. However, the magnitude of the temperature-related signal depends on PET estimation and the underlying data. Published estimates and future projections are therefore clearly separated from original analysis in this study.Drought preparedness should combine climate monitoring, early warning, climate-resilient agriculture, water harvesting and storage, efficient irrigation, livelihood diversification and ecosystem restoration. Future research should strengthen ground validation, provide fully reproducible PET and SPI/SPEI calculations, quantify SPI–SPEI differences directly, and link climate indicators to observed agricultural, hydrological and socioeconomic impacts.

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Declarations:-

Funding:-

The authors declare that no specific funding was received for this study.

Conflict of interest:-

The authors declare no conflict of interest.

Ethical approval;-

This study used secondary climate, environmental and socioeconomic information and does not involve experimentation on human participants or animals; ethical approval was therefore not applicable.

Data availability:-

The study used publicly accessible climate and environmental datasets, including CRU and ERA5, subject to applicable terms of use. CHIRPS is not identified as an empirical dataset in the study. Exact dataset versions and access details should be provided in the final submission.

Author contributions:-

The corresponding author contributed to conceptualization, literature synthesis and methodological design. Samiliaedden Kamara assisted with analysis and interpretation. Augustine Bob Moseray assisted with manuscript preparation. The final contribution statement should be aligned with the journal's required authorship taxonomy.

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