



Climate Variability and Drought Trends in Pastoral and Agro-Pastoral Districts: Spatial-Temporal Perspectives in Guji and West Guji Zones

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Abstract

This study examines the spatial and temporal patterns of climate variability and drought trends in the Guji and West Guji zones of Ethiopia, focusing on their effects on pastoral and agro-pastoral communities. A mixed-methods, cross-sectional design was used, combining household surveys, key informant interviews, focus groups, and remote sensing. A multi-stage sampling method selected four districts per zone based on vulnerability to climate shocks, with 382 households sampled using Yamane's formula. Climate data, including rainfall and temperature, were obtained from Ethiopia's Meteorology Institute and complemented with satellite imagery (Landsat, Sentinel-2) analyzed via ArcGIS and ERDAS Imagine. Quantitative analysis involved calculating the coefficient of variation (CV), rainfall concentration index (PCI), and Standard Precipitation Index (SPI) to assess variability and drought severity across districts and seasons. Findings reveal high inter-annual rainfall variability ($CV > 50\%$), with eastern and southern areas experiencing more unpredictable rainfall, thus increasing drought risk. SPI results show recurrent severe drought episodes during autumn and spring, with some districts facing drought over 60% of the time. Spatial drought hotspots include Liban, Dugda Dava, and Saba Boru, indicating uneven vulnerability. Climate variability has caused water shortages, pasture degradation, and livestock mortality, severely affecting livelihoods. Drought frequency has increased over the past two decades, intensified by rising temperatures. The study emphasizes the need for district-specific adaptation strategies such as water harvesting, drought-resistant crops, and resilient pastoral practices. It advocates for integrated climate monitoring and community resilience programs to reduce risks and promote sustainable livelihoods in vulnerable districts.

Key words: Climate variability, drought trends, spatial-temporal analysis, pastoral communities.

Introduction

Climate variability is a complex phenomenon involving fluctuations in the average state and statistical properties of climate systems across various temporal and spatial scales. Unlike isolated weather events, climate variability encompasses persistent patterns and shifts that influence the overall climate regime of a region over extended periods (IPCC, 2014). These fluctuations manifest through changes in temperature, rainfall, wind patterns, and other climatic factors, often driven by natural phenomena such as El Niño and La Niña, as well as human activities like greenhouse gas emissions (IPCC, 2013). Understanding the significance of climate variability is essential, given its profound impacts on ecosystems, agriculture, water resources, and human livelihoods especially in vulnerable regions with limited adaptive capacity. It is important to recognize that these variations are not random but are part of broader climate trends that can have cumulative and long-term effects (Ebi, 2015).

Over the past century, observable and measurable changes have occurred in the global climate system. The most notable indicator is the rise in global mean temperature, which has increased by approximately 0.78°C from 1850 to 2012 (IPCC, 2013). Projections suggest that, if current emission trends persist, global temperatures could rise by an additional 1.5°C to 2°C by 2100 (IPCC, 2014). These warming trends are associated with melting ice caps and glaciers, rising sea levels, and shifts in weather patterns, leading to more frequent and intense extreme weather events. Such climate shifts threaten the stability of natural and human systems, challenging infrastructure, disrupting agricultural cycles, and threatening biodiversity. Addressing these issues requires urgent and coordinated global efforts to mitigate and adapt to ongoing climate changes.

The impacts of climate variability are particularly critical in the context of food security. Variations in temperature and precipitation directly influence agricultural productivity, water availability, and ecosystem health (Ebi, 2015). For instance, prolonged droughts and irregular rainfall can cause crop failures, reduce pasture availability for livestock, and lead to water shortages, especially in regions heavily dependent on rain-fed agriculture. Elevated temperatures further exacerbate these issues by increasing evaporation rates, reducing soil moisture, and heightening heat stress on crops and animals (Zhang et al., 2011). Consequently, climate variability becomes a significant driver of food insecurity, malnutrition, and economic instability, notably in communities lacking resilient infrastructure and social safety nets.

In Africa, these challenges are heightened by limited adaptive capacities and socio-economic vulnerabilities. Many countries on the continent face a double burden they are highly exposed to climate variability and change, yet possess limited resources and institutional capacity to respond effectively (Amsalu et al., 2014). Climate change has been linked to increased frequency and severity of droughts, floods, and heatwaves across Africa (IPCC, 2017). These events threaten agricultural productivity, disrupt water and energy supplies, and exacerbate poverty and food insecurity. Smallholder farmers and pastoralists, who form the backbone of rural economies, are especially vulnerable because their livelihoods depend heavily on climate-sensitive resources. This socio-economic instability can lead to increased migration, social conflicts, and hinder long-term development, underscoring the need for comprehensive targeted interventions.

Precipitation and temperature are among the most critical climatic variables affecting water resources and agricultural output. Variability in rainfall influences the distribution and seasonality of water supplies, which are essential for irrigation, livestock, and domestic use (Zhang et al., 2011). Changes in rainfall patterns can lead to droughts or floods, disrupting planting and harvesting cycles and damaging crops. Elevated temperatures further complicate these dynamics by increasing evaporation and crop water requirements (Alemayehu & Bewket, 2016). In Ethiopia, where agriculture is predominantly rain-fed, such climatic fluctuations pose significant risks to food security (Alemayehu & Bewket, 2016). To develop effective adaptation strategies, it is crucial to analyze historical climate data, forecast future trends, and design resilient water and agricultural management systems.

Ethiopia is particularly vulnerable to the adverse effects of climate variability, with recurrent droughts, irregular rainfall, and rising temperatures severely impacting agricultural and pastoral communities (Lautze et al., 2003). Historical drought episodes, such as those in the 1970s, 1980s, and more recent crises in 2015–2016, have led to widespread famine, crop failures, and livestock losses, aggravating food insecurity and socio-economic hardships (IPCC, 2007). These recurrent shocks reveal the fragility of Ethiopia's reliance on rain-fed agriculture and pastoralism, especially in arid and semi-arid zones. Limited access to resources, low-income levels, and inadequate safety nets further heighten community vulnerability, making resilience-building and adaptive policies essential for safeguarding livelihoods (Hurst et al., 2012).

The manifestations of climate variability in Ethiopia include increased incidences of drought, flooding, and temperature extremes, which are linked to broader climate change phenomena (IPCC, 2007). These extreme events contribute to environmental degradation, soil erosion, and reduced land productivity, resulting in socio-economic hardships (Kebede et al., 2019). Droughts, in particular, have become more frequent and severe, significantly impacting water and food security (Kebede et al., 2019). The complex nature of drought classified into meteorological, agricultural, hydrological, and socio-economic categories poses significant challenges for prediction, early warning, and management, especially in resource-limited contexts with data scarcity (Mokhtar et al., 2021). Although technological advances in drought monitoring exist, Ethiopia's capacity for early warning and proactive response remains limited, hampering efforts to mitigate impacts effectively (Yanto et al., 2017).

In Ethiopia's southern regions, such as the Guji zone, climate variability has intensified existing vulnerabilities among pastoral communities reliant on livestock (Ayal et al., 2018). Recurrent droughts, irregular rainfall, and rising temperatures have led to pasture degradation, water shortages, and livestock mortality, threatening socio-economic stability (Dirriba, 2016). Despite the importance of understanding these climate impacts, most existing studies focus on localized assessments, lacking comprehensive spatial and temporal analyses that integrate climatic and socio-economic data. This gap hinders the development of targeted, evidence-based policies that can effectively build resilience and promote sustainable livelihoods (Guye et al., 2022; Mekuria et al., 2021). Addressing this research gap through integrated climate and vulnerability assessments is essential for designing adaptive strategies suited to the specific needs of pastoral communities.

Although there is a growing body of research on climate variability in Ethiopia, much of it remains geographically limited, focusing primarily on the northern, central, or eastern regions (Yanto et al., 2017). Few studies have conducted large-scale spatial and temporal analyses of climate variables such

as rainfall and temperature in southern pastoral zones like Guji. Moreover, existing research often overlooks the explicit links between climate variability, food security, and community coping mechanisms, which are critical for developing effective adaptation policies. To address this gap, integrated studies combining climatic data analysis with socio-economic assessments are necessary. Such research would provide a holistic understanding of climate impacts at regional levels and inform interventions tailored to vulnerable populations' needs.

Research Methodology

Research Approach and Design

In this study, both quantitative and qualitative research approaches were employed. Utilizing a mixed-method approach enabled the researchers to address the research questions with sufficient depth and breadth (Enosh et al., 2014). This approach also facilitated the generalization of findings and implications of the studied issues to the entire population. According to Johnson and Onwuegbuzie (2004), a mixed-method approach offered the best opportunity to answer research questions by combining the strengths of both methods while compensating for their respective weaknesses. According to Degefa (2005), combining qualitative and quantitative research techniques proved more effective than using either method alone for addressing issues related to household food security and livelihood status. In the quantitative phase, household surveys were conducted to gather relevant data from selected households. The questionnaire focused on household social characteristics, livelihood systems including activities, assets, and income food security determinants, physical resources, risks, and coping strategies. In terms of research design, this study adopted a cross-sectional research design to assess the overall activities related to the impact of climate variability on household livelihoods and food security. It also aimed to characterize the spatiotemporal pattern of meteorological drought over southern Ethiopia, specifically within the Guji and West Guji zones of selected districts with diverse population characteristics. Data were collected at a single point in time to make inferences about the broader population based on the sample outcomes.

Data Sources

For methodological drought and satellite images, data on temperature and rainfall were obtained from Ethiopia's Meteorology Institute (EMI). Additionally, meteorological data were downloaded from <https://drought.unl.edu> (drought monitoring//SPI/SPIprogram.aspx) to address any gaps in data obtained from EMI. Data from the POWER Data Access Viewer (DAV) Web Mapping Application, which contains geospatially enabled solar, meteorological, and cloud-related parameters for assessing and designing renewable energy systems, were also utilized and downloaded from <https://power.larc.nasa.gov/data-access-viewer/>. Secondary data were collected from various governmental offices, satellite imageries, ancillary sources, NGOs, the internet, library books, and other published and unpublished documents related to climate variability, food security status, and its determinants. This included data from CSA, the Agricultural Development governmental office/Bureau, reports from NGOs, and data collected from EFDR Agricultural Office, Oromia Agricultural Office, as well as Zonal and Woreda Agricultural offices.

In addition to this, questionnaires, field observations, focus group discussions, and key informant interviews. Questionnaires, designed in both closed and open formats and translated into Afaan Oromo, were used to gather information on demographics, livelihood activities, food security, household assets, income, climate variability, and coping strategies. Key informant interviews with 48 experts and community leaders provided insights into climate impacts and adaptation strategies. Focus group discussions with pastoral community members explored livelihood activities, food security, and socio-economic challenges. Participant observation was conducted throughout the fieldwork to

observe the effects of climate variability on agriculture and livestock, supported by photographs and videos. Secondary data from offices, NGOs, and documents complemented the primary data collection. Satellite imageries and ancillary data was collected to assess drought risk in the study area.

Table 1: Data Source specification

No	Data and software Type	Path/Row	Spatial Resolution	Source
1	Rainfall and Temperature data			NASA POWER
II Software type				
2	ArcGIS 10.8v.			
3	DrinC Software			

Rainfall and Temperature Variability Analysis

Analysis concerns climate trends and annual climate variability across seasons of temperature and rainfall. Additionally, the Coefficient of variation (CV), percentage departure from mean (anomalies), standard deviation (SD), and mean are used to determine the variability. The coefficient of variation is used to measure the variability of rainfall and temperature. A better value of CV is the indicator for longer variability and vice versa which is computed in the following formula:

$$CV = \frac{\sigma}{\mu} \times 100 \text{-----equation 1}$$

Where CV is the coefficient of variation, σ is the standard deviation and μ is the mean precipitation. CV is employed to classify the degree of variability of rainfall events as, less when $CV < 20$, moderate when between $20 < CV < 30$, and high when $CV > 30$ (Hare’s, 2003), and a higher CV value indicate that higher variability, moderate value indicates moderate and fewer values indicate low variability.

The precipitation Concentration Index (PCI) is used as a statistical description of rainfall variability and the coefficient of variation is used. The PCI values are to calculate using the following equation 4 as indicated in (Oliver 1980).

$$PCI \text{ annual} = \frac{\sum \epsilon Pi^2}{(\sum \epsilon Pi)^2} \times 100 \text{----- Equation 2}$$

Where Pi is the rainfall amount of the i^{th} month; and Σ = summation over the 12 months. According to Oliver (1980), PCI values less than 10 indicate the uniform monthly distribution of rainfall, values between 11 and 20 indicate high concentration, and values of 21 and 21 above indicate very high concentration.

In addition, seasonal PCI is calculated as follows:

$$PCI \text{ seasonal} = \frac{\sum_{i=1}^4 pi^2}{(\sum_{i=1}^4 pi)^2} \times 25 \text{.....Equation 3}$$

Where: Pi is $\frac{1}{4}$ the rainfall amount of the i^{th} month.

PCI values of less than 10 indicate the uniform monthly distribution of rainfall (low precipitation or rainfall concentration), values between 11 and 15 denote moderate concentration, values from 16 to 20 indicate high concentration, and values of 21 and above indicate very high concentration (Oliver, 1980).

The standard deviation is calculated by the square root of variance using the classification stated by Reddy (1990), and the stability of rainfall is computed as:

$$SD = \sqrt{(\sum_{i=1}^n 1(Xi - X)^2)} \text{..... Equation 4}$$

Where SD is Standard Deviation, $SD < 10$ means very high stability, $10 < SD < 20$ high stability, $20 < SD < 40$ is moderate Stability, and $SD > 40$ indicates less stability (Reddy, 1990).

Methods of Meteorological Drought Analysis
Standard Precipitation Index (SPI)

The Standard Precipitation Index (SPI) is a widely used tool for assessing rainfall deviations and drought impacts over various time scales, such as 3, 6, 12, 24, and 48 months. It is based on fitting long-term rainfall data to a Gamma distribution and converting it into a standard normal distribution (z-score). The SPI indicates how much rainfall deviates from the average, with positive values signifying wet conditions and negative values indicating drought. Calculations involve estimating distribution parameters, including adjustments for zero rainfall. SPI values are categorized into five drought levels based on percentiles, following U.S. Drought Monitor standards, allowing for objective drought assessment in the study. As was stated, SPI calculation includes density function fitting of Gama probability on rainfall frequency distribution for a specific station. G(x) Gama density function is obtained by this formula;

$$g(X) = \frac{1}{\beta^\alpha \Gamma(\alpha)} X^{\alpha-1} e^{-x/\beta} = 1 \dots \dots \dots \text{Eq 7}$$

In this equation, α is the parameter of the form; β the parameter of scale; x the amount of rain and $\Gamma(\alpha)$ is Gama function. The density distribution parameters of Gama probability from the sample data is estimated by method of maximum likelihood for each station and for elective time scale and each month of year; by using this method, McKee and coworkers estimated α and β coefficients based on the below relation (McKee *et al.* 1993).

$$\hat{\alpha} = \frac{1}{4A} \left[1 + \sqrt{1 + \frac{4A}{3}} \right], \beta = \frac{x}{\hat{\alpha}} \dots \dots \dots \text{Eq 9}$$

$$A = \frac{\sum \ln(x)}{n} \dots \dots \dots \text{Eq 10}$$

n is the number of rainfall observations; furthermore, is the average of aggregate rainfall for one month during a statistical period. Because Gama function is not defined for x=0 (0 mm rainfall) and rainfall distribution may have the value of zero, the total aggregate probability which also includes the value of zero is obtained by this relation:

$$H(X) = q + PG(X) \dots \dots \dots \text{Eq11}$$

In which q is the probability of zero rainfall amount and p=1+q. if m is the number of zero rainfall data in a time series of n, q can be obtained by this relation: $q = \frac{m}{n}$

After calculating the total aggregate probability (H(X)) standard normal random variable value, the probability is calculated with the aforementioned probability which has zero average and standard deviation 1. This value is SPI index. These relations offer Z or SPI from the values of H(X).

If $(0 < H(X) \leq 0/5)$

$$Z = \text{SPI} = \left[t - \frac{c_0 + c_1 + c_2 t^2}{1 + d_1 + d_2 t^2 + d_3 t^3} \right]$$

If $(0/5 < H(X) \leq 1)$

$$Z = \text{SPI} = + \left[t - \frac{c_0 + c_1 + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right]$$

If $0 < H(X) \leq 0.5$

$$t = \sqrt{\ln\left(\frac{1}{H(X)^2}\right)}$$

If $0.5 < H(X) \leq 1$

$$t = \sqrt{\ln\left(\frac{1}{1-H(X)^2}\right)} \dots\dots\dots \text{Eq12}$$

In these relations, c0, c1, c2, d1, d2 and d3 are fixed value and H(X) is aggregate probability. The SPI, often called the z score, is the number of standard deviations from the mean at which an event occurs. Thus, the 3-month SPI value provides a comparison of accumulated precipitation over that specific 3-month period with the mean precipitation total for the same annual period as calculated over the full study periods.

$$\text{Z score} = \frac{x_i - \bar{x}}{\text{Standard deviation}} \dots\dots\dots \text{Eq13}$$

Where, Z score is SPI value X_i = is precipitation for particular month \bar{x} = is mean rainfall for “x” months.

Results

Spatial distribution of rainfall across districts

The spatial variability of seasonal and annual rainfall in Dugda Dawa district reveals critical insights into the region’s hydrological dynamics and their implications for agriculture and water resource management. The data indicates that spring rainfall exhibits relatively low variability (coefficient of variation, CV < 30%) in the northern and western parts of the district, suggesting a certain degree of reliability in these areas for planting and cropping activities dependent on spring rains. However, moving towards the central and eastern regions, the rainfall becomes increasingly unpredictable, with CVs rising to 30-50% and exceeding 50%, respectively. This heightened variability in the eastern parts signifies a substantial risk for farmers relying on spring rains, as unpredictable rainfall can adversely affect crop germination, establishment, and yields. Such spatial heterogeneity underscores the necessity for location-specific adaptation strategies, such as drought-resistant crops or rainwater harvesting, particularly in the more variable eastern zones.

Autumn rainfall displays a similar spatial pattern but with notable differences. The westernmost areas of Dugda Dawa are characterized by high predictability, with CVs less than 20%, which implies more stable rainfall conditions during this season. In contrast, the eastern and southern regions experience the highest variability during autumn, with CV values exceeding 50%. This variability heightens the risk of drought during critical post-harvest periods or fallow seasons, potentially leading to food insecurity and water scarcity. The high variability in these regions suggests that farmers and local authorities need to implement contingency planning, such as water conservation measures and diversifying cropping calendars, to mitigate the adverse effects of unpredictable autumn rains.

The most significant insight from the rainfall variability analysis is that, on an annual scale, the coefficient of variation (CV) values consistently exceeds 50% across the entire district. This high year-to-year variability indicates that total annual rainfall remains highly unpredictable throughout Dugda Dawa. Such pervasive unpredictability presents substantial challenges for long-term planning in rain-fed agriculture, as it increases the risk of crop failures and food insecurity. This variability also affects socio-economic stability, leading to price volatility, reduced food availability, and heightened vulnerability among subsistence farmers. Ultimately, the district faces a persistent risk of climate-induced shocks, underscoring the need for resilient agricultural practices and diversified livelihood strategies.

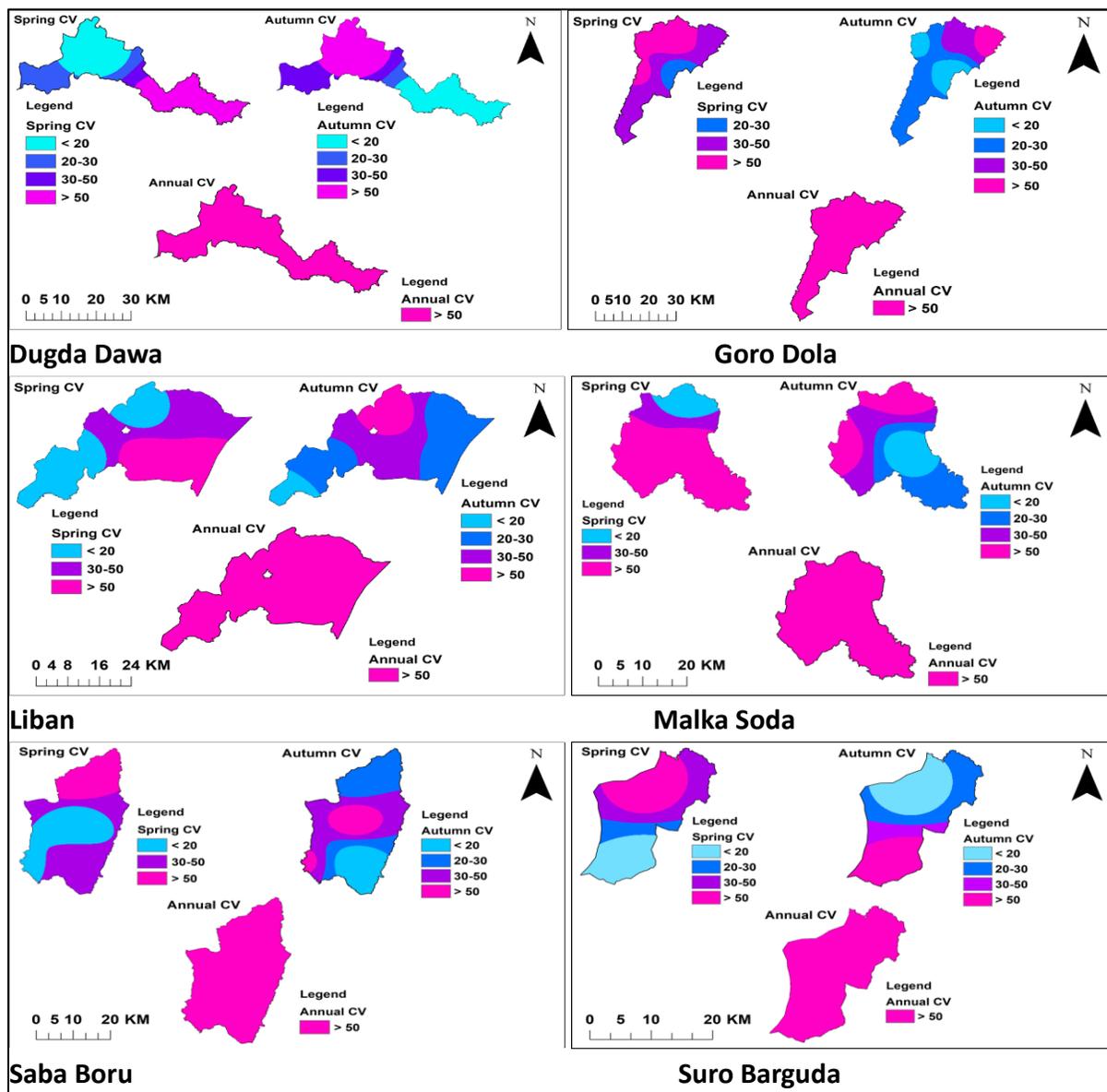


Figure 1: Spatial distribution of rainfall across districts

When examining the spatial distribution of rainfall variability in Goro Dola district, the maps based on the Coefficient of Variation (CV) for spring, autumn, and annual precipitation reveal notable heterogeneity. During spring, the western and northern parts exhibit relatively low CVs between 20-30%, indicating more predictable rainfall patterns. In contrast, the central and eastern regions show higher CVs, ranging from 30-50% and over 50%, respectively, making these areas more susceptible to erratic spring rainfall and early planting risks. Autumn rainfall further emphasizes this heterogeneity; the western zones have low CVs below 20%, suggesting reliable water availability, while the eastern and southern regions experience high CVs exceeding 50%, increasing drought vulnerability during the

critical autumn period. These patterns highlight the importance of localized water management techniques, such as small reservoirs and soil moisture conservation, in the more vulnerable areas.

At the annual scale, Goro Dola exhibits uniformly high rainfall variability across all regions, with CVs exceeding 50%. This consistent pattern indicates that total yearly rainfall is inherently unpredictable everywhere within the district. Such pervasive high variability hampers planning for water resource allocation and rain-fed agriculture, as farmers and policymakers cannot reliably anticipate water availability from year to year. This situation underscores the necessity of adopting climate-resilient agricultural strategies, including crop diversification, water harvesting, and insurance schemes, to buffer against unpredictable rainfall patterns and improve food security.

In Liban district, the spatial variation of drought variability, as shown by CV maps for spring, autumn, and annually, reveals complex patterns critical for drought risk management. During spring, the western and northwestern parts display low CVs (<20), indicating relatively stable drought conditions and reliable rainfall. Conversely, the central, eastern, and southeastern areas show high CVs (>50), reflecting significant fluctuations and a higher likelihood of severe drought episodes. Autumn variability presents a different pattern; the western and southwestern zones have CVs below 20, while the eastern and southeastern regions experience CVs exceeding 50, increasing drought risk during this season. These divergent spatial patterns emphasize the need for targeted drought mitigation efforts tailored to each region's specific vulnerabilities.

At the annual level, Liban's rainfall variability remains predominantly high, with CVs over 50 across the entire district. This widespread high variability underscores the overarching challenge of unpredictable annual rainfall, which hampers sustainable water and agricultural management. The high inter-annual fluctuations necessitate comprehensive resilience strategies, including rainwater harvesting, crop diversification, and climate-smart policies. Addressing this high variability is essential for reducing drought risks and enhancing the district's capacity to adapt to climate variability.

In Malka Soda district, the spatial patterns of rainfall variability across seasons and annually demonstrate a highly dynamic hydrological system. During spring, the southern and eastern regions experience the highest CVs, exceeding 50%, indicating a significant drought risk during this critical planting period. Conversely, the northern and central zones show lower CVs, below 20%, offering more stable conditions. Autumn patterns mirror this distribution, with high CVs in the southern and eastern areas and lower variability in the north and center. These regional differences highlight the need for targeted drought mitigation measures, such as water conservation and climate-resilient cropping practices, particularly in the most vulnerable zones. The annual rainfall CVs remain high (>50%) across the district, emphasizing the inherent unpredictability of water availability and the importance of adaptive strategies like water harvesting and crop insurance to buffer against climate shocks.

Finally, the rainfall variability in Saba Boru district, analyzed through CV maps, reveals distinct spatial patterns with significant implications for drought risk management. During spring, the western and north-central parts show low CVs (<20), indicating relatively predictable rainfall conducive to early planting. In contrast, the northernmost and eastern areas exhibit high CVs (>50), increasing drought susceptibility during spring and risking crop establishment. Autumn patterns show low CVs in the western and southern fringes, while the northeastern and southeastern zones face high variability,

raising drought risks during this critical season. The annual CV map highlights widespread high variability (>50), emphasizing the unpredictable nature of total yearly rainfall across the district. These spatial differences underscore the importance of geographically targeted drought resilience measures, including drought-resistant crops, water conservation, and climate-smart interventions tailored to each area's specific variability profile.

Temporal trends of rainfall across districts

Based on the analysis of rainfall variability presented in (Figure 2), a comparison across the depicted districts reveals a consistent trend of increasing variability in both seasonal and annual rainfall levels. A common observation across Dugda Dawa, Goro Dola, Liban, Malka Soda, Saba Boru, and Surro Barguda is a discernible rise in rainfall variability, particularly evident from the early 1990s through 2000 and continuing with significant fluctuations thereafter, suggesting a broader climatic shift impacting rainfall predictability.

Examining the variability in seasonal versus annual levels, most districts show an initial increase in Spring CV from around 20% in the early 1990s to higher levels between 40-80%, and even exceeding 100% in Liban and Malka Soda by 2000. Post-2000, Spring CVs generally remain elevated and exhibit considerable year-to-year fluctuations, indicating reduced predictability in spring rainfall (Fig.). Autumn CVs, while often more erratic throughout the period, also show a mirroring trend, starting at moderate levels and reaching high variability (over 80-100%) in later years. The Annual CV reflects these seasonal trends, showing a general increase in variability over time. Notably, Liban and Malka Soda exhibit particularly high Annual CVs, frequently exceeding 100%, signifying substantial year-to-year deviations and a heightened risk of both drought and flood events annually. While the trend of increasing variability is widespread, its intensity varies by district. Liban and Malka Soda stand out with the highest CV values, indicating the most pronounced shifts towards unpredictable rainfall. Dugda Dawa, Saba Boru, and Surro Barguda show a more moderate but still significant increase, while Goro Dola, though showing increasing volatility in its Autumn and Annual CVs, has a somewhat more stable Spring CV for a longer period (Figure 2).

The implications of this increasing variability in seasonal and annual rainfall levels are significant and align with broader climate research. Researchers consistently highlight that increased rainfall variability poses a major threat to rain-fed agriculture, prevalent in many developing regions (Kebede et al., 2020).

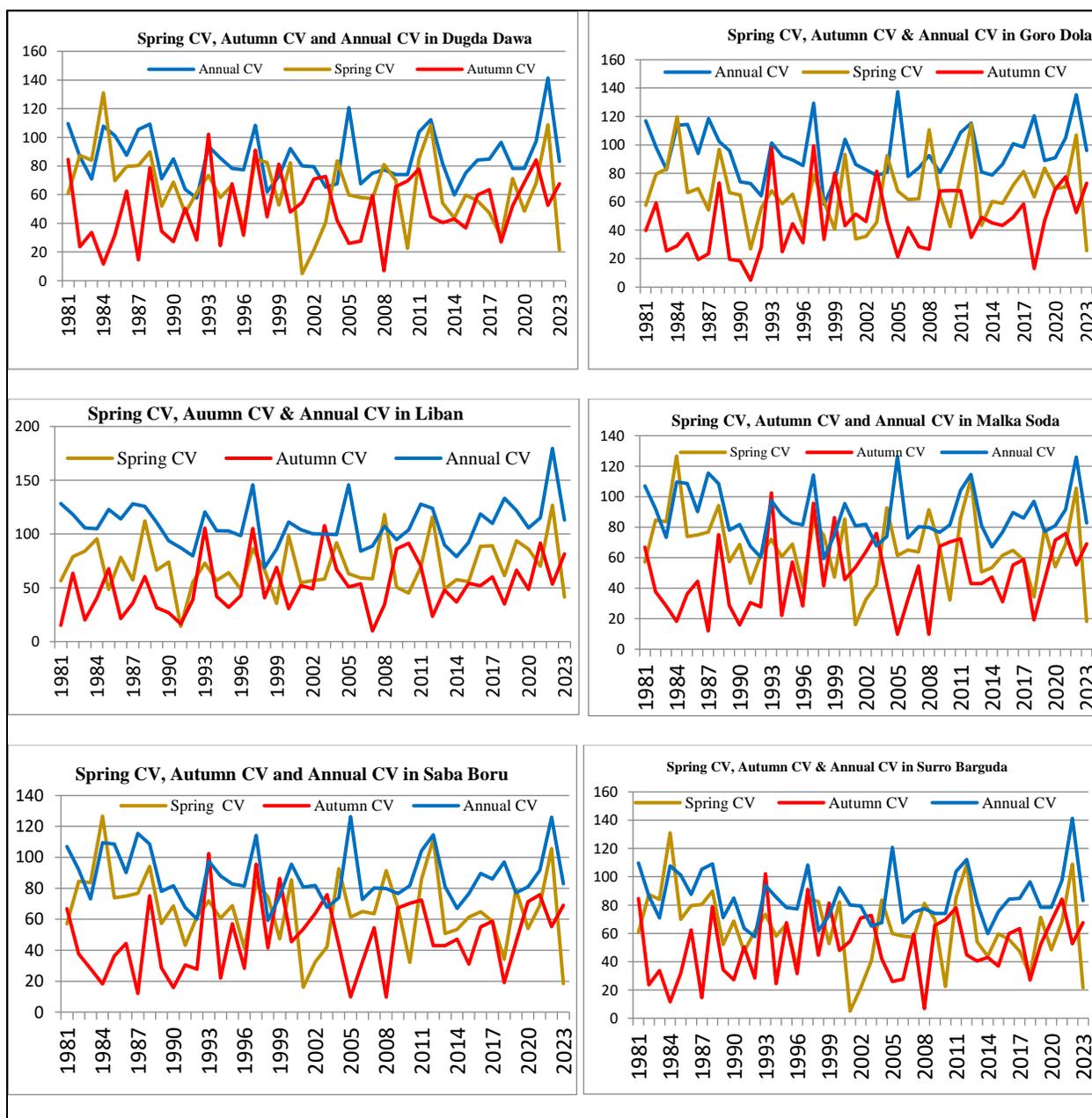


Figure 2: Temporal distribution of rainfall across districts

The higher CVs in spring and autumn seasons make planting and harvesting cycles more precarious, potentially leading to reduced food security and income for farmers. As documented in Intergovernmental Panel on Climate Change (IPCC) reports, this increased variability is linked to a higher frequency and intensity of extreme weather events like droughts and floods. Furthermore, elevated annual CVs create considerable uncertainty in total water availability, posing challenges for water resource management, including planning for storage, irrigation, and domestic use. Periods of drought can be exacerbated, and flood risks can increase during years of exceptionally high rainfall. Recent research, including studies confirms the global trend of increasing extreme weather events,

making average rainfall less representative of actual conditions (Tadesse et al., 2019). These agricultural and water resource challenges translate into socio-economic impacts such as food price volatility, increased poverty, and migration, as water scarcity can lead to conflicts and hinder development (World Bank, n.d.; Bewket, 2014). The findings from (Figure 2) therefore underscore the urgent need for robust climate change adaptation strategies, including promoting drought-resistant crops, improving water management techniques, and developing early warning systems, as advocated by organizations like the World Bank (World Bank, n.d.). In essence, the data from figure mentioned suggests these districts are experiencing a significant shift towards more unpredictable rainfall patterns, a phenomenon widely recognized by climate scientists as a consequence of climate change, with far-reaching implications for livelihoods, economies, and overall resilience.

Temporal analysis of drought condition in the study district

Dugda Dawa District, situated within a predominantly arid climate zone, exhibits persistent dry conditions across multiple temporal scales, underscoring its vulnerability to water scarcity. The Standardized Precipitation Index (SPI) analysis reveals that the district frequently experiences negative values during autumn, with severe drought episodes (SPI below -2.0) recurring notably in 1999 and 2005. These severe droughts highlight the region's susceptibility to prolonged dry spells, which severely impact agricultural productivity and water availability. The spring SPI also consistently leans toward dryness, with many years showing significant negative anomalies, implying that springs are often parched and unreliable. The 12-month SPI, which amalgamates seasonal variations, mirrors these persistent dry trends, indicating that, regardless of seasonal fluctuations, the overall climate remains arid. Despite the absence of a clear, long-term increasing or decreasing trend, the recurrent severe droughts suggest an inherently water-scarce environment that demands comprehensive adaptation strategies to withstand recurring drought impacts (IPCC, 2021).

Goro Dola District faces similar challenges with recurrent dry spells amidst considerable variability, especially during autumn and spring seasons. The autumn SPI (green bars) exhibits episodes of severe drought, with SPI values plunging below -2.0 in the early 1980s, mid-1990s, and early 2000s. These events coincide with critical periods of water demand, affecting both crop yields and livestock health. The spring SPI (dark blue bars) also frequently dips into negative territory, indicating dry springs that threaten agricultural cycles and water reserves. The annual SPI (red bars) reflects these seasonal patterns, with several years marked by drought conditions. Like Dugda Dawa, Goro Dola does not display a consistent trend of increasing or decreasing drought severity over the span of more than four decades; rather, it demonstrates a climate prone to intermittent but severe dry spells. This persistent pattern underscores the need for resilient water management systems and drought preparedness plans, particularly in agricultural communities (Swain et al., 2018; Williams et al., 2020).

Liban District's SPI analysis reveals a pattern of recurring drought, especially during spring and autumn. The spring SPI (dark blue bars) often falls below zero, with notable severe drought episodes around 1999 and 2015, indicating that the season's rains are frequently insufficient. Similarly, the autumn SPI (green bars) shows frequent dry spells, with some droughts (SPI below -1.5) occurring in the late 1990s and mid-2000s. The annual SPI (red bars) generally aligns with these seasonal trends,

confirming that dry years have been common throughout the observational period. Interestingly, recent years particularly from 2021 onward show signs of improved moisture conditions, with positive annual SPI values suggesting a possible shift towards wetter conditions. This emerging trend warrants close monitoring, as it might indicate a climatic transition or variability that could influence future water resource planning and agricultural practices (Dai et al., 2018; Heim, 2002).



Figure 3: Temporal analysis of drought condition

Malka Soda District presents a more dynamic climate with fluctuating water availability, characterized by alternating wet and dry periods. The seasonal SPI values reveal instances of drought during autumn and spring, notably in the late 1990s and early 2000s, yet these are interspersed with periods of above-average rainfall, particularly in 1995 and 2017. The annual SPI demonstrates significant variability, with some years experiencing extreme wetness and others marked by drought. This oscillation indicates that Malka Soda’s climate is strongly influenced by broader climatic oscillations, making water resource planning challenging. The district’s water availability pattern is less predictable, requiring flexible management strategies that can adapt to both drought and flood conditions, emphasizing the importance of climate resilience measures (Gao et al., 2019).

Saba Boru District is characterized by persistent aridity, with a pronounced tendency toward drought throughout the entire observation period. The autumn SPI (green bars) often registers values below -2.0, indicating severe drought episodes in early 1980s, late 1990s, and mid-2000s. Similarly, the spring SPI (blue bars) frequently falls into the drought category, often below -1.5, reflecting ongoing water

deficits during critical planting and water-demand periods. The annual SPI (red bars) consistently mirrors these dry conditions, illustrating that Saba Boru remains highly vulnerable to drought impacts over decades. The absence of any clear long-term trend toward wetter conditions further underscores the need for sustained drought mitigation and water conservation measures, including rainwater harvesting, sustainable land management, and drought-resistant cropping systems (IPCC, 2021; Mishra & Singh, 2010).

Suro Barguda District exhibits a notable climatic transition over the observed period, shifting from predominantly dry conditions to wetter scenarios in recent years. In the early decades (1980s and 1990s), the SPI indicates frequent dry spells, with several years experiencing severe droughts. However, from the late 1990s onwards, a clear trend emerges toward positive SPI values across all seasons and annually, indicating a shift toward increased precipitation and reduced drought frequency. The most recent years (2017–2023) show a consistent pattern of above-average rainfall, with SPI values reflecting a marked departure from previous drought-prone conditions. This transition suggests changes in regional climate dynamics which could positively influence water availability, agriculture, and ecosystem health, opening new opportunities for climate adaptation and sustainable development (Gao et al., 2019; Swain et al., 2018).

Despite the overall aridity in Dugda Dawa and Saba Boru, the variability in drought intensity and occurrence across different periods highlights the complex nature of climate and hydrological responses in semi-arid regions. The persistence of severe drought episodes indicates that natural climate variability, possibly compounded by anthropogenic influences such as land degradation, exacerbates water scarcity issues. These recurring droughts threaten the livelihoods of vulnerable populations, emphasizing the importance of implementing integrated water resource management approaches, including rainwater harvesting, drought-resistant agriculture, and ecosystem-based adaptation (IPCC, 2021; FAO, 2018). Such strategies are essential to build resilience against future climate uncertainties and ensure sustainable livelihoods in these highly vulnerable districts.

Spatial distribution of drought condition in the area

The spatial distribution of drought conditions in Goro Dola reveals significant seasonal and regional variability. During spring, the northeast and northwest experience severe drought, highlighting the vulnerability of early-year water availability and agriculture. The northern and central zones face moderate drought, while the western part remains relatively near normal, emphasizing the critical importance of spring rainfall for crop planting and water resources. In autumn, drought severity shifts, with eastern areas showing improvement and western and southern regions still facing drought, demonstrating the dynamic nature of precipitation variability and its impact on drought mitigation strategies (Swain et al., 2018). The overall annual assessment indicates persistent vulnerabilities, especially in the north, where severe droughts recur, suggesting long-term climatic or land-use drivers behind chronic water scarcity.

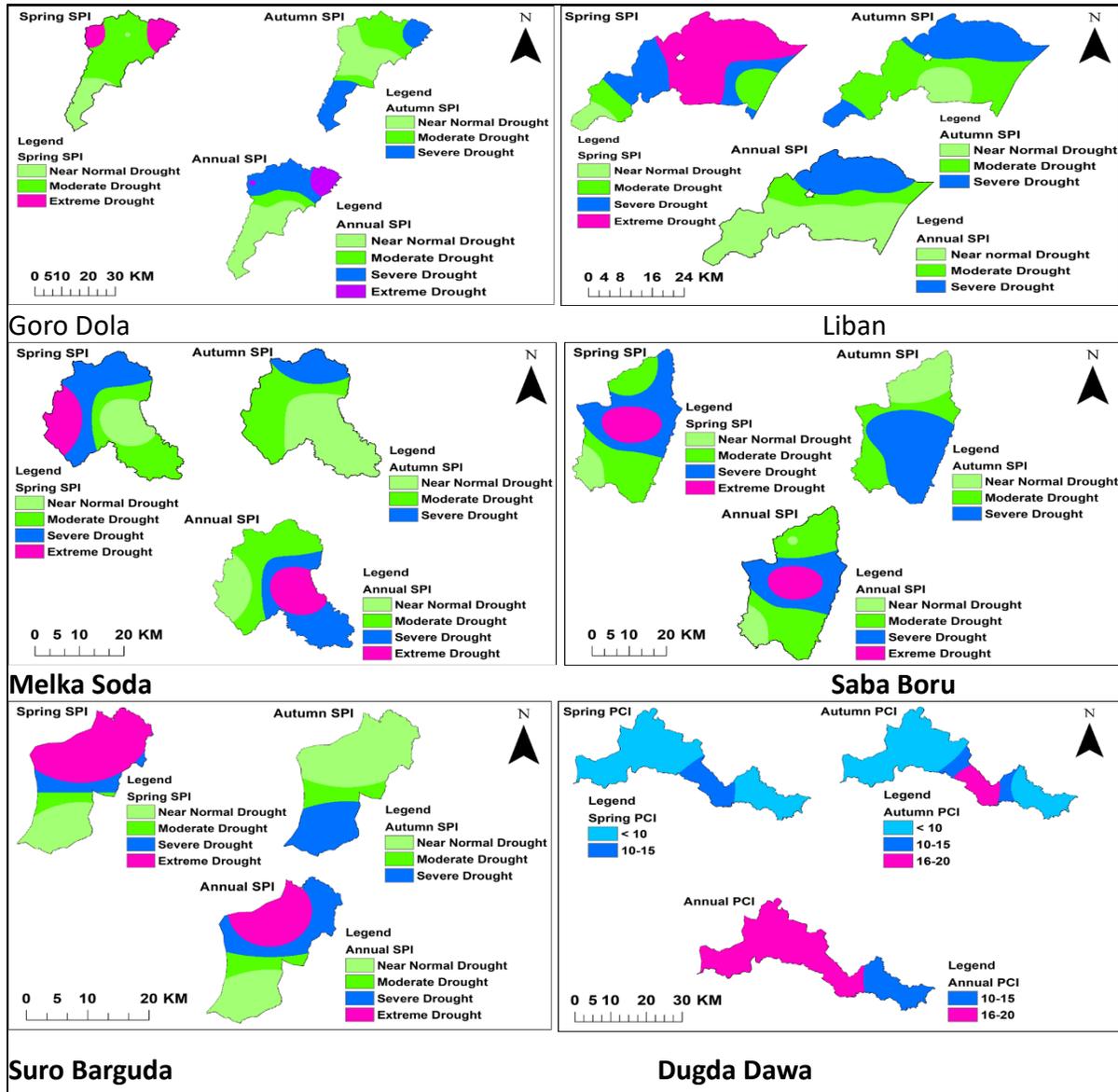


Figure 4: Spatial distribution of drought condition in the area

In the Liban region, drought patterns differ, with spring drought severity concentrated in the northern and central-eastern areas, which face extreme drought conditions during the planting season. Conversely, western and southwestern SPI zones experience less severe drought, mainly moderate or severe, reflecting local climatic or topographical influences. Autumn shows some relief, with central and eastern parts near normal, but the western and northwestern areas continue to face severe drought, highlighting ongoing vulnerabilities (Dai et al., 2018). The annual SPI map indicates a complex pattern, where most of the region maintains near-normal conditions, particularly in the south and southeast, but northern and western zones suffer from persistent moderate to severe droughts, likely driven by underlying climatic factors such as orographic effects and land use.

Suro Barguda district exhibits a similarly complex drought pattern. Spring conditions feature significant extreme drought zones in the central area, marking a critical period for water stress. During autumn, drought severity lessens, with severe drought mainly confined to the central region and no extreme drought recorded. The annual drought assessment shows mostly near-normal or moderate conditions, with some localized severe drought zones. These intra-annual variations underscore the importance of targeted drought resilience measures in vulnerable regions, emphasizing the need for adaptive strategies to address both seasonal fluctuations and long-term climate trends.

Across all districts, the recurring theme is that spring is generally the most drought-prone period, aligning with global findings that early-year rainfall deficits severely impact water and food security (Anderson et al., 2019). The spatial heterogeneity, with certain zones consistently facing severe or extreme drought conditions across seasons and years, indicates underlying climatic or land management factors that exacerbate drought vulnerability. Persistent drought hotspots, especially in the western and northern parts, call for long-term adaptation strategies, including water harvesting, crop diversification, and climate-smart agriculture.

Furthermore, the literature emphasizes that drought impacts are exacerbated by climate change, which has increased the frequency and intensity of dry spells in East Africa (IPCC, 2021). The observed spatial patterns in the maps align with such findings, suggesting an urgent need for integrating climate resilience into regional planning. Seasonal and long-term drought assessments like these inform policymakers about critical periods and vulnerable zones, enabling targeted resource allocation and drought mitigation efforts.

Discussion

The observed spatial variability of seasonal and annual rainfall across districts such as Dugda Dawa, Goro Dola, Liban, Malka Soda, Saba Boru, and Suro Barguda reveals the complex hydrological dynamics characteristic of semi-arid and variable climate zones. These patterns are reflective of broader regional and global trends, where rainfall unpredictability significantly influences agricultural productivity, water resource management, and socio-economic resilience. Extensive research demonstrates that semi-arid and arid regions inherently experience high variability in both seasonal and annual rainfall, which poses significant constraints on sustainable development. Unpredictable water availability hampers crop planning, water storage, and resource allocation, increasing vulnerabilities among farming communities (IPCC, 2014; Mishra & Singh, 2010).

In Ethiopia, the heterogeneity in rainfall variability mirrors these global patterns. Districts like Dugda Dawa show moderate spring rainfall variability in the north and west, while the eastern parts face heightened unpredictability. Such regional differences align with findings by Nicholson (2014), who emphasizes that localized climate heterogeneity results in diverse drought risk profiles, necessitating tailored adaptive responses. This underscores the importance of designing climate strategies specific to each locality, including drought-resistant crops, rainwater harvesting, and soil moisture conservation, which are increasingly supported by scientific literature as effective climate mitigation measures (FAO, 2018).

Research across Africa further confirms that rainfall variability at intra-annual (seasonal) and inter-annual (year-to-year) scales directly impacts food security, especially in regions heavily reliant on rain-fed agriculture. Williams et al. (2020) highlight that high coefficients of variation (CV) during critical planting and harvesting periods pose substantial risks to crop yields, necessitating the development of climate-smart agriculture practices and improved water management systems. The high annual rainfall variability, with CVs exceeding 50% in studied districts, aligns with climate model projections indicating increased unpredictability due to climate change. Without strategic intervention, the frequency and severity of droughts are likely to escalate, further destabilizing agricultural systems and exacerbating socio-economic vulnerabilities (Gao et al., 2019).

Ethiopia's diverse topography and climatic zones contribute to complex, spatially heterogeneous rainfall patterns, similar to those observed in this study. Western regions tend to experience more stable rainfall, contrasting sharply with highly variable eastern zones, as highlighted in national climate assessments (Girmay et al., 2020). These disparities influence local agricultural practices, water availability, and food security, with districts like Liban and Saba Boru demonstrating persistent high CVs in rainfall. Climate change projections further exacerbate these challenges by predicting increased drought frequency and intensity across Ethiopia (IPCC, 2021). Addressing these issues requires region-specific adaptation measures, including drought-resistant crops, efficient water conservation technologies, and enhanced climate monitoring systems integral to national resilience strategies.

From a global scientific perspective, high rainfall variability undermines the reliability of agricultural systems and hampers long-term planning, especially in regions lacking adequate infrastructure for water storage and distribution (Mishra & Singh, 2010). The high CVs across districts underscore the necessity of integrating climate information services into local planning. The adoption of early warning systems and climate-smart agriculture practices in African countries exemplifies how scientific data and community-based approaches can reduce vulnerability and increase adaptive capacity (Swain et al., 2018). Such localized, data-driven approaches are essential to effectively address unique vulnerabilities and build resilient systems capable of withstanding climatic shocks.

Global experiences with drought resilience demonstrate that a multi-faceted approach combining technological innovations, institutional reforms, and community participation is vital. Evidence from Australia's drought policies and Sahel's pastoral resilience programs indicates that diversified cropping systems, water harvesting infrastructure, and social safety nets significantly buffer communities against climate extremes (Heim, 2002; Gbetibouo & Hassan, 2005). In Ethiopia, where high rainfall CVs are common, integrating scientific monitoring, indigenous knowledge, and participatory governance reinforces the need for holistic strategies. The recurrent seasonal and annual variability emphasizes the urgent need for flexible, adaptive strategies capable of accommodating both predictable patterns and unforeseen fluctuations.

The spatial distribution and seasonal fluctuations of drought, such as negative SPI values during critical agricultural periods, align with global understanding that drought is a multifaceted hydrometeorological phenomenon driven by natural variability and influenced by anthropogenic climate change (Dai et al., 2018; IPCC, 2021). Large-scale climate oscillations, especially ENSO, have been linked to drought episodes in Africa, including Ethiopia, often intensifying dry conditions during key periods (Gao et al., 2019). Recognizing these connections underscores the importance of

integrating climate prediction models with local drought monitoring systems to enhance early warning capabilities. This integration is vital for proactive planning, risk reduction, and resilience building in drought-prone districts like Dugda Dawa and Saba Boru.

Conclusions

This study underscores the critical and escalating nature of rainfall variability across districts in the Guji and West Guji zones of Ethiopia, revealing a trend of increasing unpredictability over the past three decades. The consistently high coefficients of variation (CV), often exceeding 50% annually and during key agricultural seasons, reflect the profound challenges faced by local communities in managing water resources, maintaining crop yields, and sustaining livestock productivity. Spatial analysis highlights that eastern and northern regions are particularly susceptible to high rainfall fluctuations and recurrent drought episodes, as evidenced by negative SPI values and severe drought events recorded in multiple years.

The intensification of rainfall variability is largely linked to broader climate change impacts and regional climatic oscillations such as ENSO, which have exacerbated water scarcity, led to crop failures, and increased socio-economic vulnerabilities among pastoral and agro-pastoral communities. These findings call for urgent, targeted adaptation measures tailored to each locality's specific climatic context. Such strategies include the cultivation of drought-resistant crops, the implementation of rainwater harvesting and soil moisture conservation techniques, and the development of robust early warning systems that integrate climate data with indigenous knowledge.

Furthermore, addressing these complex challenges necessitates a multi-dimensional approach that combines technological innovations, community engagement, and supportive policy frameworks. Strengthening local capacities for climate resilience, promoting sustainable water and agricultural practices, and fostering decentralized, participatory planning are essential to mitigate risks and build adaptive capacity. Ultimately, proactive and integrated interventions are vital to safeguard food security, enhance socio-economic stability, and ensure the sustainable development of these vulnerable districts amidst ongoing and future climate uncertainties.

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