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Abstract

Drought is a natural climate-related hazard that significantly affects agricultural sectors, water resources, and livelihoods in moisture-deficient areas of the region. This study evaluated future drought using CMIP6 scenarios over East Borena Zone, Ethiopia, using the Standardized Precipitation Index. Precipitation data of eight GCMs under (SSP2-4.5) and (SSP5-8.5) were obtained from Copernicus Climate Change Store, whereas Historical ENACTs data (1991-2020) from Ethiopia meteorology institute. GCMs' performance were evaluated using Coefficient of correlation (R2), Coefficient of determination (BR2), root mean square error (RMSE) and percent of bias (PBIAS) statistical metrics. Ensemble mode was best-performing depending on metrics R2(0.32) BR2=0.03,PBIAS=-0.867 and RMSE=3.394), followed by bias correction using empirical quantile mapping technique.SPI-3 (MAM) indicated NN (20-28), wet (3-10), whereas SPI-3 (SON) indicated NN (24-28), Wet (1-5) under both scenarios.SPI-6 (March-August) indicated NN (20-28), Dry (1-2), and Wet (2-10), whereas SPI-6 (September-February) indicated NN (15-28), Wet (2-10), Dry (1-4) years in both scenarios. Annual SPI-12 values indicated NN (15-28), Wet (3-11), and Dry (2-4) under both scenarios. Overall, this study strives to assess SPI with multiple scales using two scenarios the value indicated dominant NN, with slightly wet and dry events. This study was solely precipitation-based, resulting in dominant NN events were projected. To obtain a comprehensive picture of future drought, consider future increasing temperature, which significantly aggravates evaporation and evapotranspiration. Therefore, decision-makers should not directly interpret the near-normal event as the absence of drought risk, but should parallelly consider temperature-induced drought impacts on agricultural production, water resources, and rangeland condition.

Keywords: CMIP6 scenarios, Future drought, Standardized precipitation index

1. Introduction

Climate change, driven by both natural processes and anthropogenic activities, influences rainfall and temperature patterns worldwide. Global mean temperature has increased by approximately 1.1 °C above the pre-industrial level, contributing to widespread impacts on natural and human systems [1]. These changes are expected to increasingly affect socioeconomic sectors across East Africa in the coming decades [2]. In this region, increasing daily temperature trends of approximately 0.016–0.053 °C year⁻¹ have been reported [3]. Frequent and intense heavy rainfall events can exacerbate flood occurrence and alter seasonal rainfall patterns [4]. Rising temperatures enhance atmospheric evaporation and consequently influence the hydrological cycle and water availability [1,5]. Annual rainfall has shown increasing trends in some parts of the Borena region, whereas decreasing trends have also been observed in other areas [6]. Furthermore, rainfall exhibits substantial spatial and temporal variability across the Borena Zone [7]. Such variability can affect water availability, agricultural production, and the vulnerability of local communities to drought. Drought is a natural climate-related hazard characterized by a prolonged deficiency of precipitation relative to normal conditions [8,9]. It can adversely affect livelihoods, agricultural production, water resources, and socioeconomic systems. Drought can cause significant reductions in agricultural yield and productivity [10,11]. Prolonged drought can also reduce water supply, streamflow, and water availability for hydropower generation [12], [13]. At the national scale, recurrent drought can cause substantial economic losses, particularly in countries whose economies depend heavily on agriculture [14–16]. Large-scale oceanic and atmospheric interactions can further aggravate drought conditions in vulnerable regions [5], [17]. The risk of drought is expected to increase under continued global warming. Climate change can alter precipitation amount, seasonality, and atmospheric water demand, thereby influencing the frequency, duration, and severity of drought events [18], [19]. Future projections indicate changes in drought characteristics across many regions of the world [20–22]. East Africa is among the regions projected to experience substantial changes in drought patterns, particularly in already dry and drought-prone areas [23]. Drought occurrence is also widespread across Africa, where climate variability, population growth, and future climate change may increase drought risk [24]. Changes in seasonal rainfall patterns can further exacerbate drought development in vulnerable regions [25]. Climate models provide an important means of assessing potential future changes in climate variables and associated drought conditions. Global climate models simulate future temperature and precipitation under different socioeconomic and radiative forcing pathways and therefore provide essential information for evaluating future drought characteristics. The Coupled Model Intercomparison Project Phase 6 (CMIP6) provides an advanced generation of climate model simulations and incorporates Shared Socioeconomic Pathways (SSPs) for assessing future climate conditions under different forcing scenarios [26,27]. CMIP6-based climate projections have therefore become an important framework for investigating potential changes in drought frequency, duration, and severity under future climate conditions [18,28,29]. Drought indices are widely used to quantify drought conditions using meteorological and hydrological variables. A drought index provides a numerical measure representing the severity of dry or wet conditions over a specified period [30]. Among the available indices, the Standardized Precipitation Index (SPI) is one of the most widely used indicators for monitoring and characterizing meteorological drought because it is precipitation-based and can be calculated over multiple time scales [31,32]. Shorter time scales, such as SPI-3, are useful for identifying relatively short-term precipitation deficits, whereas SPI-6 and SPI-12 can represent medium- and longer-term precipitation anomalies relevant to agricultural and water-resource conditions [30]. Although numerous studies have investigated climate-change impacts on drought in Ethiopia and East Africa, future drought characteristics under CMIP6 scenarios have not been sufficiently investigated in the newly established East Borena Zone. Recent studies have

examined future drought in different parts of Ethiopia and East Africa [23,33–36]. However, limited information is available on the projected frequency, temporal characteristics, and trends of precipitation-based drought at multiple time scales across meteorological stations in East Borena Zone under different CMIP6 scenarios.

Therefore, this study aims to model future drought characteristics over the East Borena Zone of Ethiopia using a multi-model ensemble of CMIP6 climate projections under the SSP2-4.5 and SSP5-8.5 scenarios. Specifically, the study aims to:

1. Characterize future drought trends using the Standardized Precipitation Index at 3-, 6-, and 12-month time scales (SPI-3, SPI-6, and SPI-12).
2. Identify the frequency and temporal characteristics of wet and dry events across the selected meteorological stations under future climate scenarios.

The findings are expected to provide scientific information to support drought early-warning systems, agricultural planning, water-resource management, and climate-change adaptation strategies in the East Borena Zone.

2. Materials and Methods

2.1. Description of the Study Area

This study was conducted in the newly established East Borena Zone located in the southern parts of Oromia Regional State, approximately between latitudes of 3°36'29" - 6°22'25" N and 38°23'20"-41°34'54"E longitude. Bordered by North(Bale zone), West(Guji, West Guji zone), East (Somale regional state), and South (Borena zone). The zone covers about 44,634 km² with varying elevation ranges between 206 to 2,679m mean above sea level (ma.s.l) and includes Liban, Goro Dola, Mada Walabu, West Walabu, Wachile, Arero, Dhas, and Gumi Eldalo districts Figure 1(middle). Major land use land cover composition range land, trees, and crops 51.9%, 45.8%, 2.1% respectively (Figure 1.left)

2.2. Climate characteristics

East Borena zone is characterized by bimodal rainfall regime Belg (March-May) major whereas Bega (September –November) second rainfall season. The highest amount of rainfall is received in April and October, respectively. Figure).Based on (1991-2020) rainfall data analysis, seasonal rainfall contribution ranges Belg (46-57.4%), Bega (32.6-40.9%), and Kremit (8.8-20.7%), respectively. Figure). Annual mean maximum temperature is recorded in February, whereas the minimum mean is in November (Figure 2). Major large-scale atmospheric and ocean systems influencing rainfall patterns are ENSO, IOD, ITCZ, and subtropical westerly jet (STWJ) and Arabian High [37-39].

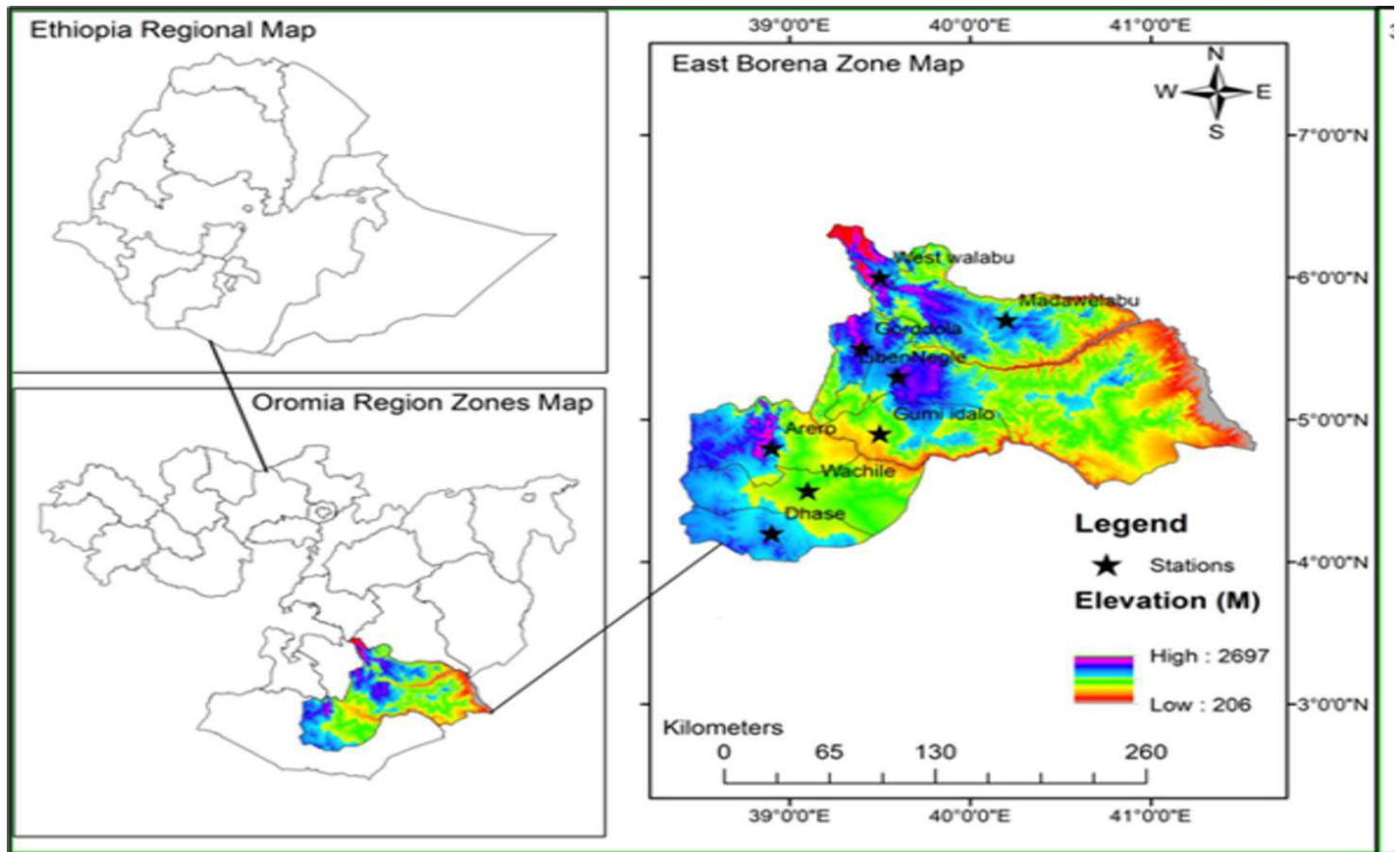


Figure 1: Location of the Study Area with Digital elevation model

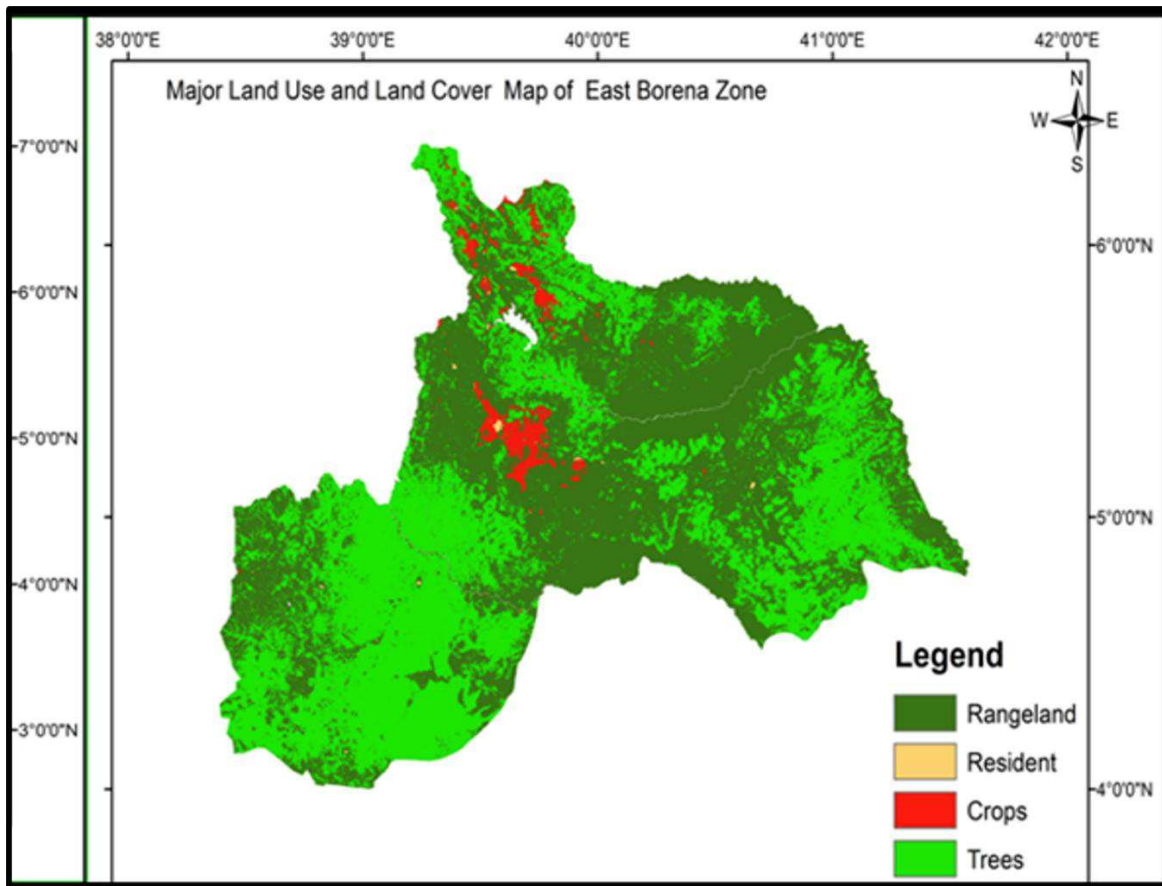


Figure 2: Land Use land Cover Map of 2025

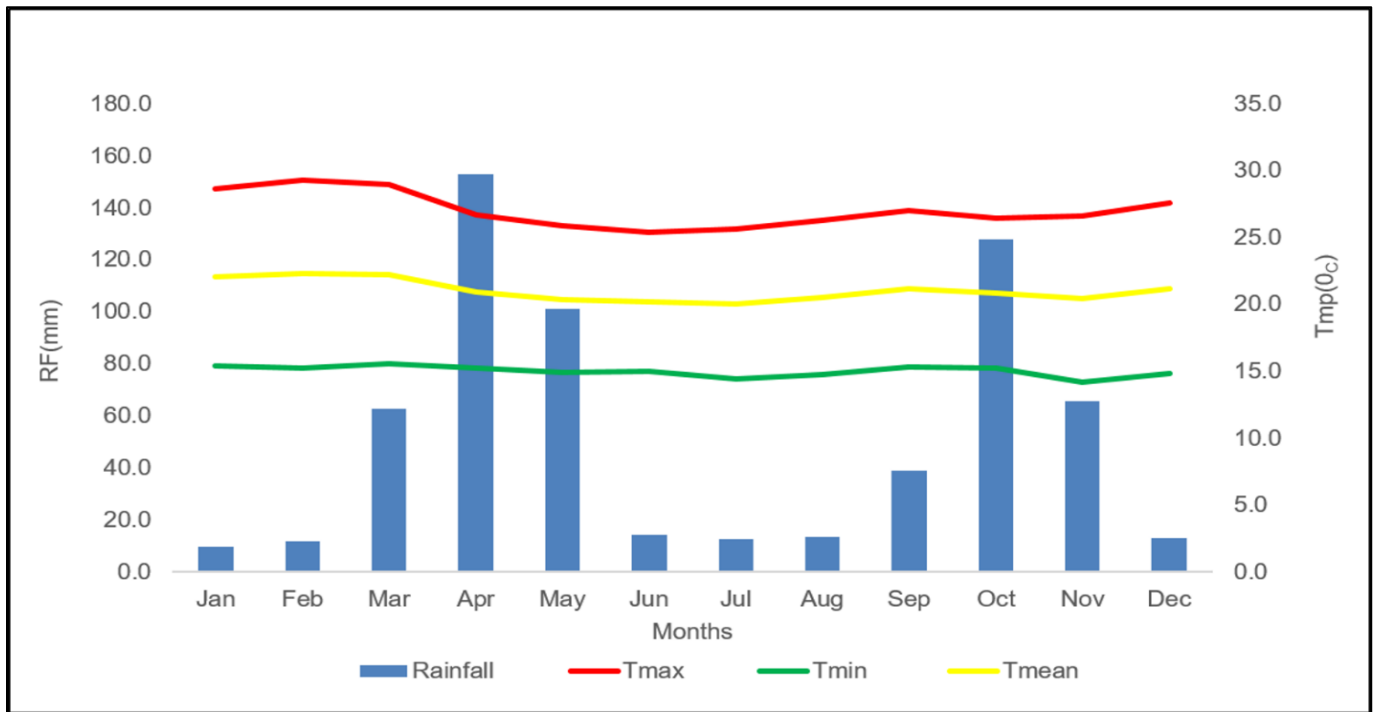


Figure 3:Monthly Climatology of Rainfall, Tmax, Tmin and Tmean over the study Area

During baseline (1991-2020) period using ENACTs data

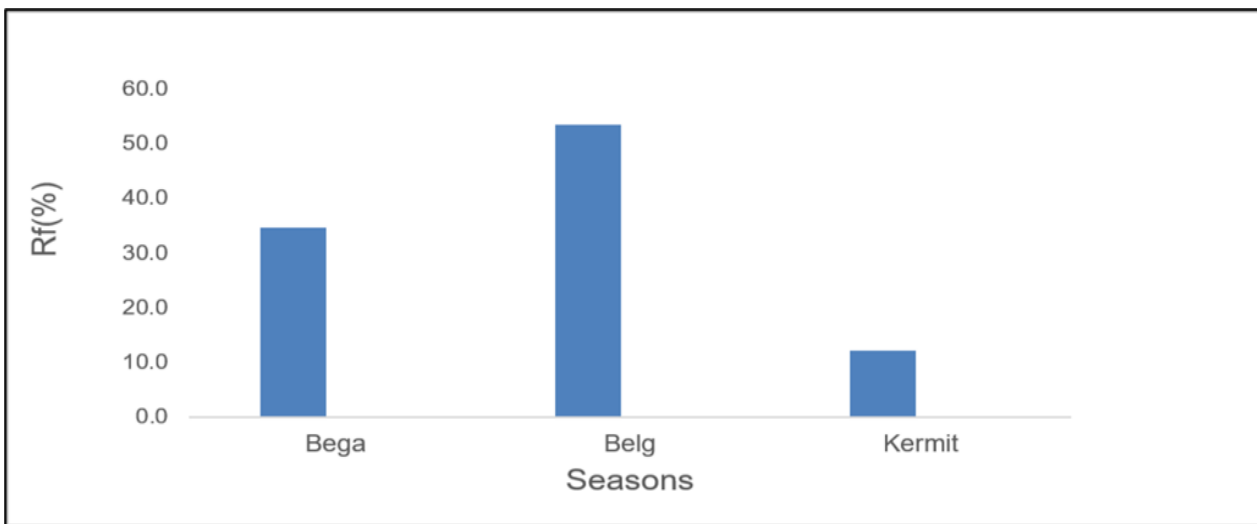


Figure 4:Seasonal Rainfall contribution (%) during Bega,Belg and Kermit periods Based on (1991-2020) ENACTs data over the study area.

Note Bega (Oct-Jan), Belg (Feb-May) Kermit (June-Sep) time period Seasonal classification of Ethiopia

2.3. Data Collection

2.3.1. Gridded ENACTs data

Historical daily gridded rainfall data for the period 1983-2022 with spatial resolution 4×4 km were collected from Ethiopia Meteorology Institute (EMI). ENACT Gridded data were employed for this study because long-term station data cannot be accessed. ENACTs Initiative addresses the limitations of the availability and accessibility of climate datasets through combining quality-controlled station observations with global satellite data to support climate services and research [40].

2.3.2. Climate Models data

Climate models play a vital role in simulating historical and future precipitation and temperature data. For this, historical daily precipitation data from 1983-2014 and future 2015-2100 were obtained from eight CMIP6 (Climate Model Intercomparison Project 6) climate models, Copernicus Climate Change Service (C3S) (Table 1). The study employed under SSP2-4.5 (medium-emission) and SSP5-8.5 (high-emission) scenario pathways. CMIP6 data were generated using Earth system models considering radiative forcing associated with greenhouse gas emissions and human activities during the historical and future period 1750–2100 [41], [42], [43], [44]. Climate models simulate future scenarios by considering radiative forcing and human activities to assess future climate change [45], [46], [47]. Climate forcing and human activities may exacerbate drought events; therefore, climate scenarios are important for characterizing the event and intensity [48–51].

Table 1: CMIP6 GCM models for this study

GCM/Models	Institute /country	Horizontal resolution (°)
ACCESS-CM2	Australian Community Climate and Earth System Simulator coupled model version 2 CSIRO (Australia)	1.25×1.88
BCC-CSM2-MR	Beijing Climate Center Climate System Model high resolution(China)	1.13×1.13
Can ESM5	Canadian Centre for Climate Modeling and Analysis, Environment and Climate Change (Canada)	1.25×1.88
CNRM-CM6-1	Centre National de Recherche Météorologiques, France coupled model 6-1(France)	1.40×1.40
EC-earth-CC	Swedish meteorological and hydrological institute /SMHI) Sweden	0.13×0.13
GFDL-ESM4	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory (USA)	1.00×1.25
IPSL-CM6A-LR	Pierre Simon Laplace, Paris 75252 (France)	1.25×2.50
MPI-ESM1-2-LR	Max Planck Institute Earth System Model (MPI-ESM1.2) for the Low-Resolution Model Hamburg, (Germany)	1.88×1.88

2.4. Data preparation

2.4.1. ENACTs Gridded data preparation

Gridded data were extracted for the period 1983-2022 for nine meteorological stations over the study area. ENACTs data were passed through intensive quality check process; therefore, users can directly use the data for analysis purposes without extra quality check activities. ENACT rainfall data were generated by blending Tropical Applications of Meteorology using satellite-driven estimate data (TAMSAT) with outlier and homogeneity test-checked observation data [52].

2.4.2. Climate Model Data Preparation

To characterize future drought events, state-of-the-art CMIP6 under SSP2-4.5(medium-emissions) and SSP5-8.5 (high-emissions) pathways were employed. The future study period was classified with mid-term (2041-2070) and far-term (2071-2100) time horizons depending on WMO climatological normal classification IPCC [53]. GCM model data are network common data format (netCDF). The data preprocessing includes unit conversion, standard Calander,regridded bilinear common high resolution(4×4)km ENACT was applied with CDO [54,55]. Climate models have different spatial resolutions; therefore, remap to a common spatial resolution is necessary to evaluate their performance [56], [57], [58].The historical performance of climate models were evaluated against ENACT's data with correlation coefficient(R^2), root mean square error(RMSE), Pearson correlation (BR^2), and percent of bias (PBIAS) statistical metrics. The most convenient GCM model for climate change assessment was selected with a similar technique, based on historical performance against observed data [59–63].

Table 2: GCMs Performance Evaluation Statistical Metrics

Performance evaluation statistical metrics formula	Description
Correlation (r) = $\frac{n \sum xy - (\sum x)(\sum y)}{\sqrt{[n \sum x^2 - (\sum x)^2] [n \sum y^2 - (\sum y)^2]}}$	Correlation coefficient
$RMSE) = \sqrt{\sum_{i=1}^n (\frac{X-Y}{n})^2}$	Root means square error
$PBIAS) = \frac{\sum_{i=0}^n (X - Y)}{\sum_{i=0}^n X} * 100$	Percent of Bias
$R^2 = 1 - \frac{\sum_{i=1}^n (X_i - y_i)^2}{\sum_{i=1}^n (x_i - \bar{x})^2}$	Coefficient of determination

X is historical /ENACTs data

Y is hitorical GCM data

2.4.3. GCM Data Bias Correction

Climate models have limitations in capturing local climate features, either overestimate/underestimates future climate simulations. A bias correction approach was carried out to reduce systematic model errors and improve local representativeness of climate projections. For this study, Empirical Quantile Mapping (EQM) approach was employed. To minimize climate model errors, Empirical Quantile Mapping was a prominent bias correction technique using observed data quantile distributions for adjusting model projections [64–67]. Improved climate data were produced by reducing systematic errors of GCMs [68]. For precipitation data, empirical distributions were predominantly used rather than fitting theoretical distributions bias correction method [69].

For CMIP6 future projections, the correction is commonly applied as:

$$P_{future,bc} = F_{obs}^{-1}(F_{mod,hist}(P_{future}))$$

where:

- $P_{future,bc}$ = future CMIP6 precipitation
- $F_{mod,hist}$ = CDF of the model's historical simulation
- F_{obs}^{-1} = inverse empirical CDF (quantile function) of the observed data.
- P_{future} Future CMIP6 precipttaion

Mean of the corrected data

The mean is calculated after bias correction as:

$$\bar{p}_{future,bc} = \frac{1}{n} \sum_{i=1}^n p_{bc,i}$$

Substituting the EQM formula gives:

$$\bar{p}_{future,bc} = \frac{1}{n} \sum_{i=1}^n F_{obs}^{-1}(F_{mod,hist}(p_{future,i}))$$

where n is the number of observations.

During the calibration period, the corrected mean is typically close to the observed mean

2.4.4. Drought Analysis Using Standardized Precipitation Index

Standardized Precipitation Index is widely recognized for quantifying and characterizing drought with multiple time scales. The index is used to characterize drought extent, severity, and magnitude over different climatic and hydrological locations relies on only rainfall data [70,71]. The World Meteorological Organization recommend for quantifying meteorological drought [72]. The short time

scales SPI-1 and SPI-3 indicate soil moisture conditions, whereas above SPI-4-time scales are related to hydrological drought over surface ground water and stream flow conditions. It is computed by summing precipitation over k months termed accumulation period, and fitting these accumulated values to a parametric statistical distribution, from which probabilities are transformed into the standard normal distribution ($\mu = 0$, $\sigma = 1$) [82–85]. Positive SPI values indicate (wetness) whereas negative values indicate dryness compared with the long-term mean. For this study, SPI was computed for SPI-3, SPI-6, and SPI-12 timescales.

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}$$

$$\alpha = \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{3}} \right)$$

$$\beta = \frac{\bar{x}}{\alpha}$$

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$$

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}$$

$$(H) = q + (1 - q)G(x)$$

Where α (shape factor) parameter of the gamma probability density function, β (Scale factor) parameter of the gamma probability density function, n is the number of precipitation observations, and $\bar{x}$ Is the mean precipitation.

Table 3. Characterization of drought intensity based on standardized precipitation index

SPI Value	Description
2.0 and greater	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-.99 to .99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2.0 and less	Extremely dry

3. **Results and Discussion**

To assess future drought events, precipitation data were obtained from eight GCMs from the Copernicus Climate Change Service Data Store (Table1). The performance CMIP6 models' evaluation models were under taken using Spatial average rainfall with respect to ENACTs using volumetric statistical technique. The result indicated the CDF of Ensemble of individual models' value close near to ENACTs distribution. therefore, Ensemble individual models were considered best performing rainfall data for future drought assessment over the study area(Figure 5). Ensemble of multiple models indicated better performance over individual members [33,87]. Future assessment of precipitation, temperature, and drought condition were under taken with a multi-model ensemble [75,76]. The statistical metrics ranks approach indicated that Ensemble model was selected best performing with correlation coefficient ($r = 0.317$) and R^2 (0.032), RMSE (3.394), and PBIAS (-0.867%) relative to the individual models for future drought assessment. According [77], multiple CMIP6 models performance evaluation undertaken and ranked using similar ways for future climate change assessment. The finding of this study was consistent with [35] that CMIP6 performance was evaluated for future drought assessment with standardized precipitation index. Five statistical performance metrics and ranking technique were applied for CMIP6 for future climate change assessment over upper bule nine basin [78]. Overall, Ensemble of multiple models was selected using both model performance evaluation approach therefor Ensemble model best performing than individual models. Individual models either under estimate/overestimate future climate conditions; therefore, the multi-model ensemble reduces the bias [79]. Climate models inherently have systematic errors; therefore, a bias correction approach is necessary to reduce errors and adjust model output with observation data [78–80]. For the study empirical quantile mapping bias correction technique was applied. The CDF value indicated the difference between before and after correction future bias correction and improved future rainfall data at Lon and Lat location provided for future drought assessment with standardized precipitation index Figure. Bias correction improves data quality and representation of local-scale climate features [81–82].

Spatial Average

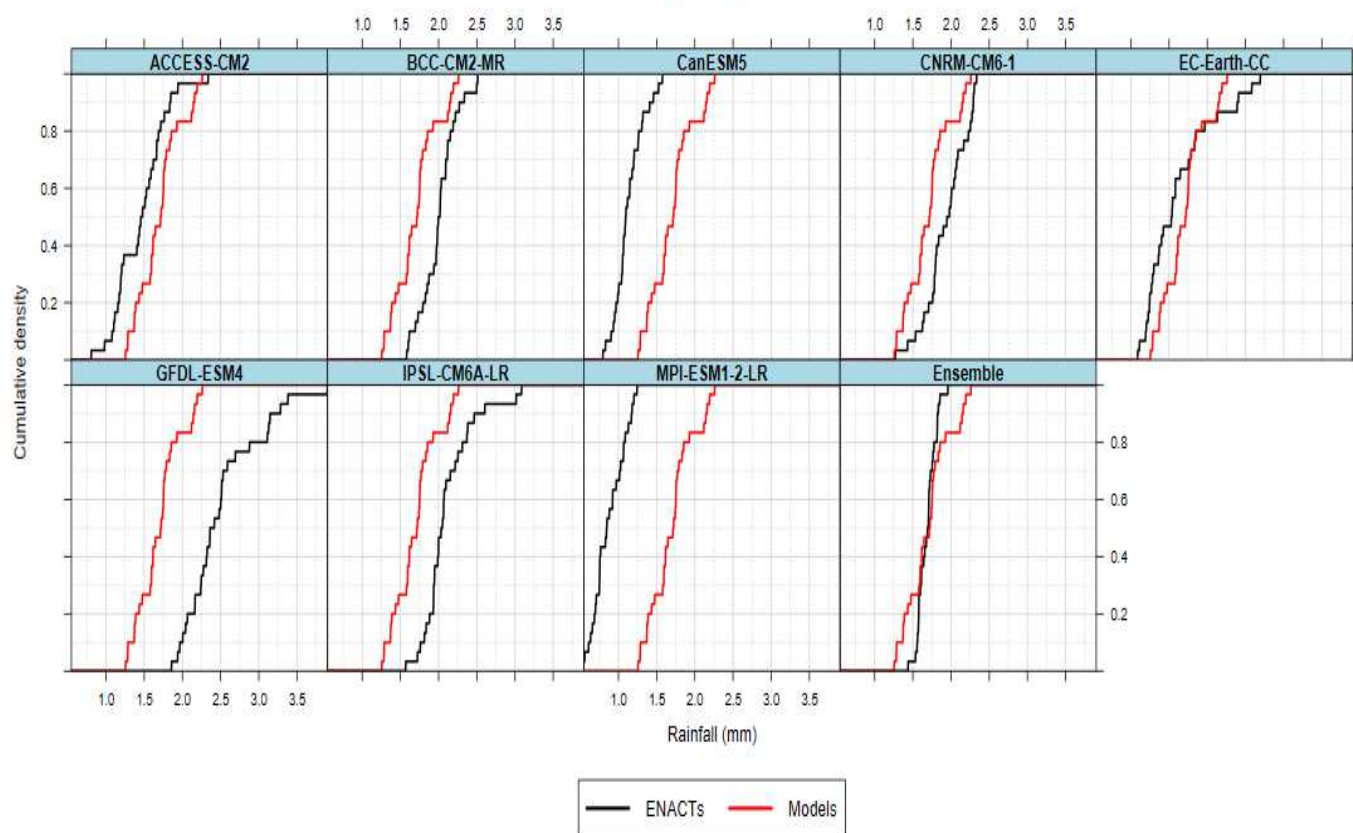


Figure 1 performance evaluation of CMIP6 model data against ENACTS using spatial average approach

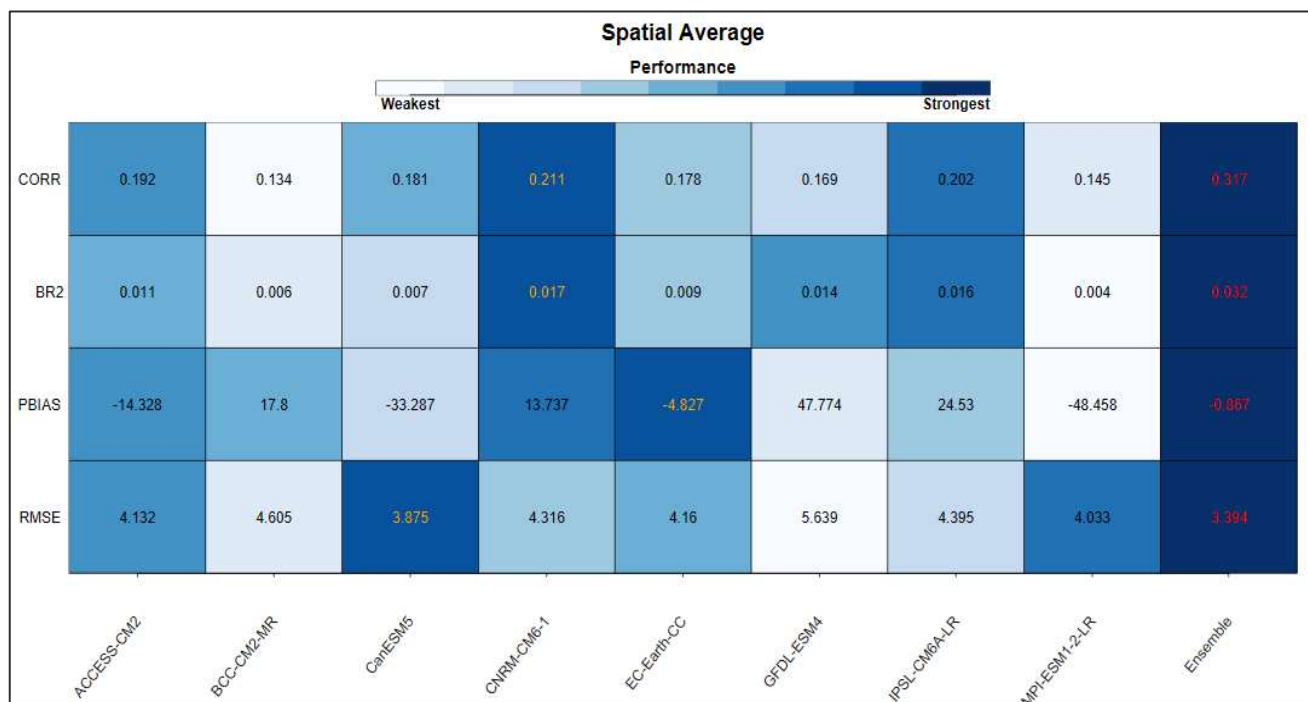


Figure 2: performance evaluation and ranking of CMIP6 models compared with ENACTs using Statistical metrics statistical metrics

CDF Plots of Rainfall for Randomly Selected Lat: 39.5 Lon: 4.9

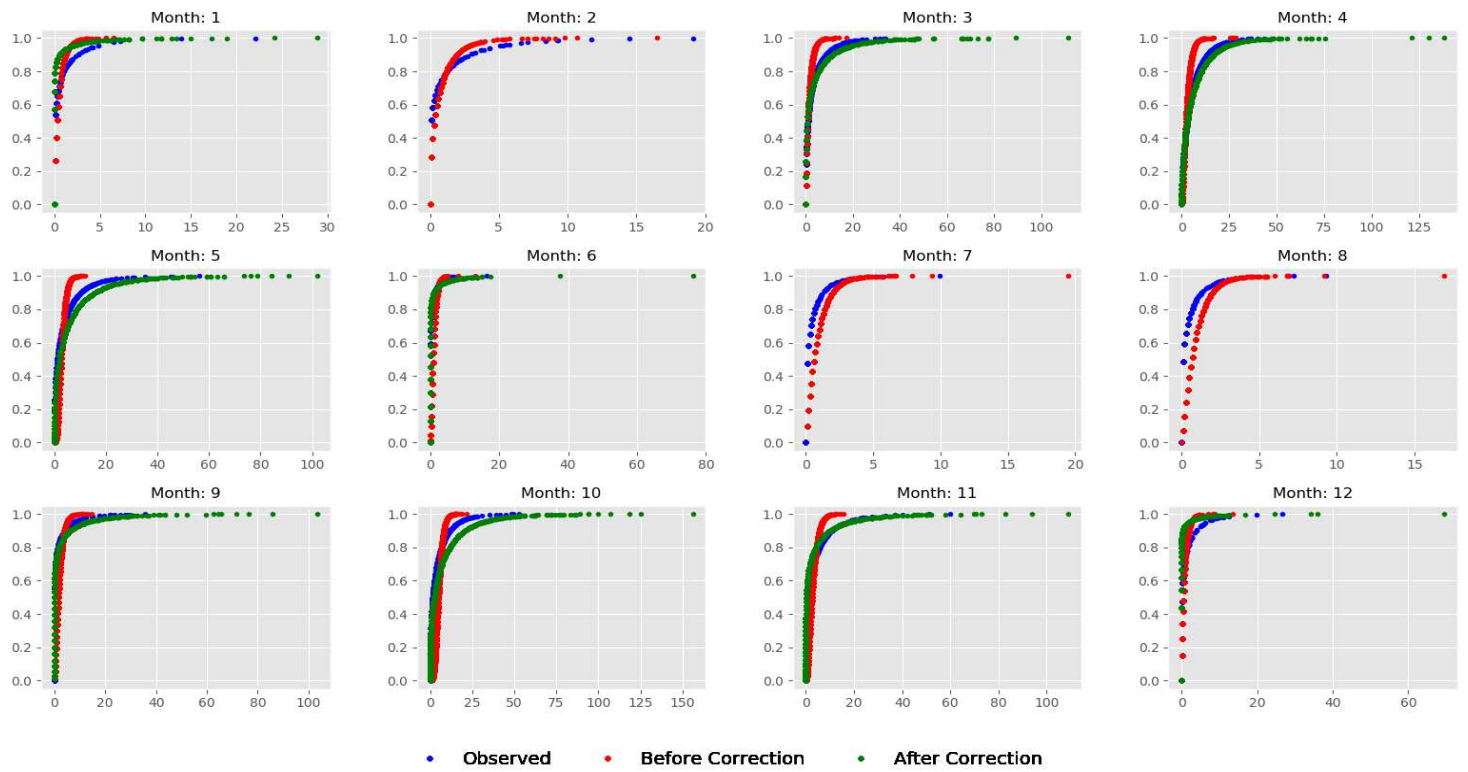
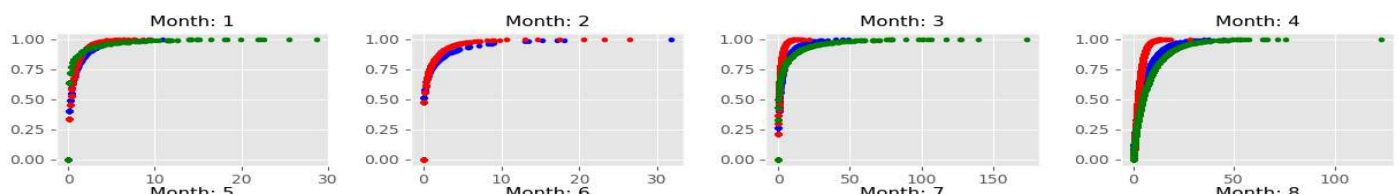


Figure 3: Cumulative distribution functions (CDF) of future rainfall before and after bias correction of selected Ensemble CMIP6 model Using Empirical quantile mapping method with respect ENACTs.

CDF Plots of Rainfall for Randomly Selected Lat: 40.2 Lon: 5.7



3.1. Future Drought Assessment using SPI-3(MAM)

Future drought conditions were analyzed using SPI-3 for (March-April-May) months under SSP2- 4.5 and SSP5-5.8 scenarios across nine districts over the study area. Under the SSP2-4.5 scenario, very wet (VW) conditions were projected occurs in Arero(3), Dhas(2), Liben (2), Medawelabu (1), Negele (2), Whereas Moderately wet (MW) will also expected Dhas(1), Gorodola(3), Gumiidalo(1), Liben(2), Medawelbu (4), Wachile (3), Westwelabu (2) in years. The remaining years are predominantly projected in Near Normal (NN) category across the districts Table3. Under SSP5-8.5 scenario, VW condition were projected Arero(1) dhas (1) ,whereas MW conditions were projected Dhas (1), Gorodola (1) Liben (1) Medawelabu (1), Negele(1), Wachile (1), West Welabu(1) in years. The computed SPI-3(MAM) indicated Near Normal category with ranging 26 to 28 years under both scenarios with limited wet and dry conditions. Previous Studies on future drought projection exhibited predominant with Near Normal and limited wet years [85–87]. The future drought events under CMIP6 scenarios more inclined in Near Normal condition [88]. In Near-future period, drought occurrence and intensity characterized by less frequent [89–91]. The frequency of drought decrease relative to historical period under SSP2-4.5 and SSP5-8.5 scenarios in the near future period [34]. Future drought assessment using SPI revealed that wet and dry events are expected [92]. Future GHG emissions associated with human activities increase precipitation; this in turn, improves wet conditions over specified areas [93]. Subsequently, predominantly Near Normal year with limited wet and dry years were exhibited insignificant increases in future precipitation. Under SSP2-4.5 scenario during the far-term (2071-2100) SPI-3 (March-April- May) revealed EW events Arero (2), VW event Arero (4) and Dhas(4), whereas MW events Arero (5) Dhas(9) Gorodola (7), Gumiidalo (10), Liben (9), Medawelabu (10), Negele (9) Wachile (9) Westwelabu (9) in years. Under SSP5-8.5 scenario during the far-term (2071-2100) SPI- (March-April-May) showed EW events Arero(3), Dhase (4), Liben (1), Medawelabu (1), Negele (1) Wachile (1) VW events Arero (3), Dhas(3), Gorodola (4), Gumiidalo (3) Liben (4) Medawelabu (3) Negel (3), Wachile(3) Westwelabu (4) in years. In the far-future period, a high amount of greenhouse emission contributing rainfall intensity, which in turn modulates drought status [94]. Under CMIP6 scenarios a warmer atmosphere contributing for wetter condition accounts 13-30% far- future period [2]. Under SSP2-4.5 and SSP5-8.5 scenarios precipitation is projected to increase in annual and seasonal timescales for the far-future period across Ethiopia [2]. Drought occurrence is projected to decrease over specific areas during the near-future period [95]. Trend of future drought of SPI-3(MAM) showed both significant and non-significant increasing trend under the SSP2-4.5 near term (2041-2070) period generally predominantly toward near normal condition Figure 8. Future drought severity and occurrence assessment based on SPI and SPEI under climate change scenario indicate variability across Ethiopia [96]. According to [97] future precipitation expected to increase under future climate scenario reduce the occurrence drought based standardized precipitation index. Future drought based on SPI under the SSP5-8.5 during the near term period (2041-2070) is projected predominantly near normal with increasing trend across most stations Figure 9. Future precipitation is projected to increase by 18% (SSP2-4.5) and 41% (SSP5-8.5) scenarios relative to the baseline period (1991-2020) associated with climate change impact [98]. The SPI value under the SSP2-4.5 during the far-term (2071-2100) period were predominantly near normal with significantly decreasing trend across most stations, this suggests near normal shifts to dry condition across most stations Figure 10. According to [99], higher amount rainfall is projected over highland areas whereas less amount over low land areas, this suggests future drought occurrence vary with spatial scale.

Under the SSP5-8.5 scenario during the far-term (2070-2100) SPI value indicates predominantly near normal with significantly increasing trend across most stations Figure 11.

Stations	SPI-3 index MAM near-term years (2041-2070)						SPI-3 index (MAM) far-term years (2071-2100)						
	Scenarios SSP-2 4.5			Scenario (SSP-58.5)			Scenarios SSP-2 4.5				Scenario (SSP-58.5)		
	SPI index years)			SPI index years)			SPI index(years)				SPI index years)		
	VW	MW	NN	VW	MW	NN	EW	VW	MW	NN	EW	VW	NN
Arero	3		27	1		29	2	4	5	19	3	3	24
Dhas	2	1	27	1	1	28		4	9	17	4	3	23
Gorodola		3	27		1	29			7	23		4	26
Gumidalo		1	29			29			10	20		3	27
Liben	2	2	26		1	29			9	21	1	4	24
Medewelabu	1	4	25	1	1	28			10	20	1	3	26
Negele	2		28		1	29			9	21	1	3	26
Wachile		3	27		1	29			9	21	1	3	24
WestWelabu			30		1	29			9	21		4	26

Table 4: SPI-3 for March–May (MAM) under SSP2-4.5 and SSP5-8.5 across stations in the study area.

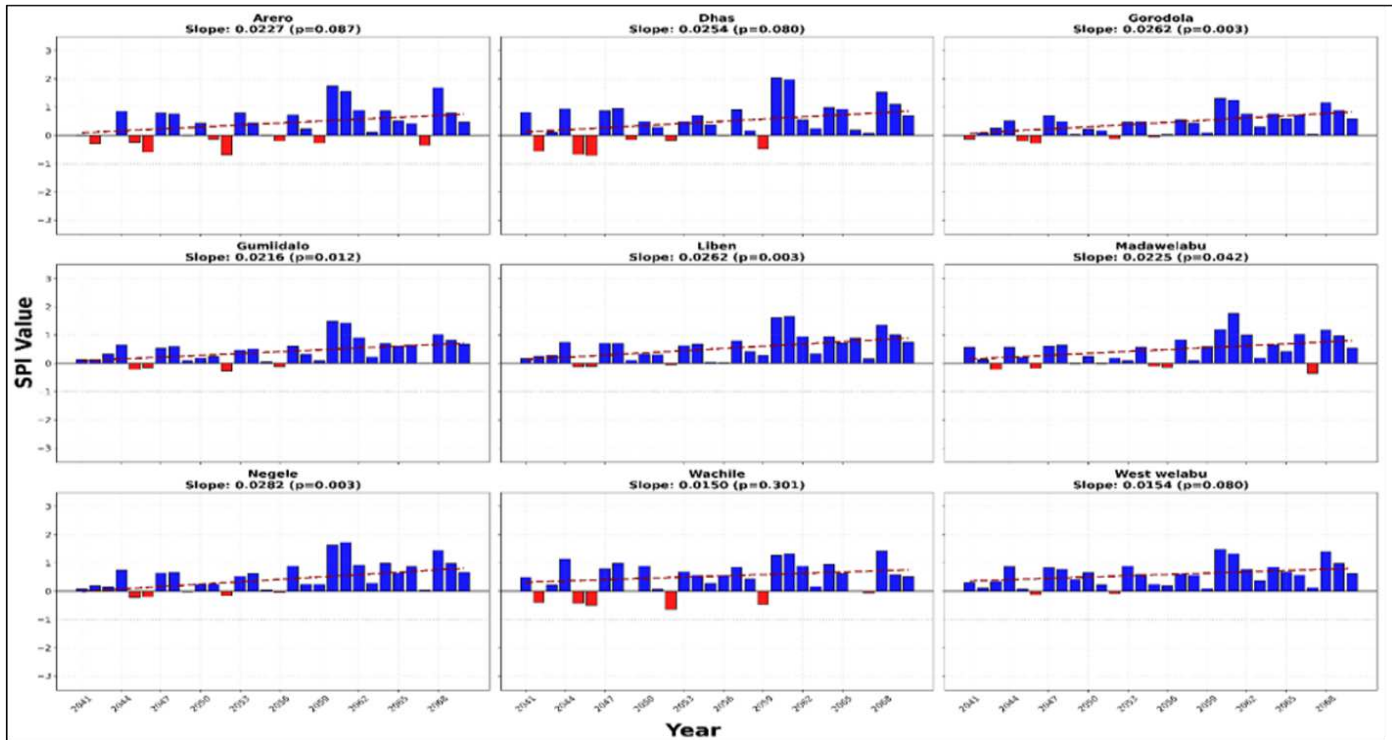


Figure 4: Future drought intensity during near-term (2041-2070) for (March–May) under the SSP2-4. Scenarios based on Standardized precipitation index across stations.

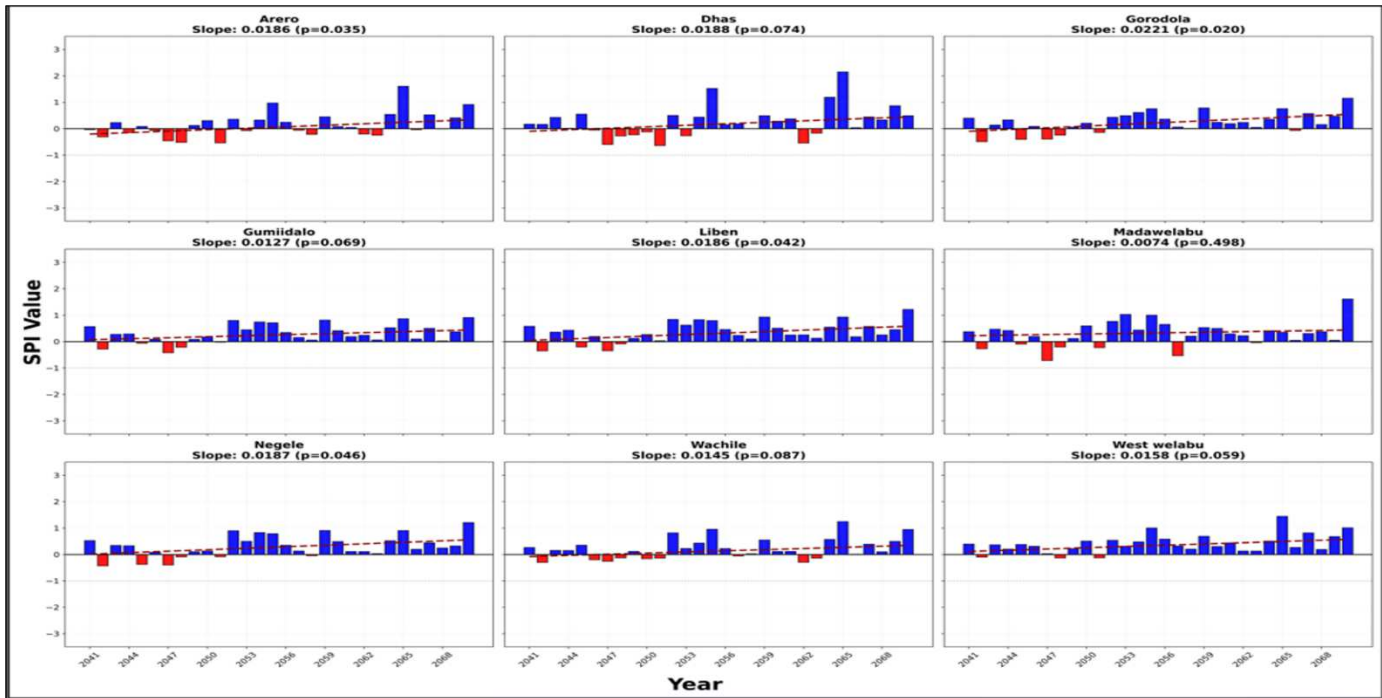


Figure 5: Future index across sta

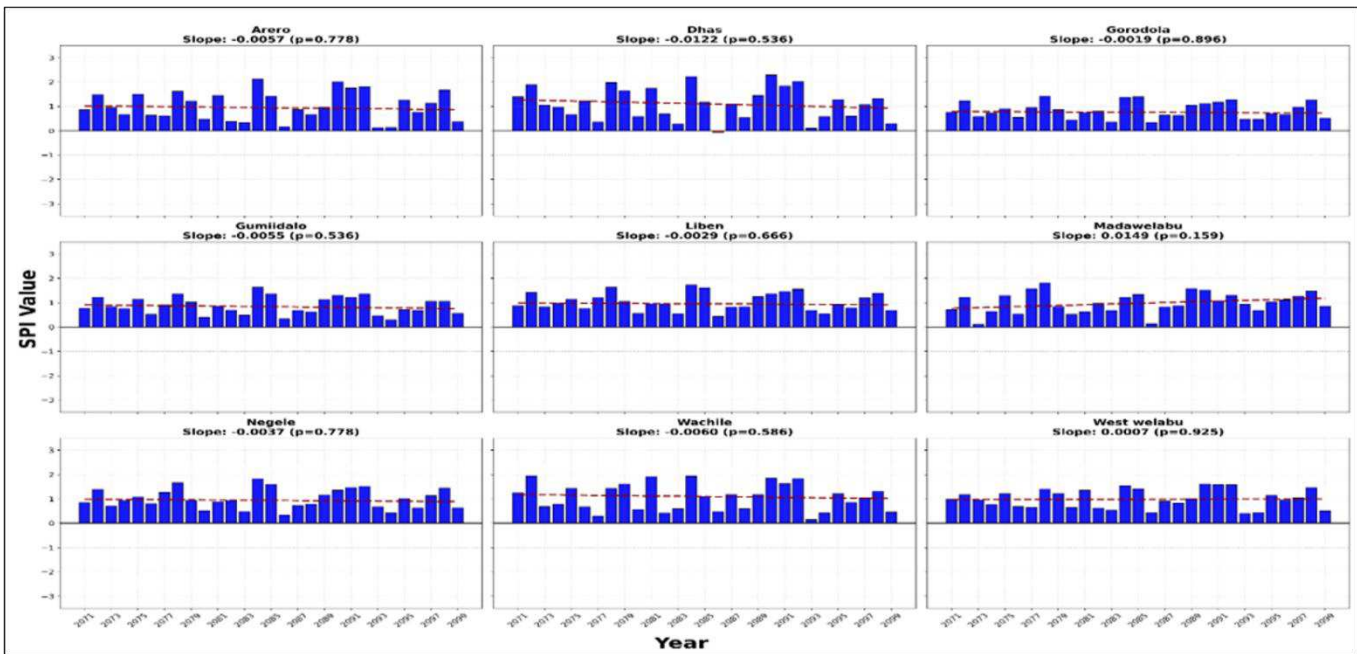


Figure 6: Future drought intensity during the far-term period (2071–2100) for (March–May) under SSP2-4.5 scenario based on Standardized precipitation index across stations.

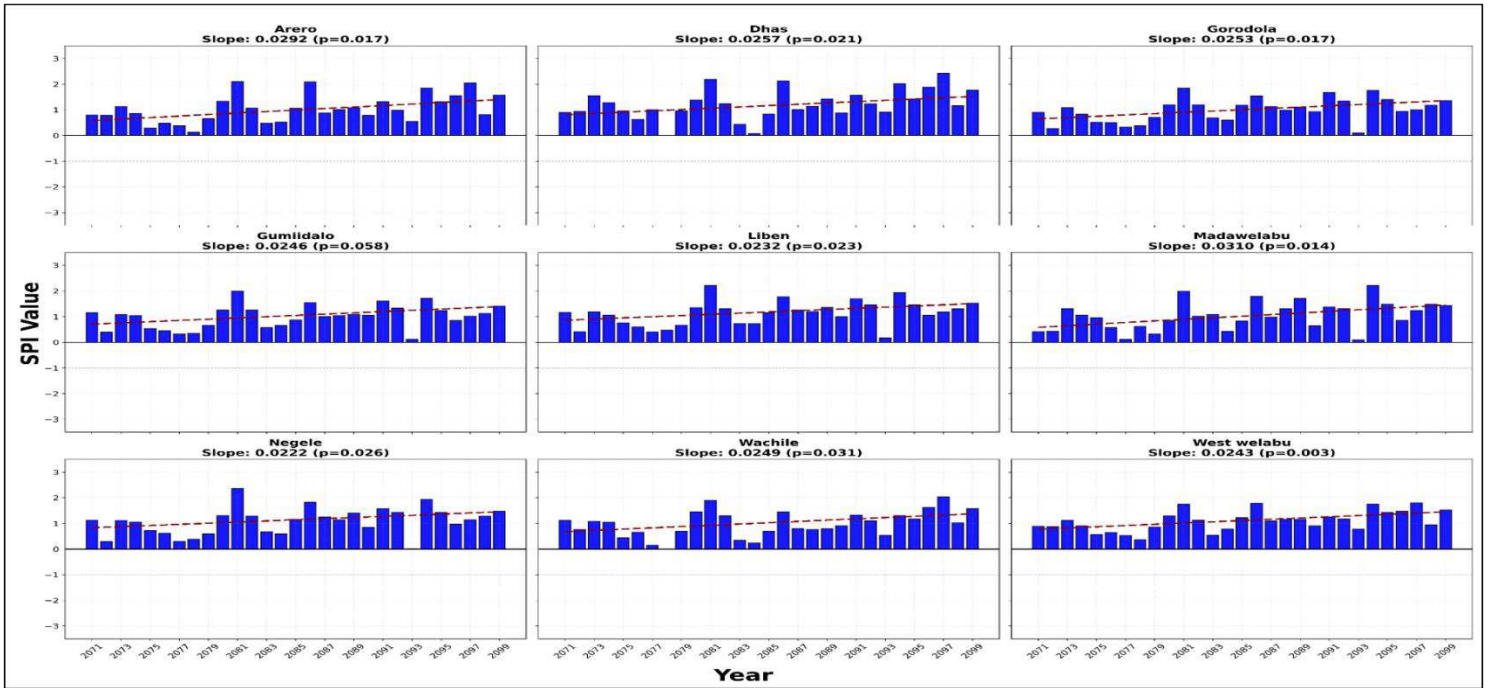


Figure 11: Future drought intensity during the far-term period (2071–2100) for (March–May) under SSP5-8.5 scenario based on Standardized precipitation index across stations.

3.2. Future Drought Assessment Using SPI-3(SON)

Future SPI-3 (September–November–December) phenomena were assessed under the SSP2-4.5 and SSP5-5.8 scenarios across nine districts during the near-term (2041–2070) period. Under the SSP2-4.5 scenario SPI-3 very wet (VW) events were expected Gumiidal (1), moderately wet (MW) events were expected Arero (2), Dhas (2), Gorodola (1), Liben(1), Medawelabu (1), Negele (1), Wachile (2) in years whereas, moderately dry (MD) events were expected Arero(1), Liben(1), Negele(3) and Wachile(2) districts in years Table 5. Under SSP5-8.5 moderately wet (MW) events were expected Arero(1) Dhas(2), Medawelabu (2), Wachile (1) years. Conversely, moderately dry (MD) events were expected Dhas(1), and severely dry (SD) Dhas and West Welabu in years. Subsequently, both scenarios SPI-3(SON) Near Normal (NN) events, were predominantly expected. Drought trends declined across selected stations under SSP5-8.5 during far-term future period[100]. During the far-term period (2071–2100) under the SSP2-4.5 scenario, very wet (VW) events were expected Arero(2), Dhas(2), Liben(1), and moderately wet(MW) were expected in Arero(6), Dhas(2), Gorodola(3), Liben(1), Medawelabu (3), Negele (1), and Wachile(1) in years. Under the SSP5-8.5 extremely wet (EW) events were expected Arero(2), Dhas(2), very wet (VW) events were expected in Arero(3) ,Wachile(2), moderately wet (MW) event were expected in Arero(11), Dhas (8), Gorodola(2), Gumiiodalo (2), Liben (1), Medawelabu (4), Negele (1) ,Wachile (3) while the remaining years were projected near normal (NN)events Table 5. Future drought index revealed predominantly near-normal events, with limited wet and dry events. This suggests future precipitation pattern expected to be less variable [101–103].

Future drought assessment SPI-3(SON) under the SSP2-4.5 scenario during the near-term period (2041-2070) is predominantly near normal index with increasing trend across most stations Figure 12. Future drought assessment SPI-3(SON) under the SSP5-8.5 scenario during the near-term period (2041-2070) is predominantly near normal index with non-significantly increasing trend across most stations Figure 13. Future drought assessment SPI-3(SON) under the SSP5-8.5 scenario during the far-term period (2071-2100) is predominantly near normal index with non-significantly increasing trend across most stations Figure 14 .

Table 5: Standardized Precipitation index SPI-3(SON) SSP-2 4.5 and SSP-5 8.5 scenarios

Stations	SPI-3 (SON) Near term (2041-2070)								SPI-3 index (SON) far term (2071-2100)							
	Scenarios SSP-2 4.5				Scenario (SSP-58.5)				Scenarios SSP-2 4.5				Scenario (SSP-58.5)			
	SPI index(years)				SPI index (years)				SPI index(years)				SPI index (years)			
	VW	MW	MD	NN	MW	MD	SD	NN	VW	MW	NN	EW	VW	MW	NN	
Arero		2	1	27	1			29	2	6	21	2	3	11	13	
Dhas		2		28	2	1	1	26	2	2	25	2	1	8	18	
Gorodola		1		29				30		3	26			2	27	
Gumiidalo	1			29				30			29			2	27	
Liben		1	1	28				30	1	1	27			1	28	
Medewelabu		1		29	2			28	1	3	25			4	25	
Negele		1	3	26				30		1	28			1	28	
Wachile		1	2	27	1			29		1	28		2	3	24	
WestWelabu				30			1	29							30	

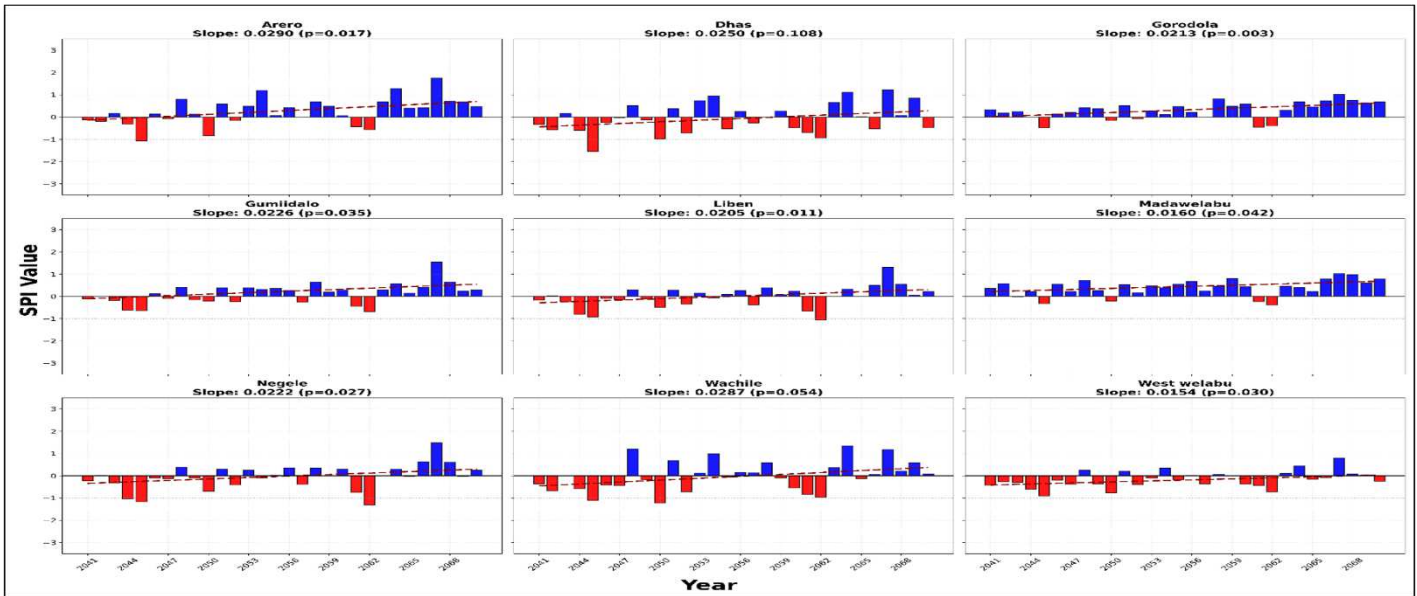


Figure 7: Future drought intensity during the near-term period (2041–2070) SPI-3 for (Sep-Nov) under SSP2-4.5 scenario across stations over the study area.

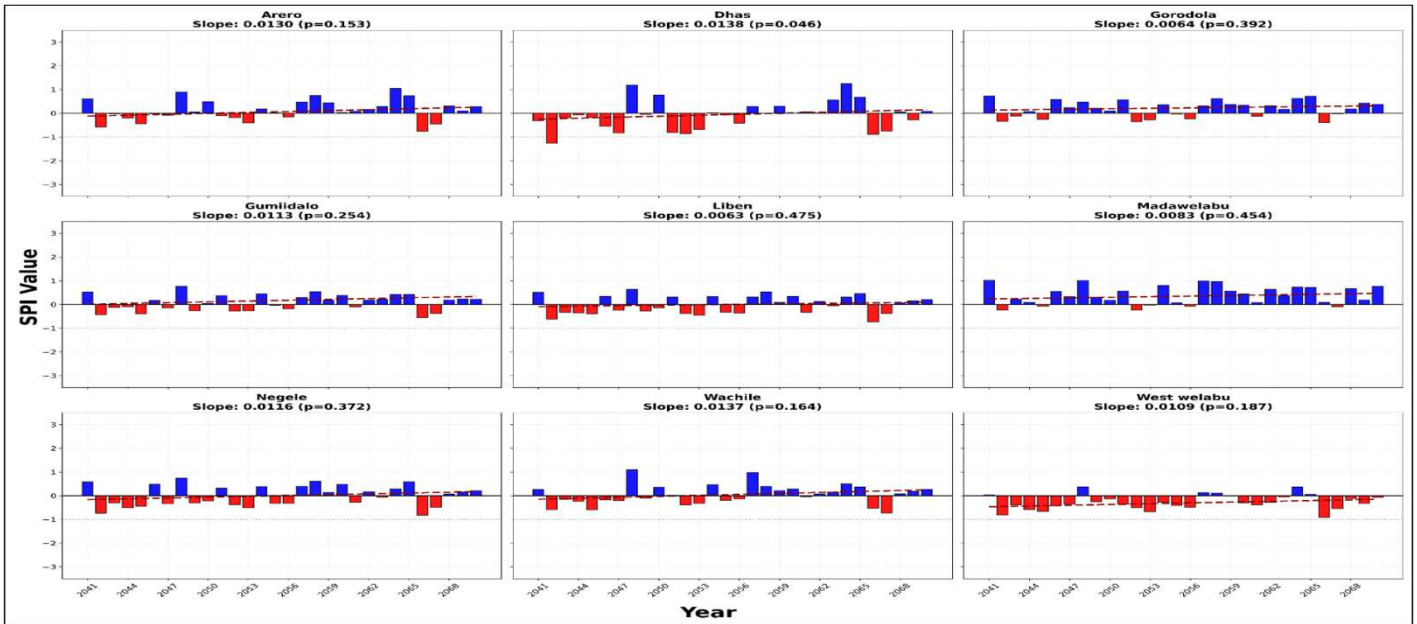


Figure 13: Future drought intensity during the near-term period (2041–2070) SPI-3 for (Sep-Nov) under SSP5-8.5 scenario across stations over the study area.

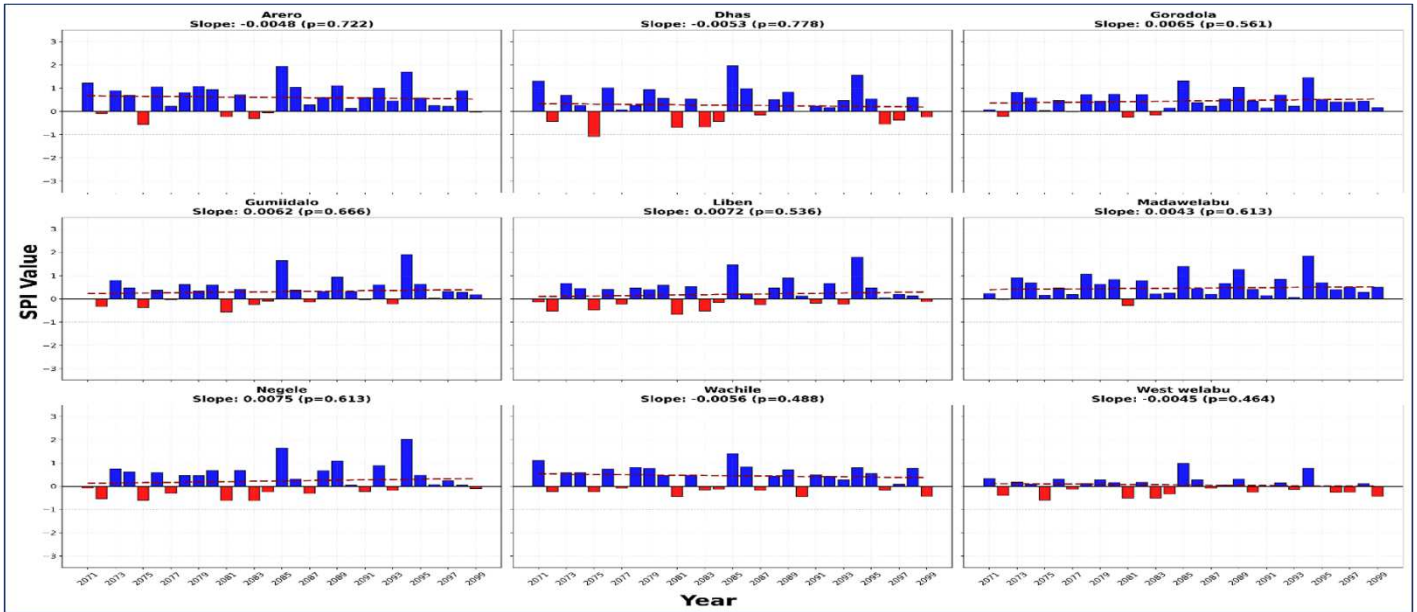


Figure 14: Future drought intensity during the far-term period (2071–2100) SPI-3 for (Sep-Nov) under SSP2-4.5 scenario across stations over the study area.

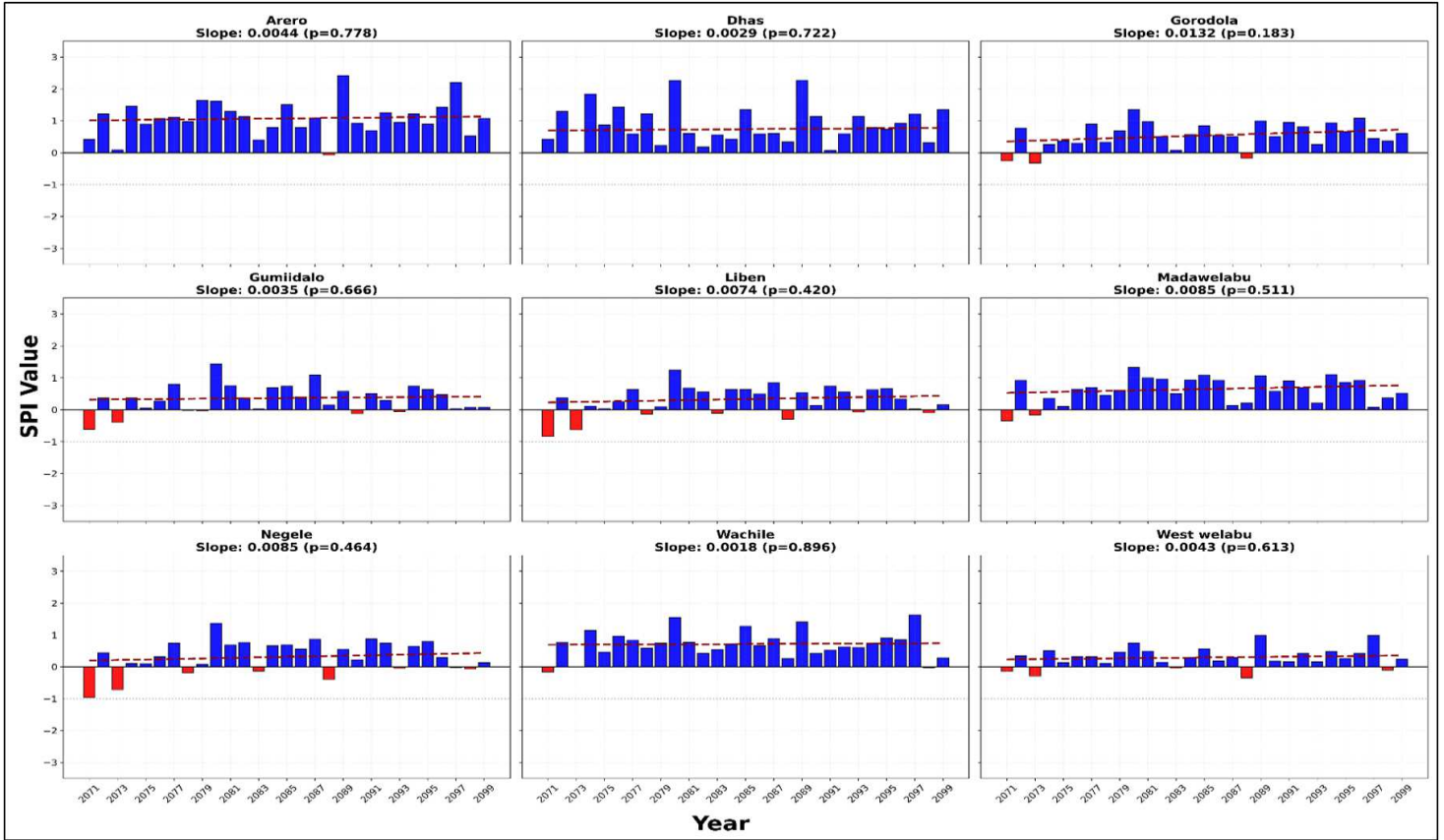


Figure 8: Future drought intensity during the far-term period (2071–2100) SPI-3 for (Sep-Nov) under SSP5-8.5 scenario across stations over the study area.

3.3. Future Drought assessment using SPI-6 (March -August)

Future SPI-6 (March-August) drought events were projected under the SSP2-4.5 and SSP5-8.5 scenarios across nine districts during the near-term (2041-2070) and far-term (2071-2100) periods. SPI-6(March-August) under the SSP2-4.5 and SSP5-8.5 scenarios revealed predominantly near-normal conditions, with limited wet and dry events expected. Future drought was projected dominantly Near normal year sporadic wet and dry years were identified[104]. SPI-6 drought index under the SSP5-8.5 scenario revealed near-normal conditions predominantly, combined with slight dry and wet events projected[105]. Drought occurrence and intensity may reduce during the future period [106]. Subsequently, SPI-6(March-August) during the far-term period under both scenarios revealed several years near normal with sporadic wet and dry events. Under SSP2-4.5 future near term period SPI-6 (March-August) exhibited increasing wet trend across most station over the study area Figure 16. Under ssp5-8.5 scenarios during the near-term future drought spi-6(March-August) exhibited increasing wet trend across most stations over the study area Figure. Under ssp2-4.5 scenario future

SPI-6(March-August) during far term period projected slightly increase wet condition across most stations Figure 18. Under ssp5-8.5 scenario future SPI-6(March-August) during far term period projected increase wet condition across most stations over the study area Figure 19.

Table 6:Standardized precipitation index SPI-6(March-August) under the SSP-2 4.5 and SSP-5 8.5 Scenarios

	SPI-6index (March -August) near term years (2040-2070)										SPI-6index March -August) far term years (2071-2100)							
	Scenarios SSP-2 4.5					Scenario (SSP-58.5)					Scenarios SSP-2 4.5				Scenario (SSP-58.5)			
	SPI index(years)					SPI index years)					SPI index(years)				SPI index years)			
Stations	EW	VW	MW	SD	NN	VW	MW	SD	MD	NN	EW	MW	MW	NN	EW	VW	MW	NN
Arero		2		1	27	1	1			29		5	6	18		4	6	19
Dhas		1	1	2	26		1			29	1	6	2	20		5	11	13
Gorodola			2		28		1		1	28			9	20	1	7	4	17
Gumiidalo		2	1	1	26					30		1	9	19	1	7	7	14
Liben		2	1		27		2			28		2	10	17	3	5	7	14
Medewelabu		2	1		27	1		1	1	27		5	5	19	3	4	6	16
Negele		2	1		27		1			29		1	10	18	3	4		22
Wachile		2	1		27		1			29		7	5	17	1	4		24
WestWelabu	1	1			22		1			29		5	7	17		9		20

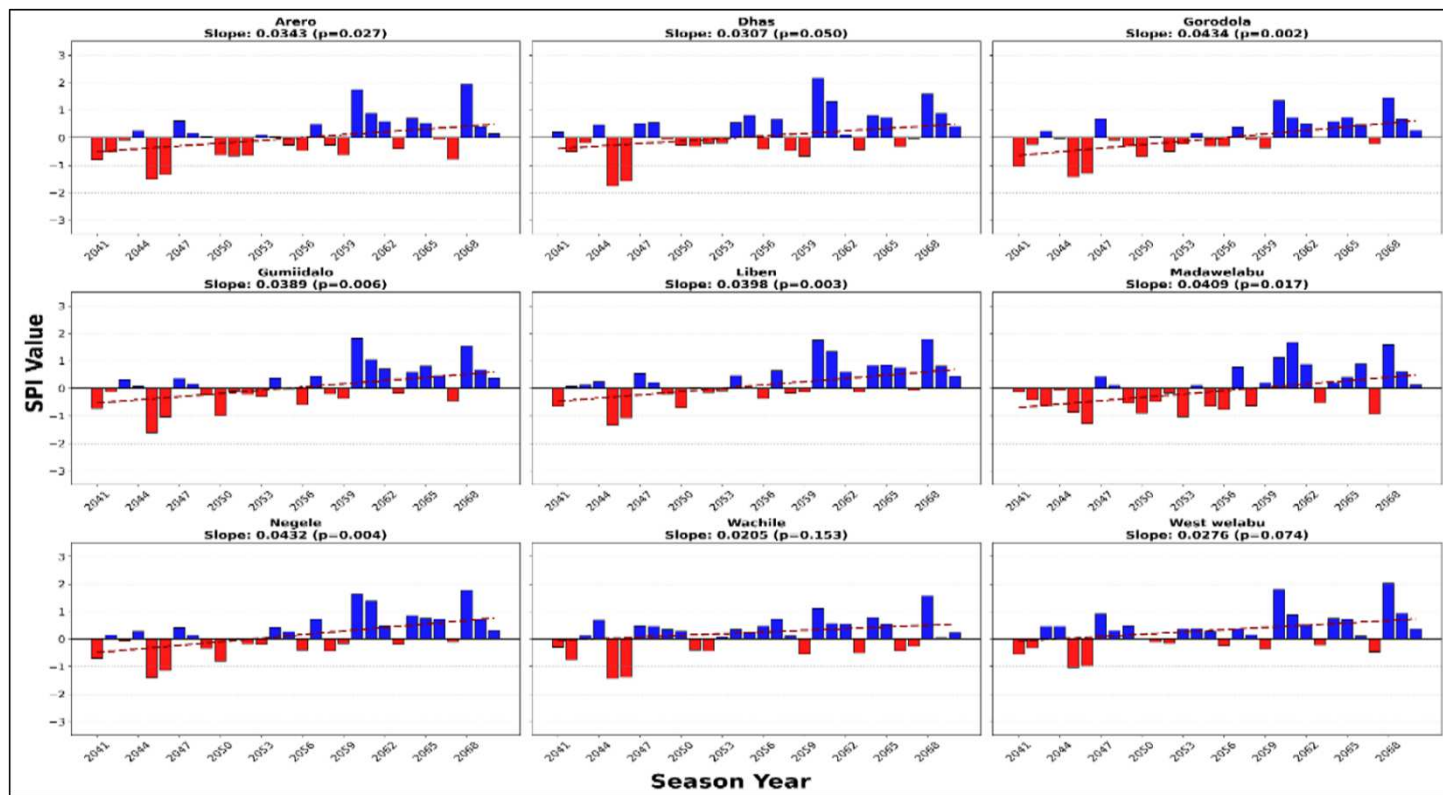


Figure 9: Future drought intensity during the near-term period (2041–2070) SPI-6 for (March–August) under SSP2-4.5 scenario across stations over the study area

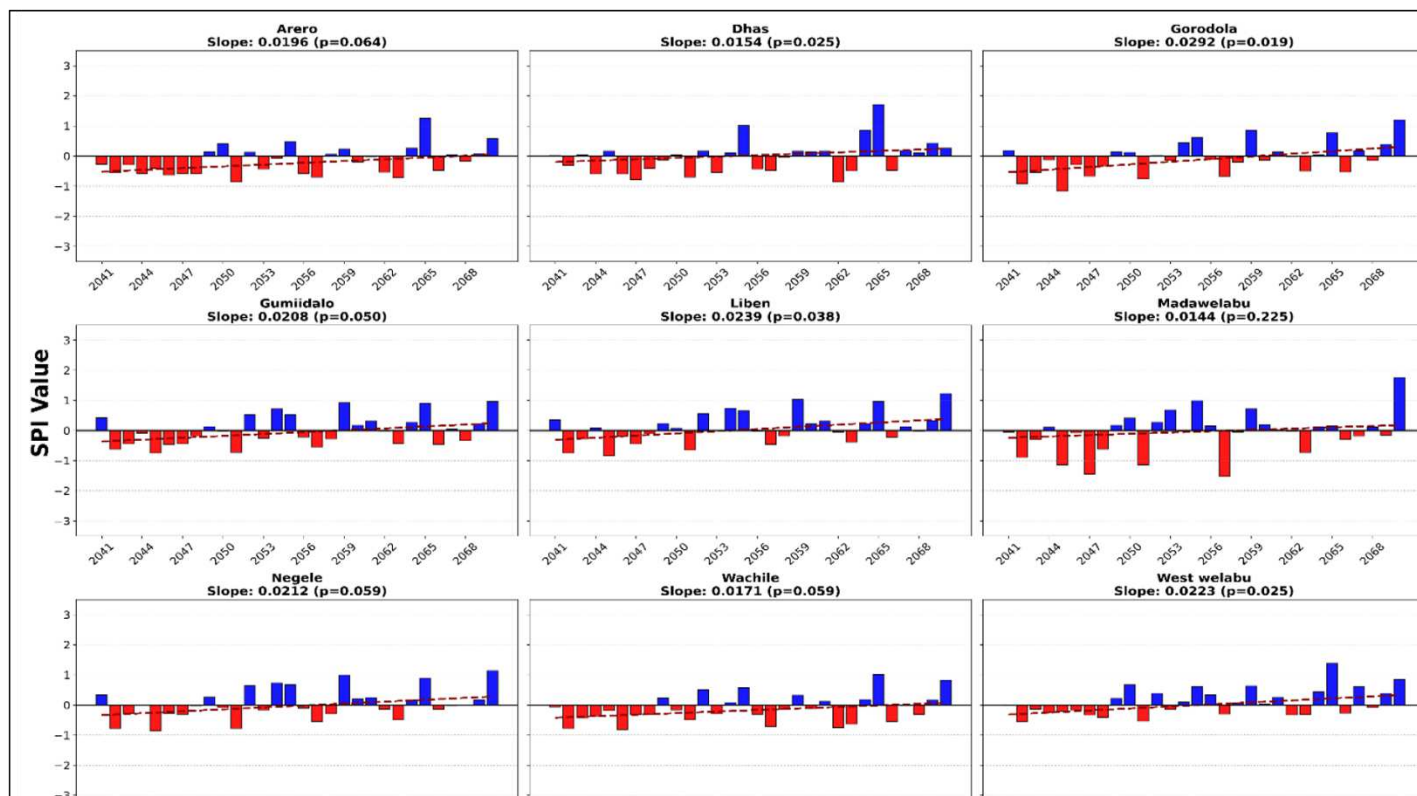


Figure 17: Future drought intensity during the neat-term period (2041–2070) SPI-6 for (March–August) under SSP5-8.5 scenario across stations over the study area.

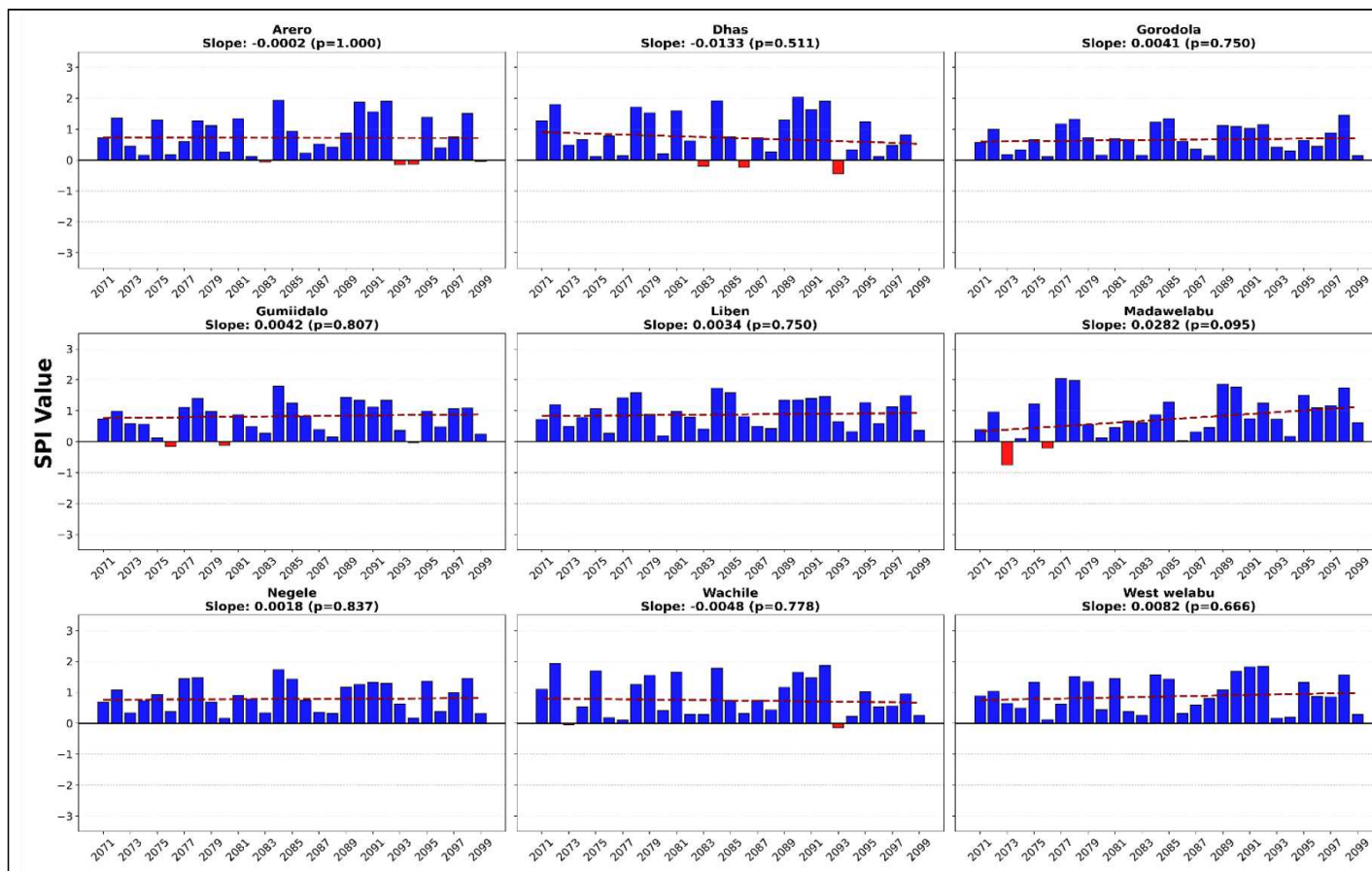


Figure 18: Future drought intensity during the far-term period (2071–2100) SPI-6 for (March–August) under SSP2-4.5 scenario across stations over the study area.

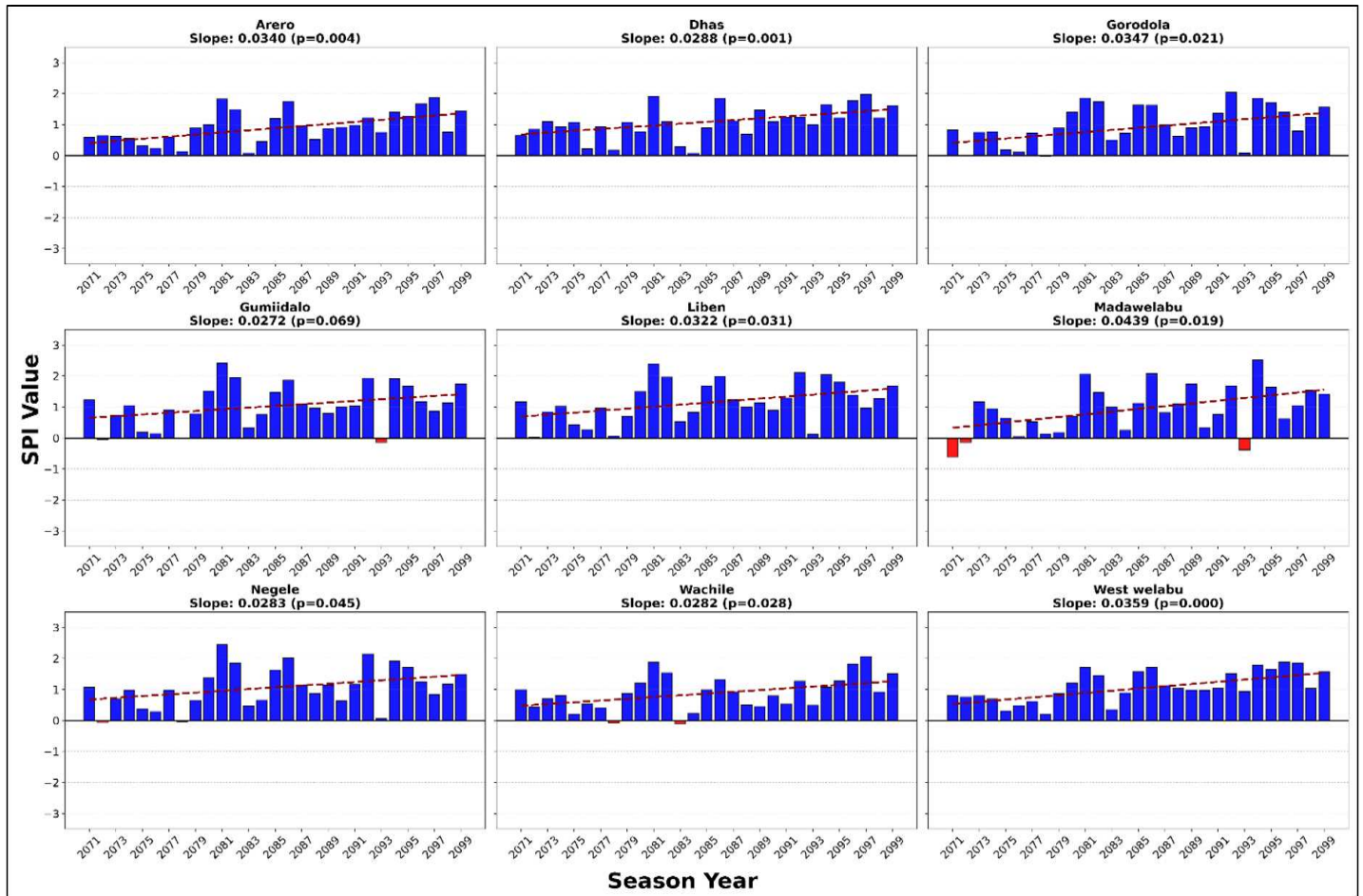


Figure 19: Future drought intensity during the far-term period (2071–2100) SPI-6 for (March–August) under SSP5-8.5 scenario across stations over the study area.

3.4. Future Drought Assessment Using SPI-6 (September–February)

SPI-6 (September–February) drought events under the SSP2-4.5 and SSP5-5.8 across nine districts in the near-term period (2041–2070) were projected dominantly as near-normal (NN), with limited wet and dry events. Future drought was projected dominantly near-normal, ranging from 22 to 29 years events combined with sporadic wet and dry conditions Table 7. The occurrence of both wet and dry events were projected under SSP2-4.5 and SSP5-8.5 scenarios during far and near-term periods[35]. Future drought projection exhibited an inconsistent pattern under the SSP5-8.5 scenario[76]. Overall, Near Normal (NN) events were projected during the near-term period, whereas during the far-term period wet events were projected to increase under SSP5-8.5 scenarios. Under SSP2-4.5 scenario SPI-6(September–February) during near term period trend test indicating wetter conditions over most stations over most stations Figure 20. Under ssp5-8.5 scenario future SPI-6(September–August) during near term indicating wetter condition across most stations over the study area Figure 21. Under ssp2-4.5 scenario during far future period decreasing trend over wachile

Dhase west welabu whereas the remaining stations exited increasing trends Figure 22. Under SSP5-8.5 during the fartern future SPI-6 indicates weak wet trend across most stations Figure 23.

Table 7:Standardized precipitation index SPI-6(September- February) SSP-2 4.5 and SSP-5 8.5 Scenarios

Stations	SPI-6 (September -February) (2041-2070)									SPI-6 (September -February) (20712099)									
	Scenarios SSP-2 4.5					Scenario (SSP-58.5)				Scenarios SSP-2 4.5					Scenario (SSP-5 8.5)				
	SPI index(years)					SPI index years)				SPI index(years)					SPI index years)				
	V W	MW	E D	MD	N N	V W	MW	MD	N N	EW	MW	MW	MD	NN	EW	VW	M W	MD	NN
Arero		1	1	3	26			1	29		2	3	1	23	1	2	9		15
Dhas	1		1	6	22		1	3	26		2	2	3	22		2	6		21
Gorodola		1		3	26			3	27	1	1	1	1	25			7		22
Gumiidalo			1	4	25		1	3	26	2		1	1	25		2	5		22
Liben	1			5	24			4	26	2		1	3	24			7	1	21
Medewelabu		1		3	26		3	1	26	1	2	1	1	24			7	1	21
Negele			2	4	24		1	4	25	2		2	3	22		1	7	1	20
Wachile	3				27	1		1	28			3		26		1	9		19
WestWelabu	1							2	28			2	1	26			4		25

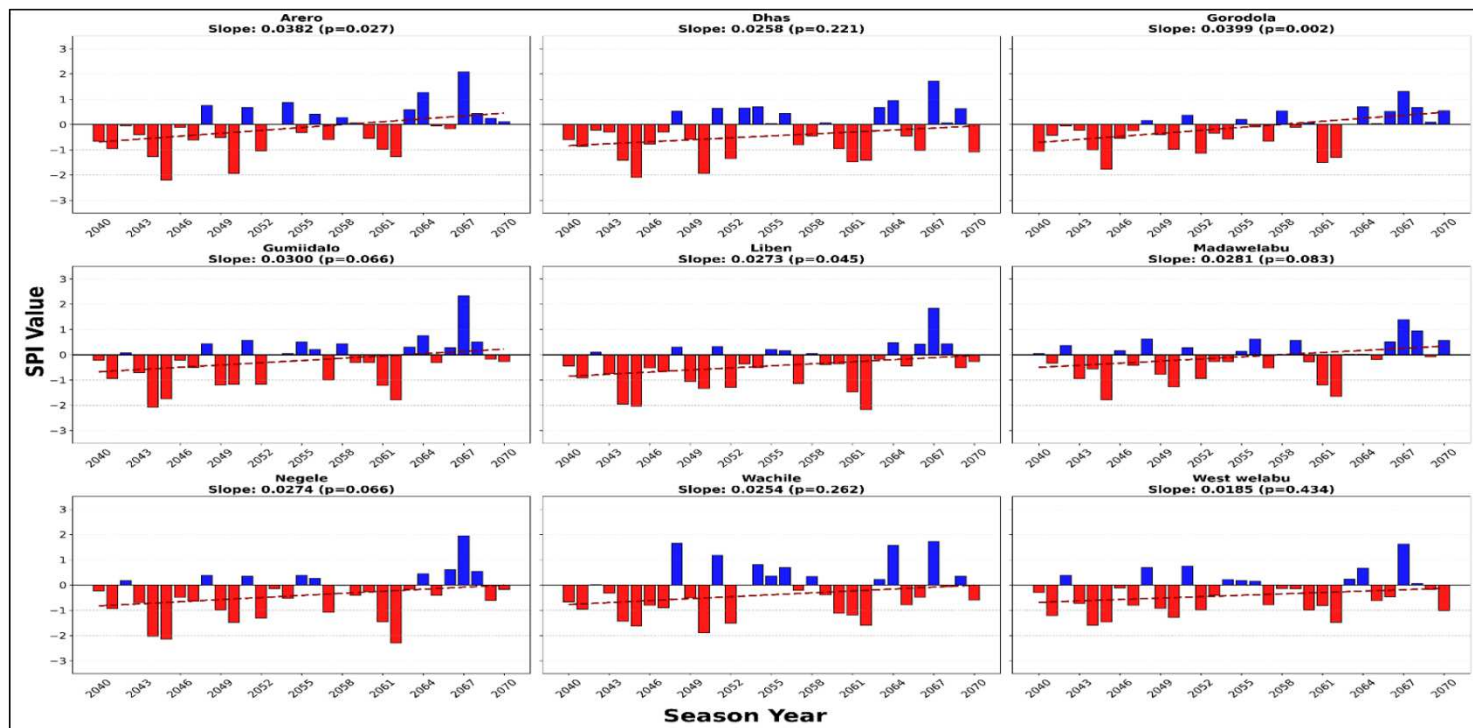


Figure 20: Future drought intensity during the far-term period (2040–2070) SPI-6 for (September–February) under SSP2-4.5 scenario across stations over the study area.

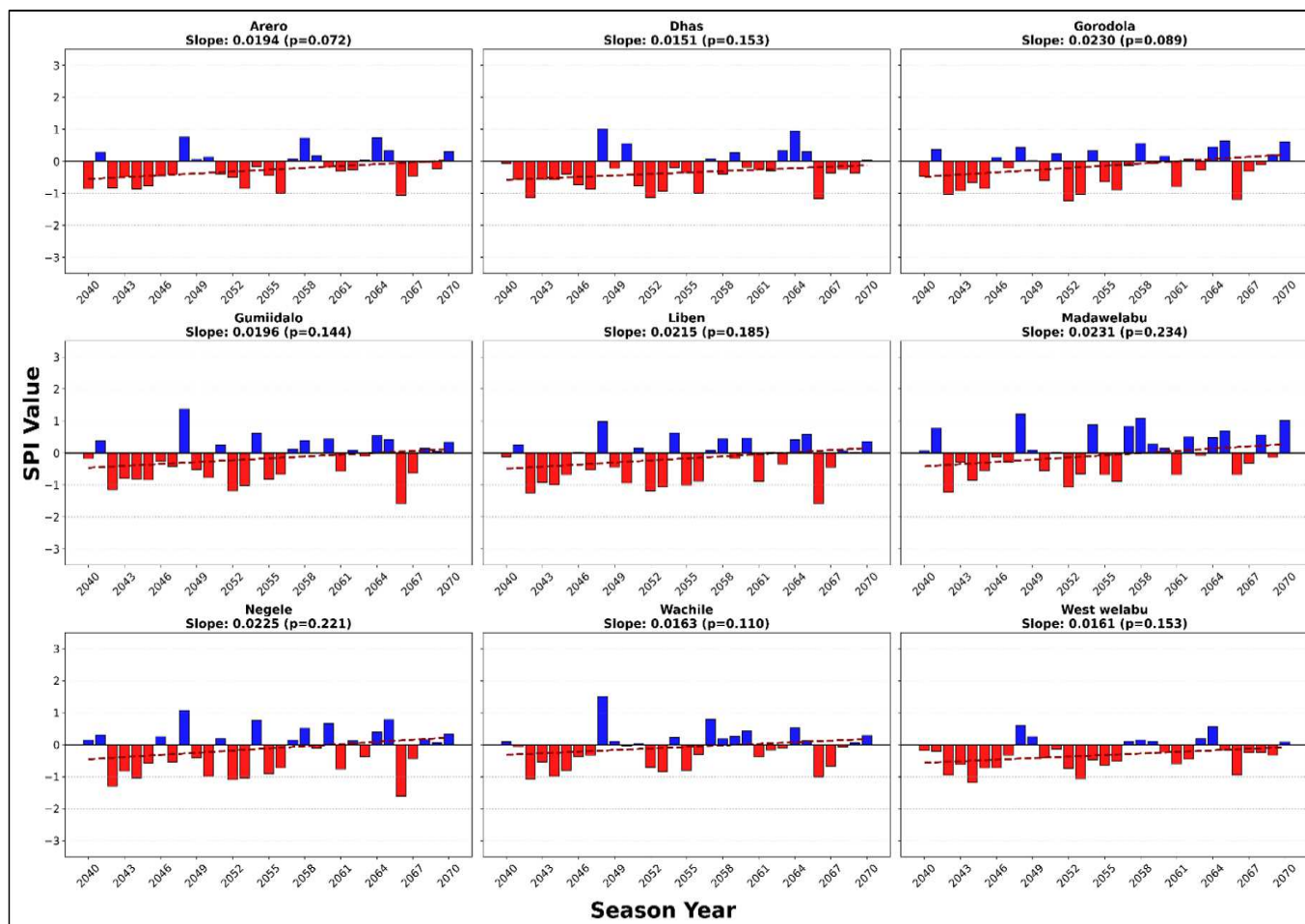


Figure 21: Future drought intensity during the far-term period (2040–2070) SPI-6 for (September-February) under SSP5-8.5 scenario across stations over the study area.

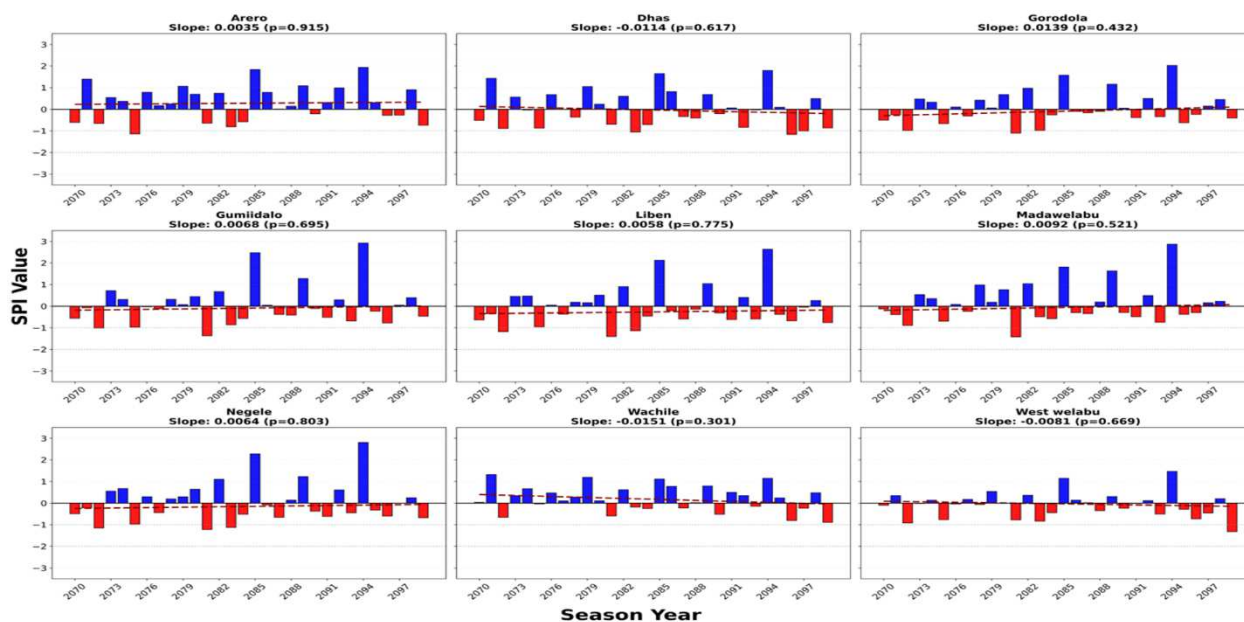


Figure 22 Future drought intensity during the far-term period (2071–2100) SPI-6 for (September-February) under SSP2-4.5 scenario across stations over the study area

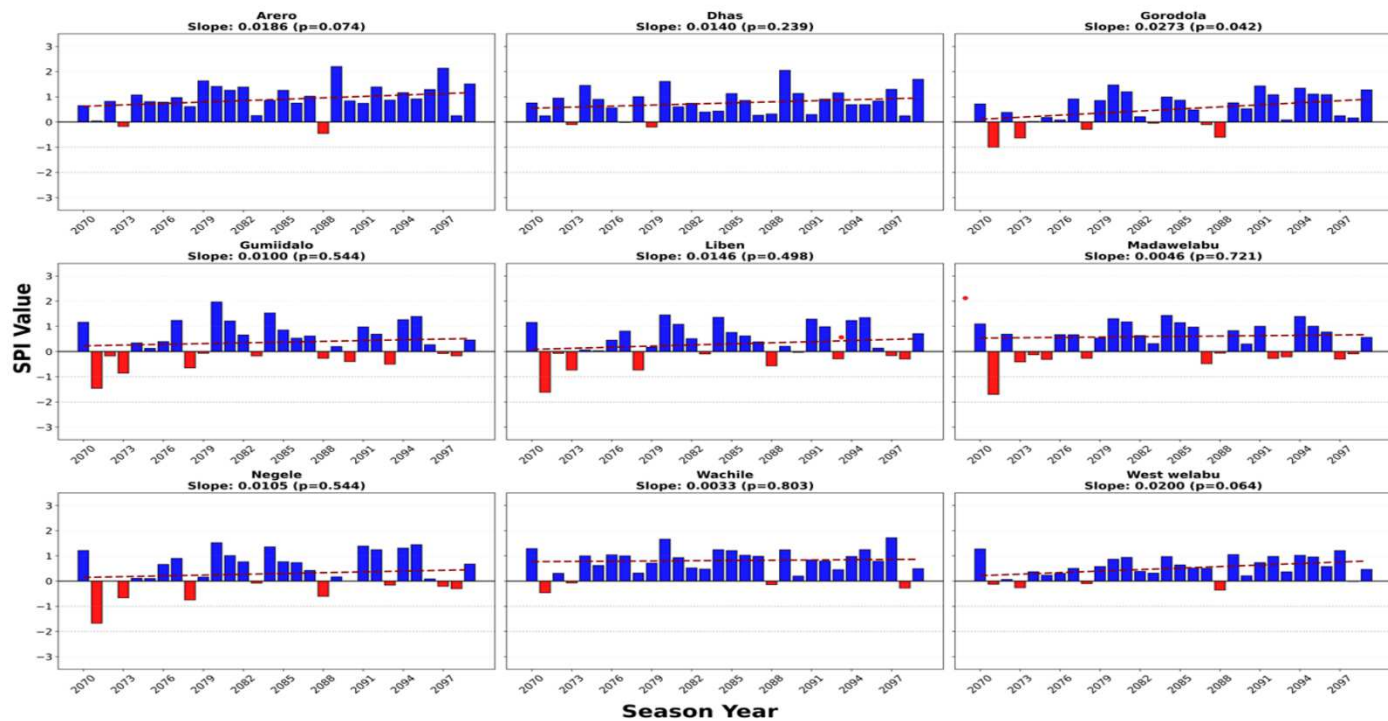


Figure 23: Future drought intensity during the far-term period (2071–2100) SPI-6 for (September–February) under SSP5-8.5 scenario across stations over the study area.

3.5. Future drought Assessment using SPI-12 (Annual) period

The annual SPI-12(September-August) was computed for near-term and far-term periods under the SSP2-4.5 and SSP5-5.8 scenarios across nine districts of study area. Annual (September-August) during near-term (2041-2070) near normal index is projected predominantly under the SSP2-4.5 ranging (20-25) whereas, under SSP5-8.5(22-29) across most stations. During near future period drought frequency reduced about 20-60% under SSP scenarios[107]. Annual SPI-12(September-August) during the far term period (2071-2100) is projected ranging (15-22) and 29 years under the SSP2-4.5 and SSP5-8.5 scenarios respectively. Overall annual SPI-12 under SSP5-8.5 scenario normal years is projected more predominantly than SSP2-4.5 thesis implies less better rainfall pattern is expected under the SSP5-8.5 scenarios this in turn the occurrence of meteorological drought. According to [97] future frequency drought under SSP585 is less than SSP-24.5 scenarios. under ssp2-4.5 scenario Annual SPI-12 during the near term (2041-2070) indicates increasing trends across most stations Figure. During both near and far term period under SSP2-4.5 future rainfall indicated increasing this in turn also increase future annual SPI value[108]. Under ssp5-8.5 scenario annual SPI during the near-term period (2041-2070) increasing trend across most station Figure 25. Annual SPI value under SSP2-4.5 during the far term period indicate mixed trends decreasing trend over Dhas, Gumidalo, and Wachile whereas as increasing trend across Arero, Gorodola, Liben, Madawelabu, Negele, and West Welabu (stations Figure 26. Drought trend under future climate scenario exhibited heterogenous spatial pattern across station over the study area [109].Under SSP5-8.5 scenario during the far term period future drought events exhibited heterogenous trends across Arero, Gorodola, Liben, Moyale, **Wachile: Westwelabu** whereas decreasing trend across Dhase, Gumidalo medewelabu across stations over the study area.Figure 27. Under climate scenario during far term period future precipitation is projected to enhance across east Africa this indirectly increase future wetness condition[99].

Stations	SPI-12index Near term (2040-2070)											SPI-12 index far term (2071-2100)										
	Scenarios SSP-2 4.5							Scenario (SSP-58.5)				Scenarios SSP-2 4.5				Scenario (SSP-58.5)						
	SPI index(years)							SPI index (years)					SPI index(years)				SPI index (years)					
	EW	V W	M W	E D	SD	M D	NN	V W	M W	S D	M D	N N	E W	V W	M W	N N	V W	M W	S D	M D	NN	
Arero	1		2	1	2	1	23		1		1	2 8	2	7	5	15					29	
Dhas		2	3	2		3	20	1			1	2 8	2	2	8	19					29	
Gorodola	1		2	2	1	1	23				4	2 6		5	6	18					29	
Gumiidalo	1		2	1	2	1	23				3	2 7	3	4	5	17					29	
Liben	1		1	2	1	2	23				3	2 7	2	4	5	18					29	
Medewelabu	1		2		1	4	22	4	2	2	2	2 2	2	3	3	21					29	
Negele	1		1	2	1	4	21				3	2 7	2	4	1	22					29	
Wachile		1		1	1	2	25	1				2 9	2	5	6	16					29	

WestWelabu	1	1	2	1	1	3	21	1	1	$\frac{2}{8}$	5	7	17	29
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Table 8: Standardized precipitation index SPI-12 SSP-2 4.5 and SSP-5 8.5 Scenarios

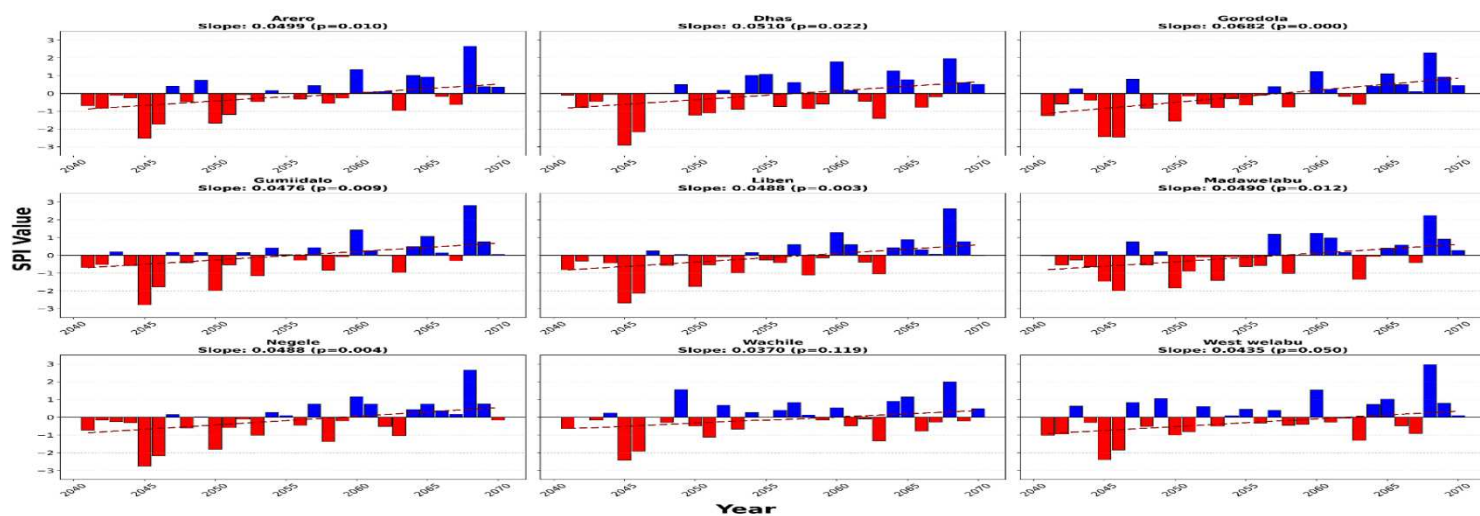


Figure 24: Annual drought intensity during the near-term period (2041–2070) under the SSP2-4.5 scenario across *stations* over the study area.

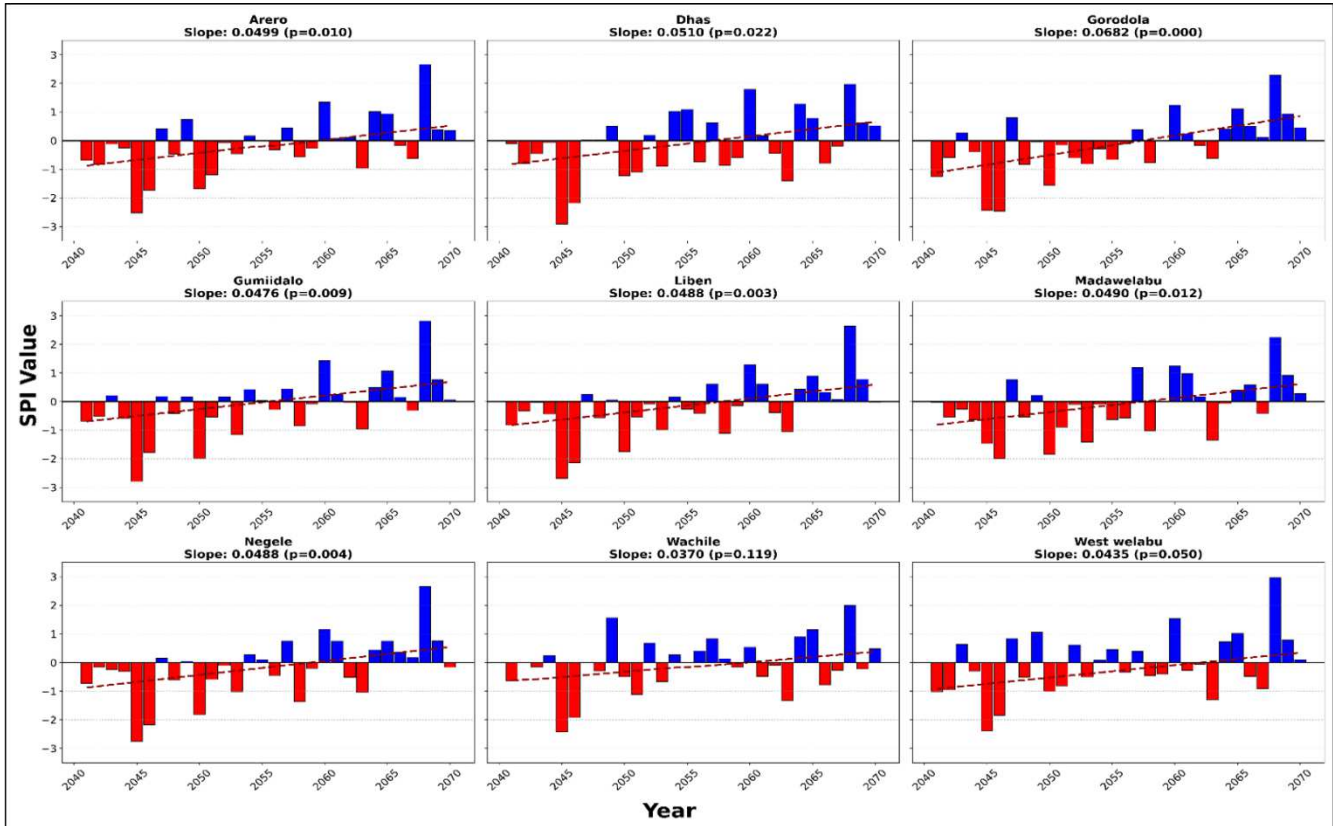


Figure 25: Annual drought intensity during the near-term period (2041–2070) under the SSP5-8.5 scenario *across stations over the study area.*

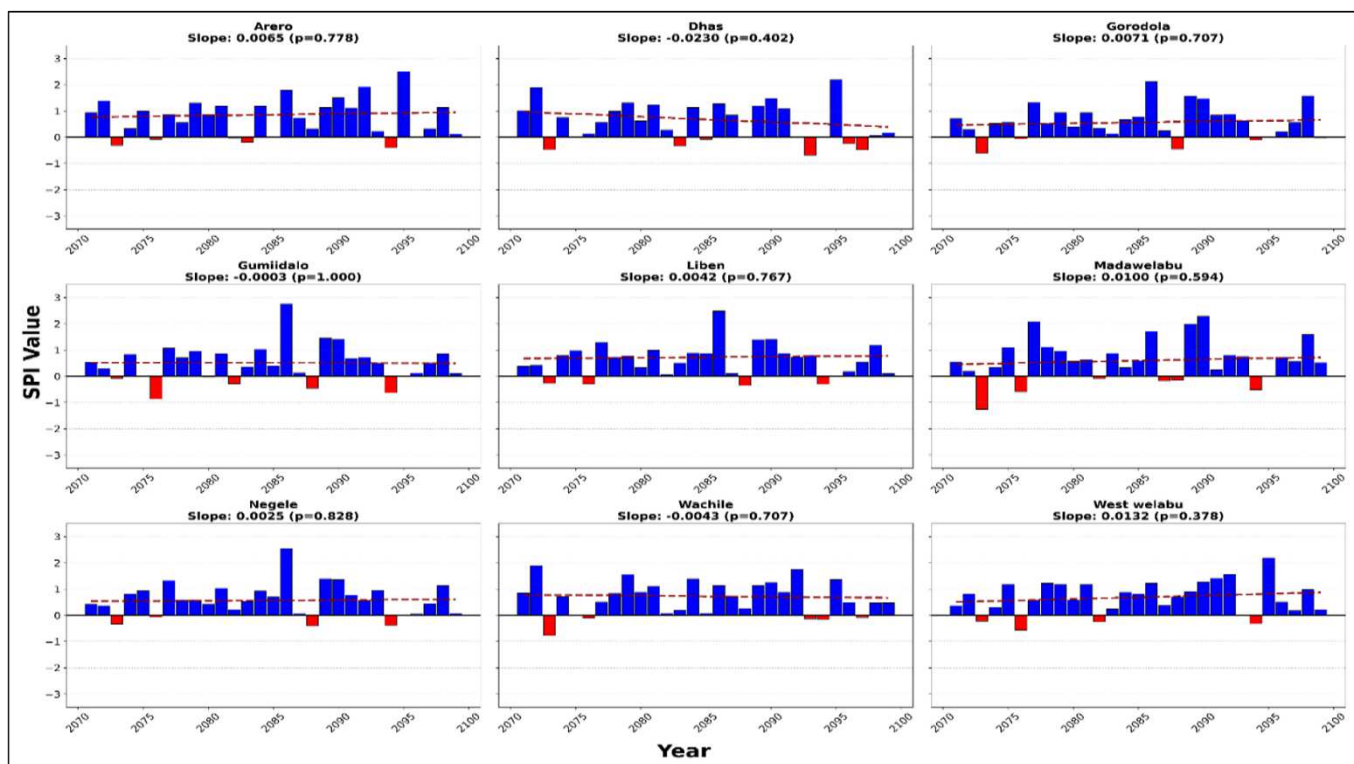


Figure 26: Annual drought intensity during the far-term period (2071–2100) under the SSP2-4.5 scenario, across stations over the study area.

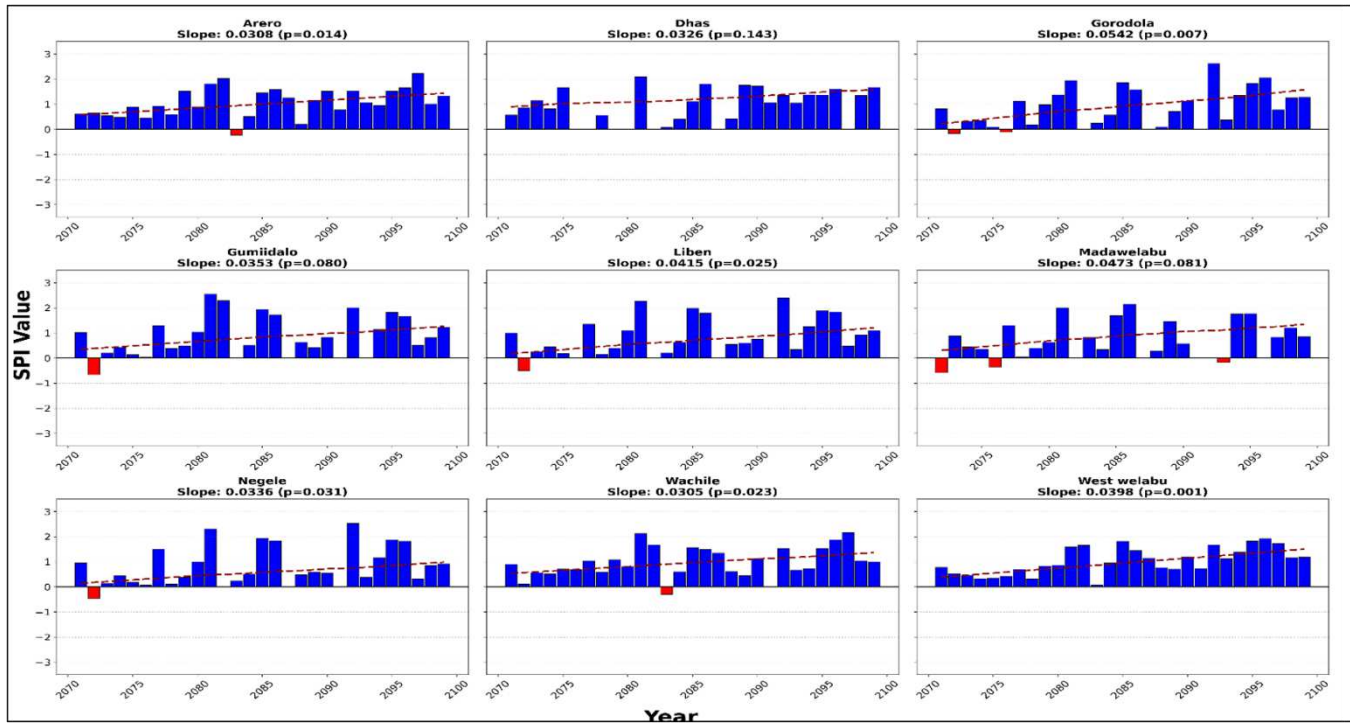


Figure 27: Annual drought intensity during the far-term period (2070–2099) under the SSP5-8.5 scenario across stations over the study area

4. Conclusion and Recommendation

The study concerned projection of future drought projection using the standardized precipitation index (SPI) under the SSP2-4.5 and SSP5-5.8 scenarios in both near-and (2041-2070) far-term (2071-2100) periods. Eight CMIP6 GCMs were obtained from C3S data store. Model performance was evaluated against observed data using statistical metrics; then ensemble of individual member models showed the best performance with statistical metrics $R=(0.32)$ $BR2=0.03$, $PBIAS=-0.867$ and $RMSE=3.394$, then selected for future drought projection. Selected Ensemble Model errors were reduced and improved representativeness for local climate features using empirical quantile mapping approach. The projected SPI (SPI-3, SPI-6, SPI-12) timescales under both scenarios predominantly showed near normal, combined with limited wet and dry events. Since the assessment depended only on precipitation data, the dominance of near-normal and limited wet and dry events could be considered from a precipitation perspective. Future warming anomalies associated with climate change increase evaporation and evapotranspiration; this leads to depletion of soil moisture and water stress. This may potentially shift drought signal. Subsequently, the study results provide insight for early warning, preparedness, and drought monitoring for long-term planning. This study recommends incorporating additional indices further in future drought projection assessment.

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Author's contributions: Dejen Terefe brings the idea of research, goals, data preparation, reviews literature analysis, methodology, and writing the manuscript; Melkamu Diriba Ujulu: reviewed, edited, and supervised the general work. Finally, both authors discussed and finalized the original manuscript.

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Data availability statement datasets generated for the current study are available from the Ethiopian Meteorology Institute (EMI) and the Copernicus Climate Change Service (C3S) Climate Data Store <https://cds.climate.copernicus.eu>

Declarations

Ethical statement declaration not applicable.

Consent to participate declaration not applicable

Consent to Publishing declaration not applicable

Clinical trial declaration not applicable

Competing interests the authors announce no competing interests.

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