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Research Article

Rainfall Trend and Variability over Western Amhara, Ethiopia

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Abstract

Climate change has become a pressing global challenge, with rural communities in Ethiopia among the most vulnerable due to their dependence on rain-fed agriculture. This study examined rainfall variability and trends in Western Amhara, Ethiopia, from 1992 to 2021 using daily rainfall data from eleven meteorological stations. Analytical methods included the Coefficient of Variation (CV), Precipitation Concentration Index (PCI), Standardized Rainfall Anomalies (SRA), and Mann-Kendall trend tests, supported by Climate Data Tool (CDT) software. Results revealed considerable spatiotemporal rainfall variability, with annual totals ranging from 995 mm to 1783 mm and a mean of 1316 mm. The PCI analysis indicated irregular to strongly irregular rainfall distribution, particularly in Bahir Dar, Metema, and Nefas Mewucha. The lowest precipitation concentration index was found at Chagni and Debre Markos stations, with a value of 16.6. Seasonal analysis showed that the Kiremt rains contributed the largest share of annual totals, with higher variability compared to annual averages. Standardized anomalies highlighted alternating wet and dry years, signaling recurrent drought and excess rainfall events. These findings underscore the importance of rainfall variability as a determinant of food security, agricultural productivity, and water resource management. Understanding such variability is crucial for designing adaptive strategies to enhance resilience among farming communities in Ethiopia.

Keywords

Trend, Variability, Precipitation Concentration Index, Standardized Rainfall Anomalies, Western Amhara

1. Introduction

1.1. Background of the Study

Climate change is one of the most pressing global problems since the beginning of the industrial revolution It has been associated with the increasing trend in carbon dioxide and other greenhouse gases (GHGs) in the atmosphere, presenting a critical challenge, especially in rural communities heavily reliant on seasonal weather conditions for their livelihoods [46]. Smallholder farmers in Africa are particularly vulnerable to the impacts of climate change [1-3].

Projections indicate that by the end of the twenty-first century, climate change could lead to a median temperature increase of 1.4–5.5°C and a median precipitation increase of 2–20% in East Africa [4], resulting in an overall decrease in the production of staple crops [5] by shortening the length of the growing season, intensifying water stress, and increasing the frequency of pest and disease outbreaks [6]. In Ethiopia, where rain-fed agriculture dominates, insufficient precipita-

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tion and accompanying drought are major contributors to hunger and food scarcity [7]. The National Meteorological Agency (NMA) of Ethiopia has revealed that climate variability and change in the country mainly manifest through the variability and decreasing trend in rainfall [8]. The country's climate is characterized by a history of climate extremes, including droughts and floods, as well as increasing and decreasing trends in precipitation [8]. Studies also indicate changes in mean precipitation over time, with high variability observed in the average annual rainfall (NMSA, 2001).

Ethiopia currently stands as one of the most vulnerable countries to the impacts of climate change and variability [9].

However, studies on rainfall variability and trends in Ethiopia have yielded inconsistent results due to the country's diverse geographical and topographical features [10]. Rainfall trends vary from region to region, with some studies reporting decreasing trends while others show increasing trends or both in different areas [11, 12]. Conversely, other studies have shown an increasing trend in annual rainfall [13-16]. Other studies revealed both an increasing and decreasing rainfall trend in different areas [17-19].

In western Amhara, Ethiopia, rainfall trends exhibit both increasing and decreasing patterns, with a predominant monomodal nature characterized by long rains during the Kiremt season [20]. Accurate knowledge of rainfall onset and cessation dates is crucial for farmers and planners to make informed decisions regarding crop selection and planting schedules, as well as to mitigate potential crop yield losses [21].

Access to baseline data on rainfall intensity, distribution, and onset dates is essential for farmers to avoid confusion, seed losses, and reduced crop yields due to mistimed planting [22]. Changes in the length of the growing season may also impact animal species, crop types, invasive species, and irrigation needs, while rainfall timing can influence disease transmission by affecting the life cycles of disease vectors.

Annual and seasonal rainfall information is indispensable for addressing social and economic challenges faced by farmers dependent on rainfall for their agricultural activities. However, in a changing climate, traditional reliance on prior weather knowledge may no longer suffice. Therefore, research on climate change and rainfall variability is crucial for improving agricultural management practices, developing adaptation strategies, and enhancing resilience among farming communities [23].

Previous studies in Ethiopia [20, 24-26] have not utilized the CDT tool which is an open-source R-based program with a simple graphical user interface for analyzing meteorological data. This applies to data quality and data analysis, which enhances the accuracy of the result. Second, most studies are conducted at broader scale such as [25] *Kiremt* rainy season over Ethiopia from 1943 to 1999. Studies on the trend of rainfall at the national level may not accurately reflect the localized trend of rainfall. This is due to the country's varied altitude and complicated topography [27]. However, No detailed studies have been conducted on the timing of rainfall and the temporal variability of climate variable elements in the country, particularly in Western Amhara. This study was going to fill these gaps.

1.2. Objectives of the Study

1.2.1. General Objective

The general objective of the study was to examine the rainfall, trend and Variability from the period 1992-2021 over Western Amhara, Ethiopia.

1.2.2. Specific Objectives

To investigate the temporal variability of rainfall in western Amhara from 1992 to 2021.

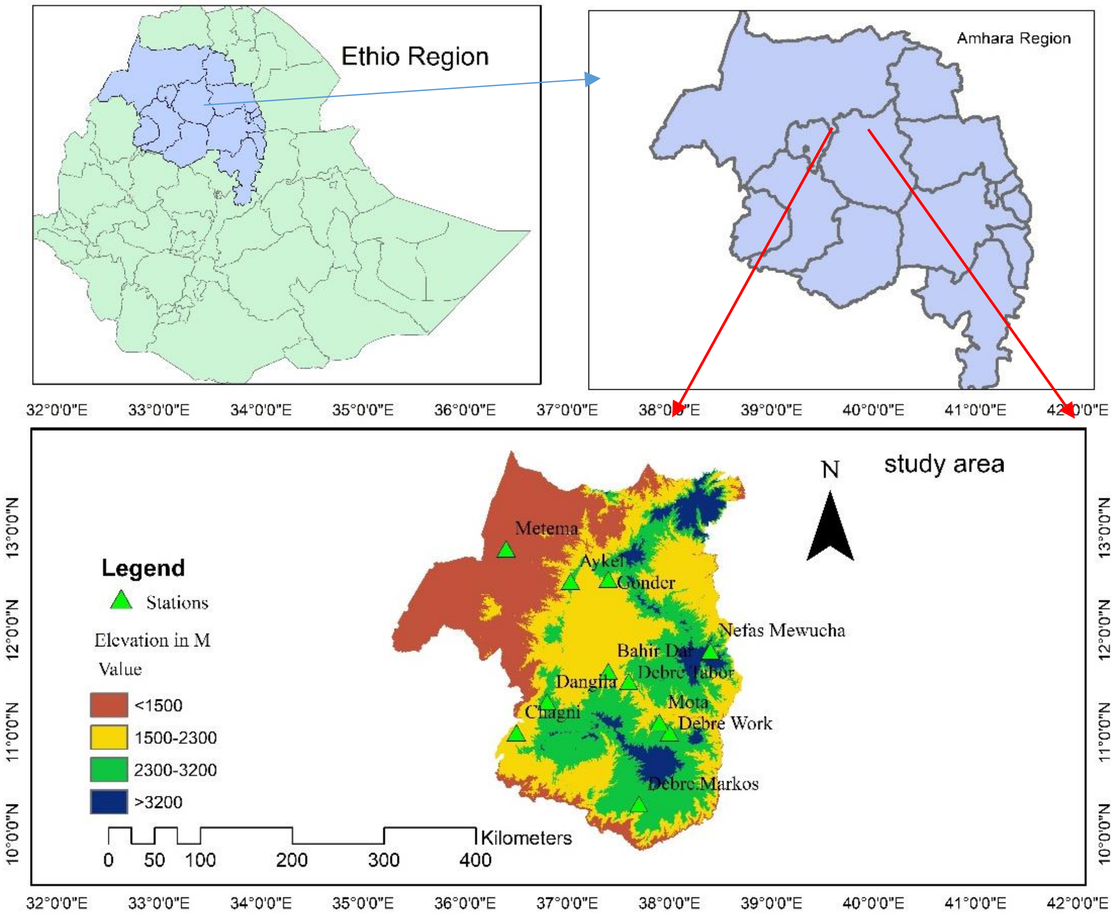
To examine the seasonal and annual rainfall trends in western Amhara from 1992 to 2021.

2. Methodology

2.1. Descriptions of the Study Area

Amhara region is one of the regional states in Ethiopia and is located in the northwestern part of the country. It has around 20 million people, of which more than 82 percent reside in rural areas [28]. Geographically, it lies between Amhara region and is located between Latitude: 11° 20' 57.929" N and Longitude: 37° 58' 42.451" E. Its area is estimated at 170,000 square kilometers and is divided into 11 administrative zones. Elevation ranges from 700 m to 4,620 m a. s. l. The western part of Amhara has the lowest elevation, while the eastern and northeastern parts have the highest elevations. Most of the region is on the highland plateau above 1,500 m and is characterized by rugged mountains, hills, valleys, and gorges. The majority of the population in the region depends heavily on rain-fed agriculture for their livelihoods. The region is characterized by erratic rainfall, and high rate of poverty [29]. Erratic rainfall patterns and frequent extreme events cause crop failure and threaten the food security and livelihoods of the people in the region. Therefore, knowledge on rainfall trends in the region helps the local community to better plan sustainable adaptation and secure sustainable agricultural production.

Majorly as a result of natural hazards, uneven rainfall distribution, land degradation, and pest damage, all of which are related to climate variability. In the region as a whole, 2-3 million people face severe food insecurity, making up one-third of all vulnerable and chronically starving populations in the country's [30]. The mean annual temperature of the region ranges from 15°C and 21°C. But in the valleys and marginal areas the temperature exceeds 27°C. There are different ways of classifying the climatic systems of Ethiopia, including the traditional, the Köppen's, the Throthwaite's, the rainfall regimes, and the agro-climatic zone classification systems [31]. The most frequently used classification systems are the traditional and the agro ecological zones (AEZs). According to the traditional classification system, which mainly depends on altitude and temperature this divides into five categories based on altitude and temperature. These are *Bereha* (hot lowlands <500 meters), *Kolla* (lowlands, 500-1500 meters), *Woina Dega* (midlands, 1500-2300), Dega (highlands, 2300-3200), *Wurch* (highlands, 3200-3700) and Kur (highland, >3700). The population of the region comprises 25.5 percent of the total population of the country, while in terms of area, the region contributes only 15.4 percent [32]. Consequently, if the current trend in population growth continues, the population size of the region would double within 25 years. In terms of settlement patterns, almost all, approximately 89 percent of the population, reside in rural areas and are primarily engaged in agriculture. The highlands are more densely populated than the lowlands.



Source Ethio- region shape file

Figure 1. *Map of the study area and location of meteorology stations.*

2.2. Research Design

Descriptive research design was used to conduct this research. A descriptive research design aims to identify trends of rainfall. A quantitative research approach was used to consider numeric data.

Secondary data was used from Ethiopia's Meteorology Institute, the main office found in Addis Ababa, which is long-term record of daily rainfall data. To select meteorological stations located in the study area, purposive sampling method was used based on the availability of daily data, long-year rainfall data, quality, and being representative of the study area.

2.3. Data Sources and Data Collection

Daily rainfall and minimum and maximum temperature data for eleven stations: Bahir Dar D/markos, Motta, Dangla, D/tabor, Gonder, Metema, Nefassmewucha, D/work, Aykel, and Chagni were obtained from the main office of Ethiopia's Meteorology Institute found in Addis Ababa to show the trend of rainfall over western Amhara from 1992-2021. WMO suggested 30 years and above, hence 30 years of data were utilized to examine western Amhara [33].

Table 1. Description of the study meteorological stations.

	Station	Latitude	Longitude	Elevation in m	Year of observation
East Gojjam	Debre-markos	10°20'	37°43'	2446	1992-2021
	Motta	11°5'	37°5'	2417	1992-2021
	Debre-work	10°66′	38° 16′	2508	1992-2021
Awi zone	Dangila	10°16'	36°56'	2116	1992-2021
	chagni	10°95′	36° 5′	1614	1992-2021
South Gondar	Debretabor	11°51′	38°10′	2613	1992-2021
	Nefassmewucha	11°81′	38° 36′	3098	1992-2021
North Gondar	Gonder	12°6'	37°46'	1973	1992-2021
	Aykel	12°48′	37°03′	2254	1992-2021
	Metema	12°58′	36°12′	790	1992-2021
West Gojjam	Bahir dar	11°36'	37°23'	1800	1992-2021

Source: Ethiopia Meteorology Institute

2.4. Sampling Techniques

Meteorological stations were purposively selected, based on the availability of daily rainfall, minimum temperature and maximum temperature data, and fair distribution of the station in the study area. Quality, long-year rainfall data, and being representative of the study area.

2.5. Missing Data

Missing data is one of the major issues that frequently arise in meteorological analysis. It may be caused by absence of an observer, equipment failure or breakage, and due to conflict or a wide range of factors. When data are missing, it may be useful to fill these data sets from observations made in other nearby and reliable stations. Additionally, the missing data were filled with gridded data, arithmetic average method, and climatological mean of the day.

2.5.1. Arithmetic Average Method

If the normal annual rainfalls at nearby gauges are within 10% of the normal annual precipitation at the stations concerned, then the arithmetic procedure could be used to estimate the missing data [34]. It is fast and easy to calculate because its calculation is straightforward and its meaning is known to everybody, arithmetic average is also more comfortable to use as input for further analyses and calculations. But Sensitive to extreme values.

This method is used when normal annual precipitations at various stations show variation within 10% w. r. t station X.

The annual precipitation values at neighboring stations are P1 (station 1) P2 (Station 2), P3 (Station 3). Pm (Station M).

To determine annual precipitation $P_{X \text{ at}}$ station X.

$$P_X = \frac{1}{?}(P_1 + P_2 + \cdots P_? \tag{1}$$

2.5.2. The Climatological Mean of the Day (CMD)

This technique utilizes the long-term average value of the same day of interest V_{est} is the estimated value, V_i is the value of the variable for the i^{th} day of year j, and T is the number of years data are available [35].

The output of Eq. 2 is simply a temporal average of the j^{th} day value.

$$V_{est,i} = \frac{\sum_{j=1}^{T} V_{ij}}{T} \tag{2}$$

2.6. Data Quality Control

There were some missing values in the observed data obtained from the Ethiopian Meteorology Institute most missing values were filled at the source. However, some rainfall station data are missed; for example, Chagni from 1993–97, Debre-markos 1993 (12–25 days), Debre-work 2009 from February to October, Nefassmewucha 2007 and 2008 January and May are missed, and Dangla 1992 May month is missed. To complete such values, a simple gap-filling method is used, which is called the climatological mean of the day

[36], Arithmetic average method, and gridded data were used. a very small number of temperature data exchanges of values, maximum with minimum temperature, and reciprocally, and have no missing value shown.

Outliers are observations that deviate from or are disproportionally different from the rest of the data [37] and could be caused by problems such as instrumentation error, human error, and changes in the environment. Because outliers could affect the quality of the data and the results of analysis, excluding them from the data set is a crucial activity. There are numerous outlier detection techniques have been developed [38]. The Enhancing National Climate Services (ENACTS) initiative of the International Research Institute for Climate and Society Columbia University, has been addressing these data quantity and quality gaps it develops the Climate Data Tool (CDT).

The overall process for quality checks implemented in CDT includes the following steps:

2.6.1. Checking for Station Coordinates

It would be difficult to automatically check for the accuracy of the coordinates of a given station. This is done by checking whether the station coordinate is within the country boundary or not. It also displays the location of the stations on Google Maps. CDT can also check for duplicate and missing coordinates, which happen frequently [39].

2.6.2. Outliers Check

There are various techniques for identifying outliers or suspicious observations. The methods implanted in CDT include limit check, internal consistency check, temporal check, and spatial check [39].

Limit check involves comparing observation to previously define upper and lower limits of the specific element for the specific climate.

In internal consistency to determine whether there is physical and climatological consistency between two observations, internal consistency entails comparing the observation to other meteorological parameters. It is done either for the time the observation denotes or for the time series. As some of the meteorological parameters are physically related, checking the consistency between these variables informs us about whether the observation is an outlier or not.

Temporal consistency checks when comparing an observation from a given station for a certain month to the long time series for that particular month, temporal consistency is used to determine whether the difference is significant this test is based on the fact that many climatological variables show significant serial correlation. In CDT, this comparison is done for each of the 12 months separately to make sure data from climatological periods check for homogeneity of climate time series.

The spatial check makes comparisons between the observation and information from surrounding stations or between the expected value for the station in question and information from nearby stations. It can be done using interpolation either by checking against numeric values calculated based on the values from surrounding stations, or by comparing statistics. The data that considerably deviate from the anticipated values are marked as potential outliers.

The CDT outlier test indicated that precipitation data of some Meteorological stations (Chagni, Motta, Debretabor,) had some very small numbers of outliers. Most of the outliers occurred during data entry, and some of the outliers were tolerated and taken as normal data. See figure 8 to figure 14.

2.6.3. Homogeneity Test

If a climate time series is homogeneous over a longer period, it can be determined using homogeneity checks. The two basic components of the homogenization of climatic data are as follows: identifying breaks and adjusting the particular segment for inhomogeneity [40]. For detecting breaks in a climate time series, the CDT provides four methods. the primary approach is the Pettit test, which is a nonparametric rank-based method used to identify changes in the mean value of the distribution of the variable under study [41] The other approach adopted in CDT is the normal standard test (SNHT) [42]. The other two methods rely on the cumulative sum (CUMSUM) approach with and without trends [43].

CDT offers two techniques for adjusting in homogeneity mean and quantile matching. Quantile matching compares quantiles before and after the break while the mean method compares the mean before and after the break [40].

When evaluating the homogeneity of climate data in climate research, the Standard Normal Homogeneity Test (SNHT), Pettit-nonparametric test, and Buishand Range Test are commonly used [37, 44].

Normal Homogeneity Test (SNHT), the test was used to check the homogeneity of time series data (temperature and precipitation).

As illustrated in the appendix Figure 13 to Figure 23, the appendix presents homogeneity tests. The monthly rainfall of six stations (Aykel, Chagni, Debre markos, Debre work, Dangila, and Motta) stations was homogeneous and Bahir dar, Debre Tabor, Gonder, Nefassmewucha and Metema had a single break in SNHT homogeneity tests.

2.7. Method of Data Analysis

For the analysis of rainfall, a variety of methods have been developed. These methods typically come under the categories of variability and trend analysis. Parametric and non-parametric tests are used to identify trends and analyze them, but only when the data is consistent. The advantage of a non-parametric statistical test over a parametric test is that the former is more suitable for non-normally distributed data. In this study, the coefficient of variation (CV) was used in the analysis of variability. And this study used the Climate Data Tool (CDT) version 7.0, R programming, and Excel 2013 to conduct statistical analysis of the meteorological data for the study area. CDT is an open-source R-based program with a simple graphical user interface for analyzing meteorological data. The primary functions of CDT include station data organization, quality control, and processing; estimates and the reanalysis of data [39, 45, 46].

The CDT tool was developed to address critical gaps in climate services and applications, particularly in Africa [47, 48] This occurs as a result of a problem with access to and availability of climatic data.

2.7.1. Rainfall Variability Analysis

i). Coefficient of Variation

The coefficient of variation (CV) was computed as the ratio of standard deviation to the mean in a given time series as used by [49] to quantify the extent of variability, which is expressed as a percentage. The CV values are classified as follows: if CV < 20 it is low variability, if 20 < CV < 30, it is moderately variability if CV > 30, it is strong variability [50].

$$CV = \frac{SD}{\bar{X}} * 100 \tag{3}$$

Where, CV, is the coefficient of variation, SD, is the standard deviation while $\bar{x}$ is the long-term rainfall mean. On the other hand, the standard deviation was computed as the square root of variance. The standard deviation is a statistic that expresses the amount of variation in a measured process characteristic. Specifically, it calculates how much an individual measurement should be expected to deviate from the mean on average http://www.textbooksfree.org/Excel-Statistics-Book.htm

Where SD can be computed [51]

$$SD = \sqrt{\sum_{i=1}^{n} \frac{(x-\bar{x})^2}{n}} \tag{4}$$

Where $\bar{x}$ is the mean

Standard deviation is measured in the same units as the mean. Using the classification of Reddy S. J [52] the stability of rainfall is examined as follows: when standard deviation <10 as very high stability, 10-20 as high stability, 20-40 as moderate stability, and >40 as less stability.

ii). Precipitation Concentration Index

The precipitation concentration index (PCI) is a powerful measure of the temporal distribution of precipitation which is essential for the evaluation of annual and seasonal precipitation variability, which is a crucial aspect of water resource planning and the management of natural resources [53]. Recently, this index has been widely used [54-57].

The annual PCI was computed as Eq

$$PCI_j = 100 * \frac{\sum_{i=1}^{12} Pij^2}{Pj^2} \tag{5}$$

Where PCIj is the precipitation concentration index for year j, expressed as percent; Pij is the precipitation of month i in the year j; and Pj is the annual precipitation in the year j and Σ is the summation over the 12 months.

1) PCI values of less than 10 indicate a uniform monthly distribution of rainfall,
2) values between 11 and 15 indicate moderate precipitation distribution.
3) Values between 16 and 20 indicate irregular precipitation distribution.
4) and strongly concentrated/strongly irregular distribution (PCI>20) [58].

iii). Standardized Rainfall Anomalies

The standardized rainfall anomalies were computed and graphically shown to assess inter-annual variations of rainfall in the study area over the period of observation.

$$SRA = (Pt - Pm)/\sigma \tag{6}$$

Where:

1) SRA is standardized rainfall anomaly,
2) Pt is an annual rainfall in year t
3) Pm is the long-term mean annual rainfall over a period of observation and
4) σ is the standard deviation of annual rainfall over the period of observation.

The drought severity classes

Table 2. *Standardized Rainfall Anomaly Index category.*

Drought Category	Rainfall Anomaly Index
Extremely wet	>2
Very wet	1.5 to 1.99
Moderately wet	1.0 to 1.49
severe drought	-1.65 to -1.28
moderate drought	-1.28 to -0.84
Near normal	-0.84 to 0.99

2.7.2. Rainfall Trend Analysis

i). Mann-Kendall Test

The non-parametric Mann-Kendall test, which has a lower sensitivity for outliers, is used to identify both hydrological and meteorological factors. Previous studies like [59, 60] have been applied. The Mann-Kendall equation is written as follows: -

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \mathrm{sgn}(x_j - x_i) \tag{7}$$

Where S is the Mann-Kendal's test statistics; Xj and Xi are the sequential data values of the time Series in the years i and j (j>i) and N is the length of the time series. A positive S value indicates an increasing trend and a negative value indicates a decreasing trend in the data series. The sign function is given as:-

$$\mathrm{Sgn}(x_j - x_i) = \begin{cases} +1 \text{ if } (x_j - x_i) > 0 \\ 0 \text{ if } (x_j - x_i) = 0 \\ -1 \text{ if } (x_j - x_i) < 0 \end{cases} \quad (8)$$

The variance of S, for the situation where there may be ties (that is equal values) in the x values, is given by

$$Var(S) = \frac{1}{18}[N(N-1)(2N+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t_i + 5)] \quad (9)$$

Where, m is the number of tied groups in the data set and t_i is the number of data points in the i^{th} tied group. For n larger than 10, Z_{MK} approximates the standard normal distribution and is computed as follows:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} if S > 0 \\ 0 \; if \; = 0 \\ \frac{S+1}{\sqrt{Var(S)}} if \; S < 0 \end{cases} \quad (10)$$

The presence of a statistically significant trend is evaluated using the Z_{MK} value. In a two-sided test for trend, the null hypothesis H_0 should be accepted if $| Z_{MK} | < Z_{1-\alpha/2}$ at a given level of significance. $Z_{1-\alpha/2}$ is the critical value of Z_{MK} from the standard normal table. E. g. for 5% significance level, the value of $Z_{1-\alpha/2}$ is 1.96.

ii). The Sen’s Estimator of Slope

This test is applied in cases where the trend is assumed to be linear, depicting the quantification of changes per unit of time. This method could be used with missing data and remain unaffected by outliers or gross errors [61]. The slope (change per unit time) was estimated following the procedure of [62].

$$f(t) = Qt + B \quad (11)$$

Where f(t), is the estimated data at t year, Q is the slope of trend line and, B is constant. Then the slope Q is estimated as

$$Q_i = \frac{X_j - X_i}{j-k} \text{ where } j > k \quad (12)$$

Where Qi is Sen's slope estimator, Xj and Xi are the data values at times j and i (j > i), respectively. The median of these N values Qi is represented as Sen's slope estimator and calculated;

$$\text{Sen's estimator} = \begin{cases} \frac{Q(R+1)}{2} \text{ if R is odd} \\ 0.5 * \left(\frac{QR}{2} + \frac{Q(R+2)}{2}\right) \text{ if is even} \end{cases} \quad (13)$$

A negative and positive value of Sen's estimator indicates a downward and an upward trend in the time series analysis respectively [63].

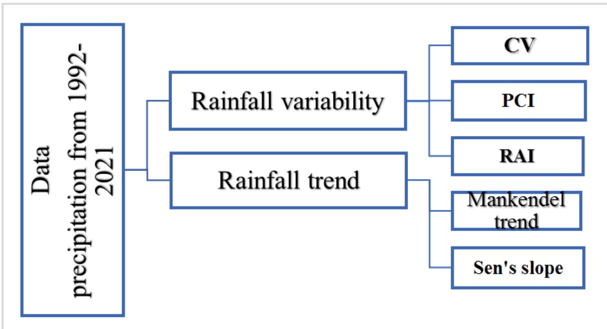


Figure 2. Methodological framework of the study.

3. Results and Discussion

3.1. Annual and Seasonal Rainfall Variability

Table 3. Mean annual and seasonal rainfall coefficient of variation (CV%), and precipitation concentration index (PCI%) for 11 meteorological stations.

Station	Kiremt CV	Kiremt Mean	Annual CV	Annual Mean	PCI
Aykel	11.3	893.9	11.3	1179.9	18.5
Bahir Dar	17.6	1211.1	14.1	1460.3	21.7
Chagni	9	1291.6	7.8	1783.5	16.6
Dangila	12.3	1245.6	14.3	1643.2	17.6
Debre Markos	13	981.1	10.8	1365.8	16.6

Station	Kiremt CV	Kiremt Mean	Annual CV	Annual Mean	PCI
Debre Work	28.6	712.3	27.5	995.9	19.0
Debre Tabor	15.6	1194.2	13.9	1518.5	20.0
Gonder	12.9	876.6	11	1132.9	19.5
Metema	18	859	18	1008	20.8
Motta	13.8	921	13.2	1250	18.6
Nefas Mewucha	20	836	17	1146	20.5
Area Mean	15.6	1002	14.4	1316.7	19

The results indicate inconsistent rainfall distribution and none of the stations in the Study area showed uniform precipitation (Table 3). Therefore, the study area falls under two classes of precipitation patterns: irregular and strongly irregular precipitation distribution. A previous study in the western Amhara of Ethiopia by [20] confirmed that the PCI values range from irregular to strong irregular precipitation. The highest PCI was recorded at Bahir Dar (PCI 20.9), followed by Motta (PCI 16.7) and Dangila (PCI 16.2). In this study three stations, namely: Bahir Dar (PCI 21.7) Metema (PCI 20.8), and Nefas Mewucha (PCI 20.5) stations, experienced strongly irregular precipitation distribution. The lowest PCI was found at Chagni and Debre Markos station, with a value of 16.6. This study concludes that the average annual PCI value for western Amhara Ethiopia is 19.0, which lies in irregular precipitation distribution for more see Table 6 in the appendix. [64] Present the spatial distribution of the mean PCI of the annual rainfall of the Amhara region varied from 14.59 to 25.60.

Table 3 shows that the study area received annual rainfall ranging from 1783.5 mm at Chagni to 995mm at Debre Work with a mean of 1316.7 and CV varied from 7.8%; to CV 27.5%) with a mean of 14.4%. At the seasonal level, *Kiremt* rainfall varied from 836-1291 mm with a mean of 1002 mm. Chagni received the maximum mean annual and kiremt rainfall followed by Dangila. *Kiremt*, CV varied from 9%; at Chagni to CV 28.6% Debre Work with a mean of 15.6%. As compared to the Annual rainfall *Kiremt* season, was more variable. This study concludes that Western Amhara Ethiopia has low rainfall variability in kiremt, and annual with a coefficient of variation of 15.6% and 14.4% respectively.

The findings of Dereje *et al*. (2012) and [65] reveal that the Amhara National Regional State receives much of the rainfall in June, July, August, and September. Likewise, the contribution of kiremt rainfall to the annual total in western Amhara is high. Generally, this agrees with the findings of previous studies conducted in Ethiopia by [26, 66] they showed that the seasonal variability was higher than the annual variability.

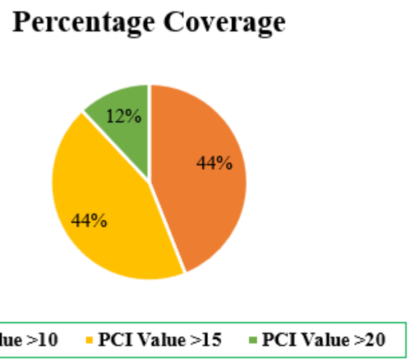


Figure 3*. Percentage coverage of precipitation concentration index.*

The result shows that the PCI value <10 covers 0%. This implies that the studied stations in western Amhara have no uniform distribution of rainfall. And (PCI value > 10) and (PCI value > 15) cover 44%; this implies that most of the studied stations in western Amhara receive irregular to strongly irregular precipitation distributions. The PCI value > 20 shows 12%, which implies that few studied stations in western Amhara receive strongly irregular precipitation distributions. Rainfall irregularities can cause hydrological hazards like droughts and floods to arise [67]. The analysis of PCI values revealed that there was an irregular temporal distribution of rainfall in the study area.

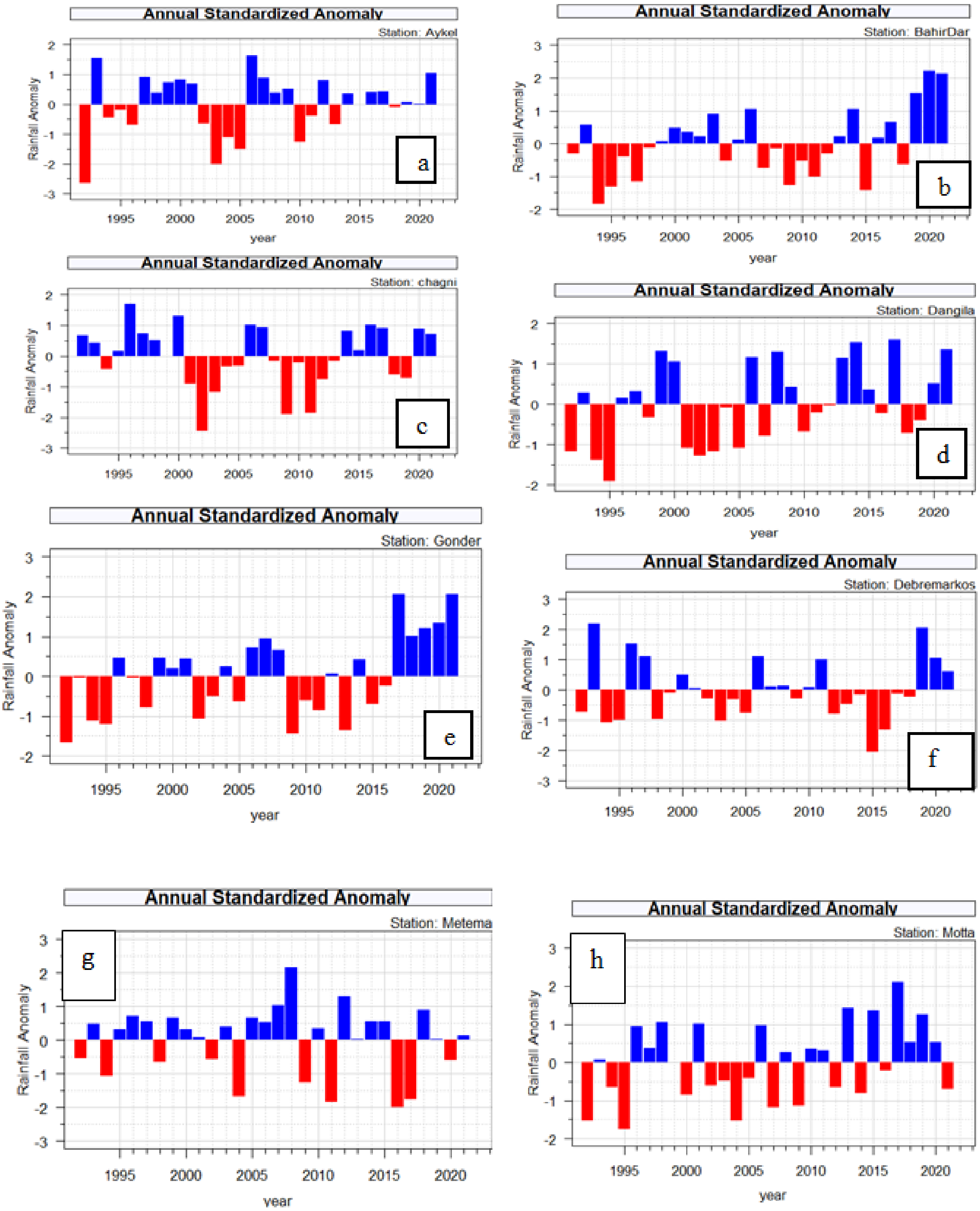
Irregularity in the rainfall amount, intensity, onset, and cessation days has a direct impact on agricultural activities, crop patterns, and livelihood.

The annual and seasonal rainfall variability in the western Amhara region of Ethiopia is significant and has important implications for agriculture, water resources, and livelihoods in the area.

Monitoring and Research: Monitoring rainfall variability and trends in the western Amhara region is essential for understanding climate dynamics, assessing risks, and developing adaptation strategies. Local meteorological agencies, research institutions, and international organizations conduct ongoing research and monitoring to provide data, forecasts, and early warning information to support decision-making and resilience-building efforts in the region. By understanding the annual and seasonal rainfall variability in the western Amhara region, stakeholders can better prepare for climate-related risks, implement sustainable water management practices, and promote agricultural resilience to ensure food security and livelihood sustainability in the face of changing climate conditions.

3.2. Standardized Rainfall Anomalies

The standardized rainfall anomalies were used to calculate the negative and positive anomalies of rainfall fluctuations in a certain region. It helps to identify the drought period by determining the dry and wet years of the recording period [68-71]. See Appendix Table 5.



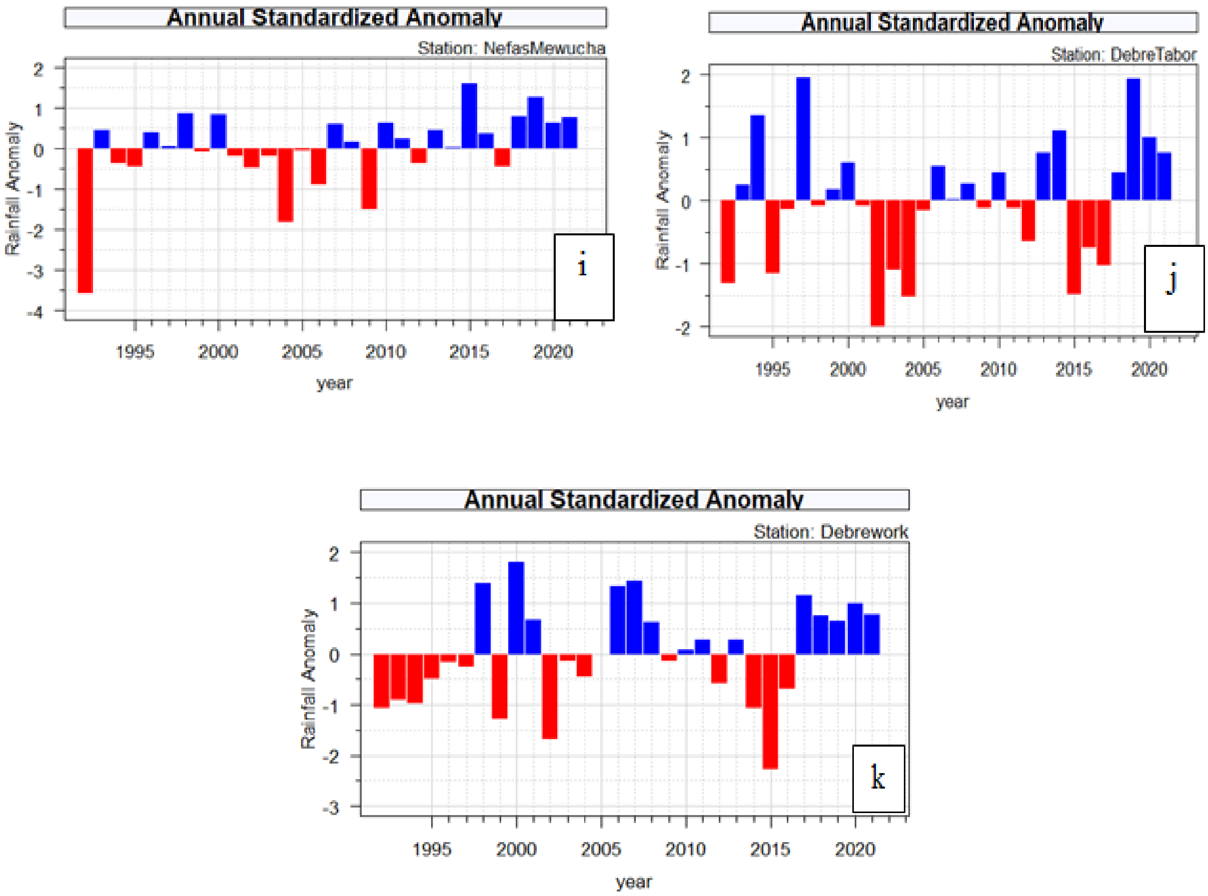


Figure 4. *Annual standardized rainfall anomaly of each station over western Amhara region for the period 1992-2021.*

In Aykel, annual rainfall shows negative anomalies for the years 1992, 1994-1996, 2002-2005, 2010, 2011, 2013, and 2018. The remaining positive anomaly has occurred. In Bahir dar, annual rainfall shows negative anomalies for the years 1992, 1994-1998, 2004, 2007-2012, 2015, and 2018 the remaining positive anomalies have occurred. In Chagni annual rainfall shows negative anomalies for the years 1994, 2001-2005, 2008-2013, and 2018-2019. the remaining positive anomaly have occurred In Debre Markos, annual rainfall shows negative anomalies for the years 1992, 1994-1995, 1998-1999, 2002-2005, 2009, and 2012-2018. The remaining positive anomaly has occurred. in Debre work annual rainfall show negative anomalies for the year 1992-1997, 1999, 2002-2004, 2009, 2012, and 2014-2016.

The remaining positive anomaly has occurred Dangila annual rainfall shows negative anomalies for the years 1992, 1994-1995, 1998, 2001-2005, 2007, 2010-2011, 2016, and 2018-2019. The remaining positive anomaly has occurred. in Debre Tabor, annual rainfall shows negative anomalies for the years 1992, 1995-1996, 1998, 2001-2005, 2009, 2011-2012, and 2015-2017. The remaining positive anomaly has occurred. in Gonder, annual rainfall shows negative anomalies for the year 1992, 1994-1995, 1998, 2002-2003, 2005, 2009-2011, 20013, 2015-2016. The remaining positive anomaly has occurred. In Nefas Mewucha annual rainfall shows negative anomaly for the years 1992, 1994-1995, 1998, 2002-2003, 2005, 2009-2011, 2013, and 2015-2016. The remaining positive anomaly has occurred. In Metema annual rainfall shows negative anomaly for the years 1992, 1994, 1998, 2002, 2004, 2009, 2011, 2016-2017, and 2020. The remaining positive anomalies have occurred. in Motta, annual rainfall shows negative anomalies for the years 1992, 1994-1995, 2000, 2002-2005, 2007, 2009, 2012, 2014, 2016, and 2021. The remaining positive anomaly has occurred.

The year of greatest positive value was Debre Markos in 1993, Metema in 2008, and Bahir Dar in 2020 with a Standardized rainfall anomaly index of 2.2, and the year of greatest negative value was in 1992 in Nefas Mewucha with a value of -3.6.

The number of dry years recorded from 1992 to 2021 was counted. In the last 30 years, Western Amhara has received 17, or 56.6%, wet years, while 13, or 43.3%, are dry years. The historical droughts in Ethiopia were associated with GHG events in the past [72] drought years in Ethiopia include 1984, 1987, 1991–1992, 1993–94, 2002, 2009, 2012, 2015/16 [68, 73]. The finding of the present study agrees with the above result. The results are supported by recent studies on the effect of El Niño events on Ethiopian rainfall distribution and its outcomes [69].

3.3. Annual and Seasonal Rainfall Trends

Western Amhara is found in the Amhara region, which is divided into five administrative zones: East Gojjam, Awi Zone, West Gojjam, South Gondar, and North Gondar.

Figure 5. Annual and Kiremt rainfall trend in each station and over western Amhara region.

Table 4. Annual and seasonal rainfall trend for western Amhara, Ethiopia from 1992-2021.

Stations	Annual				Kiremt		
	n	Z	p-value	S	Z	P- value	S
Aykel	30	0.35	0.72	21.0	-0.32	0.75	-19.0
Bahir Dar	30	1.90	0.06	108.0	1.82	0.07	103.0
chagni	30	-0.07	0.94	-5.0	-0.21	0.83	-13.0

Stations	Annual				Kiremt		
	n	Z	p-value	S	Z	P- value	S
Debre Markos	30	0.24	0.80	15.0	0.64	0.52	37.0
Debre Tabor	30	0.96	0.34	55.0	1.21	0.23	69.0
Debre Work	30	1.74	0.08	99.0	1.46	0.14	83.0
Dangila	30	2.25	0.02*	127.0	2.36	0.02*	133.0
Gonder	30	2.58	0.01*	146.0	2.73	0.01*	154.0
Nefas Mewucha	30	1.03	0.04	59.00	0.57	0.57	33.0
Motta	30	1.85	0.06	105.0	2.50	0.01*	141.0
Metema	30	-0.43	0.66	-25.00	0.11	0.91	7.0
Average	30	1.13	0.34	64.09	1.17	0.37	66.18

(*Significance at 0.05 level)

In this study (Table 4), Dangila and Gonder, statistically significant increasing trends of annual and *Kiremt* rainfall were noted, but in Motta, statistically significant increasing trends were noted only in *Kiremt* season. These results are in line with [74] who reported that there were statistically significant increasing trends of annual and *Kiremt* rainfall in Gonder and contrasted with statistically significant increasing trends of annual and *Kiremt* rainfall in Metema. In contrast [20] reported that there was a significant decreasing trend in Debre Markos and no significant increasing or decreasing trend in Motta from 1979 to 2008. While Debre Markos, Debre work, Debre tabor, Motta, Bahir Dar, Aykel annual rainfall, Metema *kiremt*, and Nefassmewucha showed non-significant increasing trends. The Other non-significant decreasing trends are noted in Chagni, Aykel *Kiremt,* and Metema annual. My study, in line with Getachew and Management [75] showed that Nefas mewucha annual rainfall has a non-significant increasing trend.

In conclusion, western Amhara experienced non-significant increasing trend both in annual and *kiremt* rainfall. In line with Alemu, Bawoke [64], in Amhara region,

Ethiopia the Trend analysis showed an overall increase in the annual and seasonal rainfall.

Different research results have been noted as long as the annual and *Kiremt* rainfall trends in various regions of Ethiopia are concerned the majority of which are in contradiction with one another. According to Modarres and Sarhadi [76, 77] shows a decreasing trend in the annual and seasonal rainfall in a majority of the stations. Similar to the current study, [65] in drought-prone areas of the Amhara region (Northwestern Ethiopia), [78] in central, northern, and northwestern Ethiopia and [18] in the central Ethiopian highlands and in northeastern Ethiopian highlands agreed that there is no significant and clear trend in the annual rainfall pattern.

4. Conclusion and Recommendations

4.1. Conclusion

The study concludes that Western Amhara experiences irregular and highly variable rainfall patterns both annually and seasonally. The Kiremt season dominates rainfall distribution, yet its variability is considerable, ranging from 995 mm to 1783.5 mm with a mean of 1316.7 mm, while the coefficient of variation (CV) ranges from 7.8% to 27.5% with a mean of 14.4%. At the seasonal level, Kiremt rainfall varied between 836 mm and 1291 mm with a mean of 1002 mm, and the CV ranged from 9% to 28.6% with a mean of 15.6% for the period 1992–2021. Such variability increases agricultural risks. The non-parametric Mann-Kendall test revealed statistically significant increasing trends of annual and Kiremt rainfall in Dangila and Gondar, while in Motta a significant increasing trend was observed in Kiremt rainfall only.

The prevalence of irregular precipitation patterns indicates susceptibility to both drought and flood hazards, which significantly affect livelihoods, water resources, and food security. These findings emphasize the importance of climate monitoring and localized data analysis to enhance adaptive capacity in vulnerable regions. Overall, this study demonstrates significant inter-annual rainfall variations, along with differences in rainfall amounts and trends across stations.

4.2. Recommendations

To address the challenges posed by rainfall variability in Western Amhara, several adaptive measures are essential. First, strengthening climate monitoring through the expansion and modernization of meteorological stations is crucial to provide reliable, localized, and real-time rainfall data. Equally important is the promotion of climate-smart agricultural practices, including the introduction of drought-resistant crop varieties, improved irrigation systems, and adaptive planting schedules that enhance productivity under uncertain climatic conditions. Establishing community-based early warning systems will further enable farmers to respond promptly to rainfall variability, minimizing risks associated with droughts and floods. Moreover, integrating research findings into regional policy frameworks can guide agricultural planning, water resource management, and disaster risk reduction strategies. Finally, building community resilience through capacity-building programs will empower smallholder farmers to adopt sustainable practices that reduce their vulnerability to rainfall extremes. Together, these measures can enhance adaptive capacity and support sustainable livelihoods in the face of climate change.

Abbreviations

AEZs	Agro-ecological Zones
CV	Coefficient of Variation
CDT	Climate Data Tool
DOY	Day of the Year
ENSO	El Niño Southern Oscillation
GHG	Greenhouse Gases
PCI	Precipitation Concentration Index
RAI	Rainfall Anomaly Index

Author Contributions

Behabtu Gobeze Mengiste is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares that there is no conflict of interest.

Appendix

An outlier of meteorological Station.

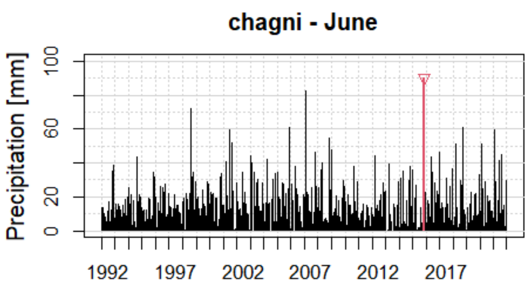


Figure 6. Data quality check: typing error during data entry: 90.2 mm rainfall data entered in place of 9.7mm.

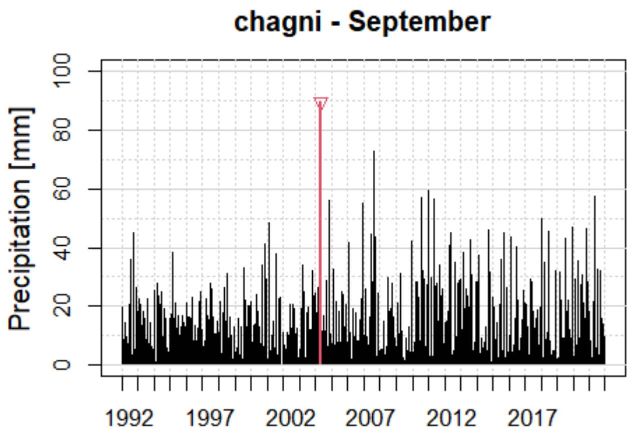


Figure 7. Data quality check: in 2004/09/11 is recorded 89.6 is an outlier but when checked a hard copy it is 89.6 is the same so accept it.

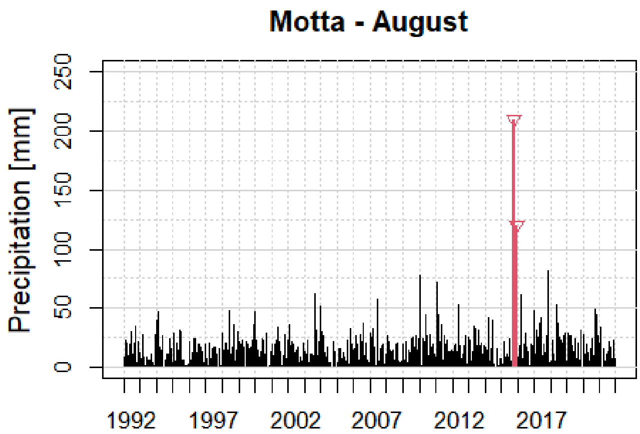


Figure 8. Data quality check: typing error during data entry: 210 mm rainfall data entered in place of 21mm.

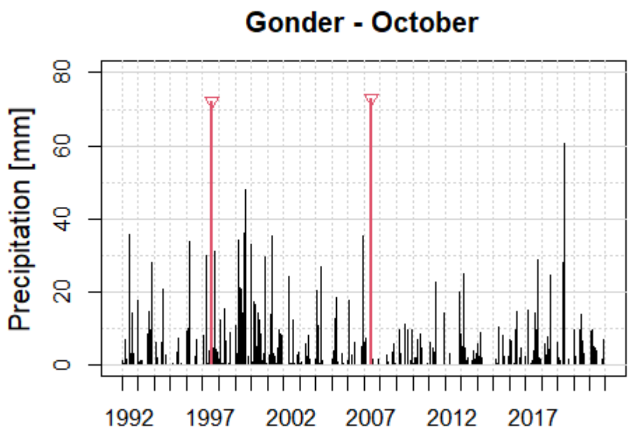


Figure 9. Data quality check: typing error during data entry: 73 mm rainfall data entered in place of 7.3 mm. And in 1997/10/19 is an outlier but when checked a hard copy it is true so accept.

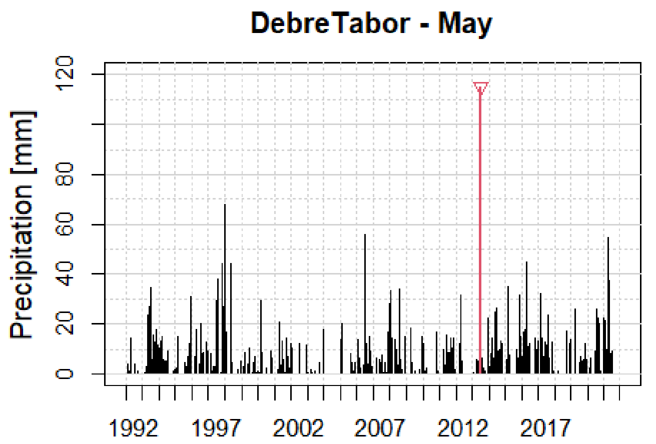


Figure 10. *Data quality check: typing error during data entry: 115 mm rainfall data entered in place of 11.5 mm.*

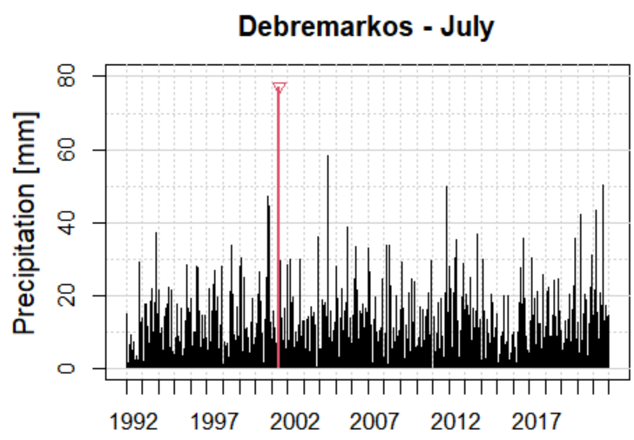


Figure 12. *Data quality check: In 2001/07/17 is recorded 77.2 as an outlier but when check a hard copy 77.2 was recorded so accept it.*

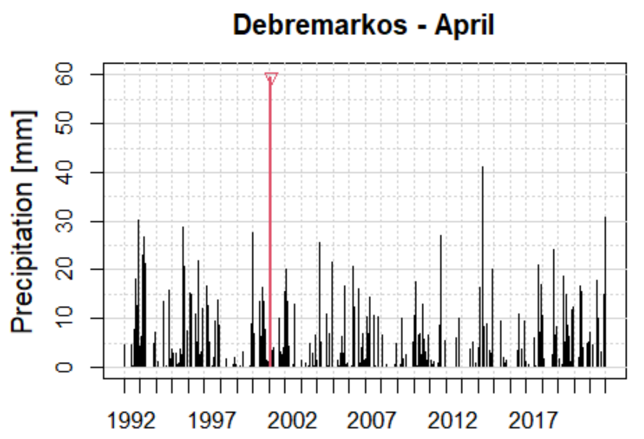


Figure 11. *Data quality check: In 2001/07/17 is recorded as 59.5 is an outlier but when checked a hard copy 59.5 was recorded so accept it.*

Monthly homogeneity test for all study station.

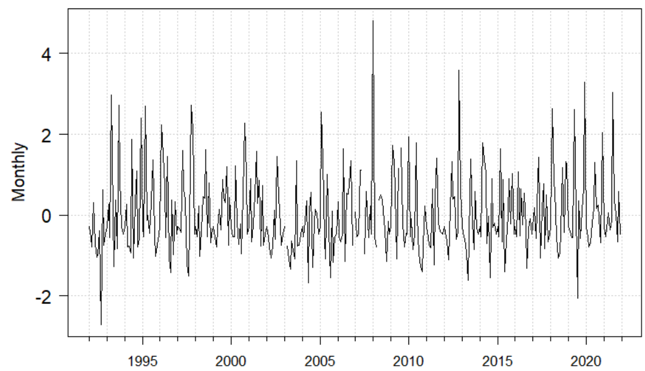


Figure 13. *Aykel monthly homogeneity test.*

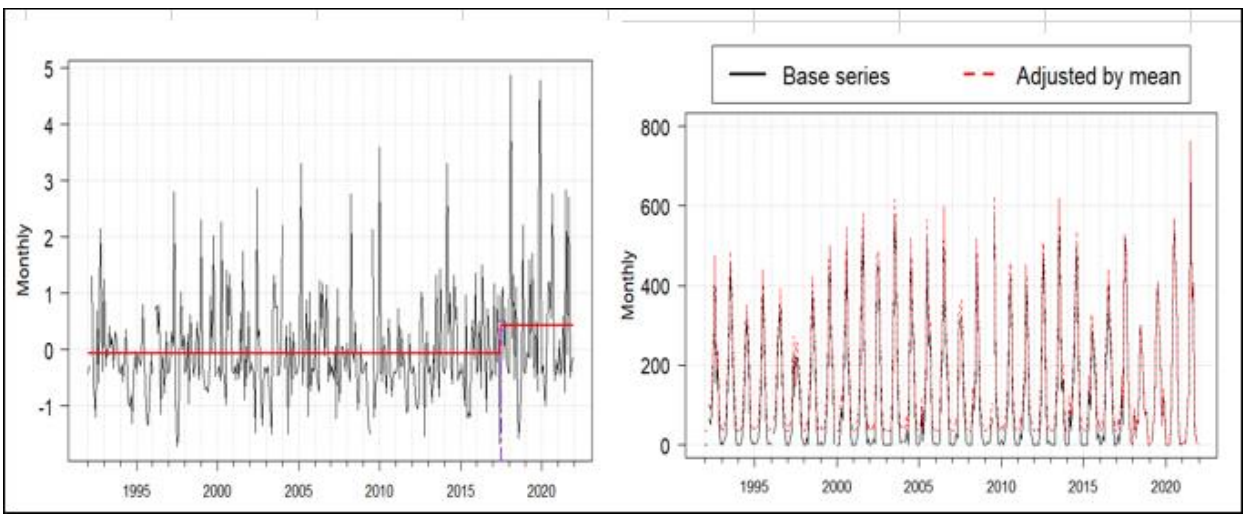


Figure 14. *Bahir Dar monthly homogeneity test.*

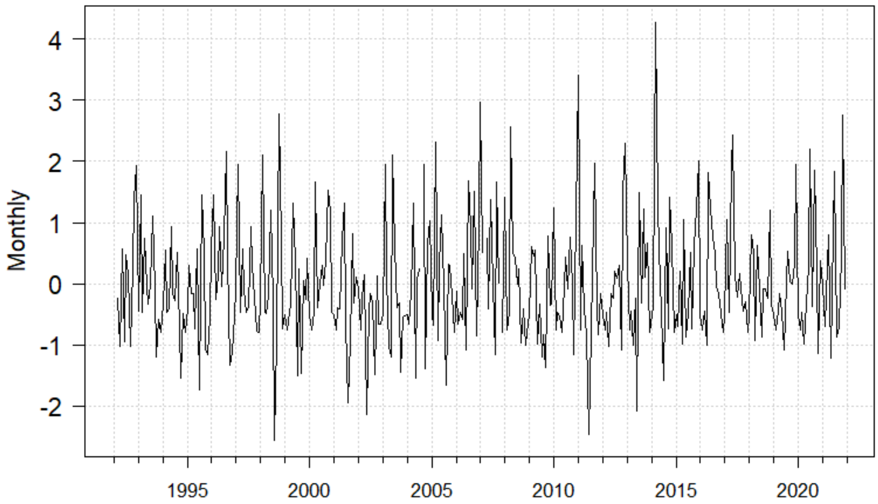


Figure 15. Chagni monthly homogeneity test.

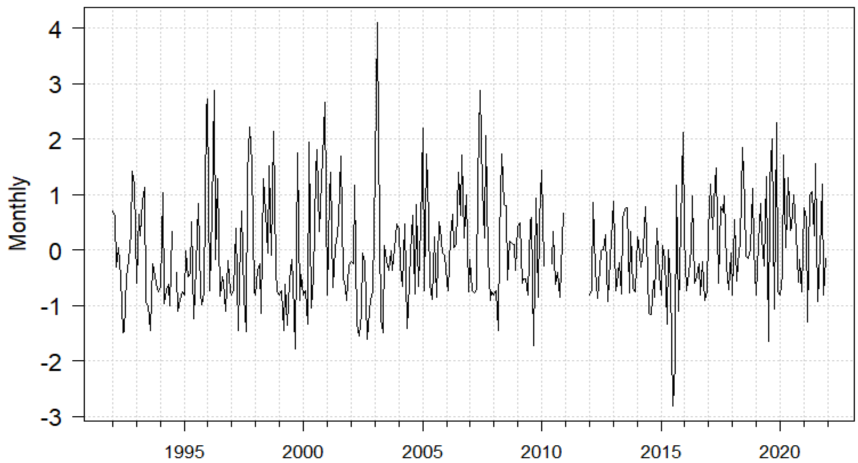


Figure 16. Debre work monthly homogeneity test.

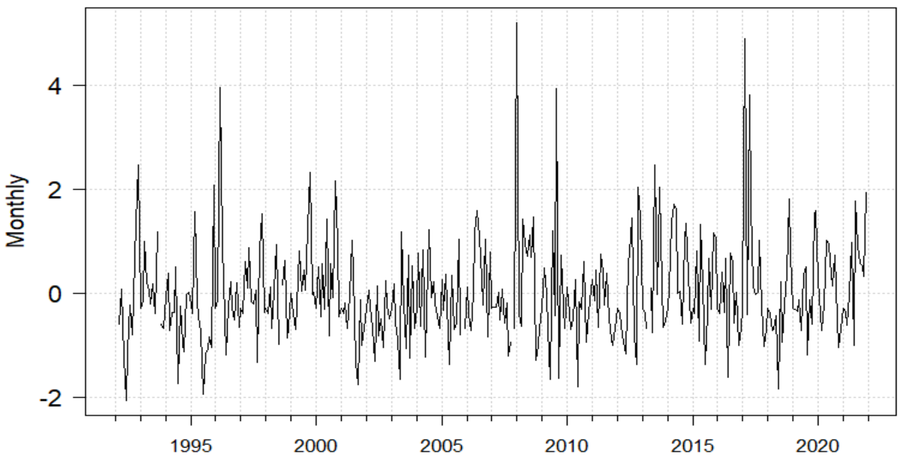


Figure 17. Dangila monthly homogeneity test.

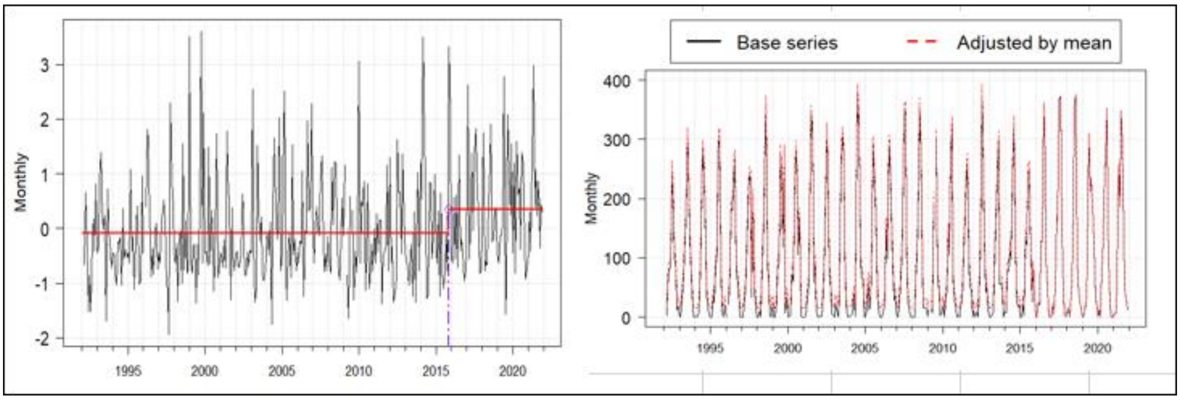


Figure 18. *Gonder monthly homogeneity test.*

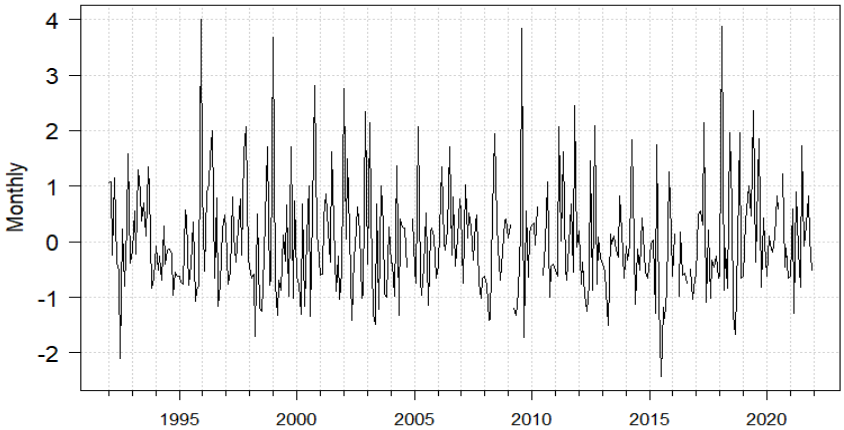


Figure 19. *Debre Markos monthly homogeneity test.*

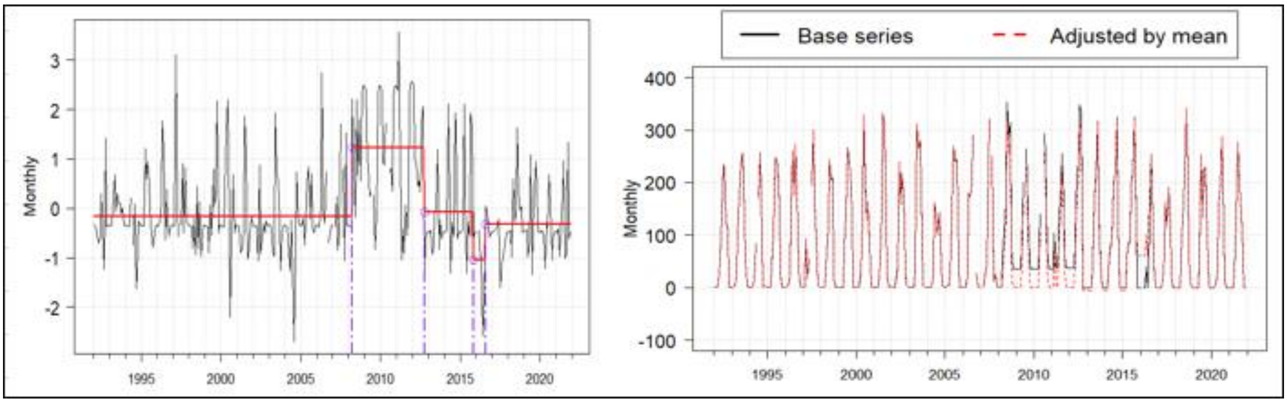


Figure 20. *Metema monthly homogeneity test.*

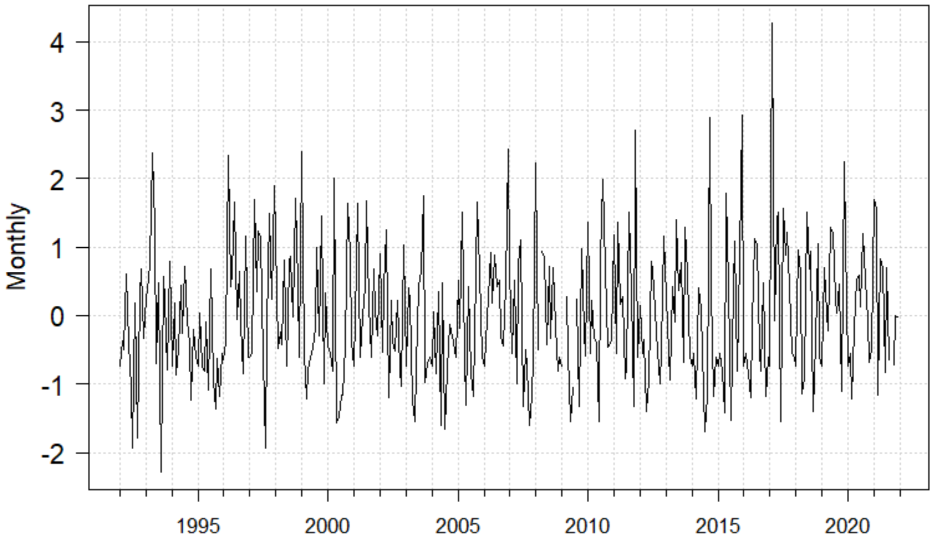


Figure 21. *Motta monthly homogeneity test.*

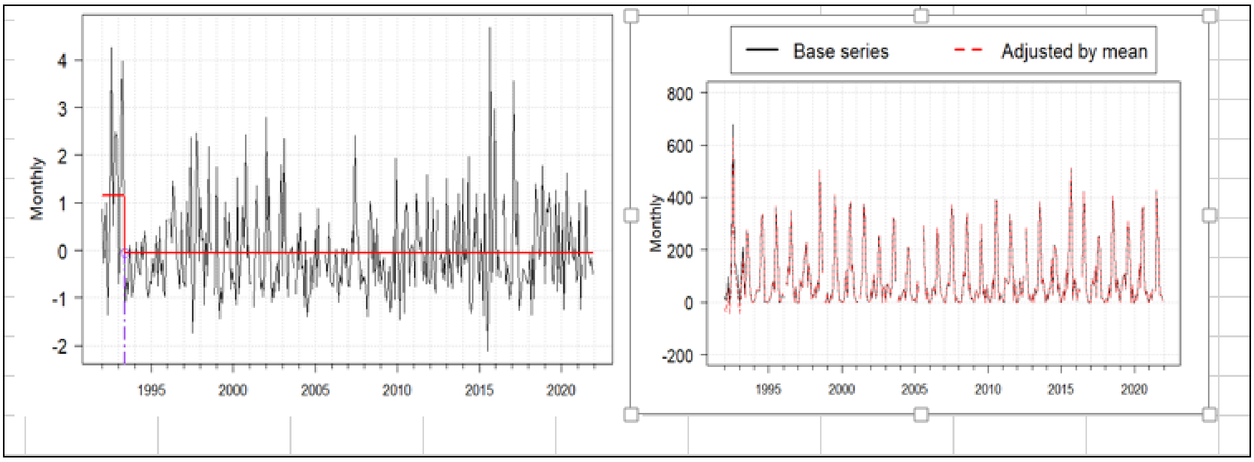


Figure 22. *Nefas mewucha monthly homogeneity test.*

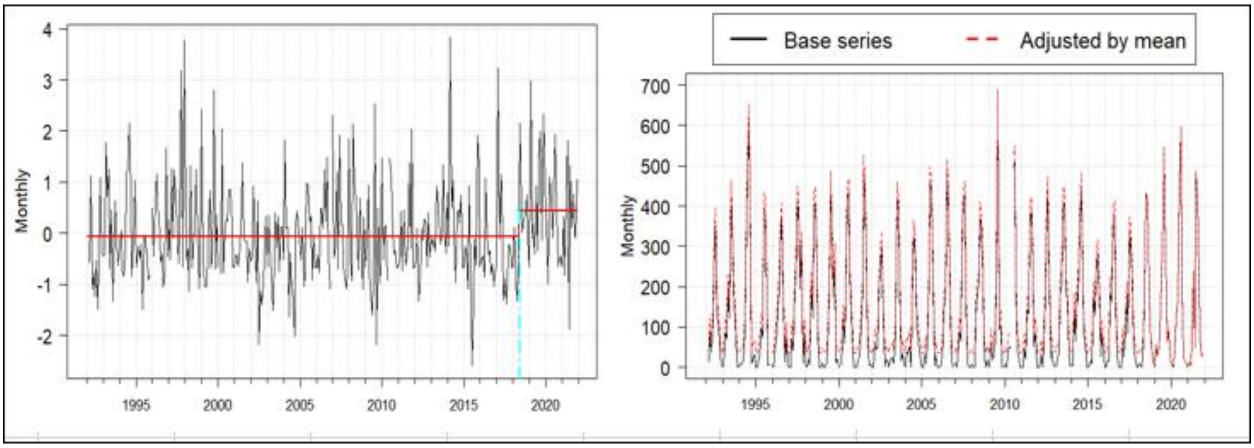


Figure 23. *Debre tabor monthly homogeneity test.*

Table 5. *Standardized rainfall anomaly of 11 stations from (1992-2021).*

ID. STN	Aykel	BahirDar	chagni	ebremark Deb	rework	Dangila	ebreTabo	Gonder	fasMewuc	Metema	Motta
LON	37.0	37.4	36.5	37.8	38.2	36.8	37.6	37.4	38.4	36.4	37.9
LAT	12.5	11.6	11.0	10.3	10.7	11.3	11.5	12.5	11.8	12.8	11.1
1992	-2.6	-0.3	0.7	-0.7	-1.1	-1.2	-1.3	-1.7	-3.6	-0.6	-1.5
1993	1.6	0.6	0.4	2.2	-0.9	0.3	0.3	0.0	0.5	0.5	0.1
1994	-0.5	-1.8	-0.4	-1.1	-1.0	-1.4	1.4	-1.1	-0.4	-1.1	-0.7
1995	-0.2	-1.3	0.2	-1.0	-0.5	-1.9	-1.2	-1.2	-0.5	0.3	-1.8
1996	-0.7	-0.4	1.7	1.5	-0.2	0.2	-0.1	0.5	0.4	0.7	1.0
1997	0.9	-1.2	0.7	1.1	-0.3	0.3	2.0	0.0	0.1	0.6	0.4
1998	0.4	-0.1	0.5	-1.0	1.4	-0.3	-0.1	-0.8	0.9	-0.6	1.1
1999	0.7	0.1	0.0	-0.1	-1.3	1.3	0.2	0.5	-0.1	0.7	0.0
2000	0.8	0.5	1.3	0.5	1.8	1.1	0.6	0.2	0.9	0.3	-0.9
2001	0.7	0.4	-0.9	0.1	0.7	-1.1	-0.1	0.4	-0.2	0.1	1.0
2002	-0.7	0.2	-2.5	-0.3	-1.7	-1.3	-2.0	-1.1	-0.5	-0.6	-0.6
2003	-2.0	0.9	-1.2	-1.0	-0.1	-1.2	-1.1	-0.5	-0.2	0.4	-0.5
2004	-1.1	-0.5	-0.3	-0.3	-0.4	-0.1	-1.5	0.2	-1.8	-1.7	-1.5
2005	-1.5	0.1	-0.3	-0.7	0.0	-1.1	-0.1	-0.6	0.0	0.7	-0.4
2006	1.6	1.1	1.0	1.1	1.3	1.2	0.6	0.7	-0.9	0.5	1.0
2007	0.9	-0.7	0.9	0.1	1.4	-0.8	0.0	0.9	0.6	1.0	-1.2
2008	0.4	-0.2	-0.2	0.1	0.6	1.3	0.3	0.7	0.2	2.2	0.3
2009	0.5	-1.3	-1.9	-0.3	-0.2	0.4	-0.1	-1.4	-1.5	-1.3	-1.1
2010	-1.3	-0.5	-0.2	0.1	0.1	-0.7	0.5	-0.6	0.6	0.4	0.4
2011	-0.4	-1.0	-1.9	1.0	0.3	-0.2	-0.1	-0.9	0.2	-1.8	0.3
2012	0.8	-0.3	-0.8	-0.8	-0.6	0.0	-0.7	0.1	-0.4	1.3	-0.7
2013	-0.7	0.2	-0.2	-0.5	0.3	1.2	0.8	-1.4	0.5	0.1	1.4
2014	0.4	1.1	0.8	-0.2	-1.1	1.5	1.1	0.4	0.1	0.6	-0.8
2015	0.0	-1.4	0.2	-2.1	-2.3	0.4	-1.5	-0.7	1.6	0.6	1.4
2016	0.4	0.2	1.0	-1.3	-0.7	-0.2	-0.7	-0.2	0.4	-2.0	-0.2
2017	0.4	0.7	0.9	-0.1	1.2	1.6	-1.0	2.1	-0.4	-1.8	2.1
2018	-0.1	-0.6	-0.6	-0.2	0.8	-0.7	0.4	1.0	0.8	0.9	0.5
2019	0.1	1.5	-0.7	2.1	0.7	-0.4	1.9	1.2	1.3	0.1	1.3
2020	0.0	2.2	0.9	1.1	1.0	0.5	1.0	1.3	0.7	-0.6	0.5
2021	1.1	2.1	0.7	0.6	0.8	1.4	0.8	2.1	0.8	0.1	-0.7

Table 6. *Annual PCI for 11 meteorological stations.*

Year	Aykel	Bahir dar	chagni	Debre work	Dangila	Gonder	Mota	Nefas Mewucha	Metema	Debre Tabor	Debre markos
1992	21.3	19.2	15.6	13.9	16.2	17.4	18.2	20.9	19.6	19.2	13.2
1993	16.7	19.6	16.6	14.7	16.1	16.1	15.4	16.4	18.7	16.1	14.4
1994	20.5	20.9	17.3	25.9	18.5	20.7	20.7	23.3	21.9	23.7	18.1
1995	19.0	23.3	17.6	22.5	15.4	21.6	23.2	22.9	19.6	23.1	16.2
1996	16.6	18.2	17.1	15.1	15.1	16.5	16.3	17.9	19.3	16.9	14.8
1997	13.7	15.4	16.1	15.6	15.0	15.9	13.4	13.5	16.6	14.9	14.2
1998	19.6	19.5	16.0	19.0	16.9	22.1	18.0	24.6	22.0	20.1	16.9
1999	18.2	22.5	16.1	24.2	15.8	17.5	20.1	25.7	18.7	20.3	16.2
2000	15.2	19.8	15.0	19.8	15.7	17.6	17.7	20.7	19.1	19.0	16.5
2001	18.4	23.6	16.0	21.7	19.1	21.8	18.8	25.6	24.8	22.3	17.2
2002	20.2	26.2	18.4	29.1	18.8	21.5	18.3	16.3	21.6	19.3	16.6
2003	20.9	26.1	19.4	17.3	21.2	22.7	23.7	21.9	23.9	24.7	19.4
2004	19.9	23.2	17.6	21.7	19.5	21.7	17.8	19.6	19.0	17.5	16.6
2005	19.7	21.4	15.8	16.8	20.4	20.0	15.9	22.8	20.1	23.4	16.2
2006	18.1	20.9	17.2	18.5	16.8	17.1	16.6	19.8	19.3	21.0	15.7
2007	16.5	20.2	15.4	18.5	17.7	21.0	18.7	21.6	21.4	21.5	16.1
2008	17.2	20.7	15.6	18.1	17.3	20.4	18.0	20.9	19.3	16.9	17.0
2009	17.9	35.4	15.7	22.3	24.9	24.5	21.1	21.9	22.3	29.3	26.4
2010	21.4	23.8	17.7	17.0	18.3	19.6	23.2	24.3	20.3	23.2	15.9
2011	20.0	21.3	18.7	16.0	18.7	17.4	18.5	17.6	21.3	18.1	14.0
2012	17.8	28.4	16.7	20.6	20.7	23.6	21.8	20.6	24.2	22.7	21.5
2013	24.1	24.3	18.0	22.7	19.7	21.1	17.6	20.9	23.0	17.8	16.5
2014	15.3	18.3	14.3	14.8	13.9	16.1	18.6	14.5	18.6	15.6	14.8
2015	16.5	18.1	15.3	16.0	15.1	16.2	16.5	22.5	18.6	16.1	15.7
2016	18.4	18.3	17.0	18.2	18.7	21.1	20.2	21.1	28.4	21.2	17.2
2017	17.9	23.1	15.3	17.4	15.0	19.0	18.4	17.1	20.1	16.6	15.2
2018	14.9	15.4	15.4	17.7	16.6	21.7	19.7	21.0	21.3	20.3	15.4
2019	17.0	16.0	16.4	16.4	16.8	16.3	15.5	16.5	20.1	17.3	15.4
2020	20.6	21.8	18.6	18.0	17.8	18.1	19.1	20.9	23.4	22.7	17.1
2021	22.7	26.0	16.0	19.0	16.9	17.2	18.5	21.8	18.9	19.7	16.3
Average	18.5	21.7	16.6	19.0	17.6	19.5	18.6	20.5	20.8	20.0	16.6

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