METEOROLOGICAL DROUGHT ANALYSIS: THE CASE OF ABAYA-CHAMO SUB-BASIN

M Sc THESIS

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METEOROLOGICAL DROUGHT ANALYSIS: THE CASE OF ABAYA- CHAMO SUB-BASIN

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A THESIS SUBMITTED TO THE
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ADVISORS' APPROVAL SHEET

This is to certify that the thesis entitled "**METEOROLOGICAL DROUGHT ANALYSIS: THE CASE OF ABAYA- CHAMO SUB-BASIN**" submitted in partial fulfillment of the requirements for the degree of **Master of Science** with specialization in **Hydraulic Engineering,** the graduate program of the **Department of Civil Engineering,** and has been carried out by **TESHOME AFIRA** Id. No. **PGHY 039/09,** under our supervision. Therefore, we hereby certify that we have read this thesis prepared under our direction and recommend that it accepted as fulfilling the thesis requirement.

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We, the undersigned, members of the Board of Examiners of the final open defense by **TESHOME AFIRA** have read and evaluated his thesis entitled "**METEOROLOGICAL DROUGHT ANALYSIS: THE CASE OF ABAYA-CHAMO SUB-BASIN**", and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering with specialization in Hydraulic Engineering.

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Final approval and acceptance of the thesis is contingent upon the submission of the final copy of the thesis to the School of Graduate Studies (SGS) through the Department/School Graduate Committee (DGC/SGC) of the candidate's department.

DEDICATION

I dedicate this thesis manuscript to my father AFIRA DULECHA and my mother SHORE MERASSA for their love and dedicated partnership in the success of my life.

DECLARATION

I hereby declare that this MSc thesis entitled ‘Meteorological Drought Analysis: The Case of Abaya-Chamo Sub-Basin’ is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

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ABBREVIATIONS

CC	Coefficient of Correlation
CV	Coefficient of Variation
L-CV	L-moments Coefficient of Variation
EA	Eastern Africa
EDI	Effective Drought Index
EM-DAT	Emergency Events Database
IPCC	Intergovernmental Panel on Climate Change
NDMC	National Drought Mitigation Centre
NMSA	National Meteorological Services Agency
PDF	Probability Distribution Function
PDSI	Palmer Drought Severity Index
P-P	Probability-Probability
PWMs	Probability Weighted Moments
R^2	Inter-site correlation squared
Q-Q	Quantile-Quantile
SPEI	Standardized Precipitation-Evapotranspiration Index
SPI	Standardized Precipitation Index
SPSS	Statistical Package for the Social Science
SWSI	Surface Water Supply Index
WMO	World Meteorological Organization

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ABSTRACT

Meteorological drought is the deficit in precipitation over a region for a period of time which in turn results in the reduction of moisture condition of the soil and then the crop yield. It has severe socio-economic and environmental impacts which require to careful monitoring of drought conditions using a suitable index. The objective of this research was to analyze meteorological drought frequency, severity and duration in the Abaya-Chamo Sub-basin using the application of SPI for monthly rainfall records. After checking the data quality and fitting the Gamma statistical distribution for each selected station as a requirement of the SPI, the analysis was done for the past 30 years of record from 1988 to 2017 for five selected stations based on monthly precipitation records using the index at 1-, 3-, 6-, 9- and 12-month timescales. The results show that, no correlation exists between successive observations, and thus, the data are independent, and there was no persistence in the time series. The inter-site correlation was less than one (R^2<1) for all the statios and hence all the stations in the sub-basin were consistent. For both convectional Cv and L-Cv based homogeneity tests the coefficient of correlation (CC) values were less than 0.3 showing the homogeneity of the stations. Gamma probability distribution was determined as the best fit statistical distribution for the data set since the typical alpha level was greater than 0.05 at 95% of confidence interval as checked using Kolmogorov Smirnov and Shapiro Wilk's test using SPSS. All of the studied meteorological stations experienced drought episodes in 1988, 1989/1990, 1992/1993, 1999,2000/2001, 2003/2004 and 2007/2008 which were among the worst drought years in the history of Ethiopia, and moderate drought events ranging from the SPI values of -1.49 to -1 were pronounced with greater frequency than other dry events. Severely dry events were occurred at values between -1.99 and -1.50. The maximum SPI value of extreme dry event was -2.69. The year 1999 was the most drastic and distinct-wide extreme drought episode in all studied stations. The findings of this study have implications for drought management, early warning system, preparedness and contingency planning and climate change adaptation.

Keywords: Meteorological Drought, SPI, Abaya-Chamo Sub-Basin.

1. INTRODUCTION

1.1. Background

Drought is widely recognized as a complex, multifaceted phenomenon (Van Loon, 2015). Unlike many other natural hazards, drought develops slowly, making it difficult to pinpoint the onset and termination of an event. Fundamentally, a drought is a deficit in the expected available water in a given hydrological system (Sheffield and Wood, 2011). Drought has popularly been classified into various types as meteorological, hydrological, agricultural, environmental and socio-economic. Drought that results from a rainfall deficit is meteorological drought. Hydrological drought is related to a period with inadequate surface and sub surface water resources for established water uses. Agricultural drought usually is defined as a reduction of agricultural products and loss of plants. Continuation of rainfall deficits may cause a permanent shortage in soil moisture in the growth season; therefore, the average shortage in soil moisture over a period of several months for crops those are sensitive to soil moisture and have high water demands can be used as an indicator of drought severity.

The drought generally reflects the compartment of the hydrological cycle or sector of human activity that is affected; deficits typically propagate through the hydrological cycle, impacting different ecosystems and human activities accordingly. The impact of climate change and widespread water contamination has resulted in many irregularities in the supply and demand structure. Drought events have occurred with smaller recurrence intervals with higher peaks and levels of severity. The difference between actual demand and user perceptions about water use is the key measure used to evaluate the severity of a drought by hydrologists, meteorologists, water resources engineers, agricultural researchers, economists, and other stakeholders.

A number of definitions of drought events have been suggested by researchers. It has been described that it is not possible to define and analyze drought without paying attention to the nature of water shortage, sequence of time for discretization of drought and truncation levels that are used to separate drought from other phenomena, and regional aspects of the drought (Dracup *et. al*., 1980).

Drought can be analyzed through point (localized) drought analysis and/or regional analysis of drought. This study is about point analysis of climatic drought in Abaya-Chamo sub-basin. In point investigations, a time series of hydro-climatological factors or a drought indicator is evaluated at a specific point (station). A time sequence and then a truncation level are assigned to determine drought events in a time series in order to perform the analytical evaluation.

In point evaluation of climatic drought to detect dry events, the best probabilistic distributions should be chosen to describe the behavior and variation of precipitation at each sub-basin represented by a rain gauge. The concept of effective rainfall and excess deficit and surplus on a monthly scale can be extended to determine the onset, duration, and the severity of drought (Mohammad, 2003).

1.2. Statement of the Problem

Drought is an abnormal and prolonged deficit in the available water and has a major impact on both natural and social water resources (Mishra and Singh, 2010). Due to the large spatial and long temporal extent of drought events, they tend to have a large economic damage. Droughts are extreme water related hazards with severe consequences on the environment, societies and economy. It is a periodic phenomenon which appears in a local as well as in a global scale and threatens many aspects of life in both developed and undeveloped countries.

Drought phenomenon is water related extreme like flood and is a natural disaster. However, unlike floods the droughts are of the creeping kind; they develop in a region over a length of time and sometimes may extend to continental scale. The consequences of droughts on the agricultural production, hydropower generation and in the regional economy are well known. Further, during droughts the quality of available water will be highly degraded resulting in serious environmental and health problems (Subramanya, 2003).

According to IPCC, it has been successively warmer in the past 30 years on the Earth's surface than any decade since 1850. With the variation of precipitation distribution and rising temperature, the intensity and frequency of drought disasters are changing quickly in the whole world (IPCC, 2013). So, it is important to do research on the trend of spatial and temporal distribution of drought under changing climate.

Ethiopia has been affected frequently by drought in the past for several years, and recurrent drought and desertification are the most serious environmental problems that Ethiopia is facing (Viste *et. al*., 2012). According to the report of National Meteorological Services Agency (NMSA), over the period 1980-2010 ten major drought disasters were reported in Ethiopia. The major drought of 1984 resulted in over 300,000 deaths and affected over 7.5 million people, while drought in 2003 affected over 12.6 million people. Each successive drought makes it more difficult to recover, making the people of Ethiopia more vulnerable to climate change.

Usually, meteorological drought is the base of the other three drought types, so it is important to do research on meteorological drought in large scale which would reveal the potential trends of drought disasters (Kuo Li and Jie Pan, 2016). However, no one conducted meteorological drought analysis in the Abaya-Chamo sub-basin, and hence, this study will fill these research gap.

1.3. Objective

1.3.1. General Objective

The general objective of this study is to analyze the meteorological drought of Abaya-Chamo sub-basin.

1.3.2. Specific Objective

The specific objectives of this study are:

- To analyze meteorological drought frequency, severity, and duration in the Abaya-Chamo sub-basin.

- To detect the best fit statistical probabilistic distribution for dry events in the study area.
- To identify how standardized precipitation index analyses meteorological drought.

1.4. Research Questions

The research questions that will be addressed in this study are:

- At what frequency, magnitude and duration do the meteorological drought event occurs in the Abaya- Chamo sub-basin?
- Which statistical probability distribution that best fits to the drought events in the basin?
- How does the standardized precipitation index (SPI) analyze the drought events in the study area?

1.5. Scope of the Study

According to American Meteorological Society (1997), four types of droughts can be distinguished; meteorological, agricultural, hydrological and socio-economic droughts. These are evaluated either through point (localized) and/or regional analysis. This study is about the point analysis of evaluating meteorological drought in Abaya-Chamo sub-basin. From various available drought indices this study uses only Standardized Precipitation Index (SPI) for the analysis drought event.

1.6. Significance of the Study

This study is significant in providing basic information about occurrence, magnitude, extent and severity of meteorological drought in the region and from the analysis result one can arrive at the solutions for drought management strategies and remedial measures for existing problems at present and going to exist in the future. In addition, this research provides sufficient information to decision makers which may be used for drought early warning and preparedness before they happens.

2. LITERATURE REVIEW

2.1. General

Drought is a recurrent climatic phenomenon across the world having spatial and temporal characteristics that vary significantly from one region to another. It is erroneously considered as a rare and random event. It differs from aridity, which is restricted to low rainfall regions and is a permanent feature of climate. Drought should be considered relative to some long-term average conditions of the balance between precipitation and evapo-transpiration in a particular area. It is also related to the timing and the effectiveness of the rains (Singh, 2003).

It is a condition on land characterized by recurring scarcity of water that falls below normal average or defined threshold levels (Wambua *et. al*., 2014a). It is a naturally reoccurring climatic variability (Altman, 2013). Yet an unambiguous and precise definition of drought remains elusive (Karavitis, 1998). Due to its accumulating impacts over time and slow onset, drought remains the most devastating but least understood weather phenomena (Opiyo *et. al*., 2015). Moreover, drought lasts for extended periods of time and distresses large areas. Presently, droughts are expected likely to increase in severity and frequency with the changing climate and thus to impact environmental, social and economic sectors of vulnerable populations (IPCC, 2012).

Drought is the state of adverse and widespread hydrological, environmental, social and economic impacts due to less than anticipated water quantities (Karavitis, 1999). In contrast to aridity, droughts affect almost all climates in the world (WMO, 2006). The common factor is a deficit in normal precipitation over an extended period sufficient to cause adverse impacts. There are two main definitions of drought: conceptual and operational (WMO, 2005).

Conceptual definitions, formulated in general terms, help people understand the concept of drought. For example, drought is a protracted period of deficient precipitation resulting in extensive damage to crops, further resulting in loss of yield. Conceptual definitions may also be important in establishing drought policy. An operational definition of drought helps people to identify the beginning, end, and degree of severity of a drought. According to World

Meteorological Organization recommendations, this definition is usually made by comparing the current situation to the historical average, often based on a 30-year period of record (WMO, 2005).

The effects of droughts are severe particularly in East African countries due to high rainfall variability in space and time (Yared *et. al*., 2017). Among these countries, Ethiopia encounters frequent droughts (occurring once in every 2-3 years). Recently, the severe drought events were occurred in Ethiopia in 2011, 2012, 2014 and 2015 with most of them covering the whole country (Edossa *et. al*., 2009).

In order to mitigate the impacts of droughts in the country, proper drought monitoring and early warning systems are essential. For the purpose of appropriate drought detections, the slow developmental nature of drought is widely classified into four types; meteorological, agricultural, hydrological, and socio-economic drought (Mishra and Singh, 2010). In every drought monitoring practice more emphasis is given to meteorological drought (simple absence/deficit of rainfall from the normal) as it is the first to occur and other droughts are consequent to it. If the precipitation deficit is continuous for a longer period, all other droughts will happen one after the other (Hao *et. al*., 2017).

2.2. Types of Drought

Generally, droughts are classified as either hydrological (insufficient surface and subsurface water resources), meteorological (lack of precipitation) or agricultural (declining soil moisture) and socio-economic (Hounam *et. al*., 1975). All of them were described one by one in the following sub topics. Notably, all droughts result from a deficiency of precipitation and begin as a meteorological drought. Other types of drought and their impacts cascade from meteorological drought to other forms (WMO, 2006).

2.2.1. Meteorological drought

Meteorological drought is defined as a lack of precipitation over a region for a period of time. Precipitation data has been commonly used for meteorological drought analysis. Considering drought as precipitation deficit with respect to average values, several studies have analyzed droughts using monthly precipitation data. Other approaches analyze drought duration and intensity in relation to cumulative precipitation shortages.

It is usually defined on the basis of the degree of dryness (in comparison to some "normal" or average amount) and the duration of the dry period. Definitions of meteorological drought must be considered as specific to a region since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. It depends on precipitation deficit and duration of period with precipitation deficit (Santos, 1983).

2.2.2. Agricultural drought

Agricultural drought refers to situations with insufficient soil moisture level to meet the plant needs of water during vegetation period. Its definitions link various characteristics of meteorological drought to agricultural impacts, focusing, for example, on precipitation shortages; departures from normal; or numerous meteorological factors such as differences between actual and potential evapo-transpiration, soil water deficits, reduced groundwater or reservoir levels, and so forth. Several drought indices, based on a combination of precipitation, temperature and soil moisture, have been derived to study agricultural droughts (Wilhite and Glantz, 1985).

An operational definition of agricultural drought should account for the variable susceptibility of crops at different stages of crop development. A plant's demand for water is dependent on prevailing meteorological conditions, biological characteristics of the specific plant, its stage of growth, and the physical and biological properties of the soil. For example, deficient subsoil moisture in an early growth stage will have little impact on final crop yield if top soil moisture is sufficient to meet early growth requirements. However, if the deficiency of sub soil moisture continues, a substantial yield loss would result (Wilhite and Glantz, 1985).

2.2.3. Hydrological drought

Hydrological drought is related to a period with inadequate surface and subsurface water resources for established water uses of a given water resources management system. Streamflow data have been widely applied for hydrologic drought analysis. From regression analysis relating droughts in streamflow to catchment properties, it is found that geology is one of the main factors influencing hydrological droughts (Dracup *et. al*., 1980).

Hydrological drought is associated with the effects of periods of precipitation (including snowfall) shortfalls on surface or subsurface water supply (i.e., streamflow, reservoir and lake levels, and groundwater). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale. It occurs after longer period of precipitation deficit. Although, climate is a primary contributor to hydrological drought, other factors such as changes in land use (e.g., deforestation), land degradation, and the construction of dams all affect the hydrological characteristics of a basin (Dracup *et. al*., 1980).

2.2.4. Socio-economic drought

Socio-economic drought is associated with failure of water resources systems to meet water demands and thus associating droughts with supply of and demand for an economic good (water). It occur when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply, and when physical water shortage starts to affect people, individually and collectively (AMS, 2004).

2.3. Impacts of Drought

All the definitions of the droughts are related to the impacts of a dry spell on the human activities: the impacts of drought may be environmental, economic and social. The environmental impact is the result of damages to plant and animal species, wildlife habitat, air and water quality; forest and fires, degradation of landscape quality; loss of biodiversity, and soil erosion. Some of the effects are only short-term and normal conditions are quickly reestablished. Other environmental effects linger for some time or may even become permanent. For example, the degradation of landscape quality, including increased soil erosion, may lead to a permanent loss of biological productivity of the area.

The economic impact occurs in agriculture and related sectors, including forestry and fisheries, which depend on the surface and groundwater supplies. In addition to obvious losses in yields in crop and livestock production, drought is associated with the increase in insect infestations, plant disease, and wind erosion. Among all the natural disasters, droughts have the most impact on a country‘s economy (Mishra, 2010).

The social impact is present in periods of extreme, persistent drought. In these cases some emergency sources of water are required to take safety measure to safeguard public health. Direct impacts of drought include death/malnutrition in animals/humans, decline in food yield, forest and greenbelt; worsening water/air quality and sanitation; and higher fire prevention risk. Indirect effects include price upsurge, reduction of income, loss of jobs, and degradation of living standards among others. Droughts accounted for 50% of the 2.8 billion people affected by natural disasters between 1967 and 1992 (Mishra, 2006). Figure-1 presents commonly accepted drought types, occurrence and impacts sequence.

There is likely to be a significant increase in drought risk in Eastern Africa (EA) towards 2050s and ultimately threaten climate-sensitive economic sectors (IPCC, 2012). Populations whose livelihoods depend principally on natural resources are mostly affected by drought (Below *et. al.*, 2010; Nicholson, 2014).

Compared to other natural disasters such as floods, hurricanes, earthquakes and epidemics, droughts are tough to predict; they creep slowly and last longest. The complex nature of droughts onset-termination has made it acquire the title ‘the creeping disaster’ (Mishra, 2010). There is much uncertainty in determining when a drought begins or ends because of this creeping nature. It develops slowly, and its impacts form a complex web that spans all aspects of the life of the affected society. Hypothetically, drought prediction tools could be used to establish precise drought development patterns as early as possible and provide sufficient information to decision-makers to prepare for the droughts long before they happen. This way, the prediction can be used to mitigate effects of droughts.

An effective drought monitoring and early warning system is a way to prevent or reduce drought impacts. Impacts are the primary ways to measure drought severity. An effective drought tracking system can deliver an early warning in a case of the drought’s onset, successfully measure drought severity and spatial extent, and communicate facts to decision-making groups promptly (Hayes, 2011).

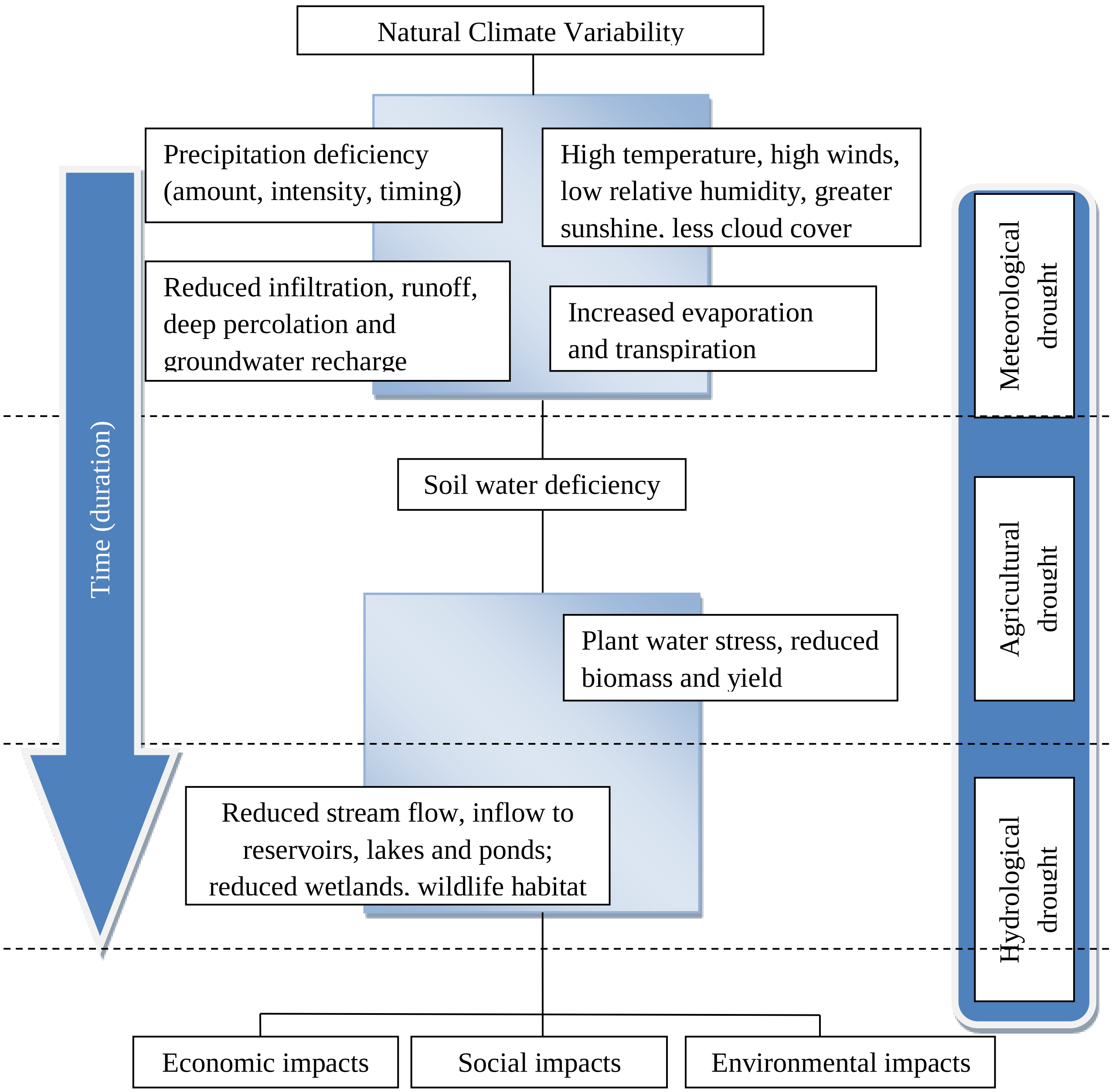

Figure 1: Common drought types, occurrence and impacts sequence

2.4. Drought Analysis

Drought analysis can be divided into two categories: point (localized) analysis or regional analysis. In the point drought analysis, drought in station or small area is investigated. In point investigations, a time series of hydro-climatological factor or a drought indicator is evaluated at a specific point. A time sequence and then a truncation level are assigned to determine drought events in a time series in order to perform the analytical evaluation (Mohammad, 2003).

The application of run theory is a fundamental method of analyzing point drought. According to this theory, one could detect a consecutive period of shortage or surplus after choosing a truncation level for existing data by assuming that they are stationary. Then, from detected consecutive shortage periods, probability distributions of drought parameters such as duration and the amount of shortage are evaluated (Yevjevich, 1967).

In the study of regional drought, severe water shortage conditions in contiguous and extended regions are investigated. In addition to defining truncation level, a critical area should also be defined. Based on this approach, regional drought occurs when the drought affected area is greater than the critical area. Many investigators used standardized normal distribution values for drought events with different return periods as a truncation level, assuming that all the specified rain gauges in the study area follow the normal distribution (Santos, 1983).

2.5. Overview of Drought Indices

Drought index is a variable which characterizes droughts on their intensity, duration and severity at a given location and time. Commonly, a drought index is a prime variable for assessing the effect of a drought and defining different drought parameters, which include intensity, duration, severity and spatial extent (Wondie and Terefe, 2016).

Several drought indices have been developed to quantify a drought, each with its own strengths and weaknesses. They include Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), Standardized Precipitation-Evapotranspiration Index (SPEI), Surface Water Supply Index (SWSI), Effective Drought Index (EDI), Percent of Normal/Departure from normal precipitation and Deciles (Vinit *et. al*., 2015).

2.5.1. Palmer drought severity index (PDSI)

PDSI is most widely used regional drought index for monitoring droughts. The index has been used to illustrate the areal extent and severity of various drought episodes and to investigate the spatial and temporal drought characteristics as well as to explore the periodic behavior of droughts, monitoring hydrologic trends, crop forecasts, and assessing potential fire severity, droughts over large geographic areas, and drought forecasting (Palmer, 1967).

It is suitable for agricultural impacts and not so much for hydrologic droughts. It also assumes that runoff only occurs after all soil layers have become saturated, leading to an underestimation of runoff, and it can be slow to respond to developing and diminishing droughts. It is sensitive to both temperature and precipitation. Because of the dependence of PDSI on climatologically appropriate rainfall, which is a function of time and varies with surface air temperature, it can be equally affected by temperature and precipitation, when both have similar magnitudes of anomalies. The effect of temperature on PDSI complicates the usage of the index in interpreting precipitation anomalies and its application in inferring precipitation variations (Hayes *et. al*., 1999).

The PDSI is based on the supply-and-demand concept of the water balance equation for a two-layer soil model using monthly precipitation and evapo-transpiration. The index is based upon the calculation of the moisture departure between actual precipitation and the precipitation expected to occur for the average conditions of the climate, which implies performing a monthly water balance and the calibration of local monthly coefficients for the various terms of the water balance. In addition, the calibration of the index is required at local or regional level. Due to computation requirements and limitations on the PDSI, usually a standardized and multi-scale drought index, like the SPI, has been preferred to facilitate the quantitative comparison of drought events at different locations and time scales.

The PDSI values depend upon the way how the soil water balance is computed, the soil available water capacity (AWC) of the underlying layer, the ET estimation method, and on the calibration procedures adopted. The drought severity classification based on the PDSI value is shown in the Table 2.1.

Table 2.1: Drought Classification by PDSI Value

PDSI Value	**Drought Classification**
4.0 or more	extremely wet
3.0 to 3.99	very wet
2.0 to 2.99	moderately wet
1.0 to 1.99	slightly wet
0.5 to 0.99	incipient wet spell
0.49 to -0.49	near normal
-0.5 to -0.99	incipient dry spell
-1.0 to -1.99	mild drought
-2.0 to -2.99	moderate drought
-3.0 to -3.99	severe drought
-4.0 or less	extreme drought

2.5.2. Standardized Precipitation Index (SPI)

The standardized precipitation index (SPI) for any location is calculated, based on the long-term precipitation record for a desired period for a variety of time scales. This long-term record is fitted to a probability distribution (especially, Gamma distribution), which is then transformed to a normal distribution so that the mean SPI for the location and desired period is zero (McKee *et. al*., 1993).

The versatility of SPI to different time scales allows monitoring short-term water supplies, such as soil moisture which is important for agricultural production, and long-term water resources, such as groundwater supplies, streamflow, and lake and reservoir levels. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the long-term precipitation anomalies. SPI has been used for studying different aspects of droughts, for example, forecasting, frequency analysis, spatiotemporal analysis and climate impact studies (Mishra and Singh, 2009). Table 2.2 shows drought condition based on the SPI values and its event probabilities. The drought event occurs any time when the SPI value is continuously negative and reaches an intensity of -1.00 or less and the event ends when the SPI becomes positive.

Table 2.2: Drought condition by SPI values and its event probabilities (McKee, 1997).

SPI Value	**Moisture Condition**	**Probability of Occurrence (%)**
2.00 or more	Extremely wet	2.3
1.50 to 1.99	Severely wet	4.4
1.00 to 1.49	Moderately wet	9.2
-0.99 to 0.99	Near normal	68.2
-1.49 to -1.00	Moderately dry	9.2
-1.99 to -1.50	Severely dry	4.4
-2 or less	Extremely dry	2.3

2.5.3. Standardized Precipitation-Evapo-Transpiration Index (SPEI)

The SPEI index is based on the original SPI calculation procedure. In this case, the input variable is the difference between precipitation and potential evapo-transpiration (PET) accumulated on a selected time scale, which is a simple measure of the theoretical water surplus or deficit for the analyzed month, but it performs like an aridity index because PET is used. The empirical statistical distribution of the input variable is fitted to a Log-logistic distribution and then, as in the SPI computation, transformed into a normal distribution. It is based on precipitation and potential PET and combines the sensitivity of PDSI and to changes in evaporation demand (caused by temperature fluctuations and trends) with the simplicity of calculation and the multi-temporal nature of the SPI (Vicente Serrano *et. al*., 2010).

2.5.4. Surface Water Supply Index (SWSI)

The surface water supply index (SWSI) was primarily developed as a hydrological drought index and it is calculated based on monthly non-exceedance probability from available historical records of reservoir storage, streamflow, snow pack, and precipitation. The purpose of SWSI is primarily to monitor abnormalities in surface water supply sources. Hence, it is a good measure to monitor the impact of hydrologic droughts on urban and industrial water supplies, irrigation and hydroelectric power generation. Four inputs required within SWSI are snowpack, streamflow, precipitation, and reservoir storage. Because it is dependent on the season, SWSI is computed with only snowpack, precipitation, and reservoir storage in winter. During summer months, streamflow replaces snowpack as a component within the SWSI equation (Wilhite and Glantz, 1985). The limitations of SWSI is that, the definition of surface water supply and the factor weights vary with spatial scale (one watershed to another) as well as temporal scale (season or month) due to differences in hydro-climatic variability resulting in SWSIs with differing statistical properties.

2.5.5. Effective Drought Index (EDI)

EDI is an intensive measure which considers daily water accumulation with weighting function for time passage. It calculates daily drought severity with a rapid detection and precise measurement of short term drought. It indicates current level of available water resources and it is able to diagnose prolonged droughts that continue for several years because it calculates the total precipitation period. The drought severity classes based on EDI analysis was presented in the following table.

Table 2.3: Drought Classes Based on EDI value

Drought classes	**Criterion**
Extreme drought	EDI ≤ 2.0
Severe drought	-2.0≤ EDI ≤-1.5
Moderate drought	-1.5≤ EDI ≤-1.0
Near normal	-1.0≤ EDI ≤1.0

2.6. Representativeness of the SPI as a Measure of Drought

The SPI benefits from being simple to calculate, depending only on precipitation, but the method also has some shortcomings. The main ones are that it is a purely statistical measure, that it depends on the assumptions of gamma-distributed precipitation and normal-distributed SPIs, and that records with low climatological precipitation may give misleading results. Recent research has shown that the SPI has many advantages over the PDSI and other indices in that it is relatively straight-forward, spatially consistent, and temporally flexible, thus allowing for observation of water deficits at different scales (Hayes *et. al*., 1999). Therefore, SPI can be used as the reliable agent for detecting emerging drought and valuable tool for assessing moisture condition and initiating mitigation and response actions.

One of the benefits of the SPI is it is uniquely related to probability, as specific values will be reached at specific frequencies, allowing comparison across time and space. The assumption that the SPI values are normally distributed further implies that wet and dry periods, as well as wet and dry climates, will be represented in a similar way. On the other hand, this also means that the SPI may not be used to identify regions that are more drought-prone than others. The frequency of extreme drought is the same for all regions, wet or dry (McKee *et. al*., 1993).

The SPI may be altered by fitting other distribution functions than the gamma function to the precipitation data. Guttman (1999), testing various functions (2-parameter gamma, 3-parameter Pearson Type-III, 3-parameter generalized extreme values, 4-parameter kappa, and 5-parameter Wakeby), concluded that the Pearson Type-III was the best universal model, as it performed well for both wet and dry events. For dry events, however, their assessment showed that there was little difference in the number, duration, intensity or regional variation of the events as portrayed by the distributions compared.

The number of data points also limits the range of the SPI, and SPIs with timescales longer than 24 months may be unreliable (Guttman, 1999). It is recommended to use the record containing at least 30 years of data when calculating the SPI (McKee *et. al*., 1993). Different lengths of records could give different results, especially for long timescales, and especially when evaluating the severity of severe droughts (Wu *et. al*., 2005).

2.7. Drought Events in Ethiopia

Ethiopia has been affected frequently by drought in the past for several years (Viste *et. al*., 2012). Recurrent drought and desertification are the most serious environmental problems that Ethiopia is facing. As per the available information, in Ethiopia, major droughts have occurred in 1965, 1969, 1978, 1983/84, 1987/89, 1992, 1997, 1998, 1999/2000, 2003/04, 2005/06, 2008/09, 2010, 2011/12 and 2015/16 (EM-DAT, 2017).

In Ethiopia, the National Meteorological Services Agency (NMSA) has attempted to collect and document the history of drought and famine, and their impact on various administrative regions of Ethiopia from various documents available nationally and internationally. The reports from 1950 onwards are well documented and contain interesting scientific data. The analysis of the rainfall data during this period indicates that 18 droughts/famines were recorded in 38 years, suggesting the occurrence of drought every two years. It can be seen that the highest frequency of droughts/famines occurred in the 2^{nd} century AD followed by the first part of the 20^{th} century, and also an increasing trend from the 16^{th} century onwards. The decadal analysis shows that the decade 1970-1979 was the worst period having seven disaster years (NMSA, 1996).

As indicated by the meteorological reports on droughts over Ethiopia**,** in the year 1971, 1973, 1975, 1977 and 1984 more than half of the administrative regions were affected by drought. The drought spells lasting three years or more occurred over Hararghe, Bale, Wellega, Tigrai, Gamo Goffa and Arsi. Tigrai was the worst affected area; it had two spells of severe droughts of 3 and 2 years in each spell, whereas Bale experienced a severe drought lasting 6 years. The longest duration of the spell was over Bale with duration of 9 years out of which 6 were severe. The variability of spring rains is highest over the major areas of the country. One can infer that most chronic drought-prone areas, generally with a probability of occurrence of 0.40 are Tigrai, Wello, Bale and Gamo Gofa (Degefu, 1987).

Over the period 1980-2010 ten major drought disasters were reported in Ethiopia. The major drought of 1984 was severe in the Northeastern half of the country, while all other parts of the country were affected at the seasonal level. The severity of the event was strengthened as all the three rainy seasons were dry in those parts of the country where they are effective. April and August were the most extreme months, and a dry October contributed to the mild to moderate drought in the South (Segele and Lamb, 2005). It resulted in over 300,000 deaths and affected over 7.5 million people, while drought in 2003 affected over 12.6 million people (NMSA, 1996). The northeastern rift valley received only 18 % of its mean annual precipitation by far the highest relative deviation in any part of the country during 1972–2010. Each successive drought makes it more difficult to recover, making the people of Ethiopia all the more vulnerable to climate change.

The year 1987 was the worst year when more than 50% of the regions constituting 70% of the area of the country were under drought in the summer season. This episode can be characterized as a summer drought in the highlands, reaching extreme levels on the 4-months scale followed by a dry fall, and then a dry spring in 1988, the drought reached extreme levels also on the 12-months scale in May 1988. The spring crops were destroyed by locust invasions, and this may have exacerbated the effect of the consecutive summer drought (Webb *et. al*., 1992).

From the year 1888 to 1892 AD the most serious droughts experienced in Ethiopian highlands and lowlands, and were known in Ethiopian history as the harsh days. During these periods both the big and small rains failed. As early as November 1888, the drought caused a large proportion of the plants to perish, while in January 1889, all the crops were burnt up by the sun. The entire period was hot and dry and the effects of drought were magnified by the catastrophic epidemic which killed 90% of the cattle and invasion of locusts. About one-third of the population perished. During the period 1895-1896 AD the whole country was affected by an unrecorded drought which was manifested through a fall in the level of Lake Rudolf. The Nile flood was also abnormally low during this period (Degefu, 1987).

During 1990–1992 all parts of the country experienced moderate, extreme or severe drought on the seasonal or annual level. 1990 and 1991 were dry years in all of Ethiopia, with the exception of a small positive deviation in the northeastern rift valley in 1990. A severely dry spring in 1992 followed, causing extreme drought on the 12-months scale in the Southern and southeastern lowlands, as well as in the northeastern rift valley and the northwestern highlands. In the southern lowlands, the spring of 1992 was the worst during 1972 to 2011, and in the southeastern lowlands the second worst. As a result, the southeastern lowlands received only 50 % of the mean annual precipitation in 1992.

Due to a dry spring followed by a dry summer, 2002 became one of the driest years during 1972 to 2011. In the southwestern rain forest this was the driest year, and in the central rift valley, the central highlands and the southern highlands the second driest. After a dry spring in 2003, a wet summer brought some relief, but 2003 was also drier than normal. In the Southwestern rain forest the drought was extreme at all timescales from 3 to 24 months, and at some timescales also in adjacent zones and in the southern highlands. At the 12-months scale, moderate to severe drought persisted in most of the highlands and the central rift valley from June to July 2002 through July 2003.

2.8. Previous Studies

The study entitled 'Meteorological Drought Monitoring across Different Rainfall Regimes of Ethiopia Using Chirps V2- Rainfall Data' has been carried out by Estifanos Lemma Goshu across the three different rainfall regimes of Ethiopia with an aim to develop a simple and effective drought monitoring system for Ethiopia using remotely sensed rainfall products for the period from 1981 to 2016. The assessment of meteorological drought was done using CHIRPS (Climate Hazard group Infrared Precipitation with Stations) monthly rainfall data and Effective Drought Index (EDI). The obtained results show that the historical drought years across rainfall regime of Ethiopia are well captured by EDI with CHIRPS rainfall product as input variable; thus, highlighting the efficacy of EDI index and CHIRPS rainfall product for operational drought monitoring in Ethiopia.

With the aims to quantify the meteorological component of drought of 2011 in the Horn of Africa and other drought episodes in Ethiopia since 1971, Diriba Korecha, in 2014, carried out the study entitled 'Recent Drought and Precipitation Tendencies in Ethiopia'. A monthly precipitation data set for 14 homogeneous rainfall zones was constructed based on 174 gauge observations. As a measure of drought, the Standardized Precipitation Index was calculated on seasonal, annual and biannual timescales for each zone. The results point to 2009 as a year of exceptionally widespread drought. All zones experienced some degree of drought at the annual scale, although in most zones, previous droughts were more extreme. On the national level, 2009 was the second driest year in the period, surpassed only by the historic drought in the year 1984. Linear regression analysis indicates a general decline in precipitation in Southern Ethiopia, during both February–May and June–September. In the Central and Northern highlands, the trend analysis did not provide evidence of similar tendencies. However, spring droughts have appeared more frequently in all parts of Ethiopia during the last 10–15 years than during the previous decades.

3. MATERIALS AND METHODS

3.1. Descriptions of the Study Area

3.1.1. Hydrology

Abaya and Chamo Lakes are two hydrologically interconnected natural lakes in the Southern part of Rift Valley Region of Ethiopia, and it crosses the country midway in the North South direction. They are said to be hydrologically interconnected, because an overflow from Lake Abaya flows into Kulfo River which in turn drains into the Lake Chamo. Many intermittent and perennial rivers joining the Lakes Abaya and Chamo are Bilate, Gidabo, Gelana, Hare, Baso, Amessa, Kulfo, Wezeka, Sego, Argoba and Sile contribute major amount of runoff to the lakes yield (Behailu and Negash, 2016).

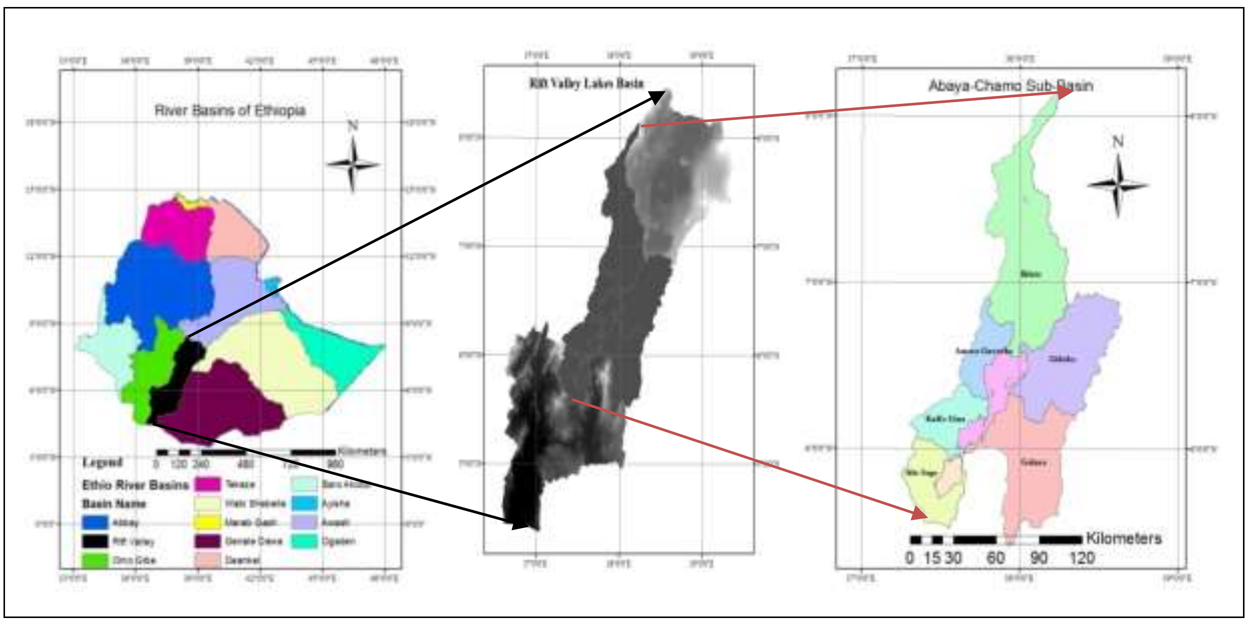

Figure 2: Location of Abaya-Chamo Sub-Basin

3.1.2. Area

The total area of Abaya-Chamo Sub-Basin including the lakes and their islands is found to be 18,599.8 Km^2. Further details about the area of the sub-basin are shown in the Table 3.1.

Table 3.1: Drainage Area of Abaya-Chamo Sub-Basin

SN	Sub-Basin	Total Area in Km^2
1	Abaya Drainage Area Excluding Lake Area	15219.62
2	Abaya Lake Area including Islands	1108.9
3	Chamo Drainage Area Excluding Lake Area and Abaya Contribution	1942.65
4	Chamo Lake Area	328.63
5	**Total**	**18599.8**

3.1.3. Climate

The climate of Abaya-Chamo sub-basin is characterized as tropical climate with hot semi-arid warm temperature, according to Ethiopian climate classification. The average annual rainfall ranges from 665mm at Bilate to 1240 mm at Chencha with average maximum temperature of 31.2^{o}C at Arba Minch and minimum average temperature of 13.9^{o}C at Chencha. Temperature variability is large due to altitude difference. The mean annual temperature is estimated to vary from 27^{o}C on the valley floor (Chew Bahir) to 10^{o}C around 3000m contour.

3.1.4. Topography

The level differences between the two lakes are 62 meters, Abaya Lake being higher than Chamo Lake. The altitude of the region varies between 4200masl (Mount Guge) and 1108masl (at the out flow from the Chamo Lake). The region is located in the range 37^0-38^0 in the Eastern longitude and 5^0-8^0 in the Northern latitude. The two lakes have been used for transport (Lake Abaya), fishery and tourism purpose. The lakes have not been used intensively for irrigation (Ababu and Bernd, 2004).

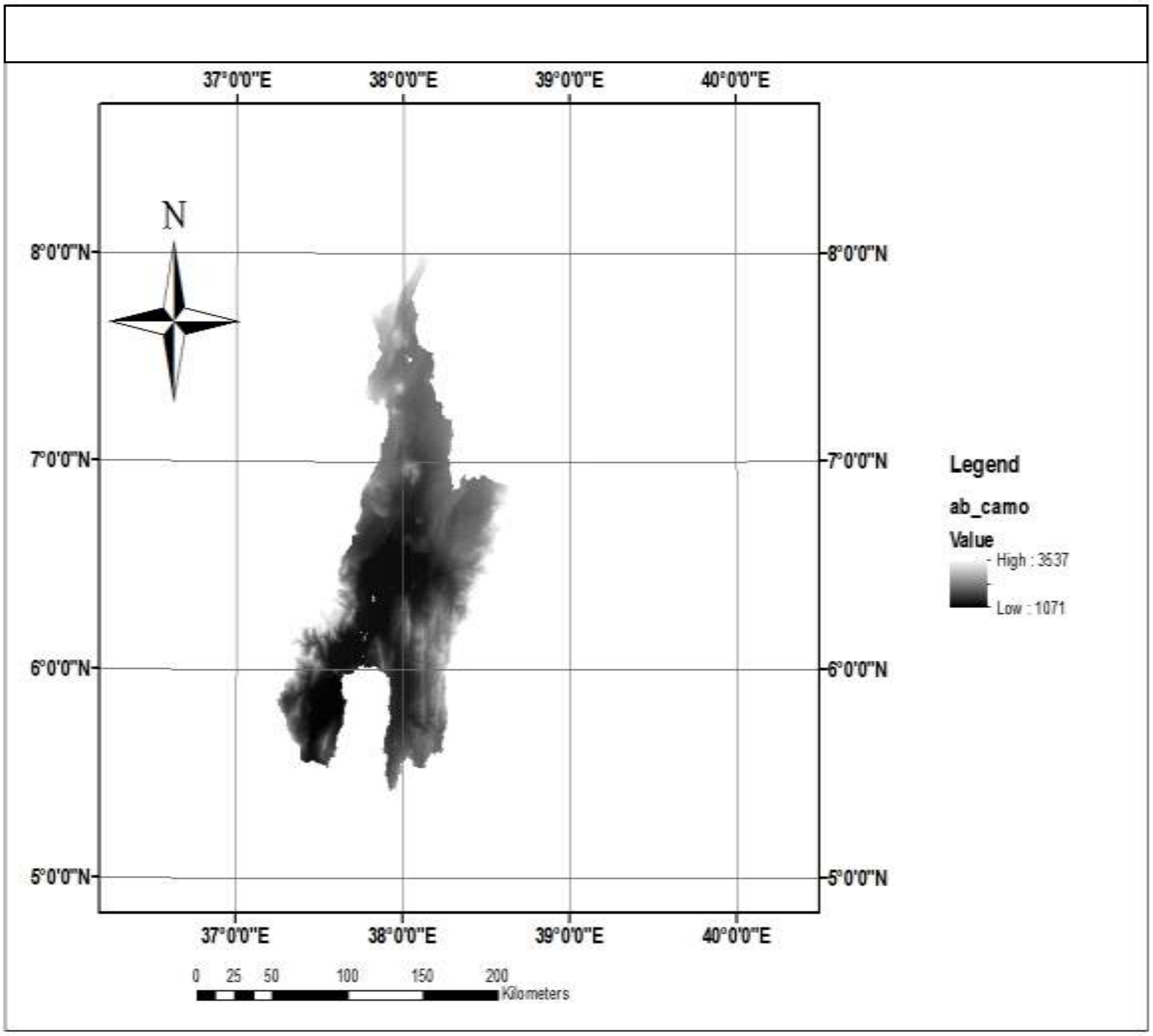

Figure 3: DEM of Abaya- Chamo Sub-Basin

3.1.5. Rainfall

Two pattern of rainfall are observed in the basin. From Lake Abaya south wards the main rain occurs during the period of March to May. North to Lake Abaya, the minimum rain occurs from July to September, often with a secondary peak in March to April. In the northern area, the rainfall pattern is generally typical of the area.

3.2. Data Collection

The most important data required for analysis of meteorological drought is precipitation data. However, past records of monthly precipitation data of about 30 years from 20 meteorological stations in the study area were collected from meteorological stations within the basin from

National Meteorological Service Agency of Ethiopia. Meteorological stations within the sub-basin and their respective location and elevation are listed in the Table 3.2 and Figure 4.

Table 3.2: Summary Meteorological Stations in Abaya-Chamo Sub-Basin

SN	Station Name	Latitude	Longitude	Elevation(m)
1	AlabaKulito	7°18'38''	38°05'38''	1722
2	AletaWendo	6°36'00''	38°25'00''	1947
3	AmaroKele	5°50'14''	37°53'52''	1659
4	Aposto	6°44'00''	38°22'00''	1762
5	Arba Minch	6°03'26''	37°33'28''	1207
6	Bedessa	6°52'08''	37°56'10''	1609
7	Bera	6°42'36''	38°25'05''	1824
8	Billate	6°49'00''	38°05'00''	1361
9	Bodity	6°57'13''	37°57'18''	2043
10	Derara	6°51'00''	38°18'02''	1950
11	Dilla	6°22'00''	38°18'00''	1579
12	Dorze	6°11'34''	37°34'10''	2505
13	Gedeb	5°54'20''	38°14'22''	2245
14	Hossana	7°34'02''	37°51'14''	2307
15	Mayokote	6°53'09''	37°51'11''	2121
16	Morocho	6°52'00''	38°24'00''	1831
17	TelamoKentise	6°50'02''	38°28'54''	1911
18	Tora	6°51'20''	38°25'14''	2001
19	Wajifo	6°20'00''	37°43'48''	1230
20	Yirgalem	6°49'01''	38°23'34''	1786

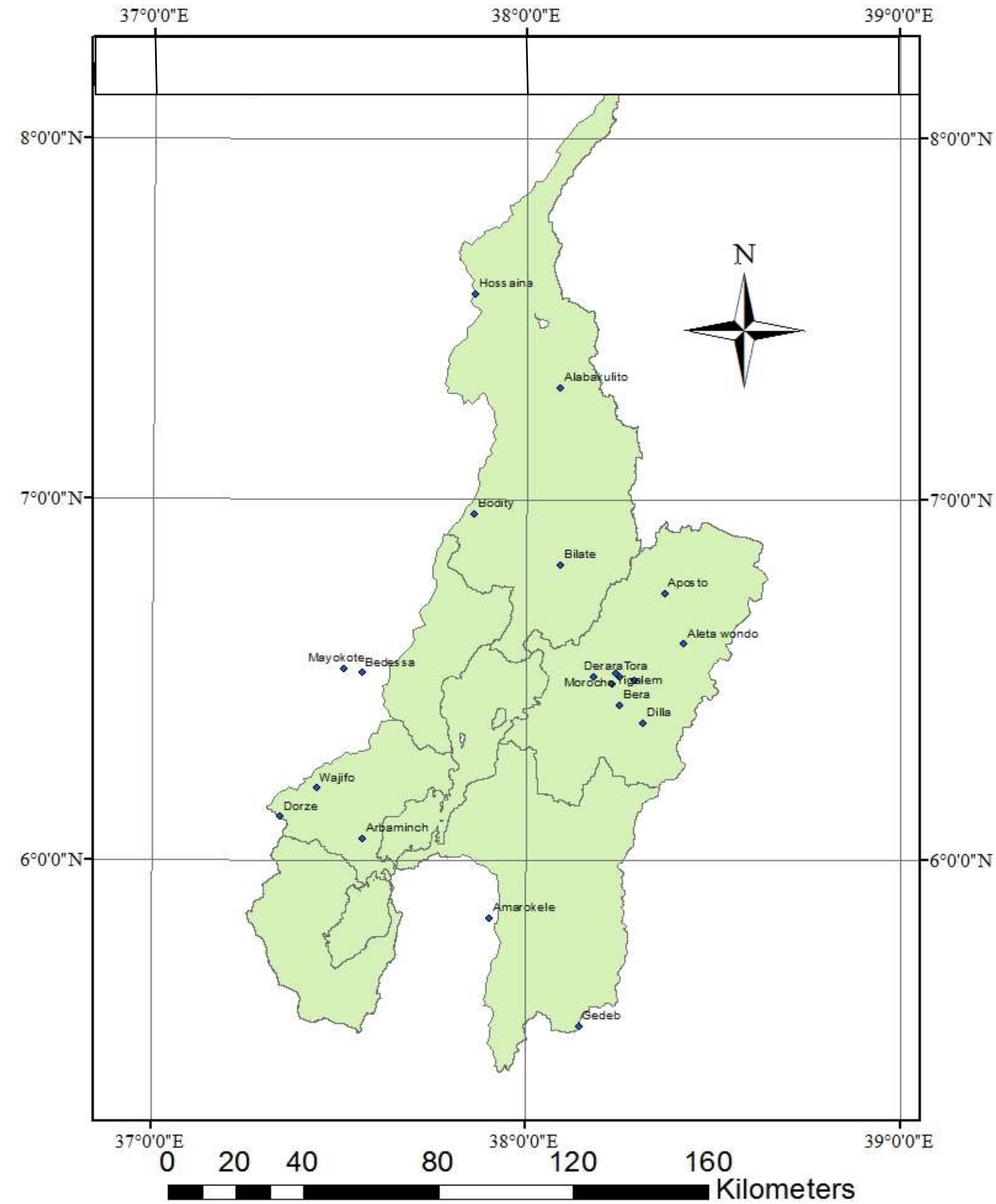

Figure 4: Meteorological Stations of Abaya-Chamo Sub-Basin

3.3. Data Quality Checking

3.3.1. Filling and Extension of Rainfall Data

At least 30 years of continuous monthly precipitation data are needed when using SPI for analyzing meteorological drought to achieve better result. Ideally, SPI program can be run with missing data, but it will affect the confidence of the results, depending on the distribution of the missing data in relation to the length of the record. For those selected stations for further analysis, data filling and extension of missed rainfall data was done by using simple arithmetic method which gives the missing precipitation at station x, P_x as:

$$P_x = \frac{1}{n}\sum_{i=1}^{n} P_i \quad \text{..} \quad (1)$$

where, n is the number of nearby stations and P_i is the precipitation at i^{th} nearby station.

3.3.2. Test for Independence

In the analysis of climatic drought for the selection of best fit statistical distribution the precipitation data collected from different rain gauge stations should be independent. Therefore, one may want to test the time series for its independence. However, in this study, Serial-Correlation Coefficient was applied to verify the independence of the data of selected meteorological stations. The serial-correlation coefficient can help to verify the independence of a time series. If a time series is completely random, the population auto-correlation function will be zero for all lags other than zero (when its value is unity, because all data sets are perfectly correlated with themselves), and the sample serial correlation coefficients will deviate slightly from zero only because of sampling effects. For our purposes, it is usually sufficient to compute the lag-1 serial-correlation coefficient, i.e. the correlation between adjacent observations in a time series. The lag-1 serial correlation coefficient, r_1, is given by the equation:

$$r_1 = \frac{\sum_{i=1}^{n-1}(x_i - \bar{x}) * (x_{i+1} - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})} \quad \text{..} \quad (2)$$

where x_i is an observation, x_{i+1} is the following observation and n is the number of data.

After computing r_1, the test hypothesis is that H_0: $r_1 = 0$ (that there is no correlation between two consecutive observations) against the alternate hypothesis, H_1: $r_1 <> 0$. The critical region, U, at the 5 percent level of significance is given as (Dahmen and Hall, 1990):

$\{-l, (-1 -1.96(n-2)^{\mathbf{0.5}})/ (n-l)\} \text{ U } \{(-1 +1.96(n-2)^{\mathbf{0.5}})/(n-1), +1\}$

The data are said to be independent (i.e., no correlation exists between successive observations), and there is no persistence in the time series if the test hypothesis H_0: $r_1 = 0$ is accepted, meaning, if lag-1 serial correlation coefficient, r_1 falls between the critical region (Dahmen and Hall, 1990).

3.3.3. Test for Consistency/Homogeneity

A time series of meteorological data should be relatively consistent, and therefore, it should be checked for its consistency. According to Dahmen and Hall (1990), a time series of meteorological data is relatively consistent if the periodic data are proportional to an appropriate simultaneous time series. In other words, relative consistency means that the meteorological data at a certain observation station are generated by the same mechanism that generated similar data at other stations. For this study, double mass curve analysis was used for checking consistency/homogeneity of each station data.

3.4. Test for Homogeneity of Stations

Different tests are available to examine regional homogeneity in terms of the hydrologic response of the stations in a region. Stations in a region can be tested for homogeneity that is fall in a region; homogeneity can be taken as a base for many criteria of the basin. There are various homogeneity tests. The homogeneity tests used in this study were:

- Coefficient of variation -based homogeneity test, and
- L-moment versus Coefficient of variation -based homogeneity test.

3.4.1. CV Based Homogeneity Test

Regionalization assumption must be made about the statistical similarity of the site in a region. To investigate whether those has been meet or not many researchers have used the values of mean coefficient of variation (Cv) and the site-to-site coefficient of variation (Cv) of both convention and L-moment of the proposed region (Cunnane, 1989). For each site in a region calculate the mean ($\bar{Q}$), the standard deviation (σ) and the coefficient of variation (CV), and finally the corresponding CC using the following relation:

$$\overline{Q}_i = \frac{\sum_i^n Q_i}{n_i} \quad \text{.......} (3)$$

$$\sigma_i = \sqrt{\frac{\sum_{i=1}^{N}(Q_i - \overline{Q}_i)^2}{n_i - 1}} \quad \text{.......} (4)$$

$$CV_i = \frac{\sigma_i}{Q_i} \quad \text{.......} (5)$$

where, Q_i is the precipitation at station i, $\overline{Q}_i$ is the mean precipitation for site i, σ_i is Standard deviation of Q_i for site i, and CV_i is the coefficient of variation of site i.

For each station, using the statistics calculated above, computed the regional mean, Cv and finally the corresponding CC using the following relation:

$$\overline{CV}_i = \sum_{i=1}^{N} \frac{CV_i}{N_i} \quad \text{.......} (6)$$

$$\sigma_{cv} = \sqrt{\frac{\sum_{i=1}^{N}(CV_i - \overline{CV}_i)^2}{N-1}} \quad \text{.......} (7)$$

$$CC = \frac{\sigma_{cv}}{\overline{CV}_i} \quad \text{.......} (8)$$

where, N is the number of site in a region, $\overline{CV}_i$ is mean coefficient of variation, σ_{cv} is standard deviation of at-site CV values, and CC is combined coefficient of variation for the region.

3.4.2. L-Cv Based Homogeneity Test

L-moments are defined as linear combinations of Probability Weighted Moments (PWMs) that have simple interpretations as measures of the location, dispersion and shape of the sample data (Hosking, 1990).

L-Cv based homogeneous test is more advantageous over CV based homogeneous test since it characterizes a wide range of distribution, its sample estimates are so robust that they are not affected by the presence of outliers in the data set, and they are less subjected to bias in estimation, so it yields more accurate estimate of the parameter of a fitted distribution (Cunnane, 1989). The procedural calculation is the same as that of the Cv, but it has its own formula and calculation. The sample PWM estimator (b_r) is given by the equation:

$$b_r = \frac{1}{n}\sum_{j=1}^{n} \frac{(j-1)(j-2)\ldots(j-r)}{(n-1)(n-2)\ldots(n-r)} X_j \qquad (9)$$

Where, X_j is annual peak precipitation value at j-th observation of the ordered sample in ascending order and n is the sample size.

The first four L-Moments are given as:

$$l_1 = b_0 \qquad (10)$$

$$l_2 = 2b_1 - b_0 \qquad (11)$$

$$l_3 = 6b_2 - 6b_1 + b_0 \qquad (12)$$

$$l_4 = 20b_3 - 30b_2 + 12b_1 - b_0 \qquad (13)$$

The first L-Moment (l_1) is the measure of mean and second L-Moment (l_2) is measure of dispersion. Third and Fourth L-Moments are l_3 and l_4 respectively. L-moments ratios of the sample are estimated using Equation:

$$t_r = \frac{l_r}{l_2} \qquad (14)$$

where, t_r is the rth sample L-moment ratio and l_r is the rth sample L-moment.

The sample L-coefficient of variation (L-cv) is $t = \frac{l_2}{l_1}$, while the sample L-coefficient of skewness (L-skew) is $t_3 = \frac{l_3}{l_2}$, and it represents the measure of degree of symmetry of a sample. Symmetric distributions have t_3 = 0 and its value lies between -1 and +1. The sample

L-coefficient of kurtosis (L-kurtos) is $t_4 = \frac{l_4}{l_2}$. It is a measure of peakedness or the flatness of the frequency distribution near its centre. Using the above procedural formula, we have:

$$L_{CV} = \frac{l_2}{l_1} \qquad (15)$$

$$\bar{L}_{CV} = \sum_{i=1}^{N} \frac{L_{CV}}{\mathrm{N}} \qquad (16)$$

$$\sigma_{L_{CV}} = \sqrt{\frac{\sum_{i=1}^{N}(L_{CV}-\bar{L}_{CV})^2}{\mathrm{N-1}}} \qquad (17)$$

$$CC = \frac{\sigma_{L_{CV}}}{\bar{L}_{CV}} \qquad (18)$$

For both Cv-based and L-Cv based homogeneous testes, the stations and regions declared to be homogeneous if $CC < 0.3$. For this study, both Cv based and L-Cv based homogeneity tests were used to test the homogeneity of the stations.

3.5. Fitting Statistical Distribution

In analysis of meteorological drought, the drought indicator is precipitation and the time sequence is usually considered to be annual. The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution; usually it involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for a meteorological station, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997).

3.6. Testing for Normality

Tests for normality calculate the probabilities that the sample was drawn from a normal population. There are several methods of assessing whether data are normally distributed or not. They fall into two broad categories: Graphical (Q-Q probability plots and Cumulative frequency (P-P) plots) and Statistical (W/S test, Jarque-Bera test, Shapiro-Wilks test, Kolmogorov-Smirnov test and D'Agostino test). Graphical methods are typically not very useful when the sample size is small. Statistical tests for normality are more precise since actual probabilities are calculated. W/S test is simple and effective, but not available in SPSS.

Two tests of normality are available in SPSS software named Kolmogorov-Smirnov test and Shapiro-Wilk tests. Kolmogorov-Smirnov test of normality is not sensitive to problems in the tails and it is used for data sets greater than 50. Shapiro-Wilks test doesn't work well if several values in the data set are the same and it works best for data sets with less than 50, but can be used with larger data sets. It is probably the better test in SPSS. Both tests are sensitive to outliers and are influenced by sample size. For smaller samples, non-normality is less likely to be detected but the Shapiro-Wilk test should be preferred as it is generally more sensitive. For larger samples (i.e. more than one hundred), the normality tests are overly conservative and the assumption of normality might be rejected too easily.

In both methods if the probability of finding an event is rare (less than 5%) and we actually find it, that is of interest. When testing for normality, the probabilities greater than 5% mean the data are normally distributed and so, accept the null hypothesis and the probabilities less than 5% mean the data are not normally distributed pointing to reject the null hypothesis.

Any assessment should also include an evaluation of the normality of histograms or Q-Q plots as these are more appropriate for assessing normality in larger samples. As long as the data is approximately normally distributed, with a peak in the middle and fairly symmetrical, the assumption of normality has been met. The normal Q-Q plot is an alternative graphical method of assessing normality to the histogram and is easier to use when there are small sample sizes. The scatter should lie as close to the line as possible with no obvious pattern coming away from the line for the data to be considered normally distributed.

The null hypothesis, Ho and the alternate hypotheses, Ha used in testing the normality of the data set are:

Ho: The sample data are not significantly different than a normal population.

Ha: The sample data are significantly different than a normal population.

In this study, both Kolmogorov-Smirnov test and Shapiro-Wilk tests were used. In addition to this, graphical Q-Q plot was also used to determine if the statistical distribution fits best with the data set. The tests were analyzed by using SPSS (statistical package for the social science).

3.7. Analysis of Moving Averages

In the moving average method, the cumulative impact of precipitation deficits and surpluses in previous years are considered. By using this method, the drought investigation is diverted from meteorological drought to hydrological (real) drought. The *n*-year moving average, X'_j in the j^{th} year, can be calculated from the following expression:

$$X'_j = \frac{1}{n}\sum_{i=0}^{n-1} X_{j+1} \qquad n = 3, 5, 9, \ldots \quad (19)$$

Usually, 3-, 5-, and 10-year moving averages are investigated to recognize drought spells and to predict their trend. For this study 3- year moving average was used.

3.8. Drought Severity and Duration

The SPI time series were analyzed in order to identify the frequency of droughts events (moderate, severe and extreme) in the whole time series. Using the index the average deficit, maximum severity and maximum duration were identified. Positive SPI values indicate greater than median precipitation and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way; thus, wet periods can also be monitored using the SPI. Negative SPI values indicate droughts and positive SPI values denote wet weather conditions.

4. RESULTS AND DISCUSSIONS

4.1. Filling and Extension of Missing Rainfall Data

From all meteorological stations listed in section 3.2, five stations such as Arba Minch, Bodity, Billate, Morocho and Bedessa stations were selected for analysis of meteorological drought in Abaya-Chamo sub-basin. For data filling purpose of those selected stations some nearby stations like Alaba Kulito, Hossanna, Aleta Wendo, Aposto, Telamo Kentise, Dilla, Amaro Kele and Gedeb stations were used. The other remaining stations were rejected from the analysis because of they have too many missing data at monthly and yearly scale; and so the filling and extending of such data is knotty.

For interpolation stations with missed data nearby index stations were selected considering the distance from the station (i.e., region of influence) with missing precipitation data to apply the above method of filling and extending the data. Selected nearby friend stations are shown in the Table 4.1.

Table 4.1: List of nearby friend stations used to fill the missed data

SN	Station with Missing Data	Nearby Stations	Extended or Filled
1	Arba Minch	Bodity, Alaba Kulito and Hosanna	Filled
2	Morocho	Aleta Wendo, Telamo Kentise, Aposto and Billate	Filled
3	Bedessa	Amaro Kele, Dilla and Gedeb	Filled

4.2. Mean annual precipitation

Mean annual precipitation of 30 years of record length starting from 1988 to 2017 of each of five selected stations after filling the missing precipitation data is presented by the graph of the year of record versus its corresponding recorded precipitation value on Figure 5. It varies slightly from station to station with in the study region.

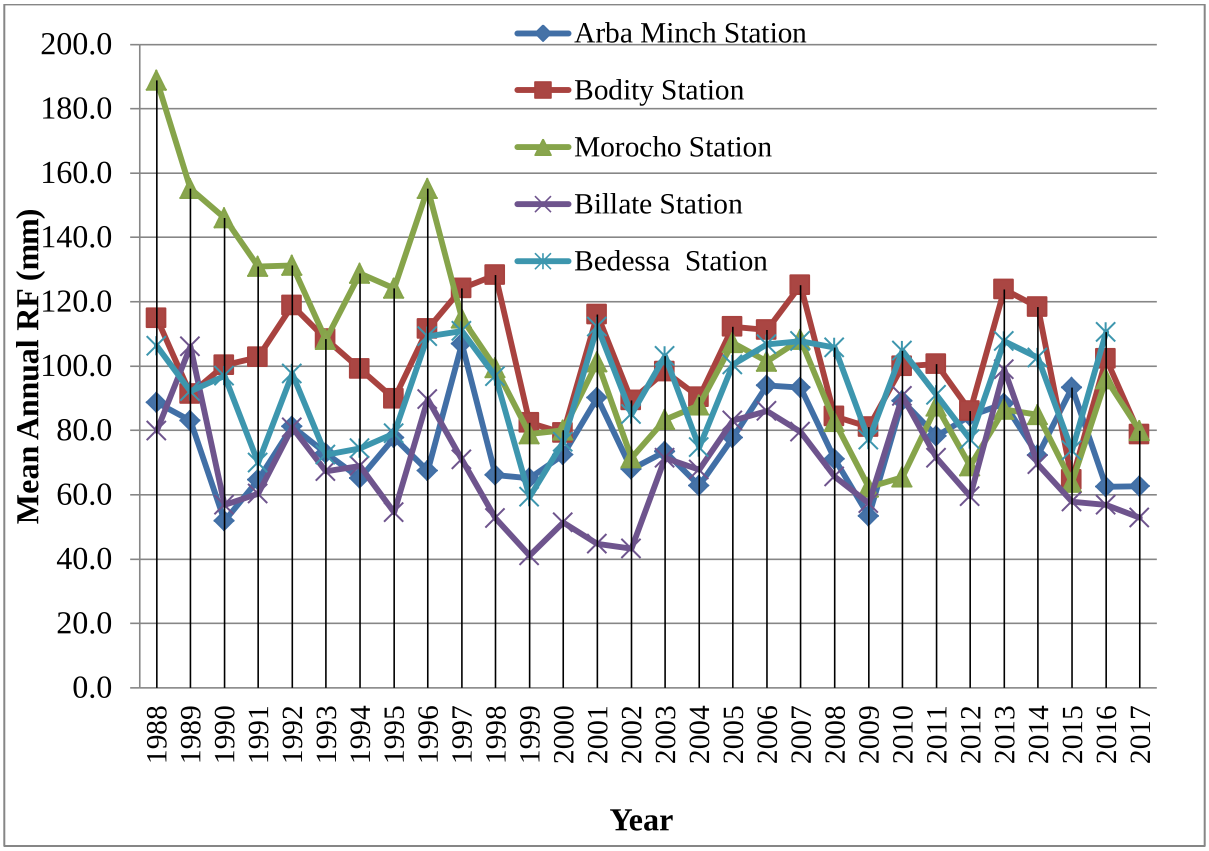

Figure 5: Mean Annual Precipitation at Selected Meteorological Station

4.3. Various Tests on Meteorological Data

Before data are going to be analyzed for meteorological drought analysis it has first pass through some of the various tests to check the meteorological data quality. Some of the common tests for the meteorological data quality analysis are presented as follows.

4.3.1. Test for Independence

As stated in Section 3.3.1, in this study, Serial-Correlation Coefficient test was used to verify the independence of the data of the selected meteorological stations. The result shows that, among all selected meteorological stations, no correlation exists between successive observations, and thus, the data are independent, and there is no persistence in the time series. The summarized results of the tests are given in Table 4.2.

Table 4.2: Data Independence Test for Selected Stations

SN	Station Name	Test Result			Remark
		Upper Class Limit	**Lower Class Limit**	**Serial Correlation Coefficient, r_1**	
1	Arba Minch	0.323	-0.392	-0.075	Independent
2	Bodity	0.323	-0.392	-0.025	Independent
3	Morocho	0.323	-0.392	0.251	Independent
4	Billate	0.323	-0.392	0.229	Independent
5	Bedessa	0.323	-0.392	-0.112	Independent

4.3.2. Test for Consistency

To check the consistency of meteorological data double- mass curve was used by comparing data for a single station with that of a pattern composed of the data from some other stations in the sub-basin. The graph of the cumulative mean annual rainfall of one station versus the cumulative mean annual rainfall of other related stations is drawn. All the stations in the sub-basin are consistent, since all points lie on and near to 45° line and the inter-site correlation squared (R^2) is less than one for all the stations as the test shows; and the graphical expression of the results are presented in Figure 6.

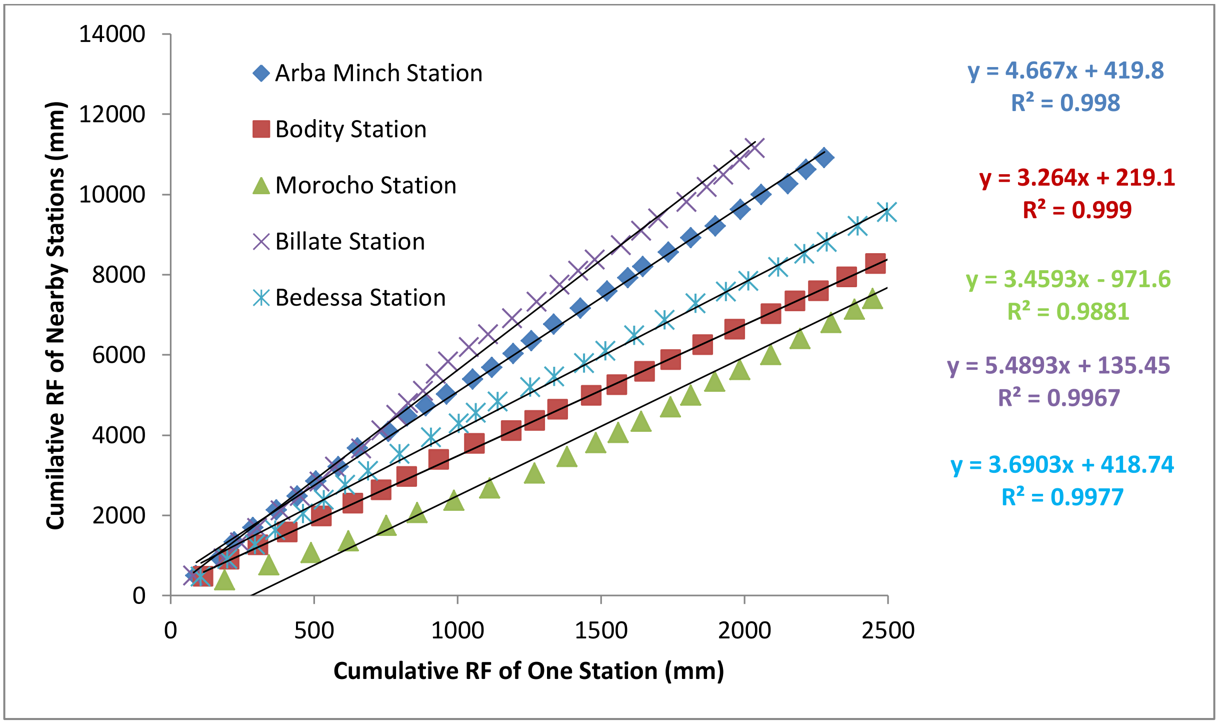

Figure 6: Double Mass Curve of Selected Station

4.4. Test for Homogeneity of Stations

The combined coefficient of variation for the stations (CC) value was computed as mentioned in Section 3.4. From the analysis result, we can conclude that the stations seem to be homogeneous for both convectional Cv based and L-Cv based homogeneity test since the CC values are less than 0.3 for both tests. The result of both tests is presented in Table 4.3.

Table 4.3: CV Based Homogeneity Test

SN	Station Name	N	Mean Rainfall (mm)	Combined Coefficient of Variation (CC)	Conclusion
1	Arba Minch	30	75.9	0.18	Homogeneous
2	Bodity	30	101.1	0.18	Homogeneous
3	Morocho	30	102.7	0.27	Homogeneous
4	Billate	30	67.9	0.24	Homogeneous
5	Bedessa	30	92.0	0.19	Homogeneous

Table 4.4: L-CV Based Homogeneity Test

SN	Station Name	L- Moments Ratio			Combined Coefficient of Variation (CC)	Conclusion
		L-Cv	*L-Sk*	*L-Kurt*		
1	Arba Minch	0.0997	0.0693	0.0714	0.233	Homogeneous
2	Bodity	0.0945	-0.0271	0.0453	0.255	Homogeneous
3	Morocho	0.1685	0.2102	0.1200	0.082	Homogeneous
4	Billate	0.1386	0.1080	0.1045	0.128	Homogeneous
5	Bedessa	0.0970	-0.1076	-0.0655	0.245	Homogeneous

4.5. Fitting Statistical Distribution

As discussed in section 3.4, computing SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for a meteorological station, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Figure 11 shows a bar histogram of a sample distribution of monthly precipitation, with the number of occurrences in each of different equally spaced precipitation classes. The red curve is the gamma probability distribution function (PDF) fitted to these data. Based on the Kolmogorov Smirnov and Shapiro Wilk's test on SPSS software the distribution was checked for its fitness to the recorded precipitation data, hence it was determined as the best fit statistical distribution at 95% of confidence interval. Therefore, the precipitation data of each meteorological station is fitted to the gamma probabilistic distribution and here below in Figure 7 and 8 the result for Arba Minch and Morocho station was presented, and for other remaining stations the result was shown in Appendix I.

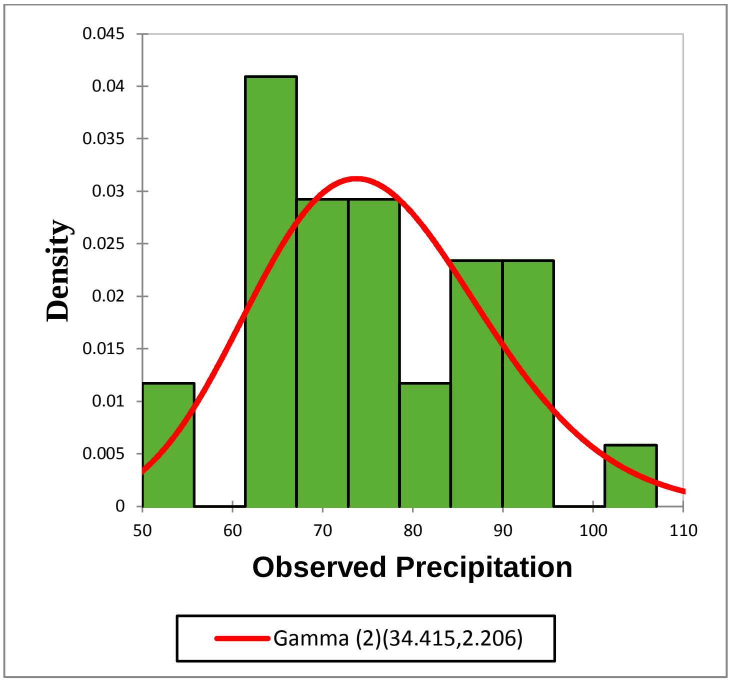

Figure 7: Gamma distribution fitting for Arba Minch station

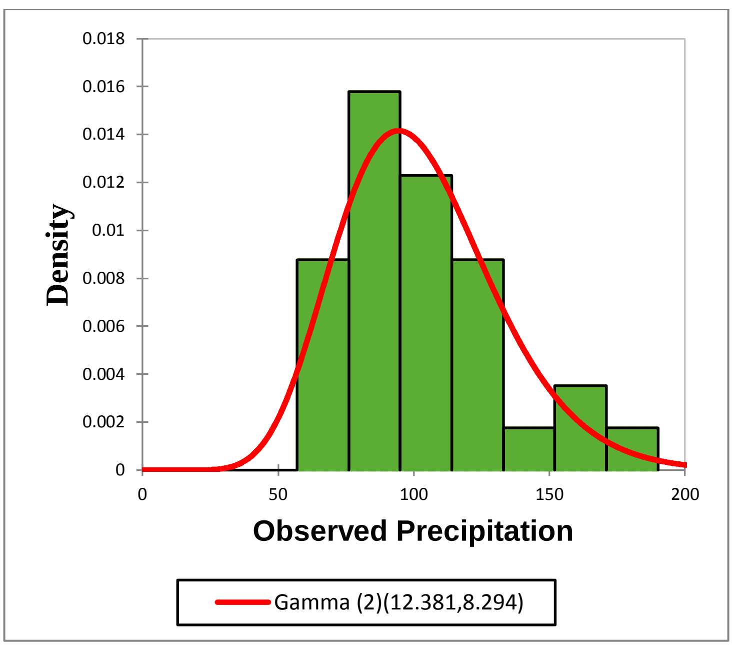

Figure 8: Gamma distribution fitting for Morocho station

4.6. Goodness of fit test

Table 4.5 shows the result of SPSS software for goodness of fit test using both Kolmogorov-Smirnov test and the Shapiro-Wilk's test. The p-value (the typical alpha level), at 95%

confidence interval, for both tests is greater than 0.05 suggesting that the data is normally distributed for all selected meteorological stations in the sub-basin except for Bedessa station based on Shapiro-Wilk's test its p-value is 0.024 which is below 5% indicating that the data is not fitted to gamma distribution.

Table 4.5: Kolmogorov-Smirnov and Shapiro-Wilk's test result

S.N	**Station Name**	**Kolmogorov-Smirnov Test**			**Shapiro-Wilk Test**		
		Statistic	N	p-value	Statistic	N	p-value
1	Arba Minch	0.110	30	0.200	0.971	30	0.564
2	Bodity	0.098	30	0.200	0.970	30	0.526
3	Morocho	0.155	30	0.064	0.935	30	0.067
4	Billate	0.105	30	0.200	0.977	30	0.755
5	Bedessa	0.151	30	0.080	0.918	30	0.024

In addition to both statistical methods discussed above, the graphical method (the normal Q-Q plot) was used, and here, the observed data are plotted against the values estimated from the fitted distribution by using software SPSS. The graphical result indicates that the observed value (precipitation) approximately appear as a straight line through the origin with 45^0 slopes for all the stations. Therefore, the selected gamma distribution is best fit statistical distribution for the data sets. The Q-Q plot of Billate station from the output of SPSS is presented in Figure 9. For other remaining stations the result of the normal Q-Q plot from SPSS was shown on Appendix II.

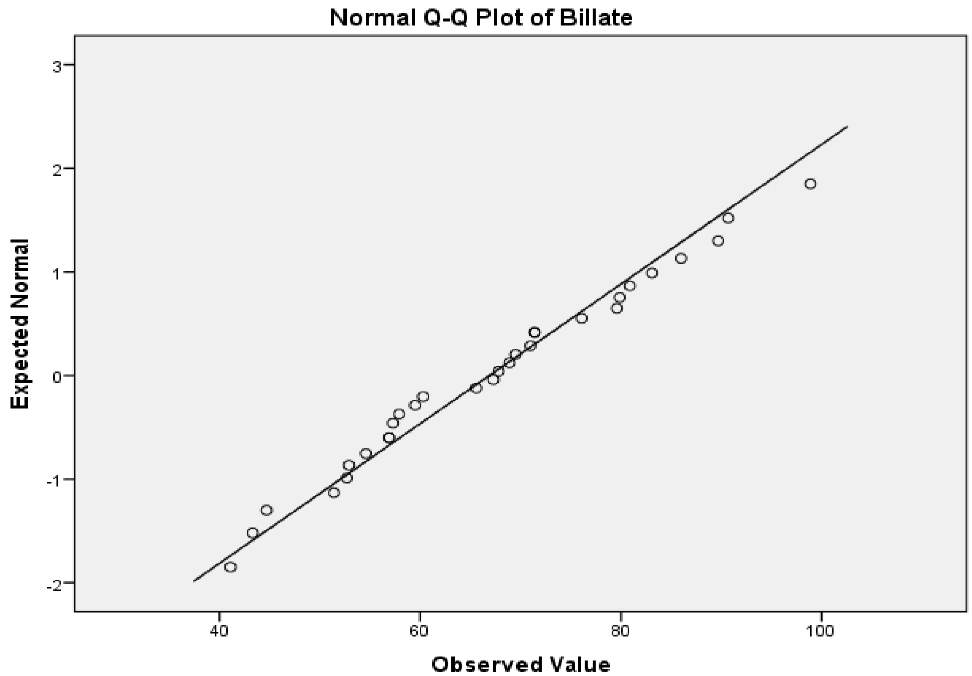

Figure 9: Normal Q-Q plot of Billate station

4.7. Analysis of Moving Averages

3-year moving averages was investigated to recognize drought spells and to predict their trend and to determine the cumulative impact of precipitation surpluses and deficits of previous months in the study area. From the analysis, generally, the region seems to have precipitation deficits going below the long-term average precipitation at present time as seen from the analysis of recorded rainfall at five representative meteorological stations in the region. Table 4.6 presents 3-year moving average precipitation at each meteorological station.

Table 4.6: 3-Year Moving Average Precipitation at Each Meteorological Station

	3-Year Moving Average Precipitation at				
Year	Arba Minch Station	Bodity Station	Morocho Station	Billate Station	Bedessa Station
1988	-	-	-	-	-
1989	-	-	-	-	-
1990	74.53	102.20	163.33	80.97	98.43

1991	66.53	98.17	144.07	74.43	86.33
1992	65.93	107.30	136.10	66.03	88.20
1993	72.93	110.00	123.50	69.50	80.03
1994	73.10	108.80	122.77	72.37	81.53
1995	71.93	99.17	120.40	63.60	75.33
1996	70.13	100.20	136.07	71.07	87.60
1997	84.03	108.53	131.43	71.77	99.77
1998	80.17	121.33	123.20	71.13	105.67
1999	79.37	111.60	97.77	54.93	89.03
2000	67.87	96.63	86.13	48.40	77.53
2001	75.90	92.57	86.70	45.73	82.67
2002	76.83	94.93	84.20	46.47	91.23
2003	77.17	101.27	85.30	53.13	100.13
2004	68.03	92.67	80.87	60.83	87.63
2005	71.33	100.27	92.83	74.10	92.73
2006	78.20	104.60	98.90	78.97	93.93
2007	88.40	116.23	105.67	82.90	104.97
2008	86.17	106.97	97.47	77.07	106.77
2009	72.60	96.87	84.40	67.50	96.90
2010	71.17	88.43	70.17	71.20	95.90
2011	73.53	93.83	71.77	73.13	90.97
2012	83.93	95.53	74.00	73.87	91.03
2013	83.70	103.53	81.00	76.60	92.00
2014	81.70	109.43	80.10	75.97	95.87
2015	84.67	102.27	78.37	75.43	94.70
2016	76.00	95.07	81.50	61.43	95.63
2017	72.83	81.90	79.87	55.90	87.10

Figure 10 to 14 shows the 3-year moving average and long-term average of precipitation for each meteorological station in the region. Arba Minch station experienced five drought periods at various periods of recorded rainfall year having different duration and severity. The precipitation at Bodity station was recorded below the long-term average for years from 2000 to 2004 and from 2010 to 2013. Morocho station also experienced the drought event in the past and the precipitation of the station is going below the long-term average precipitation starting from 2008 until the present time. At present, the rainfall is less than the long-term average at Billate station too, and finally, Bedessa station experienced more than two drought events of different duration and magnitude in the past.

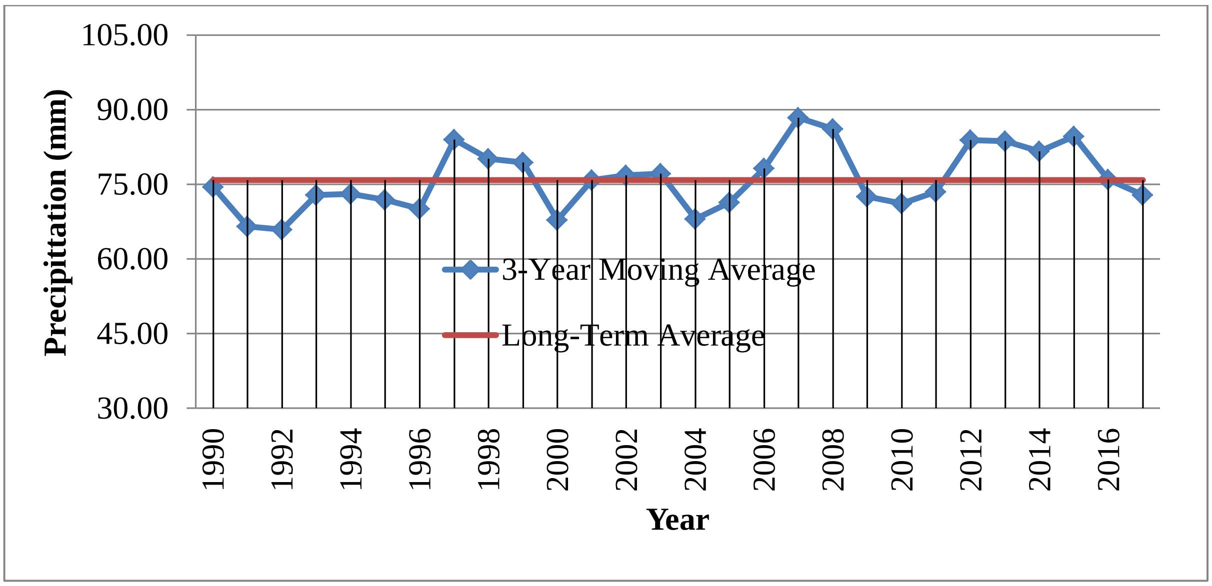

Figure 10: Long-term mean annual RF and 3-Year moving average of Arba Minch Station

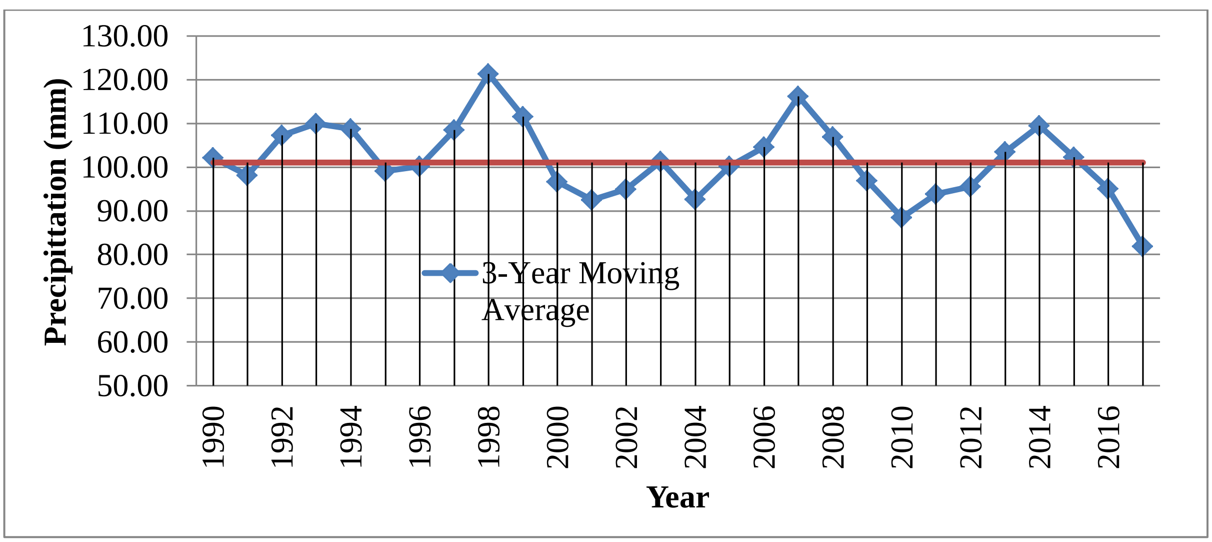

Figure 11: Long-term mean annual RF and 3-Year moving average of Bodity Station

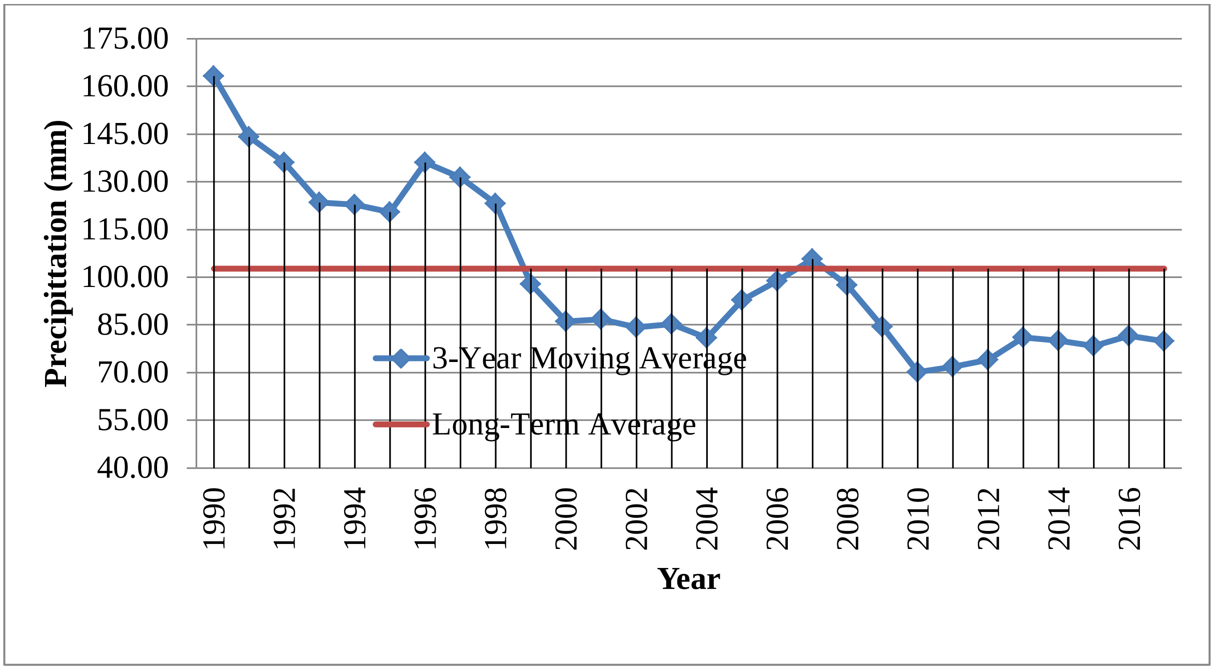

Figure 12: Long-term mean annual RF and 3-Year moving average of Morocho Station

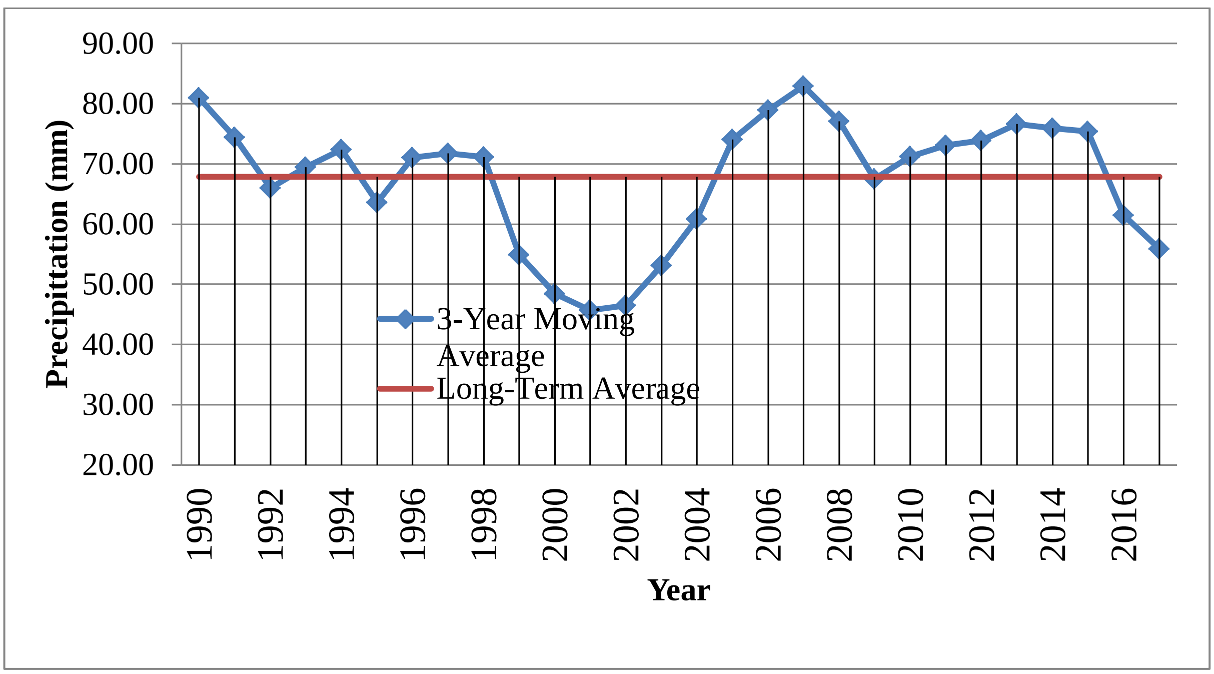

Figure 13: Long-term mean annual RF and 3-Year moving average of Billate Station

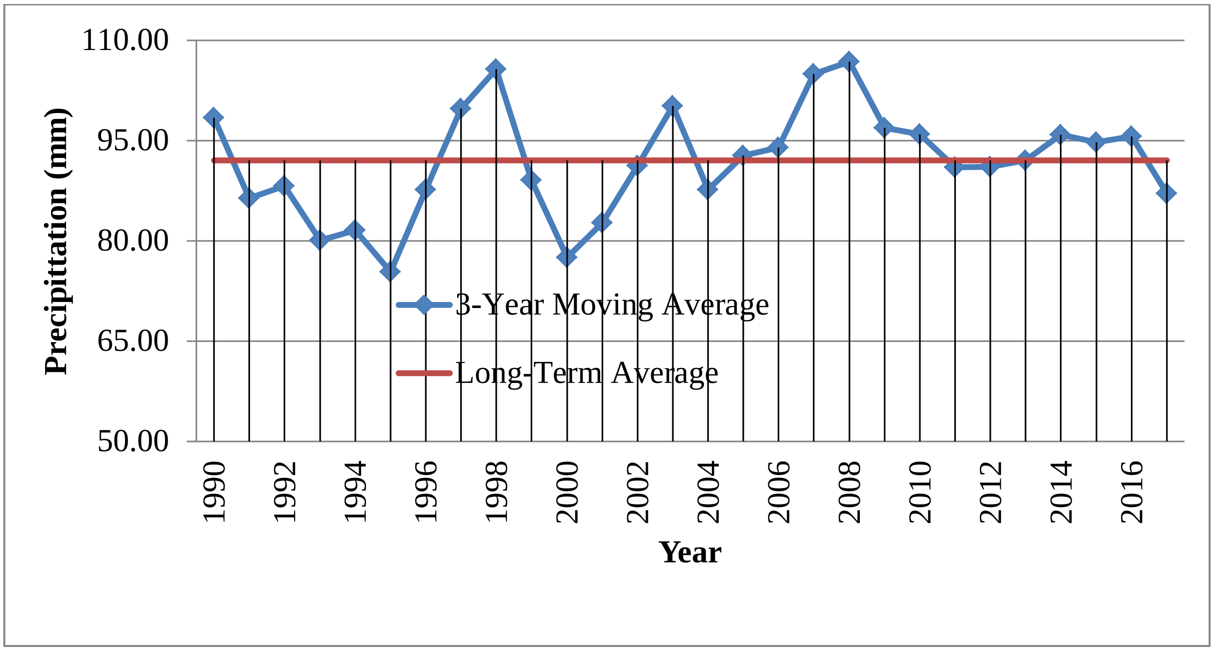

Figure 14: Long-term mean annual RF and 3-Year moving average of Bedessa Station

4.8. SPI Analysis

In this study 30 years recorded monthly precipitation from five selected stations were used for analysis of SPI for the period 1988-2017 at various timescales to estimate of the monthly SPI for meteorological stations in the region for 1-, 3-, 6-, 9- and 12- month timescales. But for characterization of meteorological drought in the region 1-, 3- and 6-month timescale analysis of SPI was used. The SPI time series were analyzed in order to identify the frequency of droughts events (moderate, severe and extreme) in the whole time series. The average deficit, maximum severity and maximum duration were identified. Meteorological drought begins when SPI value falls below zero and ends when the SPI becomes positive (McKee *et. al.*, 1995). The result of analysis was presented and described in the following sections.

4.8.1. 1-Month SPI

At Arba Minch station as determined from 1-month timescale SPI analysis, the years 1990, 1993, 1996, 1999 and 2009 were known for extreme dry events. During 1991, 2002, 2004, 2005, 2008, 2009 and 2010 at 1-month timescale severely dry events were occurred. Each year in the record period have moderate dry events at the same station according to drought severity analysis on 1-month timescale of SPI. Moderate dry events occurred more frequently than other dry events followed by severe dry events. 38, 11 and 7 droughts were occurred with moderate, severe and extreme severity respectively at different months with in 30 years of record, among them moderate dry event covers 67.9% and severe and extreme events covers 19.6% and 12.5%, respectively. The output of the index was determined and here below shown by chart in figure 19 and the SPI values of each month in record period based on 1-month timescale was tabulated in Appendix III.

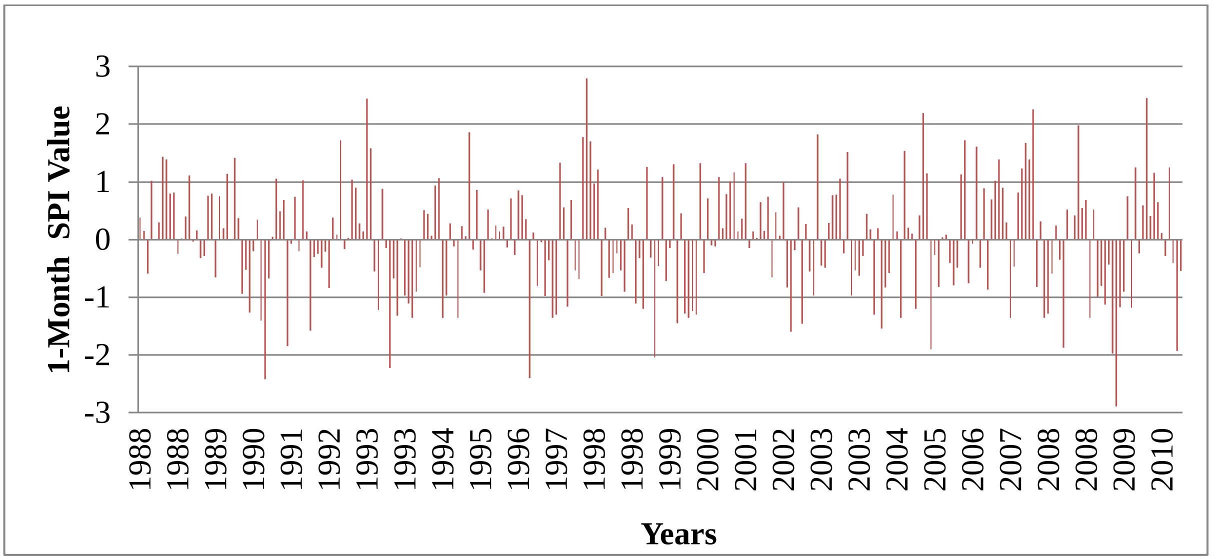

Figure 15: SPI result on 1-month timescale at Arba Minch station

Five extremely dry events was occurred during the years 1991, 1999, 2004 and 2008 at Bodity station as determined from 1-month timescale SPI analysis. It covers 3.5% of the other drought events at this station. There occurred 19 severely dry events covering 8.5% in the years 1988, 1989, 1991, 1996, 2000, 2002, 2003, 2005, 2006, 2007, 2008, 2009 and 2010. The years 1988, 1989, 1994, 1995, 1997, 1999, 2000, 2003, 2004, 2007, 2009 and 2010 were known from the result for their moderately dry events at this station. More frequent dry event at the station was moderately severe drought which covers 88% of the other drought events, but the severe and extreme events together covers only 12%. The result of SPI index for 1-month timescale at Bodity station is presented in the Figure 16.

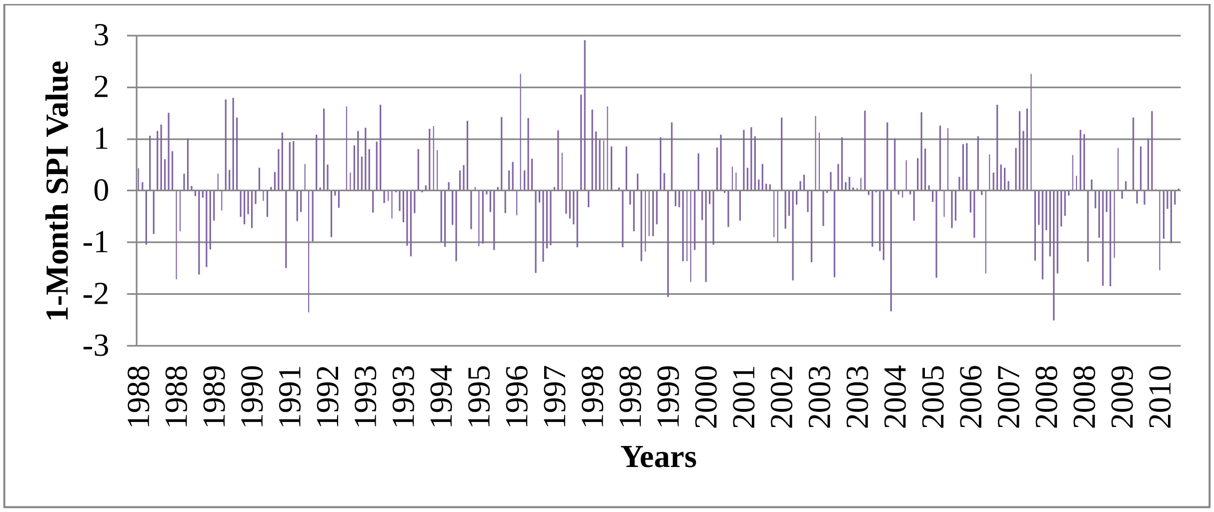

Figure 16: SPI result on 1-month timescale at Bodity station

At Morocho station as determined from 1-month timescale SPI analysis, the years 2000, 2003, 2008, 2009 and 2010 were known for 7 extreme dry events of moisture condition. Compared to the other drought events it occurred less frequently covering only 11.7% followed by 12 severe dry events and 41 moderate dry events each of them covering 20% and 68.3% respectively of total droughts throughout the record period. During 1991, 1994, 2000, 2007, 2009 and 2010 at 1-month timescale severely dry events were occurred. Each year in the record period have moderate dry events at the same station according to drought severity analysis of 1-month timescale on SPI. The result of the index was determined and shown in the Figure 17.

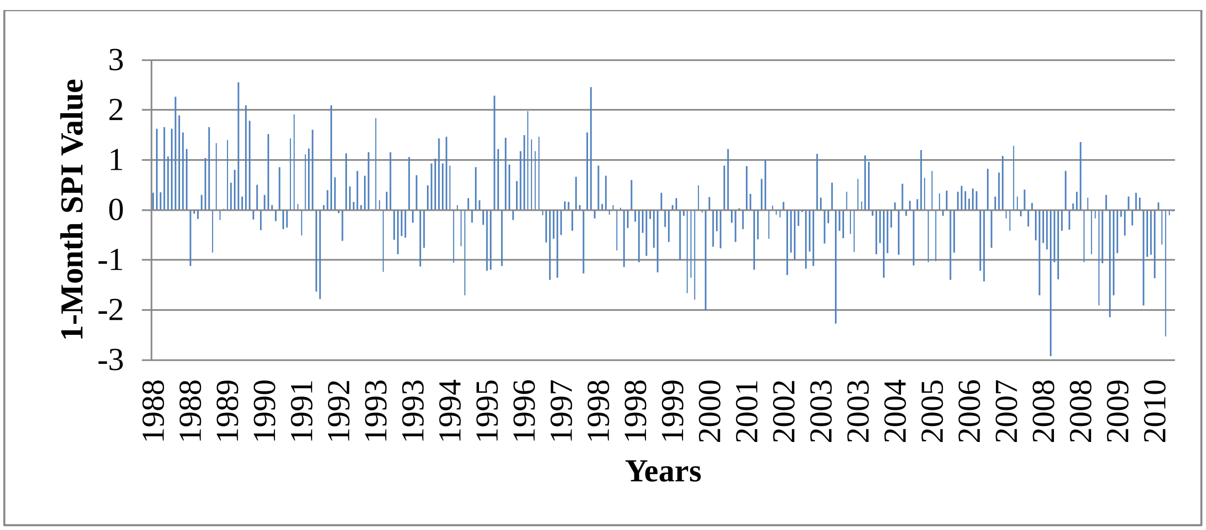

Figure 17: SPI result on 1-month timescale at Morocho station

Billate station as determined from 1-month timescale SPI analysis experienced only 1 extreme dry event throughout the historical record period in March of the year 2008 of a magnitude -2.58. This drought event covers only 1.85% of other drought events occurred at the station. There occurred 13 severely dry events in the years 1990, 1994, 1995, 1999, 2000, 2001 and 2002, which is 24.07% of the other drought events. Except the years 2005, 2006 and 2010, the other remaining historical years were known from the result for their moderate dry events of maximum frequency and coverage of 74.08% as compared with the other two drought events. The result of SPI index for 1-month timescale at Billate station is presented in the Figure 18.

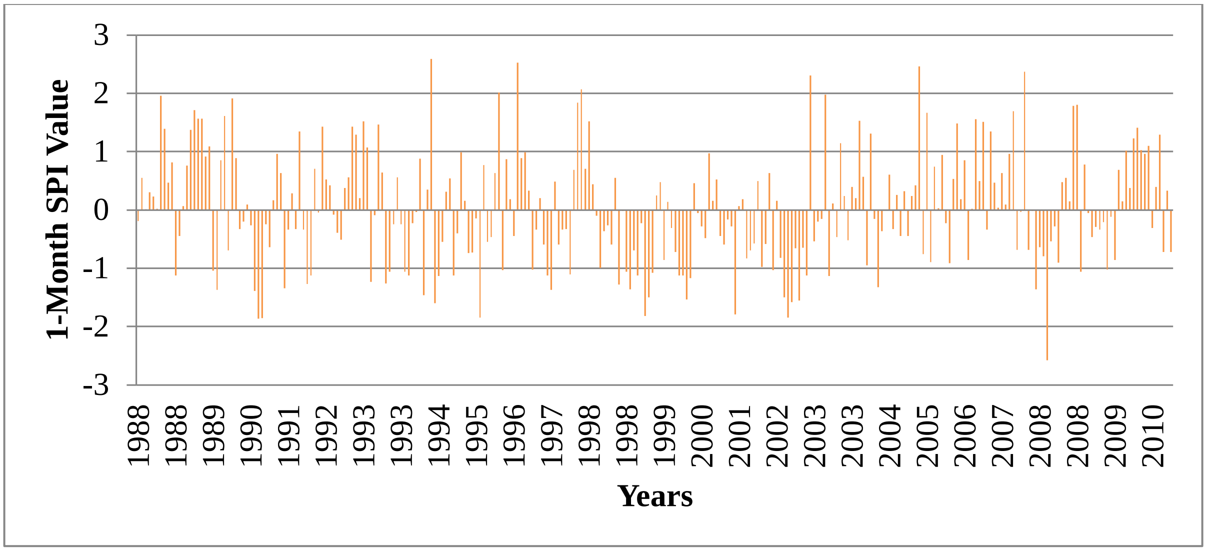

Figure 18: SPI result on 1-month timescale at Billate station

At Bedessa station as determined from 1-month timescale SPI analysis, only the year 1995 have one extreme dry event of magnitude -2.09. When compared to the other dry events it covers only 1.9% and less frequently occurred. During 1988, 1990, 1991, 1993, 1994, 1997, 1999, 2002, 2004, 2007 and 2010 at 1-month timescale 17 severely dry events covering 32.08% were occurred. More than 35 moderately dry events of a maximum frequency were occurred each year in the record period at the same station with coverage of 66.02% according to drought severity analysis on 1-month timescale on SPI. The output of the index was determined and shown in the Figure 19.

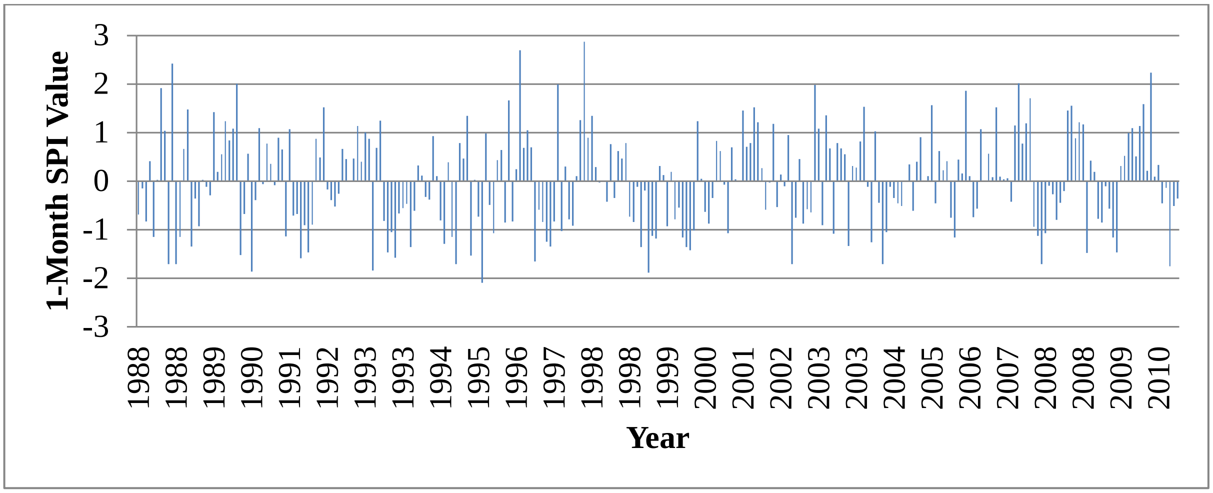

Figure 19: SPI result on 1-month timescale at Bedessa station

4.8.2. 3-Month SPI

As the analysis result of the precipitation data on SPI for 3-month timescale, at Arba Minch station, 12 extremely dry events were occurred during the years 1990, 1993, 1994, 2000, and 2009 each for one month duration from its onset. The years 1990, 1997, 1999, 2002, 2004, 2005, 2008 and 2009 were recorded as severely dry. During those years 13 severely dry events of drought were occurred with coverage of 23.64% as compared with extreme and moderate dry events each covering 21.82% and 54.54% respectively. Moderately dry events at this station occurred with more frequency and successively in each year. The drought events of moderate severity were occurred at the years 1991, 1996, 1998, 2003, 2006, 2007 and 2010. The detail of this analysis was shown in the Figure 20.

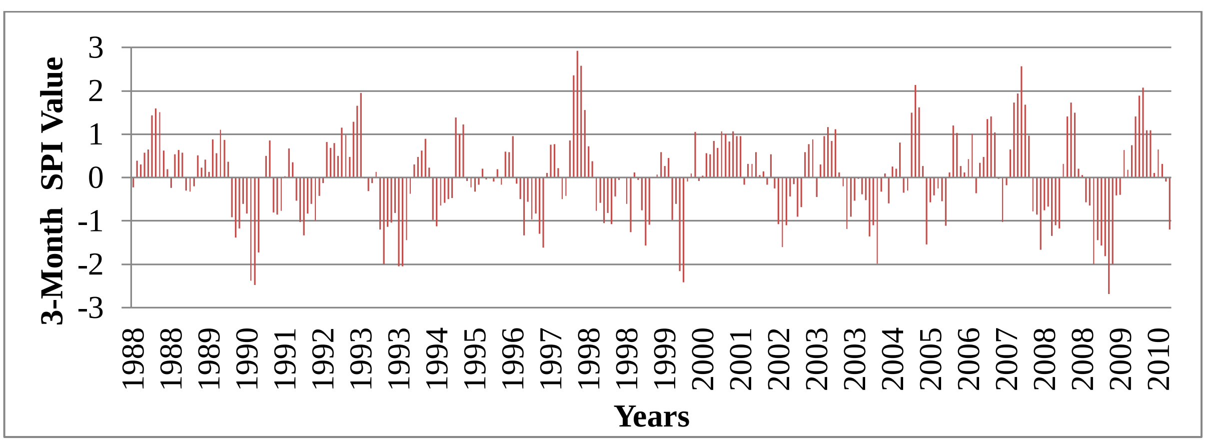

Figure 20: SPI result on 3-month timescale at Arba Minch station

3-month timescale SPI result for Bodity station indicates that 7 drought events of extreme severity were occurred since 2000 and 2008 rainfall years. At the same station, the years 1989, 1994, 1996, 1997, 1999, 2000, 2007, 2008, 2009 and 2010 have 22 severe dry events. Generally, throughout all historical record period of precipitation, different drought events with extreme, severe and moderate severity each covering 11.3%, 35.5% and 53.2% respectively were occurred at this station with varying interval of time between each event. The moisture and dry events conditions at Bodity station in the past was presented in the Figure 21 for further detail description based on 3-months timescale of SPI.

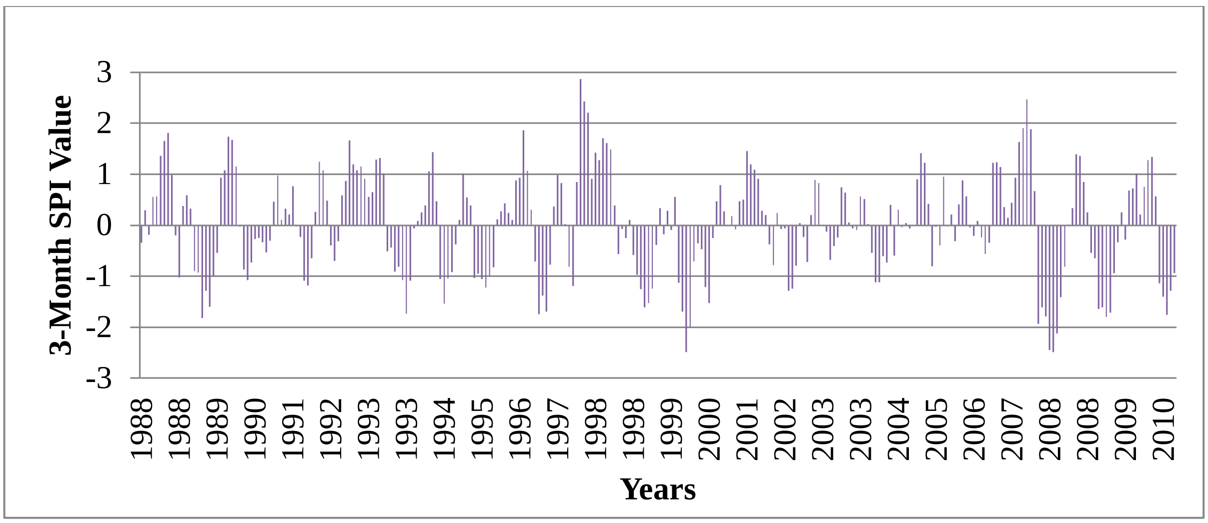

Figure 21: SPI result on 3-month timescale at Bodity station

The result of 3-month timescale SPI for Morocho station indicates that the years before 1997 were characterized by moist conditions and behind this year successive dry events with different magnitude from near normal to extreme severity was occurred until present. In addition to the extreme dry events of 1991 and 2000 the same event also occurred successively in 2008, 2009, and 2010. Totally, 9 extremely dry events of coverage 17% as compared with the other dry events were occurred. It was the least frequent dry event followed by 14 severe dry events covering 26.4% and 30 moderate dry events covering 56.5% of total drought events at the station. The more detail result of analysis was presented in Figure 22.

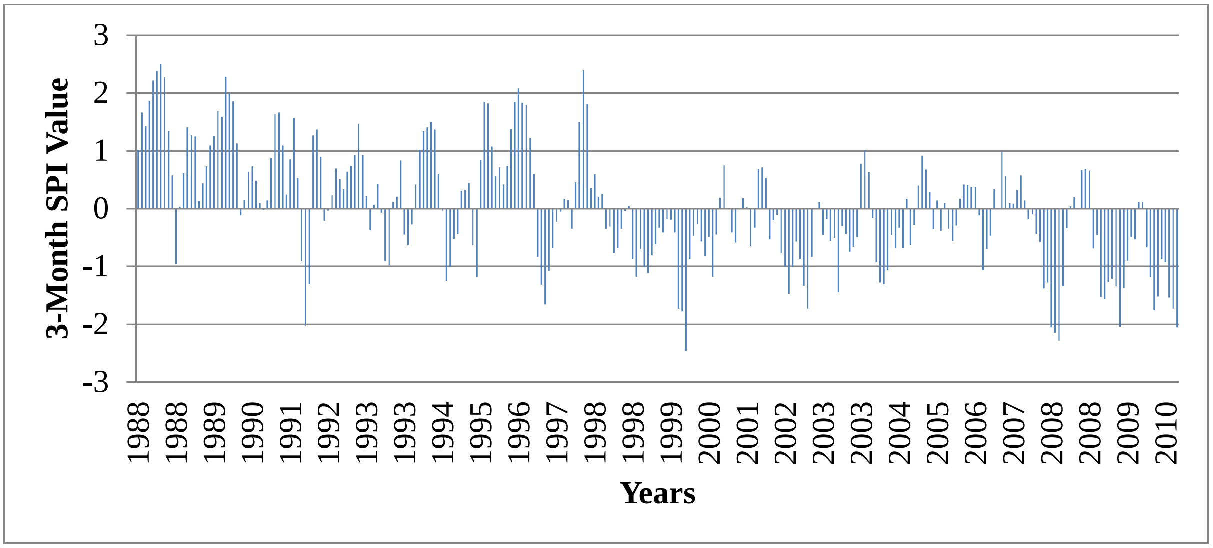

Figure 22: SPI result on 3-month timescale at Morocho station

Since 1990, 1999, 2000 and 2003 seven dry events with extreme severity were occurred, and the years 1990, 1994, 1997, 1999, 2000, 2002 and 2008 were known for 16 severe dry events at Billate meteorological station based on 3-month timescale analysis of SPI. In between the record years various drought events were occurred as we see from Figure-23 at this station. At this station extreme dry event covers 15.6% followed by 33.3% of severe and 51.1% of moderate dry events respectively. As the other stations in the region, at the Billate station extreme drought events occurred less frequently than moderate dry events which is more frequent than other drought events.

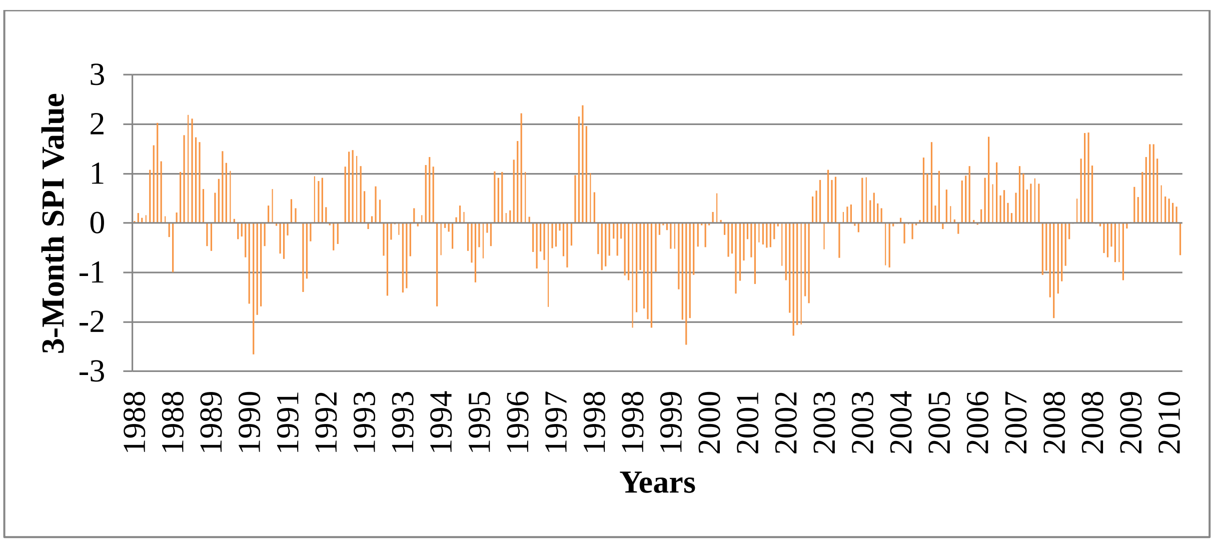

Figure 23: SPI result on 3-month timescale at Billate station

Bedessa meteorological station is characterized by variable meteorological condition with moist and dry events each with different magnitude, frequency, onset, duration and termination. As presented in Figure 24 based on 3-month timescale ten extremely dry events during 1991, 1993, 1997, 1999 and 2000 were occurred in the past. It happened more frequently in 1999 and totally covers 16.4%. Fifteen severe dry events at the same station in years 1989, 1991, 1993, 1996, 1997, 2000, 2004, 2007, 2008 and 2010 were occurred with coverage of 24.6%. The station has also thirty six moderate dry events which covering 59% of the total drought events occurred in the station.

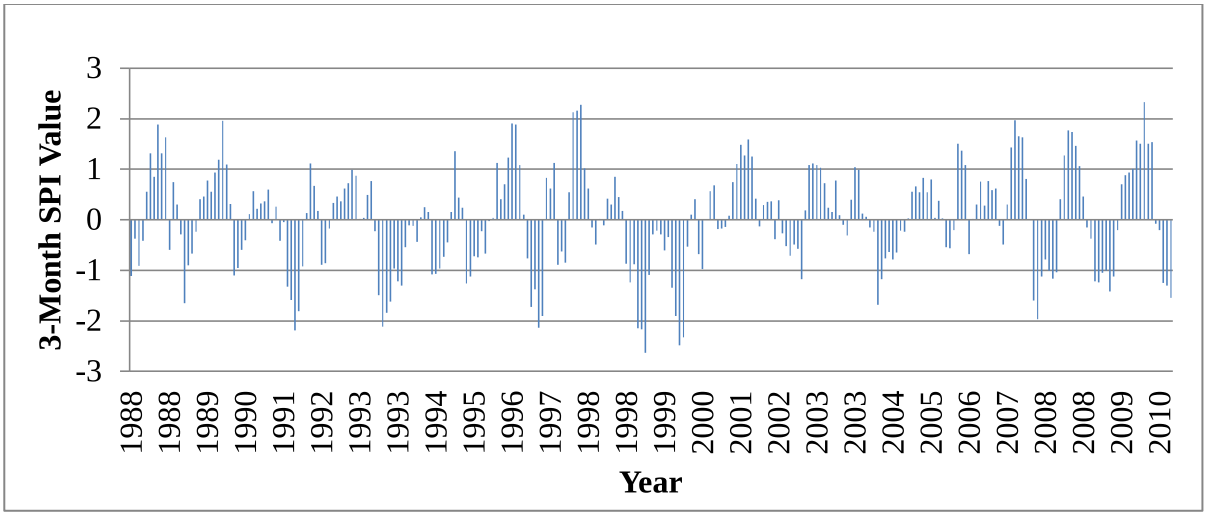

Figure 24: SPI result on 3-month timescale at Bedessa station

4.8.3. 6-Month SPI

At Arba Minch station as determined from 6-month timescale SPI analysis, the years 1990, 2000 and 2009 were known for 6 extreme dry events each with six months duration from its onset. This means, that extreme drought events lasting six months duration starting from its onset were occurred during those above listed years. During 1990, 1992, 1993, 1994, 1997, 2004, 2008 and 2009 at 6-month timescale 18 severely dry events were occurred. This severely dry event covers 29% as compared with the other two drought events at the station. Both extreme and moderate dry events cover 13% and 58% respectively at this station. 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2002, 2004, 2008 and 2009 was the years in the record period having 36 moderately dry events with more frequency of occurrence at 6-month timescale on SPI. The detail result of the index was shown in the Figure 25.

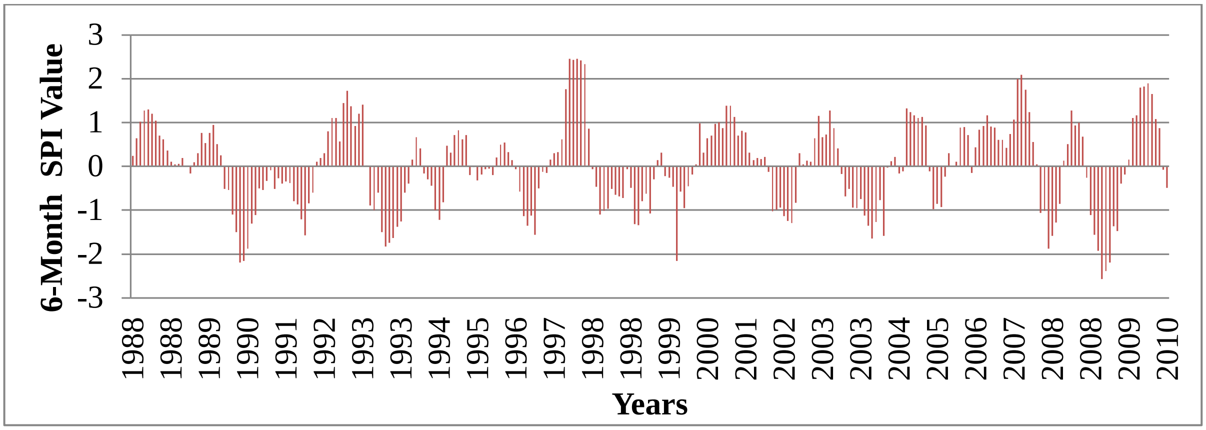

Figure 25: SPI result on 6-month timescale at Arba Minch station

The years 2008, 2009 and 2010 at Bodity station was known for 7 extreme drought events; and 1989, 1994, 1995, 1997, 1999, 2000, 2008, 2009 and 2010 was the years having 24 severe drought events as the result of analysis of SPI on 6-month timescale to determine the severity, onset and frequency of drought events during the past historical record years. In addition to this, during 1989, 1993, 1995, 1998, 1999, 2000, 2002, 2004, 2008 and 2009, 22 drought events of moderate severity were occurred. At this station, severe dry events were occurred with more frequency and coverage of 45.3% as compared to the other dry events. The least frequent drought event was the extreme dry event which covers only 13.2% followed by moderate dry events of coverage 41.5%. To show the characteristics of historical periods the result of 6-month timescale analysis of this station is presented in Figure 26.

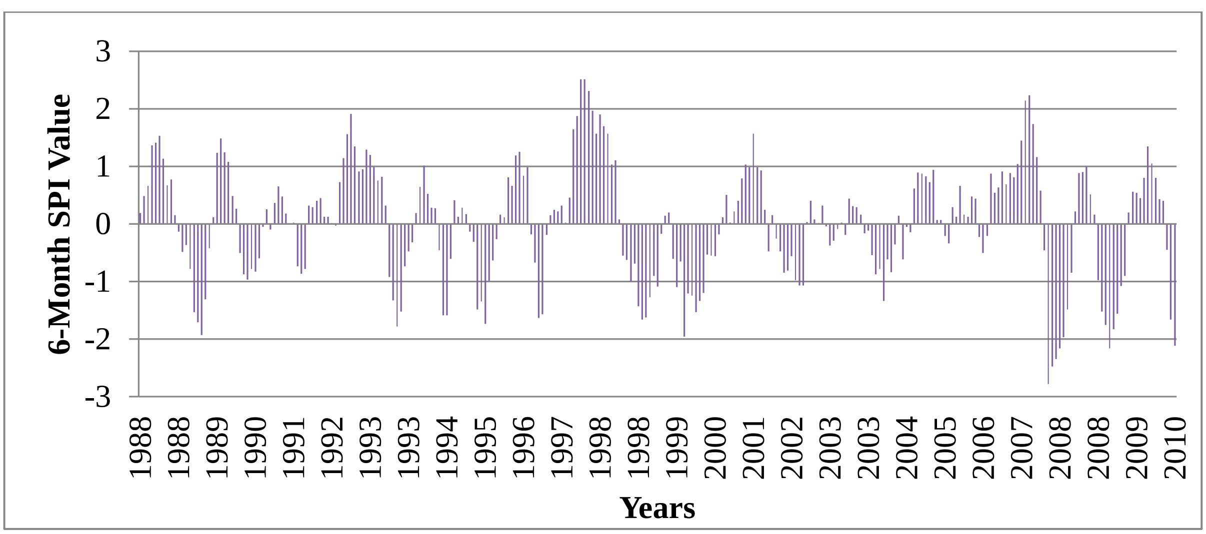

Figure 26: SPI result on 6-month timescale at Bodity station

6-month SPI result shows that no drought events of much severity were occurred from 1988 to 1996 at Morocho station showing the climate is near normal condition, and the station was experienced 3 extremely dry events during a year 2008, and 15 severe drought events during 2000, 2002, 2003, 2008, 2009 and 2010. The station has also experienced 28 drought events of moderate severity in the past. The least frequent dry event of extreme severity covers only 6.52% which is rare when compared with the severe and moderate drought events each of them covering 32.61% and 60.87% respectively. Figure 27 shows more detail analysis of SPI for Morocho station based on 6-months timescale.

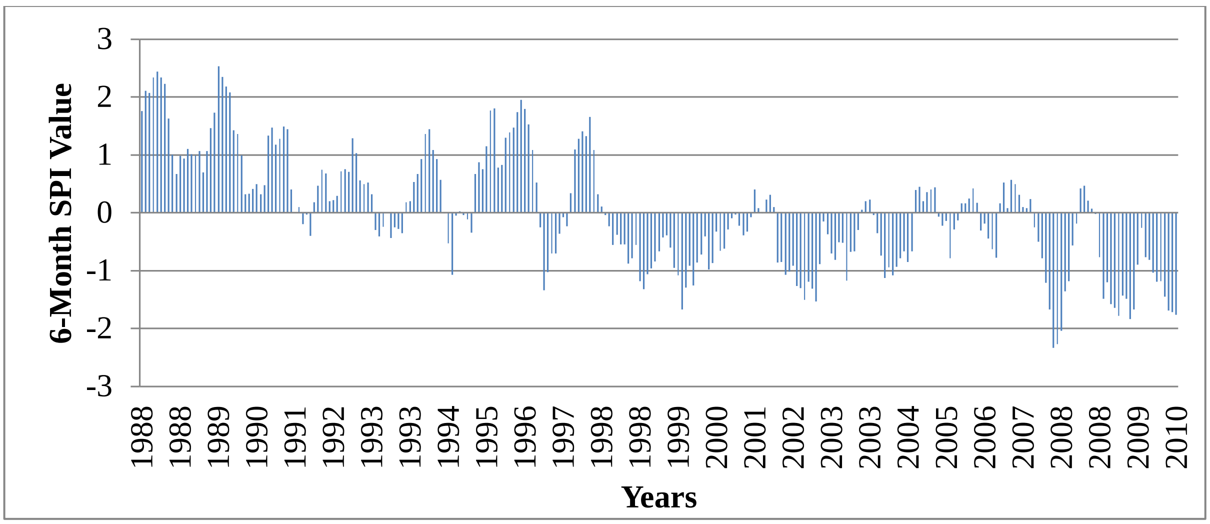

Figure 27: SPI result on 6-month timescale at Morocho station

As shown in Figure 28, 1990, 1991, 1999, 2000 and 2002 was the years of having 11 extreme drought events based on 6-month timescale analysis of the recorded precipitation at Billate station covering 19.3% of the total dry events occurred. These five years have drought events of each with six month duration of extreme magnitude. In addition to the occurrence of extremely dry events, the years 1990, 1997, 1999, 2000, 2002 and 2008 have a total of 14 severely dry events of coverage 24.56%. Each climatic year in between 1991 and 2008 experienced 32 moderately dry events which was large dry event of coverage 56.14% as compared with the other drought events of this station.

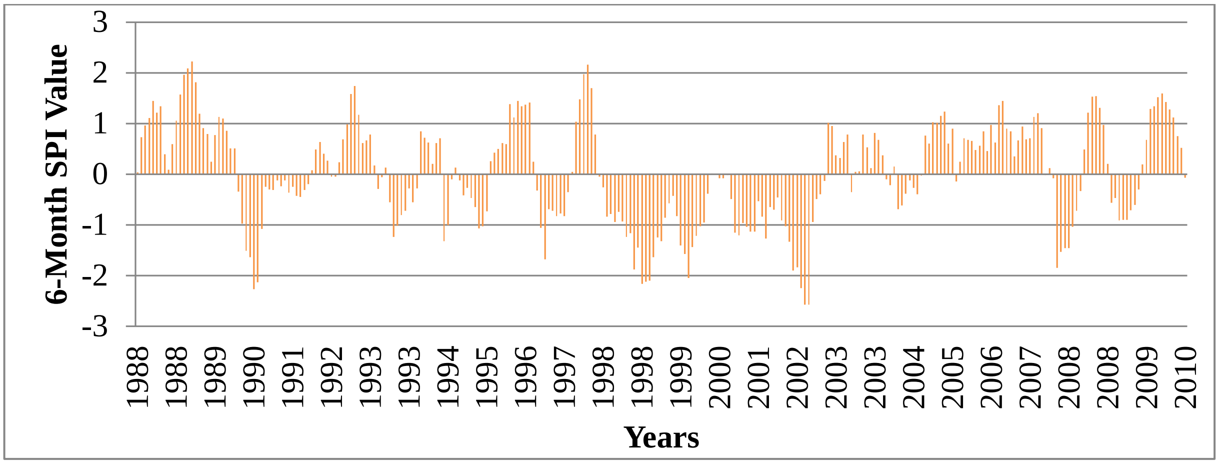

Figure 28: SPI result on 6-month timescale at Billate station

Among the meteorological stations in Abaya-Chamo sub-basin, at Bedessa station 9 extreme drought events were occurred in 1993, 1994, 1997, 1999 and 2000. This means that a meteorological drought event of extreme magnitude which ends within six months duration in these years was occurred. The coverage of this event as compared with the other events was 19.1% which was the least frequent dry event among the others. In each year various drought events with varying magnitude and frequency was occurred at this meteorological station within the record period from 1988 to 2017. Frequently 13 severely dry events and 25 moderately dry events each with the coverage of 27.7% and 53.2% respectively were happened at this station in the region. Figure 29 presents the 6-months SPI result of Bedessa station.

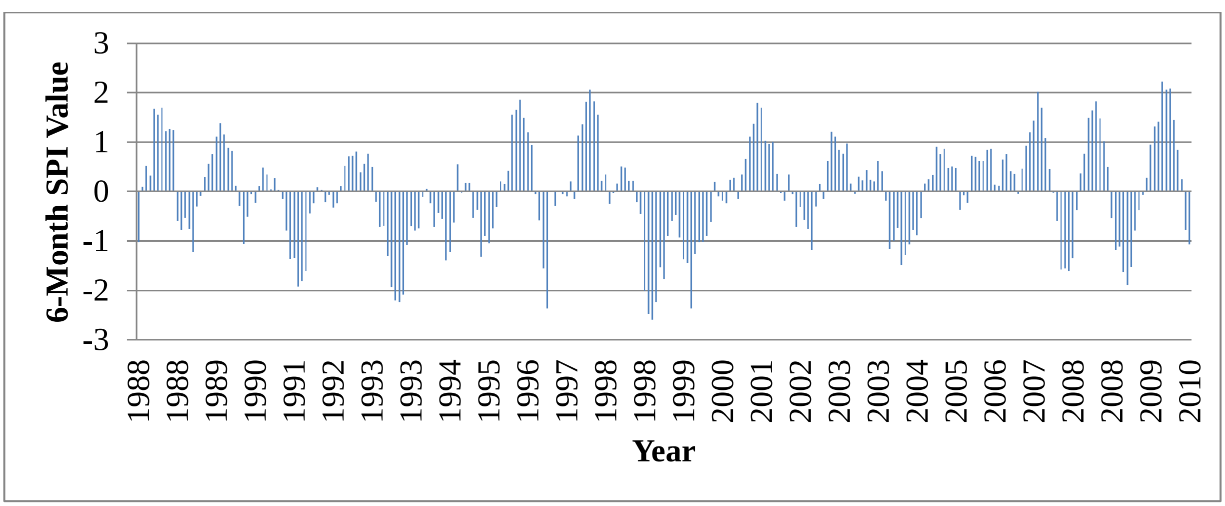

Figure 29: SPI result on 6-month timescale at Bedessa station

4.9. Regionalization of Drought Events

The drought events which were occurred with varying magnitude (i.e., extreme, severe, moderate and near normal droughts) from one meteorological station to another in the basin was existed as determined from the SPI analysis of historical meteorological recorded data in the past. These at station drought events were regionalized using ArcGIS software to assess how drought events of different magnitude were distributed throughout the study area. The SPI characteristics of analysis were used to generate drought maps for Abaya Chamo sub-basin using GIS. An Inverse Distance Weighting with Power (IDW) methodology was used for interpolation of the station data. The result of the analysis presents that the northern part and some of the southern part of the study area was experienced the drought events of extreme magnitude at different timescales. At the south western part of the region moderate drought events were occurred and the central part of the region is at near normal condition of the meteorological condition. For more visualization on how the drought events of different magnitude were distributed throughout the region the output of the analysis was presented in Figure 30.

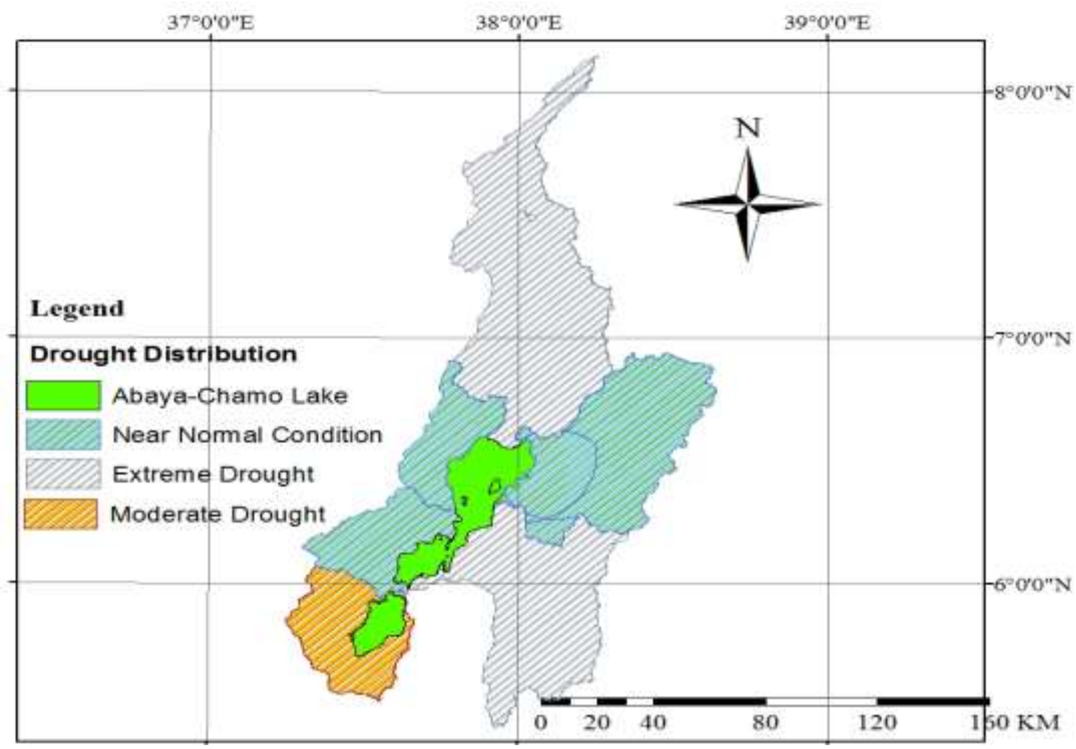

Figure 30: Spatial distribution maps of droughts

4.10. Return Period Analysis of the Drought Events

The return period (also called the recurrence interval) is the period expressed in number of years in which the annual observation is expected to return. It is in common use in hydrologic engineering and is an important parameter for design of water resource systems. When the concept of return period is applied to drought-related variables, it indicates the average time between the occurrences of events with a certain magnitude or less. For estimating drought return periods a common approach for characterizing droughts consists of fitting to sample data frequency distributions of drought characteristics. Therefore, it is important to test the type of probability distribution which fits the available data well, as the distribution is likely to vary, depending on the pattern of hydro-meteorological variables.

For this study the Gamma probabilistic distribution was determined as the best fit distribution for meteorological data. Using the fitted Gamma probability frequency distribution drought durations and magnitudes were computed, corresponding to 5, 10, 20, 50 and 100-year return periods. The calculated values were applied to develop Time scale-Magnitude-Frequency (TMF) and Time scale-Duration-Frequency (TDF) curves relationships for the mentioned return periods, and the corresponding diagrams are produced and presented in Figure 31 and 32 respectively.

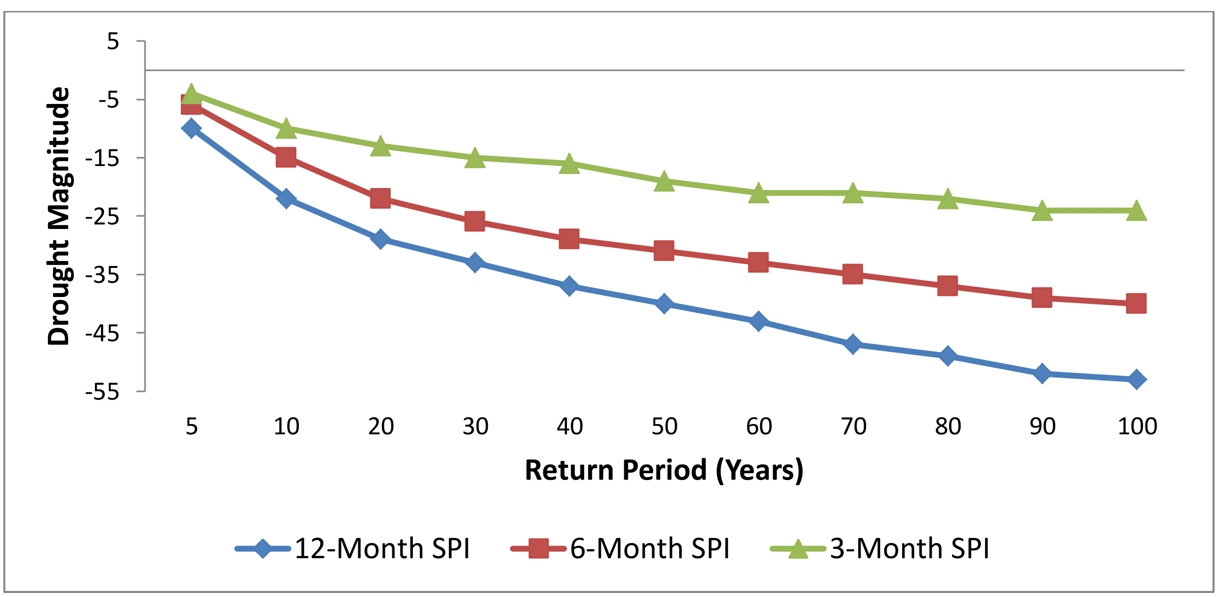

Figure 31: Time scale-Magnitude-Frequency curves of different return periods

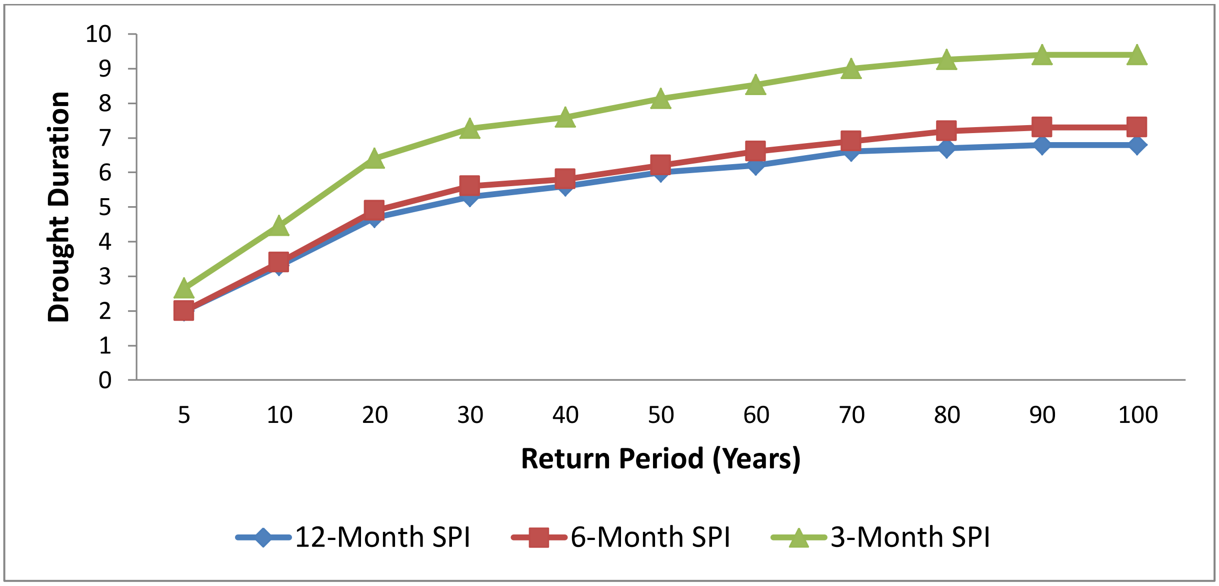

Figure 32: Time scale-Duration-Frequency curves of different return periods

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This study was done based on long time historical record of precipitation data for a period of 30 years starting from 1988 to 2017 from meteorological stations in the Abaya-Chamo sub-basin. The recorded data set was fitted to the statistical distribution and its fitness was checked using the SPSS software. The techniques used in this software for the goodness of fit test of the distribution were Kolmogorov Smirnov test and Shapiro Wilk's test. Based on the test values, the recorded precipitation data from all selected stations fits to Gamma probabilistic distribution, and therefore, it is the best fit statistical distribution for the dataset.

In this study, a brief meteorological drought analysis was presented using SPI. It is a very important tool for quantifying drought and comparing its characteristics over time and space. SPI has been used in this study to examine the magnitude and frequency, onset, duration and termination of drought occurrences. Here, drought occurrences were analyzed at 1-, 3-, 6-, 9- and 12-months time scales, and the characteristics of droughts at five stations were analyzed. Though almost all stations in the study region suffer from drought, it is important to consider that all of the stations did not experience well defined drought episode during the same periods. In other words, temporal distribution and frequency of droughts varied markedly among each station.

Moderately dry events were pronounced with greater frequency among all stations than other dry events in the study area. Extreme droughts were more pronounced in Arba Minch meteorological station during winter season. Similarly, all stations found in the study region were exposed to high frequency of severe and moderate droughts at 3-month timescale. The year 1999 was the most drastic and distinct-wide drought episode. Almost all stations experienced extreme magnitude drought at 1-, 3-, and 6-months timescales in the specified year. Generally, the entire study area in the past was affected by various drought events varying between extremely dry to moderately dry conditions, and these conditions seem to be continued at present and in the future. The patterns of drought events in the study area are varying throughout the time.

Special attention (local-scale planning) should be given by decision makers to plan and to effectively manage drought. The findings of this study have implications for drought management, early warning system, preparedness and contingency planning and climate change adaptation. In real sense, drought is a climatic event that cannot be prevented very easily, but interventions and preparedness to drought can help to cope with drought by developing more resilient ecosystems, improving resilience to recover from drought and taking various adaptation strategies like water harvesting, making irrigation system more efficient and a geographical shift of agricultural system.

5.2. Recommendations

5.2.1. Research Community

More research is needed to fill the gaps in understanding different types of drought in the region. A more elaborate way of studying drought would be used of areal averaged rainfall records. Before areal rainfall calculation is done regions are grouped into areas experiencing same climatic condition e.g. use of principal component analysis. This research used only SPI for the analysis of meteorological drought, but the future research can look into different regional/spatial scale and compare performance of different drought indices in the region since it determines drought prone areas more than analysis of it at a point. One of the limitations of the study is the availability and adequacy of dataset archives used. Therefore, improvement of meteorological monitoring over region will greatly improve drought monitoring in support of key decisions.

5.2.2. Society and Policy Makers

Considering the recurrence pattern of drought as seen from the study, drought monitoring and early warning is therefore, essential and can provide the foundation for making timely decision by decision makers and concerned subjects (i.e., farmers and national policy makers). The droughts analysis over the area of study using standardized precipitation index (SPI) varied between extreme drought and moderately dry condition. Considering the conditions of present rainfall seasons might worsen during other dry seasons, reducing the risks and therefore the impacts of drought is of utmost importance and requires that greater emphasis be placed on preparedness and mitigation.

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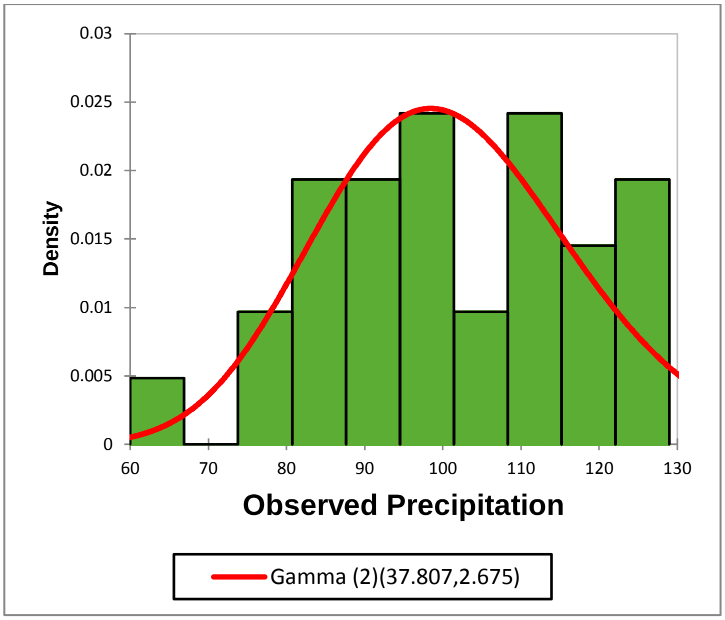
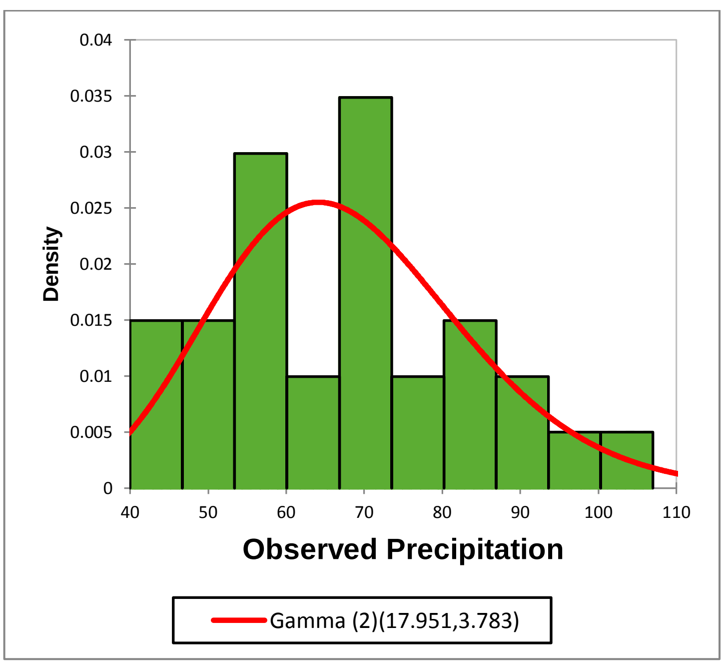
APPENDICES

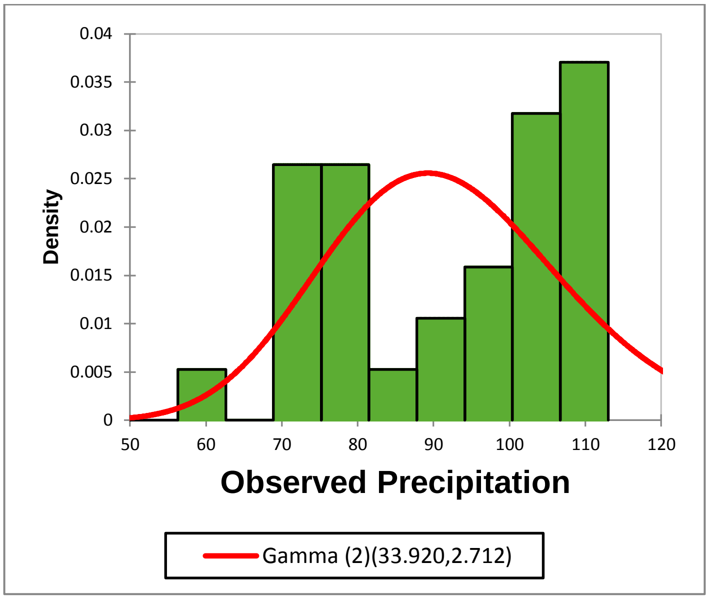
Appendix I: Gamma Distribution Fitting



Appendix Figure 1: Gamma Distribution for Bodity Station

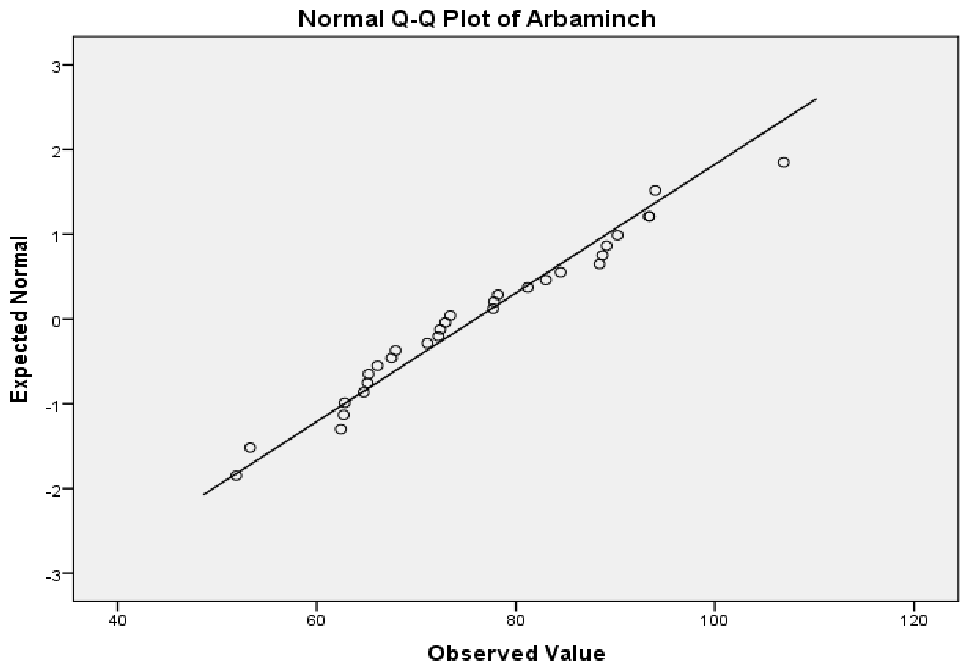


Appendix Figure 2: Gamma Distribution for Billate Station

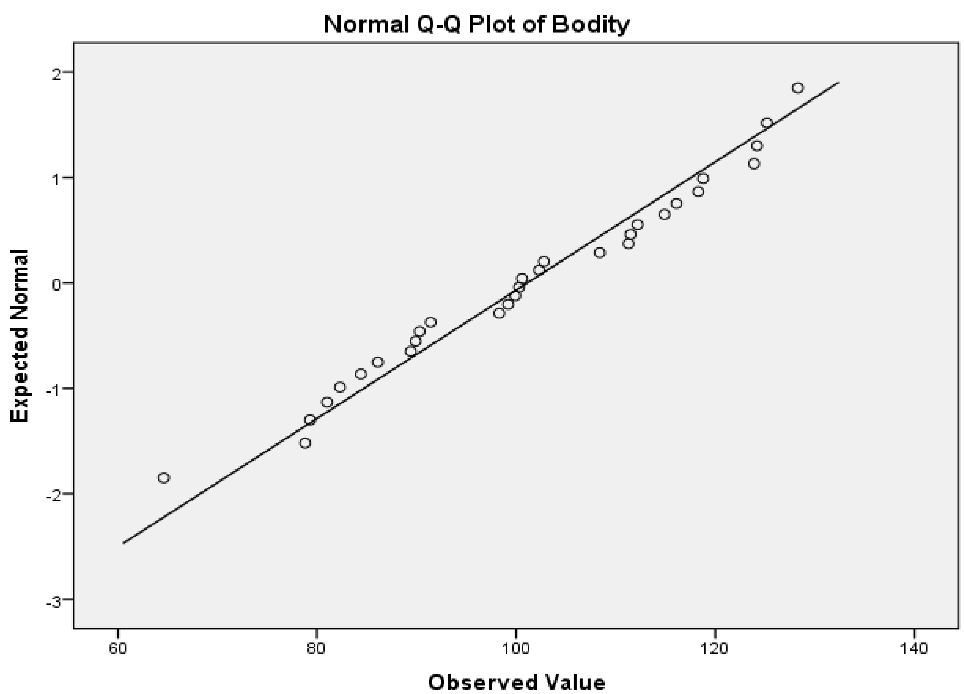


Appendix Figure 3: Gamma Distribution for Bedessa Station

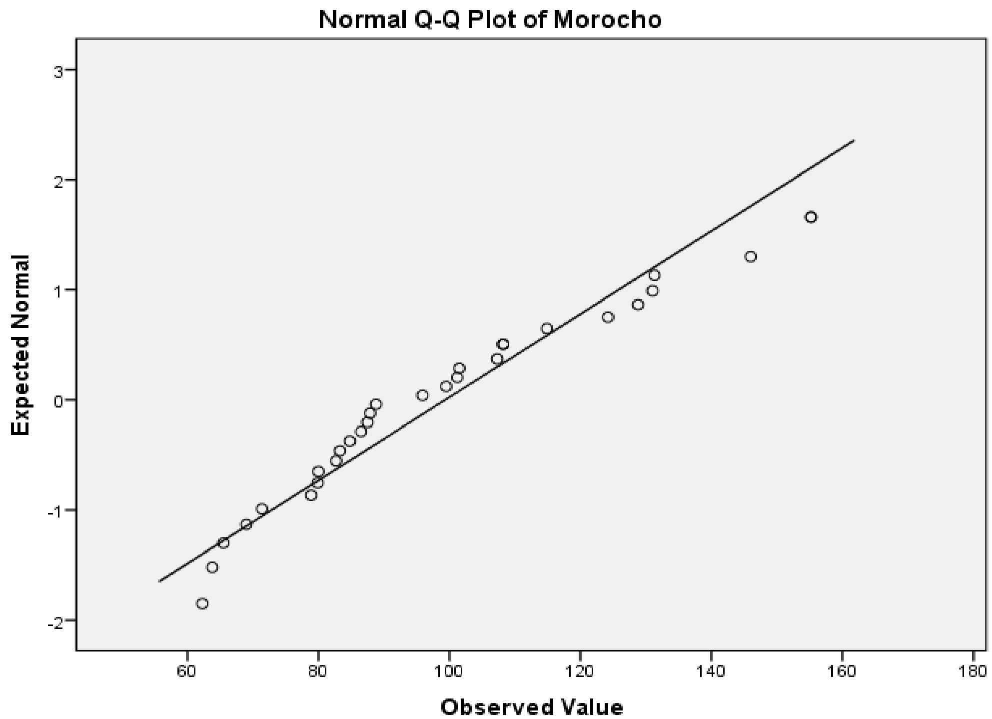
Appendix II: Normal Q-Q Plot for Stations



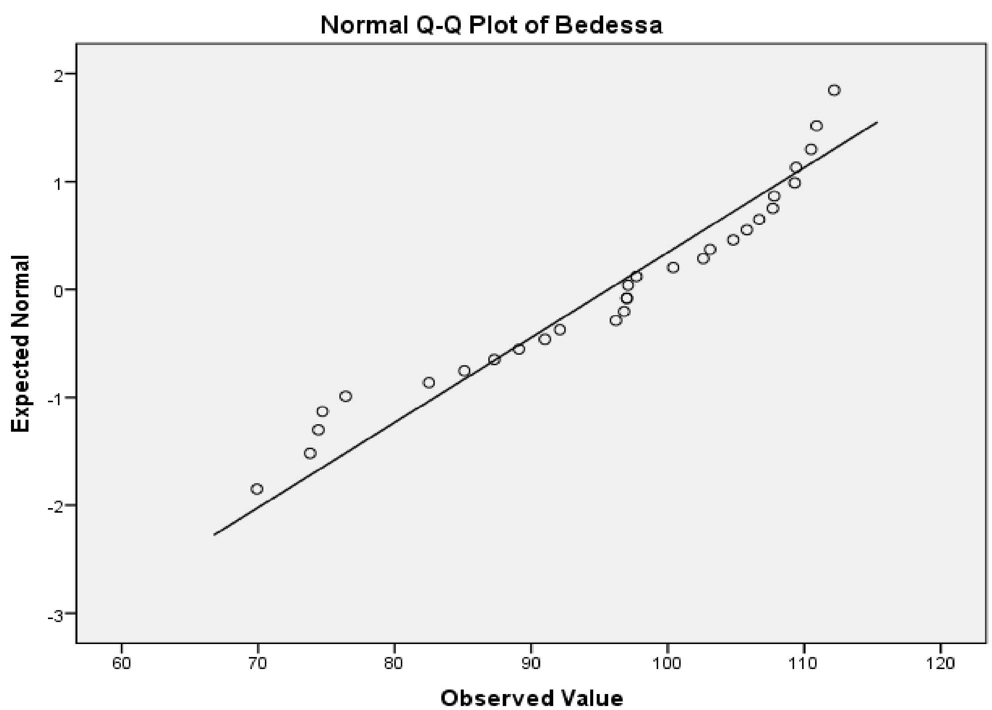
Appendix Figure 4: Normal Q-Q Plot of Arba Minch Station



Appendix Figure 5: Normal Q-Q Plot of Arba Minch Station



Appendix Figure 6: Normal Q-Q Plot of Morocho Station



Appendix Figure 7: Normal Q-Q Plot of Bedessa Station

Appendix III: SPI Analysis Results at Different Timescales

Table in Appendix 1: SPI Analysis Result for Arba Minch Station

ARBAMINCH STATION						
Year	Month	1- Month SPI	3- Month SPI	6- Month SPI	9- Month SPI	12- Month SPI
1988	1	0.38	-99	-99	-99	-99
1988	2	0.15	-99	-99	-99	-99
1988	3	-0.59	-0.22	-99	-99	-99
1988	4	1.02	0.39	-99	-99	-99
1988	5	-0.01	0.3	-99	-99	-99
1988	6	0.3	0.57	0.24	-99	-99
1988	7	1.44	0.65	0.64	-99	-99
1988	8	1.39	1.43	1.02	-99	-99
1988	9	0.8	1.59	1.27	1.06	-99
1988	10	0.82	1.51	1.3	1.26	-99
1988	11	-0.25	0.62	1.2	1.04	-99
1988	12	0.02	0.19	1.04	1.08	1
1989	1	0.4	-0.24	0.7	0.85	0.95
1989	2	1.11	0.54	0.62	1.05	1.05
1989	3	-0.03	0.64	0.36	1.01	1.08
1989	4	0.16	0.57	0.11	0.83	0.98
1989	5	-0.32	-0.3	0.05	0.33	0.87
1989	6	-0.28	-0.33	0.06	0.06	0.79
1989	7	0.76	-0.2	0.19	-0.06	0.65
1989	8	0.8	0.51	0.01	0.24	0.5
1989	9	-0.65	0.23	-0.16	0.1	0.12
1989	10	0.75	0.41	0.09	0.31	0.11
1989	11	0.2	0.13	0.3	0.02	0.22
1989	12	1.14	0.88	0.76	0.37	0.61

1990	1	-0.02	0.56	0.53	0.32	0.53
1990	2	1.42	1.1	0.76	0.8	0.57
1990	3	0.37	0.87	0.95	0.91	0.6
1990	4	-0.94	0.36	0.51	0.58	0.4
1990	5	-0.52	-0.91	0.25	0.19	0.32
1990	6	-1.26	-1.38	-0.52	0.16	0.19
1990	7	-0.2	-1.17	-0.54	-0.12	0.02
1990	8	0.34	-0.61	-1.1	-0.05	-0.06
1990	9	-1.4	-0.83	-1.5	-0.9	-0.16
1990	10	-2.42	-2.38	-2.19	-1.54	-1
1990	11	-0.67	-2.47	-2.16	-2.08	-1.18
1990	12	0.05	-1.72	-1.88	-2.27	-1.93
1991	1	1.06	0	-1.3	-1.68	-1.32
1991	2	0.49	0.5	-1.11	-1.25	-1.47
1991	3	0.69	0.86	-0.5	-0.89	-1.42
1991	4	-1.85	-0.8	-0.54	-1.59	-1.92
1991	5	-0.07	-0.85	-0.33	-1.49	-1.76
1991	6	0.74	-0.77	-0.09	-0.94	-1.39
1991	7	-0.2	0.03	-0.52	-0.46	-1.44
1991	8	1.03	0.67	-0.27	-0.01	-1.18
1991	9	0.14	0.35	-0.39	0.05	-0.75
1991	10	-1.58	-0.53	-0.34	-0.73	-0.68
1991	11	-0.3	-1.02	-0.38	-0.8	-0.59
1991	12	-0.25	-1.33	-0.79	-1.11	-0.79
1992	1	-0.49	-0.83	-0.87	-0.71	-1.01
1992	2	-0.21	-0.61	-1.21	-0.71	-0.99
1992	3	-0.84	-0.99	-1.57	-1.15	-1.33
1992	4	0.38	-0.42	-0.84	-1.03	-0.88
1992	5	0.09	-0.13	-0.6	-1.13	-0.84

1992	6	1.72	0.82	0.11	-0.65	-0.57
1992	7	-0.16	0.69	0.19	-0.29	-0.58
1992	8	0.03	0.79	0.3	-0.16	-0.78
1992	9	1.04	0.5	0.8	0.29	-0.42
1992	10	0.9	1.15	1.1	0.72	0.26
1992	11	0.28	0.98	1.11	0.75	0.4
1992	12	0.14	0.48	0.57	0.85	0.48
1993	1	2.44	1.29	1.45	1.52	1.31
1993	2	1.58	1.65	1.72	1.76	1.54
1993	3	-0.55	1.95	1.37	1.41	1.53
1993	4	-1.22	-0.01	0.92	1.3	1.4
1993	5	0.88	-0.31	1.2	1.44	1.65
1993	6	-0.15	-0.13	1.41	1.13	1.31
1993	7	-2.23	0.13	0.02	0.78	1.23
1993	8	-0.67	-1.2	-0.89	0.69	1.12
1993	9	-1.32	-2	-1	0.45	0.55
1993	10	0.02	-1.14	-0.6	-0.56	0.3
1993	11	-0.97	-1.04	-1.5	-1.28	0.08
1993	12	-1.11	-0.81	-1.83	-1.39	-0.15
1994	1	-1.36	-2.05	-1.74	-1.26	-1.16
1994	2	-0.9	-2.04	-1.64	-1.95	-1.67
1994	3	-0.48	-1.44	-1.38	-2.18	-1.69
1994	4	0.51	-0.37	-1.26	-1.69	-1.35
1994	5	0.45	0.3	-0.6	-1.13	-1.6
1994	6	0.07	0.47	-0.39	-0.79	-1.6
1994	7	0.94	0.62	0.16	-0.62	-1.17
1994	8	1.07	0.89	0.67	-0.1	-0.73
1994	9	-1.36	0.23	0.41	-0.25	-0.66
1994	10	-0.97	-0.98	-0.16	-0.37	-1.02

1994	11	0.28	-1.12	-0.29	-0.09	-0.73
1994	12	-0.12	-0.64	-0.44	-0.09	-0.75
1995	1	-1.36	-0.58	-1	-0.46	-0.6
1995	2	0.23	-0.5	-1.22	-0.6	-0.35
1995	3	0.06	-0.47	-0.82	-0.66	-0.3
1995	4	1.86	1.39	0.47	-0.08	0.2
1995	5	-0.17	1.01	0.31	-0.38	-0.05
1995	6	0.86	1.22	0.72	0.08	0.11
1995	7	-0.53	-0.08	0.83	0.3	-0.17
1995	8	-0.92	-0.22	0.62	0.15	-0.52
1995	9	0.52	-0.33	0.71	0.38	-0.08
1995	10	0.02	-0.16	-0.2	0.55	0.19
1995	11	0.24	0.2	-0.02	0.51	0.18
1995	12	0.14	-0.04	-0.32	0.48	0.21
1996	1	0.22	-0.02	-0.18	-0.23	0.43
1996	2	-0.14	-0.09	-0.06	-0.2	0.32
1996	3	0.71	0.19	-0.05	-0.26	0.41
1996	4	-0.27	-0.16	-0.2	-0.31	-0.33
1996	5	0.85	0.6	0.2	0.2	0.05
1996	6	0.77	0.58	0.49	0.22	0.03
1996	7	0.35	0.96	0.54	0.32	0.18
1996	8	-2.4	-0.14	0.33	0.09	0.11
1996	9	0.12	-0.49	0.14	0.11	0
1996	10	-0.8	-1.33	-0.06	-0.19	-0.22
1996	11	-0.04	-0.56	-0.57	-0.11	-0.28
1996	12	-0.98	-0.96	-1.13	-0.47	-0.55
1997	1	-0.36	-0.83	-1.36	-0.48	-0.53
1997	2	-1.36	-1.3	-1.12	-1.06	-0.54
1997	3	-1.3	-1.62	-1.56	-1.65	-0.91

1997	4	1.33	0.11	-0.5	-1.12	-0.44
1997	5	0.56	0.76	-0.13	-0.49	-0.6
1997	6	-1.16	0.77	-0.15	-0.69	-0.99
1997	7	0.69	0.22	0.16	-0.32	-0.94
1997	8	-0.53	-0.49	0.3	-0.35	-0.73
1997	9	-0.68	-0.42	0.32	-0.4	-0.84
1997	10	1.78	0.86	0.62	0.53	0.09
1997	11	2.79	2.36	1.76	1.71	1.28
1997	12	1.7	2.92	2.46	2.37	2.16
1998	1	0.97	2.58	2.43	2.22	2.2
1998	2	1.21	1.56	2.46	2.12	2.2
1998	3	-0.98	0.72	2.42	2.19	2.19
1998	4	0.21	0.38	2.33	2.42	2.22
1998	5	-0.66	-0.77	0.86	2.07	1.88
1998	6	-0.58	-0.58	-0.07	2.06	1.98
1998	7	-0.24	-1.05	-0.47	1.65	1.93
1998	8	-0.53	-0.82	-1.1	0.46	1.89
1998	9	-0.9	-1.07	-1.01	-0.61	1.69
1998	10	0.55	-0.43	-0.96	-0.64	1.41
1998	11	0.26	-0.05	-0.51	-0.86	0.32
1998	12	-1.11	0	-0.65	-0.9	-0.68
1999	1	-0.32	-0.61	-0.69	-1.12	-0.85
1999	2	-1.2	-1.26	-0.72	-1	-1.2
1999	3	1.26	0.12	-0.06	-0.55	-0.76
1999	4	-0.31	-0.05	-0.49	-0.69	-1.08
1999	5	-2.04	-0.75	-1.32	-1.12	-1.46
1999	6	-0.46	-1.56	-1.34	-0.95	-1.49
1999	7	1.08	-1.09	-0.8	-0.98	-1.19
1999	8	-0.72	0	-0.63	-1.16	-1.16

1999	9	-0.15	0.07	-1.08	-1.09	-0.88
1999	10	1.31	0.58	-0.3	-0.33	-0.61
1999	11	-1.45	0.27	0.14	-0.34	-0.9
1999	12	0.46	0.45	0.31	-0.62	-0.76
2000	1	-1.28	-0.98	-0.22	-0.73	-0.71
2000	2	-1.36	-0.61	-0.26	-0.29	-0.59
2000	3	-1.24	-2.16	-0.46	-0.45	-1.12
2000	4	-1.3	-2.42	-2.16	-1.29	-1.62
2000	5	1.32	-0.09	-0.57	-0.36	-0.42
2000	6	-0.58	0.1	-0.95	-0.4	-0.45
2000	7	0.71	1.05	-0.45	-0.86	-0.57
2000	8	-0.1	-0.08	-0.18	-0.57	-0.44
2000	9	-0.12	0.05	0.04	-0.8	-0.38
2000	10	1.08	0.56	0.98	-0.09	-0.52
2000	11	0.2	0.54	0.31	0.14	-0.24
2000	12	0.79	0.84	0.64	0.49	-0.18
2001	1	1.01	0.69	0.7	1.06	0.28
2001	2	1.17	1.07	0.97	0.78	0.64
2001	3	0.14	1.01	1.01	0.89	0.77
2001	4	0.36	0.83	0.87	0.96	1.28
2001	5	1.32	1.07	1.39	1.36	1.26
2001	6	-0.15	0.95	1.39	1.33	1.34
2001	7	0.14	0.96	1.13	1.14	1.3
2001	8	0.03	-0.16	0.7	1.18	1.3
2001	9	0.65	0.32	0.81	1.24	1.35
2001	10	0.15	0.32	0.78	1.02	1.18
2001	11	0.74	0.58	0.31	0.78	1.32
2001	12	-0.65	0.06	0.14	0.61	1.1
2002	1	0.47	0.14	0.19	0.61	0.91

2002	2	0.07	-0.16	0.17	0.03	0.53
2002	3	0.99	0.54	0.22	0.27	0.66
2002	4	-0.83	-0.25	-0.13	-0.01	0.43
2002	5	-1.6	-1.08	-1.03	-0.48	-0.59
2002	6	-0.18	-1.6	-0.99	-0.69	-0.62
2002	7	0.56	-1.1	-0.94	-0.68	-0.54
2002	8	-1.46	-0.44	-1.13	-1.13	-0.7
2002	9	0.27	-0.15	-1.25	-0.95	-0.74
2002	10	-0.55	-0.9	-1.29	-1.25	-1.04
2002	11	-0.97	-0.68	-0.83	-1.26	-1.47
2002	12	1.82	0.58	0.3	-0.65	-0.53
2003	1	-0.45	0.77	0.04	-0.5	-0.59
2003	2	-0.49	0.88	0.13	-0.11	-0.56
2003	3	0.29	-0.45	0.11	-0.04	-0.77
2003	4	0.77	0.3	0.64	0.12	-0.37
2003	5	0.78	0.95	1.15	0.56	0.35
2003	6	1.06	1.17	0.67	0.7	0.6
2003	7	-0.24	0.85	0.73	0.9	0.49
2003	8	1.52	1.11	1.28	1.46	0.99
2003	9	-0.97	0.12	0.87	0.55	0.68
2003	10	-0.53	-0.2	0.41	0.45	0.75
2003	11	-0.63	-1.19	-0.17	0.37	0.79
2003	12	-0.28	-0.9	-0.69	0.2	-0.09
2004	1	0.45	-0.53	-0.51	0.02	0.13
2004	2	0.18	-0.03	-0.94	-0.28	0.22
2004	3	-1.3	-0.39	-0.95	-0.83	-0.02
2004	4	0.2	-0.52	-0.74	-0.77	-0.24
2004	5	-1.54	-1.36	-1.12	-1.65	-1.05
2004	6	-0.83	-1.1	-1.35	-1.51	-1.52

2004	7	-0.58	-1.99	-1.65	-1.59	-1.64
2004	8	0.78	-0.32	-1.27	-1.16	-1.82
2004	9	0.14	0.09	-0.77	-1.09	-1.37
2004	10	-1.36	-0.59	-1.59	-1.64	-1.73
2004	11	1.54	0.25	-0.03	-0.77	-0.91
2004	12	0.21	0.21	0.12	-0.57	-0.95
2005	1	0.1	0.81	0.21	-0.67	-0.86
2005	2	-1.2	-0.35	-0.16	-0.33	-0.88
2005	3	0.42	-0.3	-0.11	-0.13	-0.65
2005	4	2.19	1.49	1.32	0.89	0.08
2005	5	1.15	2.14	1.24	1.08	0.9
2005	6	-1.9	1.62	1.17	0.82	0.82
2005	7	-0.27	0.27	1.11	1.19	0.9
2005	8	-0.82	-1.54	1.13	0.64	0.64
2005	9	0.04	-0.57	0.93	0.67	0.57
2005	10	0.09	-0.41	-0.11	0.68	0.96
2005	11	-0.4	-0.25	-0.98	0.66	0.39
2005	12	-0.79	-0.54	-0.86	0.42	0.21
2006	1	-0.49	-1.11	-0.93	-0.61	0.16
2006	2	1.13	0.12	-0.24	-0.78	0.53
2006	3	1.72	1.2	0.3	-0.02	0.8
2006	4	-0.76	1.03	0.01	-0.25	-0.11
2006	5	-0.07	0.27	0.11	-0.13	-0.67
2006	6	1.61	0.12	0.88	0.25	-0.04
2006	7	-0.49	0.43	0.9	0.19	-0.06
2006	8	0.89	1	0.72	0.53	0.27
2006	9	-0.87	-0.36	-0.15	0.51	0.07
2006	10	0.7	0.34	0.44	0.84	0.3
2006	11	1.02	0.47	0.84	0.74	0.68

2006	12	1.39	1.35	0.92	0.73	1.35
2007	1	0.9	1.41	1.16	1.15	1.49
2007	2	0.3	1.04	0.91	1.12	1.09
2007	3	-1.36	-0.03	0.89	0.63	0.55
2007	4	-0.47	-1.03	0.6	0.62	0.7
2007	5	0.82	-0.18	0.6	0.68	0.99
2007	6	1.23	0.65	0.42	1.06	0.91
2007	7	1.68	1.73	0.74	1.35	1.42
2007	8	1.39	1.94	1.07	1.43	1.5
2007	9	2.26	2.57	1.99	1.88	2.13
2007	10	-0.82	1.68	2.09	1.43	1.96
2007	11	0.32	0.97	1.75	1.28	1.77
2007	12	-1.36	-0.78	1.24	1.28	1.3
2008	1	-1.28	-0.85	0.56	1.31	0.91
2008	2	-0.59	-1.66	0.05	0.86	0.68
2008	3	0.24	-0.75	-1.06	0.66	0.83
2008	4	-0.35	-0.67	-1.01	0.16	0.97
2008	5	-1.87	-1.34	-1.88	-0.72	0.21
2008	6	0.52	-1.1	-1.58	-1.6	0.04
2008	7	0.01	-1.17	-1.28	-1.46	-0.4
2008	8	0.42	0.31	-0.85	-1.43	-0.63
2008	9	1.98	1.41	0.13	-0.33	-0.71
2008	10	0.55	1.73	0.51	0.08	-0.32
2008	11	0.69	1.49	1.28	0.38	-0.19
2008	12	-1.36	0.21	0.93	0.14	-0.27
2009	1	0.52	0.06	0.99	0.36	0.07
2009	2	-0.99	-0.57	0.68	0.65	0.05
2009	3	-0.8	-0.64	-0.26	0.43	-0.14
2009	4	-1.13	-2	-1.11	0.13	-0.39

2009	5	-0.43	-1.44	-1.56	-0.12	-0.06
2009	6	-1.98	-1.57	-1.93	-1.15	-0.43
2009	7	-2.89	-1.81	-2.57	-1.84	-0.67
2009	8	-1.17	-2.69	-2.39	-2.39	-0.88
2009	9	-0.9	-2	-2.19	-2.61	-1.8
2009	10	0.75	-0.41	-1.37	-2.19	-1.86
2009	11	-1.18	-0.4	-1.47	-1.93	-2.36
2009	12	1.25	0.63	-0.39	-1.24	-1.82
2010	1	-0.24	0.18	-0.18	-0.98	-1.73
2010	2	0.59	0.75	0.16	-0.62	-1.17
2010	3	2.45	1.41	1.11	0.43	-0.33
2010	4	0.41	1.89	1.17	0.81	0.05
2010	5	1.16	2.08	1.8	1.27	0.63
2010	6	0.65	1.09	1.82	1.49	0.98
2010	7	0.11	1.09	1.9	1.45	1.23
2010	8	-0.28	0.11	1.65	1.66	1.3
2010	9	1.25	0.65	1.08	1.76	1.64
2010	10	-0.4	0.32	0.87	1.66	1.48
2010	11	-1.93	-0.09	-0.08	1.14	1.43
2010	12	-0.54	-1.2	-0.49	0.28	1.02

Table in Appendix 2: SPI Analysis Result for Bodity Station

BODITY STATION						
Year	**Month**	**1- Month SPI**	**3- MonthSPI**	**6- Month SPI**	**9- MonthSPI**	**12- Month SPI**
1988	1	0.43	-99	-99	-99	-99
1988	2	0.16	-99	-99	-99	-99
1988	3	-1.04	-0.34	-99	-99	-99
1988	4	1.06	0.29	-99	-99	-99
1988	5	-0.84	-0.19	-99	-99	-99
1988	6	1.16	0.56	0.19	-99	-99
1988	7	1.28	0.57	0.48	-99	-99
1988	8	0.61	1.36	0.66	-99	-99
1988	9	1.51	1.65	1.36	0.92	-99
1988	10	0.76	1.81	1.41	1.19	-99
1988	11	-1.71	0.98	1.53	1.01	-99
1988	12	-0.79	-0.2	1.13	1.27	0.86
1989	1	0.33	-1.02	0.67	0.93	0.82
1989	2	1.01	0.38	0.77	1.63	1.12
1989	3	0.09	0.59	0.15	1.23	1.38
1989	4	-0.1	0.33	-0.14	0.64	0.94
1989	5	-1.62	-0.9	-0.49	-0.05	0.61
1989	6	-0.14	-0.93	-0.37	-0.44	0.27
1989	7	-1.48	-1.82	-0.78	-0.93	-0.3
1989	8	-1.14	-1.29	-1.53	-1.04	-0.59
1989	9	-0.58	-1.6	-1.71	-1.09	-1
1989	10	0.33	-1	-1.93	-1.23	-1.27
1989	11	-0.38	-0.54	-1.31	-1.69	-1.28
1989	12	1.76	0.93	-0.42	-1.2	-0.74

1990	1	0.4	1.08	0.11	-1.26	-0.71
1990	2	1.79	1.74	1.23	0.33	-0.38
1990	3	1.41	1.67	1.48	0.93	0.08
1990	4	-0.51	1.15	1.24	0.96	-0.08
1990	5	-0.65	-0.03	1.08	0.76	0.15
1990	6	-0.46	-0.87	0.48	0.72	0.09
1990	7	-0.72	-1.08	0.26	0.59	0.25
1990	8	-0.26	-0.73	-0.51	0.67	0.39
1990	9	0.44	-0.27	-0.88	0.25	0.56
1990	10	-0.2	-0.25	-0.97	0.11	0.5
1990	11	-0.51	-0.33	-0.78	-0.67	0.51
1990	12	0.07	-0.53	-0.83	-1.47	-0.1
1991	1	0.36	-0.3	-0.6	-1.36	-0.11
1991	2	0.8	0.46	-0.05	-0.74	-0.6
1991	3	1.12	0.97	0.25	-0.11	-0.76
1991	4	-1.5	0.1	-0.1	-0.4	-1.13
1991	5	0.94	0.32	0.36	0.11	-0.35
1991	6	0.96	0.21	0.65	0.24	0.03
1991	7	-0.59	0.76	0.47	0.24	0.09
1991	8	-0.41	-0.02	0.18	0.28	0.08
1991	9	0.52	-0.23	-0.02	0.42	0.12
1991	10	-2.35	-1.09	0.02	0	-0.1
1991	11	-0.98	-1.18	-0.74	-0.37	-0.16
1991	12	1.08	-0.65	-0.87	-0.54	0.06
1992	1	0.06	0.26	-0.78	-0.01	0.01
1992	2	1.59	1.24	0.32	0.16	0.34
1992	3	0.5	1.08	0.29	-0.04	0.12
1992	4	-0.9	0.48	0.4	-0.18	0.29
1992	5	-0.09	-0.4	0.45	-0.1	-0.22

1992	6	-0.33	-0.7	0.12	-0.21	-0.5
1992	7	0.02	-0.31	0.12	0.14	-0.31
1992	8	1.63	0.59	0.01	0.63	0.16
1992	9	0.35	0.87	-0.03	0.47	0.14
1992	10	0.88	1.66	0.72	0.79	0.69
1992	11	1.15	1.19	1.14	0.56	1.07
1992	12	0.66	1.08	1.56	0.65	1.1
1993	1	1.22	1.15	1.91	1.35	1.26
1993	2	0.8	0.91	1.34	1.66	1.01
1993	3	-0.42	0.55	0.91	1.58	0.79
1993	4	0.95	0.65	0.95	1.73	1.54
1993	5	1.66	1.29	1.29	1.62	2.02
1993	6	-0.24	1.32	1.2	1.32	1.91
1993	7	-0.2	1.02	0.98	1.15	1.79
1993	8	-0.54	-0.51	0.75	0.96	1.3
1993	9	-0.03	-0.44	0.82	0.85	1.1
1993	10	-0.39	-0.91	0.32	0.61	0.92
1993	11	-0.61	-0.82	-0.92	0.29	0.65
1993	12	-1.06	-1.08	-1.33	0.26	0.44
1994	1	-1.27	-1.74	-1.78	-0.44	0.1
1994	2	-0.43	-1.09	-1.52	-1.92	-0.26
1994	3	0.8	-0.06	-0.74	-1.47	0.09
1994	4	-0.03	0.08	-0.48	-1.15	-0.39
1994	5	0.1	0.25	-0.32	-0.74	-1.19
1994	6	1.2	0.39	0.19	-0.28	-0.69
1994	7	1.25	1.06	0.64	0.14	-0.25
1994	8	0.78	1.43	1.01	0.41	0.05
1994	9	-0.99	0.47	0.52	0.33	-0.08
1994	10	-1.08	-1.06	0.28	0.19	-0.2

1994	11	0.16	-1.54	0.27	0.31	-0.12
1994	12	-0.66	-1.04	-0.46	-0.08	-0.19
1995	1	-1.36	-0.92	-1.59	-0.28	-0.2
1995	2	0.39	-0.38	-1.59	-0.25	-0.02
1995	3	0.49	0.11	-0.61	-0.56	-0.14
1995	4	1.35	1.01	0.41	-0.15	0.53
1995	5	-0.74	0.54	0.12	-0.55	0.15
1995	6	0.07	0.39	0.28	-0.2	-0.13
1995	7	-1.07	-1.03	0.17	-0.14	-0.62
1995	8	-1.02	-0.95	-0.14	-0.34	-0.92
1995	9	-0.07	-1.06	-0.31	-0.27	-0.59
1995	10	-0.41	-1.22	-1.49	-0.35	-0.54
1995	11	-1.15	-0.99	-1.35	-0.61	-0.74
1995	12	0.07	-0.83	-1.74	-0.97	-0.86
1996	1	1.42	0.12	-0.99	-1.65	-0.41
1996	2	-0.43	0.27	-0.64	-1.5	-0.67
1996	3	0.39	0.43	-0.27	-1.39	-0.74
1996	4	0.56	0.24	0.16	-0.53	-1.24
1996	5	-0.48	0.11	0.11	-0.38	-1.02
1996	6	2.26	0.88	0.81	0.29	-0.26
1996	7	0.39	0.93	0.66	0.51	0.09
1996	8	1.4	1.86	1.19	0.97	0.56
1996	9	0.62	1.07	1.25	1.14	0.66
1996	10	-1.59	0.3	0.84	0.72	0.59
1996	11	-0.23	-0.71	0.98	0.76	0.69
1996	12	-1.37	-1.75	-0.18	0.58	0.64
1997	1	-1.12	-1.38	-0.67	0.21	0.26
1997	2	-1.05	-1.69	-1.64	0.13	0.16
1997	3	0.07	-0.77	-1.57	-0.89	0.06

1997	4	1.17	0.37	-0.19	-0.22	0.37
1997	5	0.73	0.98	0.15	-0.23	0.74
1997	6	-0.44	0.83	0.24	-0.38	0
1997	7	-0.54	0.02	0.22	-0.17	-0.17
1997	8	-0.65	-0.81	0.32	-0.25	-0.56
1997	9	-1.1	-1.19	0.02	-0.36	-0.8
1997	10	1.86	0.85	0.46	0.52	0.11
1997	11	2.91	2.87	1.64	1.85	1.17
1997	12	-0.32	2.43	1.87	2.08	1.43
1998	1	1.57	2.21	2.51	2.12	1.75
1998	2	1.14	0.91	2.51	2.17	2.35
1998	3	0.98	1.42	2.31	2.55	2.65
1998	4	0.97	1.28	1.96	2.63	2.68
1998	5	1.63	1.7	1.57	2.65	2.68
1998	6	0.86	1.61	1.9	2.53	2.73
1998	7	0.02	1.49	1.7	2.18	2.7
1998	8	0.06	0.39	1.57	1.57	2.61
1998	9	-1.1	-0.56	1.03	1.48	2.31
1998	10	0.86	-0.07	1.1	1.65	2.25
1998	11	-0.27	-0.25	0.08	1.29	1.46
1998	12	-0.79	0.1	-0.55	1.06	1.67
1999	1	0.33	-0.58	-0.63	0.74	1.4
1999	2	-1.36	-0.97	-1	-0.73	0.89
1999	3	-1.18	-1.25	-0.69	-1.51	0.35
1999	4	-0.88	-1.61	-1.43	-1.65	-0.43
1999	5	-0.88	-1.53	-1.66	-1.67	-1.58
1999	6	-0.65	-1.24	-1.63	-1.23	-1.86
1999	7	1.03	-0.39	-1.27	-1.21	-1.43
1999	8	0.34	0.34	-0.9	-1.13	-1.23

1999	9	-2.05	-0.18	-1.09	-1.46	-1.16
1999	10	1.32	0.28	-0.17	-1.11	-1.08
1999	11	-0.3	-0.09	0.14	-0.91	-1.17
1999	12	-0.32	0.56	0.2	-0.91	-1.44
2000	1	-1.36	-1.13	-0.61	-0.84	-1.61
2000	2	-1.36	-1.69	-1.1	-0.86	-1.74
2000	3	-1.77	-2.49	-0.65	-1.16	-1.9
2000	4	-1.15	-2.01	-1.96	-1.86	-2.09
2000	5	0.72	-0.71	-1.21	-1.21	-1.17
2000	6	-0.57	-0.36	-1.25	-0.7	-1.05
2000	7	-1.77	-0.47	-1.53	-1.55	-1.62
2000	8	-0.26	-1.21	-1.34	-1.62	-1.61
2000	9	-1.04	-1.53	-1.2	-1.84	-1.22
2000	10	0.83	-0.25	-0.53	-1.59	-1.59
2000	11	1.08	0.47	-0.55	-0.97	-1.36
2000	12	-0.04	0.78	-0.56	-0.83	-1.67
2001	1	-0.7	0.27	-0.18	-0.56	-1.57
2001	2	0.46	-0.01	0.11	-0.9	-1.23
2001	3	0.35	0.18	0.5	-0.6	-0.78
2001	4	-0.58	-0.08	0.02	-0.26	-0.62
2001	5	1.18	0.47	0.22	0.32	-0.34
2001	6	0.44	0.5	0.4	0.58	-0.07
2001	7	1.23	1.45	0.79	0.66	0.57
2001	8	1.05	1.19	1.03	0.72	0.79
2001	9	0.22	1.09	0.98	0.81	0.92
2001	10	0.52	0.91	1.57	1.1	0.94
2001	11	0.13	0.28	0.98	1.01	0.78
2001	12	0.12	0.2	0.93	1.06	0.92
2002	1	-0.9	-0.38	0.24	1.32	0.88

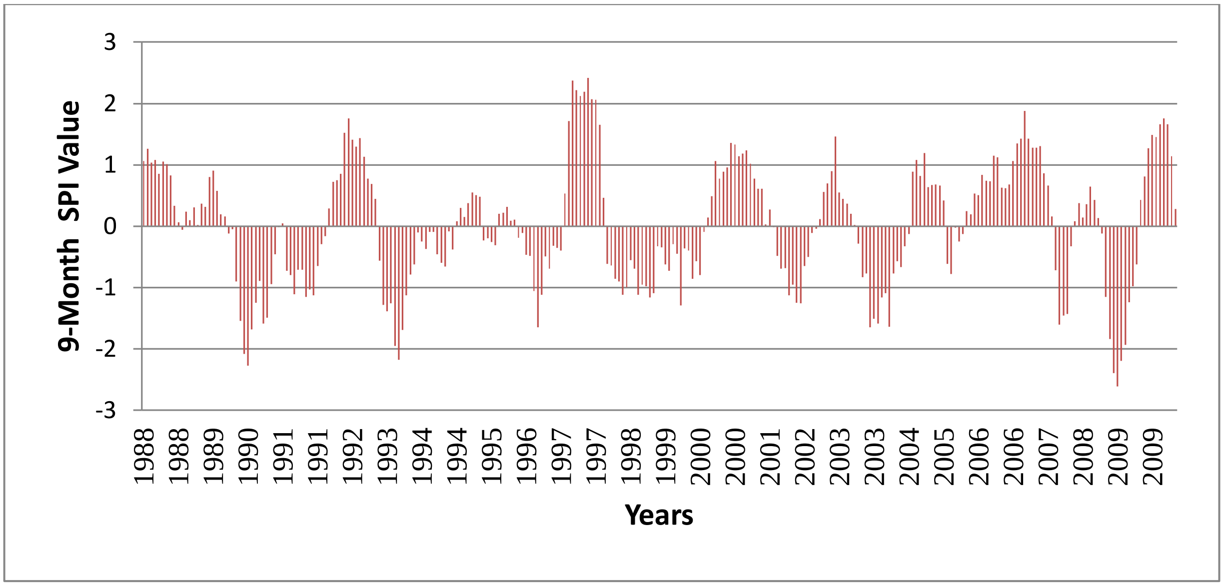
2002	2	-1.01	-0.78	-0.48	0.37	0.61
2002	3	1.41	0.24	0.15	0.79	0.99
2002	4	-0.73	-0.07	-0.26	0.03	0.99
2002	5	-0.49	-0.06	-0.48	-0.39	0.16
2002	6	-1.73	-1.29	-0.85	-0.62	-0.24
2002	7	-0.27	-1.24	-0.81	-0.79	-0.57
2002	8	0.18	-0.79	-0.56	-0.8	-0.7
2002	9	0.31	0.04	-0.98	-0.73	-0.55
2002	10	-0.41	-0.23	-1.07	-0.93	-0.87
2002	11	-1.38	-0.72	-1.07	-0.89	-1.11
2002	12	1.44	0.2	0.03	-1.09	-0.88
2003	1	1.12	0.89	0.4	-0.62	-0.55
2003	2	-0.68	0.83	0.08	-0.64	-0.55
2003	3	-0.04	0	0.01	-0.2	-1.13
2003	4	0.36	-0.13	0.32	0.1	-0.71
2003	5	-1.67	-0.68	-0.04	-0.43	-0.99
2003	6	0.51	-0.41	-0.38	-0.27	-0.44
2003	7	1.03	-0.24	-0.29	0.1	-0.07
2003	8	0.16	0.74	-0.09	0.29	-0.04
2003	9	0.27	0.64	0.02	-0.05	-0.01
2003	10	0.06	0.05	-0.19	-0.31	0.1
2003	11	0.05	-0.06	0.44	-0.17	0.22
2003	12	0.25	-0.09	0.31	-0.19	-0.25
2004	1	1.55	0.57	0.29	-0.01	-0.14
2004	2	-0.08	0.51	0.16	0.58	-0.04
2004	3	-1.08	0.02	-0.16	0.06	-0.29
2004	4	-0.03	-0.54	-0.12	-0.27	-0.48
2004	5	-1.17	-1.12	-0.54	-0.62	-0.33
2004	6	-1.34	-1.12	-0.88	-0.78	-0.68

2004	7	1.32	-0.61	-0.78	-0.41	-0.52
2004	8	-2.33	-0.73	-1.34	-0.83	-0.88
2004	9	1.01	0.4	-0.62	-0.56	-0.53
2004	10	-0.07	-0.6	-0.84	-1.06	-0.63
2004	11	-0.13	0.3	-0.36	-1.08	-0.71
2004	12	0.59	-0.04	0.14	-0.88	-0.83
2005	1	-0.07	0.04	-0.62	-1.03	-1.16
2005	2	-0.58	-0.06	-0.05	-0.73	-1.37
2005	3	0.63	0	-0.15	-0.11	-0.93
2005	4	1.52	0.9	0.61	0.29	-0.14
2005	5	0.81	1.41	0.89	0.88	0.54
2005	6	0.1	1.22	0.87	0.58	0.77
2005	7	-0.22	0.42	0.83	0.62	0.41
2005	8	-1.68	-0.8	0.72	0.46	0.48
2005	9	1.26	-0.03	0.94	0.71	0.51
2005	10	-0.51	-0.4	0.07	0.63	0.49
2005	11	1.21	0.95	0.07	1.05	0.81
2005	12	-0.72	-0.02	-0.21	0.89	0.68
2006	1	-0.58	0.21	-0.34	0.02	0.61
2006	2	0.27	-0.31	0.29	-0.42	0.83
2006	3	0.9	0.41	0.12	-0.11	0.93
2006	4	0.92	0.88	0.66	0.44	0.65
2006	5	-0.42	0.57	0.16	0.49	0.05
2006	6	-0.91	-0.04	0.12	0.01	-0.13
2006	7	1.05	-0.21	0.47	0.39	0.21
2006	8	-0.08	0.08	0.44	0.15	0.46
2006	9	-1.6	-0.24	-0.23	-0.05	-0.1
2006	10	0.7	-0.56	-0.51	0.19	0.21
2006	11	0.35	-0.34	-0.21	0.2	-0.02

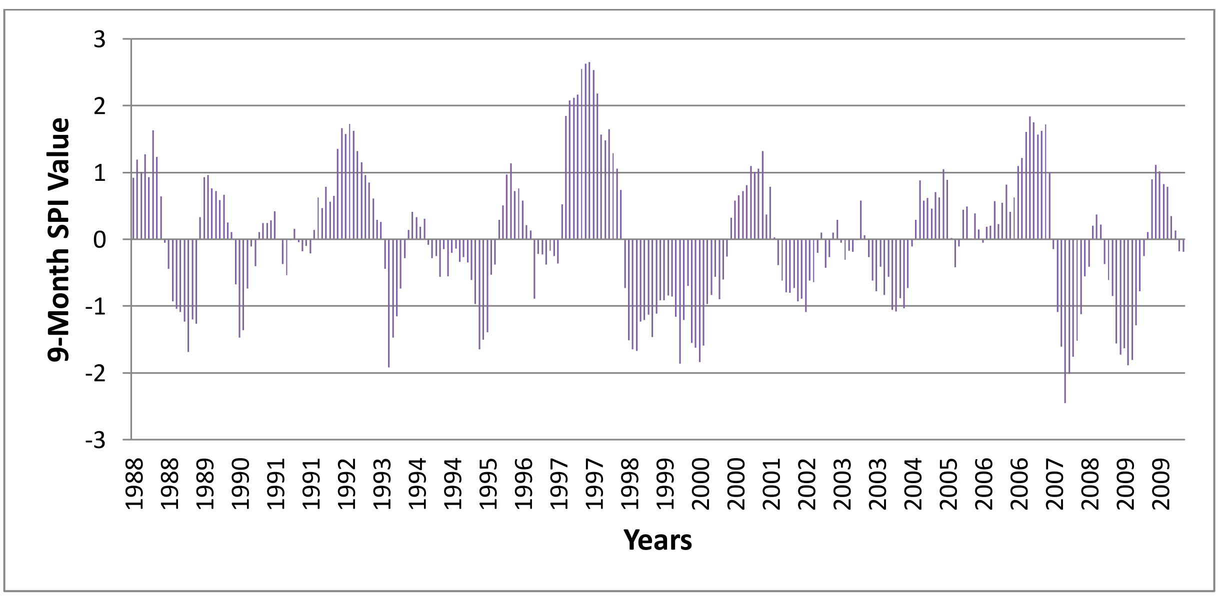
2006	12	1.66	1.22	0.87	0.57	0.62
2007	1	0.5	1.23	0.54	0.23	0.73
2007	2	0.44	1.14	0.63	0.55	0.81
2007	3	0.19	0.36	0.91	0.82	0.61
2007	4	0.01	0.15	0.69	0.41	0.21
2007	5	0.82	0.44	0.88	0.63	0.63
2007	6	1.54	0.93	0.81	1.1	1.14
2007	7	1.16	1.63	1.04	1.22	1.14
2007	8	1.59	1.9	1.45	1.61	1.38
2007	9	2.26	2.47	2.14	1.84	1.93
2007	10	-1.35	1.88	2.23	1.75	1.82
2007	11	-0.66	0.67	1.73	1.57	1.81
2007	12	-1.71	-1.93	1.16	1.62	1.49
2008	1	-0.76	-1.61	0.58	1.72	1.32
2008	2	-1.27	-1.79	-0.46	0.99	1.06
2008	3	-2.51	-2.45	-2.78	-0.15	0.64
2008	4	-1.6	-2.49	-2.48	-1.09	0.15
2008	5	-0.69	-2.12	-2.35	-1.61	-0.5
2008	6	-0.49	-1.41	-2.16	-2.45	-0.99
2008	7	-0.09	-0.81	-1.97	-2.01	-1.24
2008	8	0.69	0.01	-1.49	-1.76	-1.36
2008	9	0.29	0.34	-0.85	-1.52	-1.83
2008	10	1.18	1.39	0.22	-1.12	-1.28
2008	11	1.09	1.36	0.88	-0.55	-0.99
2008	12	-1.37	0.85	0.9	-0.41	-1.27
2009	1	0.22	0.25	0.99	0.2	-1.11
2009	2	-0.34	-0.54	0.51	0.37	-1.03
2009	3	-0.91	-0.65	0.16	0.22	-0.84
2009	4	-1.84	-1.64	-0.98	-0.37	-0.94

2009	5	-0.41	-1.61	-1.52	-0.61	-0.76
2009	6	-1.85	-1.8	-1.76	-0.85	-0.93
2009	7	-1.3	-1.71	-2.16	-1.56	-1.1
2009	8	0.82	-0.94	-1.83	-1.73	-0.96
2009	9	-0.16	-0.33	-1.56	-1.63	-0.9
2009	10	0.18	0.25	-1.08	-1.89	-1.4
2009	11	-0.01	-0.28	-0.9	-1.81	-1.83
2009	12	1.41	0.68	0.2	-1.29	-1.54
2010	1	-0.25	0.72	0.56	-0.78	-1.58
2010	2	0.86	1.02	0.54	-0.25	-1.28
2010	3	-0.27	0.21	0.45	0.11	-1.17
2010	4	1.01	0.75	0.8	0.9	-0.09
2010	5	1.54	1.28	1.34	1.11	0.73
2010	6	0.03	1.34	1.05	1.02	0.99
2010	7	-1.54	0.57	0.8	0.83	0.94
2010	8	-0.93	-1.14	0.43	0.79	0.59
2010	9	-0.35	-1.4	0.4	0.35	0.51
2010	10	-1.01	-1.76	-0.45	0.13	0.36
2010	11	-0.27	-1.29	-1.66	-0.18	0.33
2010	12	0.04	-0.94	-2.12	-0.19	-0.14

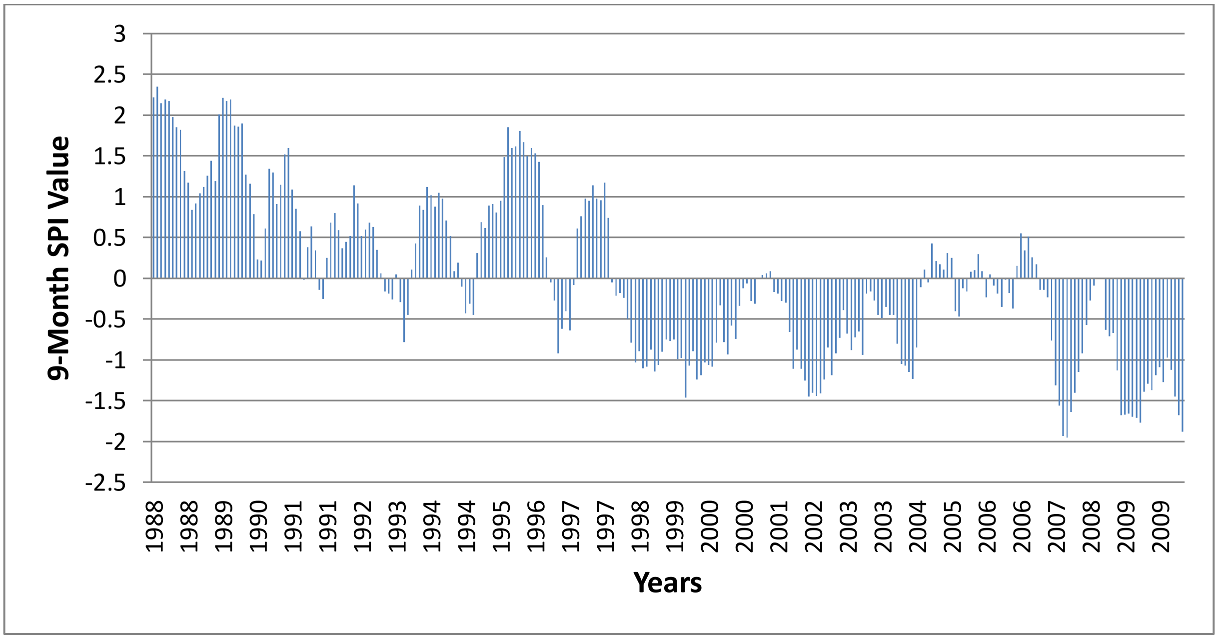
Appendix IV: 9-Month SPI for Five Meteorological Stations



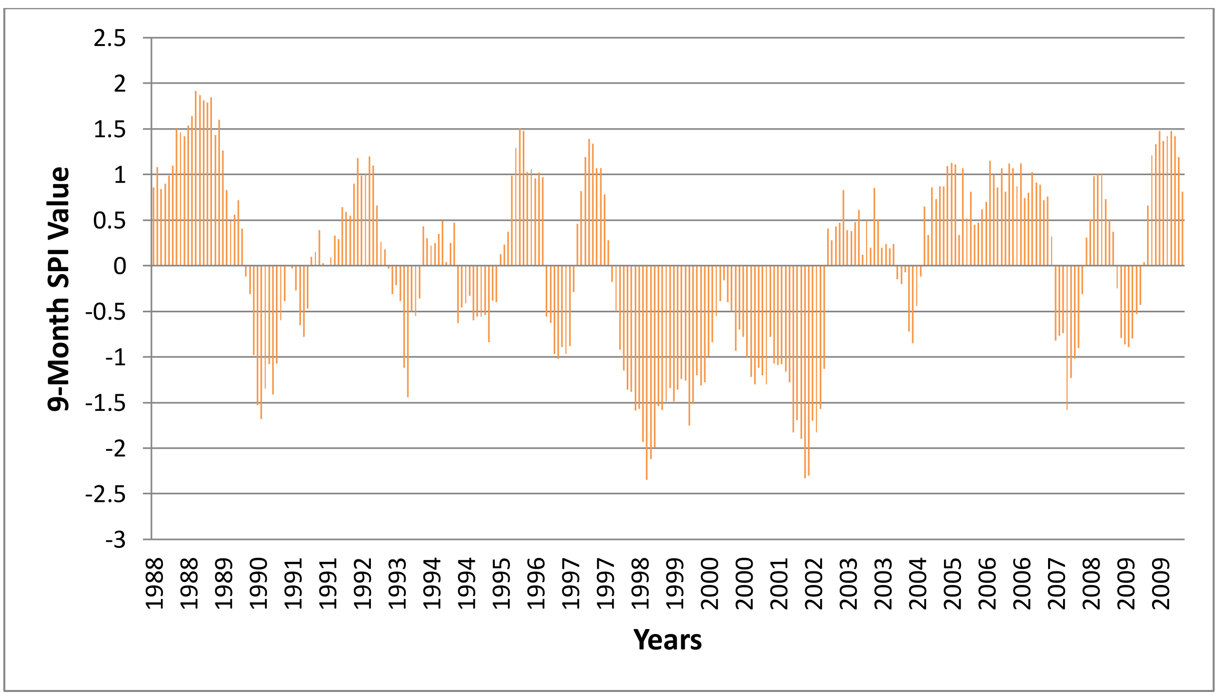
Appendix Figure 8: SPI result on 9-month timescale at Arba Minch station



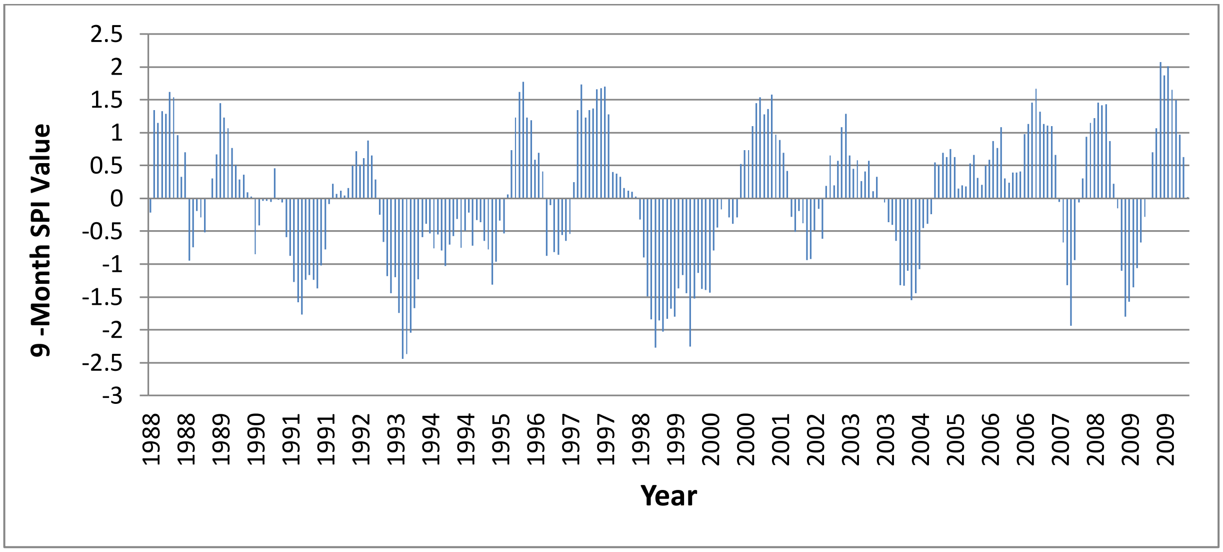
Appendix Figure 9: SPI result on 9-month timescale at Bodity station



Appendix Figure 10: SPI result on 9-month timescale at Morocho station

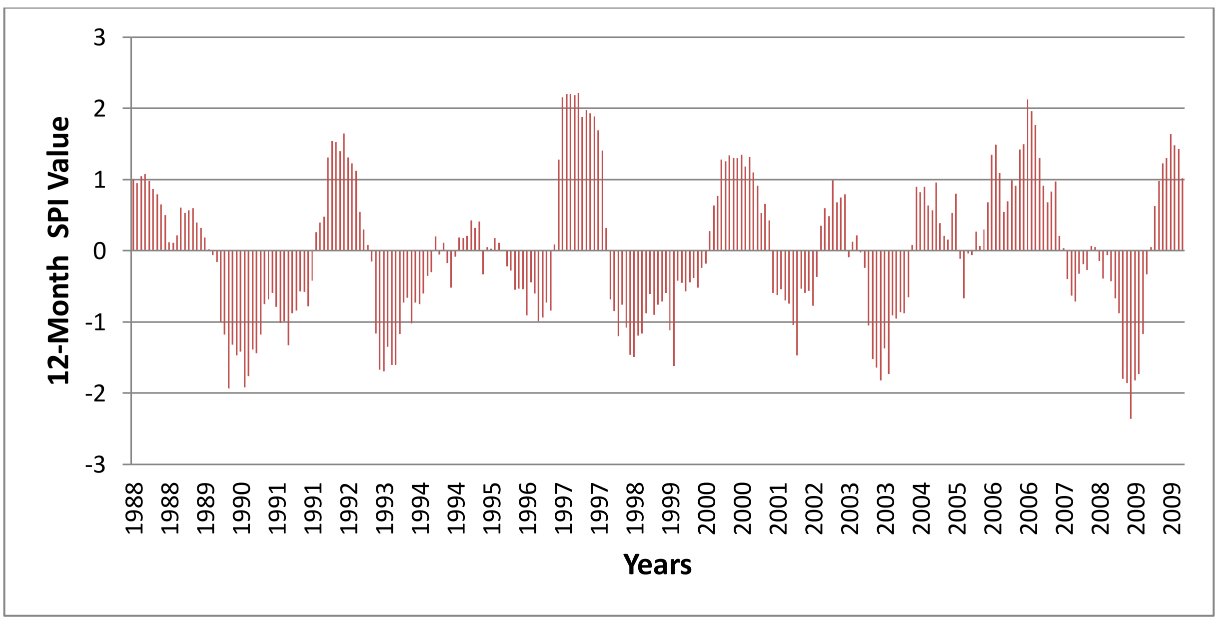


Appendix Figure 11: SPI result on 9-month timescale at Billate station

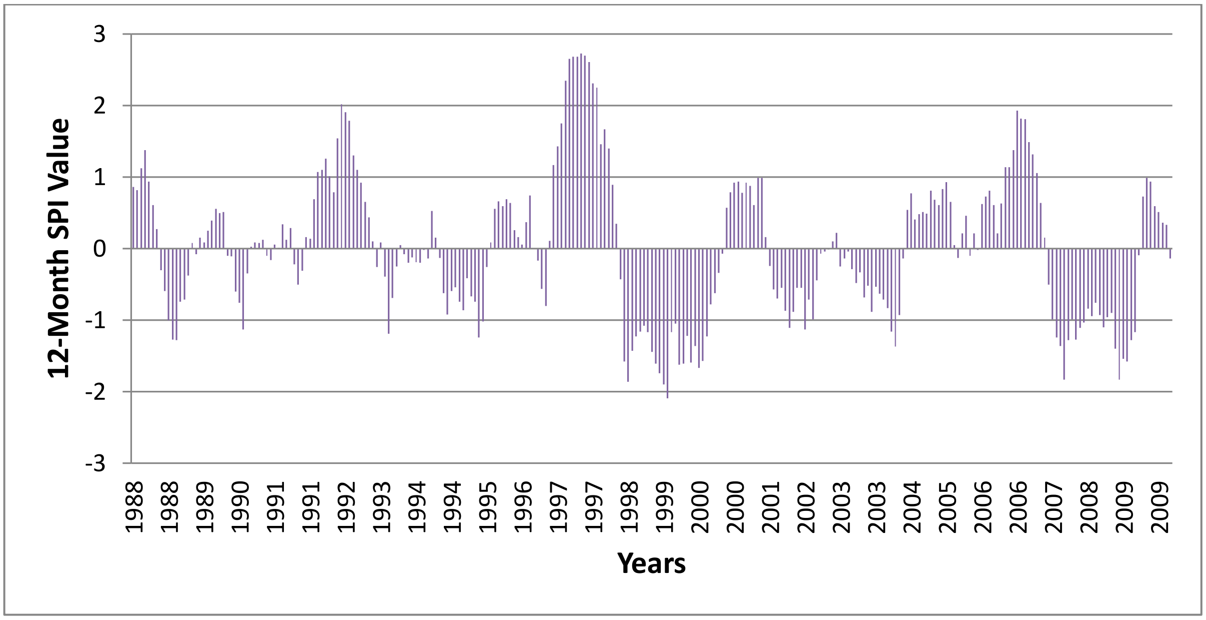


Appendix Figure 12: SPI result on 9-month timescale at Bedessa station

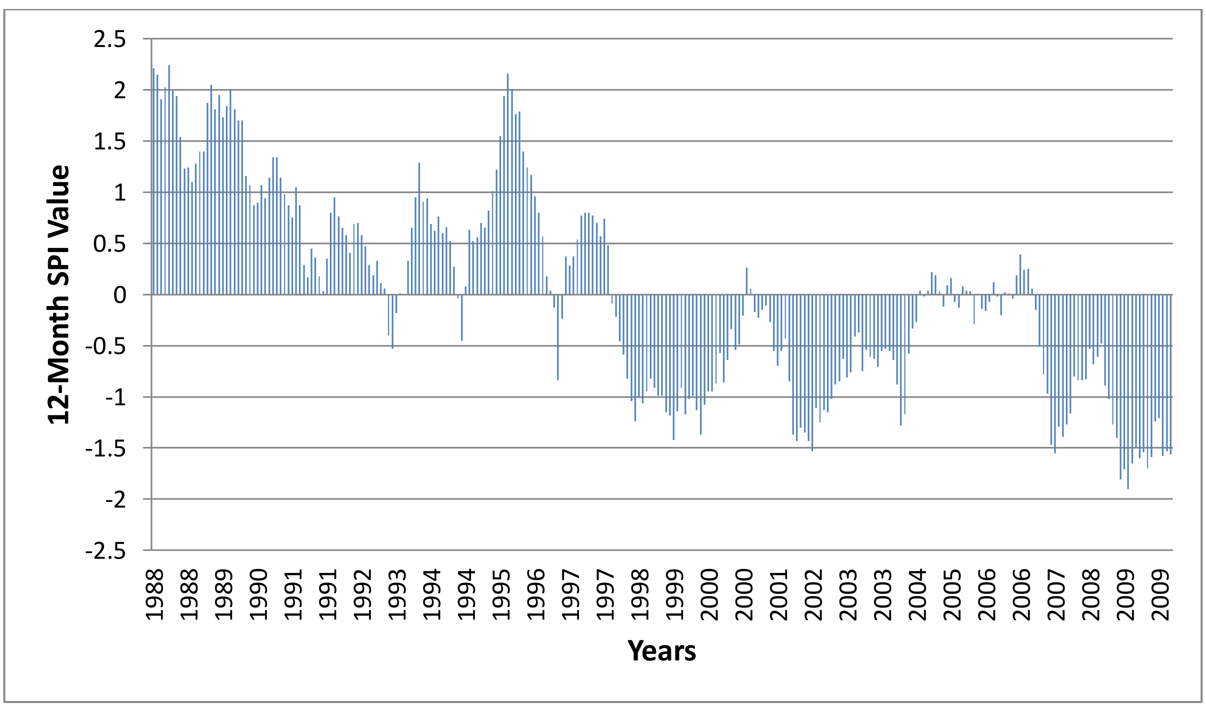
Appendix V: 12-Month SPI for Five Meteorological Stations



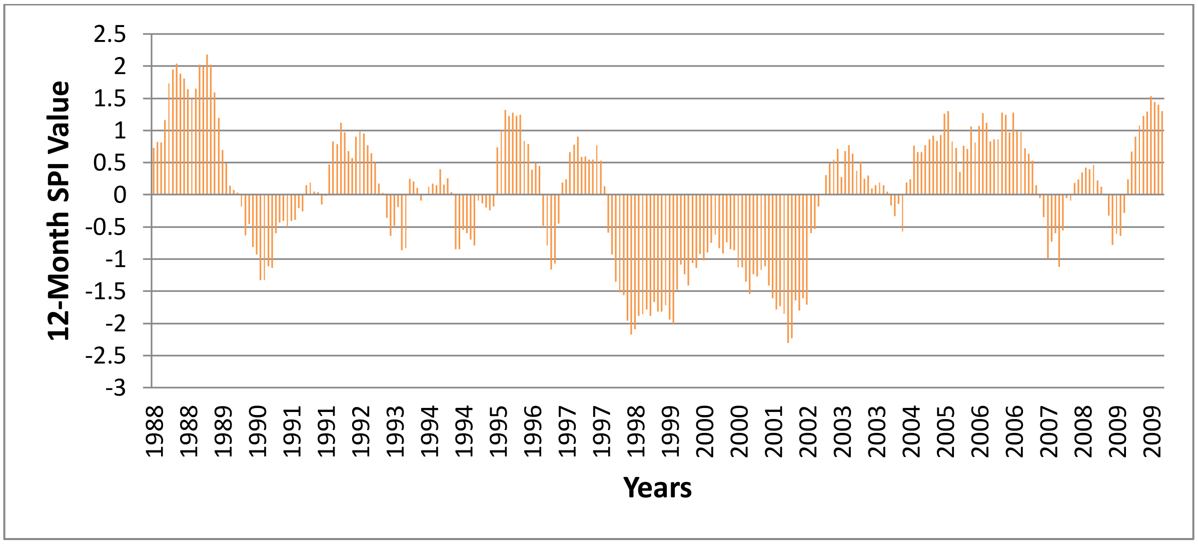
Appendix Figure 13: SPI result on 12-month timescale at Arba Minch station



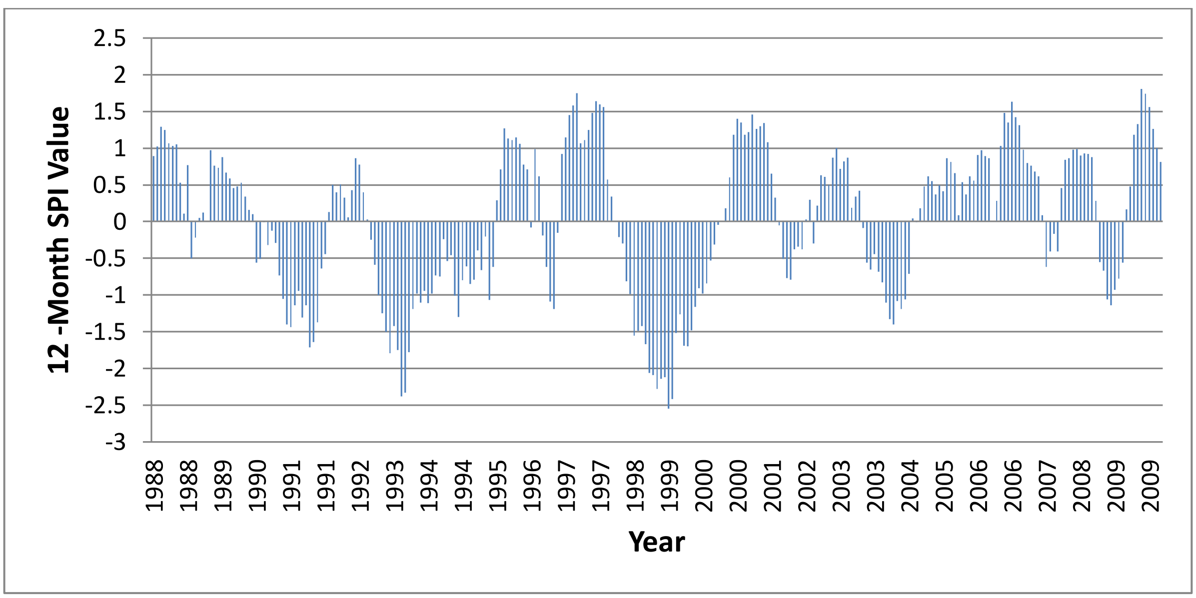
Appendix Figure 14: SPI result on 12-month timescale at Bodity station



Appendix Figure 15: SPI result on 12-month timescale at Morocho station



Appendix Figure 16: SPI result on 12-month timescale at Billate station



Appendix Figure 17: SPI result on 12-month timescale at Bedessa station