Addis Ababa University

School of Graduate Studies

Rainfall Variation and its Effect on Crop Production in Ethiopia

By Seifu Admassu

Advisor

Dr. Ing. Abdulkarim H. Seid

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Abstract

Agricultural production in Ethiopia is predominantly rainfed. Variation of rainfall in space and time affects the agricultural production system in the country. This needs accurate measurement of rainfall and close study of rainfall variation. Therefore, the objective of this thesis work is to study rainfall variability and its impact on crop production in Ethiopia.

For such type of study and other study in the country, accurate rainfall measurement over wide spatial area extent is required. NOAA provides satellite rainfall estimate in Africa since 1995. The comparison of monthly satellite estimate obtained by CPC (Climate Prediction Center) technique with 37 numbers of rain gauges data show significant correlation (R = 0.77) but generally underestimation over the period of 1996-2002. And the root mean squared error (RMSE) is 68mm in average. With better calibration of the CPC method, better estimation would be obtained.

Rainfall variation called trend has been assessed for total annual, Kiremt (June-September) and Belg (February-May) rainfall using 10 selected stations over the period of 1973-2002 in Ethiopia. Trend-free Pre-whitening Mann-Kendall statistical test at the stations show that Belg rainfall totals don't show significant trend while Kiremt rainfall totals on Gore (-7.75mm/year) and Jijiga (-5.87mm/year), Sep-Nov total rainfall on N.Borena (-3.25mm/year) and annual rainfall totals on Gore (-12.2mm/year) and N.Borena (-11.11mm/year) show significant decreasing trend during the period. It is recommended to extend the study on more number of stations to conclude at regional level.

Finally, in the thesis, total annual, Kiremt and Belg areal rainfall are regressed with main cereal production of Teff, Barely, Wheat and Maize on selected study areas over the period of 1994-2001. The result shows no significant correlation between total annual, Kiremt and Belg rainfall, and production of those cereals. This analysis, however, includes small number of sample data and thus doesn't include drought years occurred in the country. In addition, in the analysis, other agronomic factors are ignored. Therefore, large number of sample data and consideration of other factors should be used in future studies.

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1 Introduction

1.1 Background

Ethiopia is a mountainous country located in east Africa situated between 4^o and 15^o N and 32^o and 48^o E. The country has an area of 1,112,000 square kilometers with a total population of more than 67 million (CSA, 2001). The major physiographic features of the country are a massive highland complex of mountains and plateaus divided by the Great Rift Valley and surrounded by lowlands along the periphery. The diversity of the terrain is fundamental to regional variations in climate, natural vegetation, soil composition, and settlement patterns.

The economy of Ethiopia is highly dependent on agriculture, which accounts for around 45 percent of the GDP while industry accounts for 12 percent and services for 43 percent (FAO/WFP, 2002). According to FAO/WFP, 85 percent of the population gains their livelihood directly or indirectly from agricultural production, while in urban areas the bulk of economic activity is in the informal sector.

The agricultural sector is predominantly in the hands of smallholdings, mostly private peasant holdings, with traditional farming, which depend on rainfall. Agricultural production is subjected to wide variation due to variation of rainfall in magnitude and distribution both in space and time. Moreover, the agriculture in Ethiopia is practiced under the condition of diminishing farm size, high soil degradation, inadequate and variable rainfall, imperfect agricultural markets and poor infrastructure, etc (Degefe et al, 1999). As a result, agricultural production in Ethiopia reveals to be very poor and highly susceptible to minor climate change. And these have made the country vulnerable to famine.

Historically, Ethiopia was affected by drought/famine, for example, in 1913/14(Northern Ethiopia), 1920/22, 1932/34, 1953(Tigray and Wolo), 1957/58(Tigray and Wolo) and 1964/66(Tigray and Wolo), 1973/74(Tigray and Wolo) and recently, drought/famine occurred on 1983-1984, 1987-1988 and 1990-92, 1993/94 (Wolde-Georgis, 1997). The impact of 1983/84 droughts in Ethiopia has resulted in a total loss of the annual food production over some areas, while in other areas the loss was as high as 50% of the annual total (NMSA, 1996). And death in the Wolo famine during 1972/3 was estimated as between 50,000 and 100,000 according to UNICEF study[1].

Famine is a shortage of food that occurs when there is war, poverty or change of weather such as drought and flood. Drought, which is a protracted period of deficient precipitation resulting in extensive damage to crops, caused decline in food availability in 1973 and 1984 famine[2] in Ethiopia. However, the 1983/4 drought, which occurred in Africa, India, China, Brazil due to world wide climate variability, caused famine in Africa only especially Ethiopia[3]. These have therefore developed the importance of looking closely to the Ethiopian climate especially rainfall.

The climate of Ethiopia is characterized by high rainfall variation. Such climate conditions have caused major constraints to agricultural development as discussed in the previous paragraphs. Rainfall being an important climatic element, the study of its variation and the consequent impact on agricultural production are paramount importance. Accordingly this thesis work is dedicated to study rainfall variation over Ethiopia and the resulting impact on agricultural production in the country. Particularly, the thesis devotes to characterize trend (gradual change) of annual and seasonal rainfall and tries to discover the extent of relationship between annul and seasonal rainfall, and production in Ethiopia.

Long and uninterrupted rainfall data series are required to interpret such changes and relationship. Moreover, the spatial coverage of the data in the study area should be good. Both magnitude and variation of rainfall could be estimated at a reasonable accuracy using high density of rain gauge. However this would be impractical and uneconomical. Now a days, satellite based estimation of rainfall are used to get area estimation and minimize the gauge density problem. Satellite measurements of rainfall have the ability to access remote areas and are advantageous for measuring spatially averaged rainfall over large areas.

To utilize the advantage of satellite-based estimates, understanding the level of correlation between the satellite estimation and ground-based measurement is important. In addition to the study of rainfall trend and relationship of rainfall with production, the thesis work

[1] From Ethiopian famines 1973-1985: A case study by Gopalakrishna kumer (in DPPC)
[2] From Ethiopian famines 1973-1985: A case study by Gopalakrishna kumer (DPPC)
[3] From drought, famine and the seasons in sub-saharan Africa (DPPC)

devotes some efforts to compare the satellite estimates with that of ground based measured rainfall i.e. rain gauges. The objective is to understand the possibility of using satellite based estimate of rainfall where rain gauge network is less dense and not accessible at all.

1.2 Objective

The general objective of this thesis research work is to study rainfall variability and its impact on crop production in Ethiopia.

The specific objectives of this project are

- Characterize annual and seasonal rainfall trend in Ethiopia
- Study the performance of satellite based rainfall estimation
- Study on the relationships of rainfall variation and production of specific food crop in specific areas of Ethiopia

1.3 Methodology

The performance of satellite rainfall estimation is worked out by comparing it with gauged rainfall data using the technique of simple linear regression analysis. Correlation coefficient and other statistical tests will be used to describe the accuracy of the satellite estimate.

Possible recent changes of total annual and seasonal rainfall are detected and measured using statistical tests. Statistical tests are applied on gauged rainfall data, which are selected based on the length of record period and regional distributions.

Finally, selected crop production on selected area will be regressed to total annual and seasonal rainfall to see the extent of impact of rainfall on crop production.

1.4 Output of the study

This thesis research work finally shows

- Viability using satellite rainfall estimation in place of rain-gauged data where synoptic data is scarce and where estimation for large area coverage is required.

Moreover, it tries to identify the possibility of using satellite estimates in places where gauged data is missing.

- areas where total annual and seasonal rainfall change occurred in recent time in Ethiopia
- the extent of the possible impact of rainfall on crop Production keeping the effect of other factors like agricultural inputs constant.

1.5 Organization of the study

The second chapter describes the climate of Ethiopia and the meteorological mechanism that produce rainfall over Ethiopia. Chapter three is literature review, which mainly discuss about satellite based rainfall estimation, available methods of detecting trend and, situation of production and agriculture in Ethiopia. Presentation of data type and preparation is described in chapter four. Methodology used in the study is described briefly in chapter five and result and discussion of the thesis work is shown in chapter six, finally, conclusion and recommendation are described in the seventeenth chapter.

2 Climate of Ethiopia

2.1 General

Ethiopia is located in the horn of Africa with Djibouti bordering in the east, Sudan in the west, Eritrea in the north and Kenya and Somalia in the south. For administration purpose, the country is divided in to 11 regional states (Fig 2.1), 68 zones and 540 weredas.

The great East Africa Rift Valley, which runs from northeast to southeast across Ethiopia, the mountains and the highlands to the right and the left of this rift valley, the lowlands surrounding these mountainous and highlands in every direction can be described as the country's main topographic features.

The climate of the country is divided in to 11 zones (NMSA, 1996); they principally come under dry climates, tropical rainy climates and temperate rainy climates. The Northeastern and Southeastern part of the country are dominated by the dry climate with mean annual temperature ranging from 27^o to 30^o and the mean annual rainfall is less than 450mm. Usually these part of the country is characterized by strong winds, high temperature and low relative humidity.

The Northwestern, Southwestern and Eastern part of the country where elevation is up to 1750m above sea level, climate is dominated by tropical rainy with mean annual temperature is greater than 18^o and mean annual rainfall is ranging from 680mm to 1200mm. The Central, Southern and Eastern highlands are temperate rainy climate with the mean annual temperature is less than 18^o and the mean annual rainfall is greater than 20*(T+14), where T is the mean annual temperature in ^oC.

The most useful for agricultural purposes is the agroclimatic zones which used the water balance concept, the length of the growing season (including onset dates) at certain probability levels (NMSA, 1996). In this way three distinct zones can be identified namely the area without a significant growing period (N), areas with a single growing period (S) and areas with a double growing period (D) (Fig 2.1).

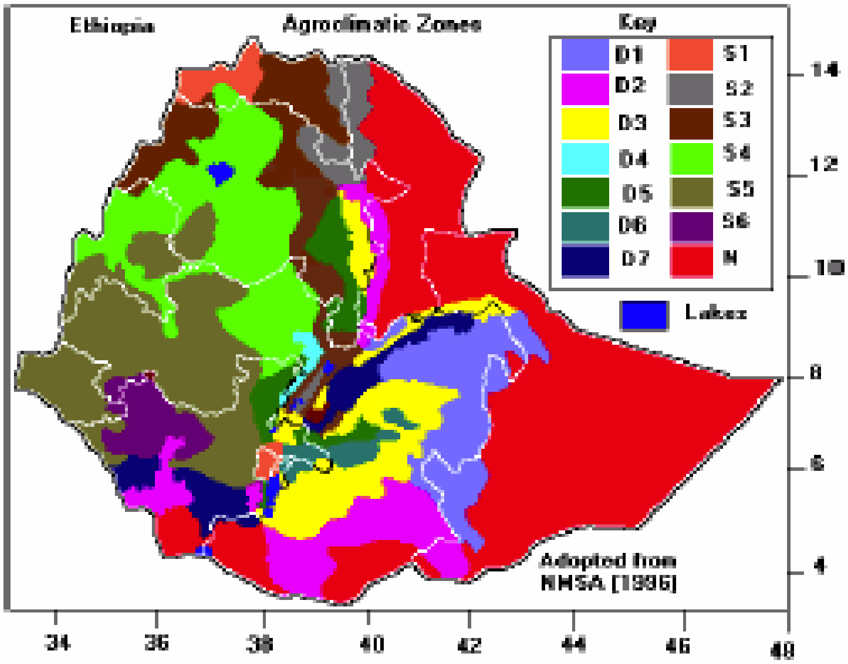

Fig 2-1 Agroclimatic Zones of Ethiopia (NMSA, 1996).

The three major growing periods are classified to 14 broad zones as shown in Fig 2.1. This agroclimatic zoning provides a condensed inventory of the agroclimatic potential and constraints as they are determined by temperature and moisture regimes in a given area (NMSA, 1996).

2.2 Rainfall regimes and Seasons

2.2.1 General

Season is defined as, meteorologically, a period when an air mass characterized by homogeneous weather elements such as temperature, relative humidity, wind, rainfall etc., dominate a region or part of a country (NMSA, 1996).

In Ethiopia, the seasons and rainfall regimes are classified based on mean annual and mean monthly rainfall distribution. There are main three rainfall regimes in Ethiopia (Bekele, 1997). These three rainfall regimes are delineated as:

a. Mono-Modal (Single maxima)

b. Bi-modal type-1 (Quasi-double maxima)

c. Bi-modal type-2 (Double maxima)

As shown in Fig 2.2 below, Mono-modal, Bi-modal type-1 and Bi-modal type-2 are designated by letter B, A and C, respectively.

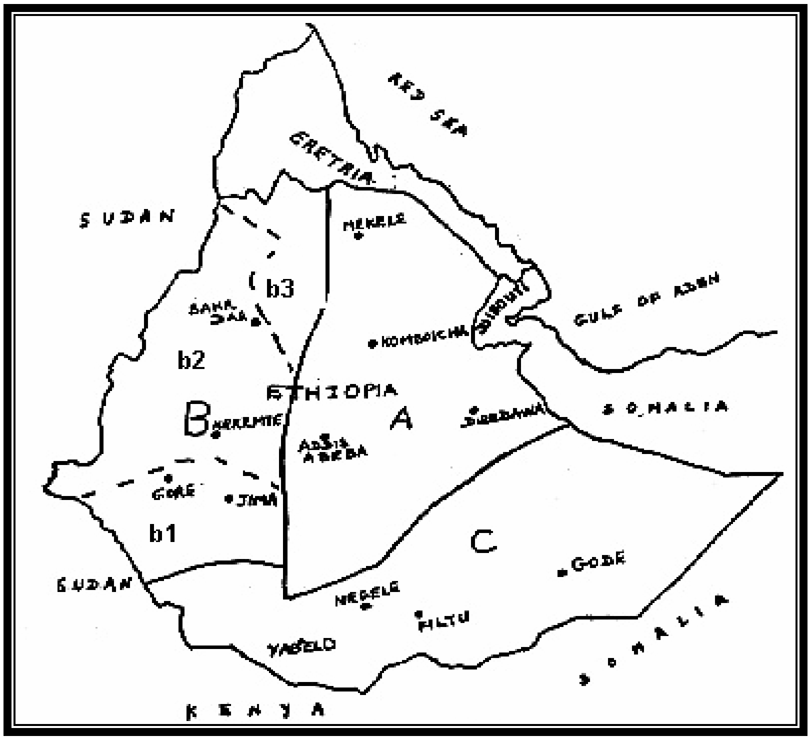

Fig 2-2 Rainfall Regimes of Ethiopia (Bekele. 1997)

2.2.2 Monomodal

The area designated as region B in Fig 2.2 is dominated by single maxima rainfall pattern. However, the wet period decreases northwards from about ten month in the south west to only about four month in the north. Thus region-B is sub-divided into three parts designated as b_1, b_2 and b_3, where the wet period runs from February/March to October/November, April/May to October/November and from June/July to August/September, respectively.

2.2.3 Bi-modal type-1

The area designated as region A is characterized by quasi-double maxima rainfall pattern, with a small peak in April and maximum peak in August.

The central and most of the eastern half of the country is included in this rainfall regime. The two rainy periods are locally known as 'Kiremt' (June to September) and 'Belg' (February to May), which are the long and short rainy periods, respectively. Short 'dry' period, which covers the rest of the year (i.e. October to January), is known as Bega.

2.2.4 Bi-modal type-2

The area identified as region C in the Fig 2.2 is dominated by double maxima rainfall pattern with peak during April and October.

The southern and the southeastern parts of the Ethiopia are included in this rainfall regime. Two rainy periods are from March to May and from September to November. Two dry periods are from June to August and from December to February.

2.3 Weather system affecting Ethiopia

2.3.1 General

The important weather systems that cause rainfall over Ethiopia are Sub Tropical Jet (STZ), Inter Tropical Convergence Zone (ITCZ), Red Sea Convergence Zone (RSCZ), Tropical Easterly Jet (TEJ) and The Somalia Jet (NMSA, 1997).

STZ, ITCZ, RSCZ, TEJ and the Somalia Jet influence region A; ITCZ along with some of those which influence region A cause rain in region B; the ITCZ causes rain in region C. In each of these regions the rainfall amount and its variability is quite different. This is mainly associated with the movement/position of rain causing mechanism with reference to a given region in different seasons and orographic conditions (NMSA, 1997).

2.3.2 Weather System

The weather system that cause rainfall for each season in Ethiopia is well described by National Meteorological Services of Agency (1996) as described below.

During Bega, the country predominantly falls under the influence of warm and cool Northeasterly winds. These dry air masses originate either from the Saharan anticyclone and/or from the ridge of high pressure extending into Arabia from the large high over Central Asia (Siberia).

However very occasionally, Northeasterly winds get interrupted when migratory low pressure system originating in the Mediterranean area move Eastwards and interact with the equatorial/tropical system resulting in the rainfall over parts of Central Ethiopia. In addition to this occasional development of the Red sea convergence zone (RSCZ) affects Costal areas.

During Belg, the season coincides with the domination of the Arabian high as it moves towards the north Arabian Sea. Major systems during the season are the development of thermal low over south Sudan; the generation and propagation of disturbance over the Mediterranean, sometimes coupled with Easterly waves; development of high pressure over the Arabian Sea; some of the interaction between mid-latitude depression and tropical systems accompanied by troughs and the subtropical jet; and occasional development of the RSCZ.

During Kiremt, the airflow is dominated by a zone of convergence in low pressure systems accompanied by the oscillatory Inter Tropical Convergence Zone (ITCZ) extending from West Africa through Ethiopia towards India. Main rain producing systems during the season are Northward migration of ITCZ; development and persistence of the Arabian and the Sudan thermal low along 20^{o}N latitude; development of quasi –permanent high pressure systems over south Atlantic and south Indian ocean; development of tropical Easterly Jet (TEJ) and its persistence; and the generation of low level ‘Somali Jet’ that enhance low level southwesterly flow.

2.3.3 Causes of rainfall change in Ethiopia

Many researchers now believe that the occurrence of various droughts in Africa, especially in southern Africa and the Horn, are caused by physical processes related to the occurrence of El Niño -Southern Oscillation (ENSO) events thousands of miles away, along with sea surface temperature (SST) anomalies in the Southern Atlantic and Indian Oceans combined with anthropogenic activities (Wolde-Georgis, 1997).

Wolde-Georgis (1997) described that El Niño (EN) is the increase in the surface temperatures (SST) in the central and eastern equatorial Pacific Ocean. EN results from changes in the pattern and direction of winds and ocean currents in the region, which have potentially catastrophic effects. There are also changes in atmospheric pressure across the Pacific Basin between Darwin, Australia, and Tahiti called the Southern Oscillation (SO). The SO is the seesaw "in atmospheric mass involving exchanges of air between eastern and western hemispheres . . . with centers of action located over Indonesia and the tropical Southern Pacific Ocean". Thus, El Niño-Southern Oscillation (ENSO) is a coupled air and ocean phenomenon with global weather implications. It is believed that ENSO is often associated with devastating droughts in Northeast Brazil, Australia, parts of Africa, the failure of the Indian monsoons, hurricanes along the east coast of North America, and so forth.

When past ENSO events are compared with drought and famine periods in Ethiopia, they show a remarkable association. Some drought years have coincided with EN events, while others have followed it.

Table 2-1 Chronology of El Niño and Drought/Famine in Ethiopia (Wolde-Georgis, 1997)

El Niño Years	Drought/Famine	Regions
1539-41	1543-1562	Hararghe
1618-19	1618	Northern Ethiopia
1828	1828-29	Shewa
1864	1864-66	Tigray and Gondar
1874	1876-78	Tigray and Afar
1880	1880	Tigray and Gondar
1887-89	1888-1892	Ethiopia
1899-1900	1899-1900	Ethiopia
1911-1912	1913-1914	Northern Ethiopia
1918-19	1920-22	Ethiopia
1930-32	1932-1934	Ethiopia
1953	1953	Tigray and Wollo
1957-1958	1957-1958	Tigray and Wollo
1965	1964-66	Tigray and Wollo
1972-1973	1973-1974	Tigray and Wollo
1982-1983	1983-1984	Ethiopia
1986-87	1987-1988	Ethiopia
1991-92	1990-92	Ethiopia
1993	1993-94	Tigray, Wollo, Addis

Both Wolde-Georgis(1997) and Bekele(1997) described that the principal cause of drought is asserted to be the fluctuation of the global atmospheric circulation, which is triggered by the

SST anomalies occurring during ENSO events. These phenomena have significant impact on the displacement and weakening of the rain-producing mechanisms in Ethiopia. The major rain-producing mechanism in Ethiopia and its vicinity - the ITCZ - was found to be weak, shallow, and shifted southeastward in drought years.

Bekele(1997) described that the classification of El Niño and La Niña (a cool event) events by their timing of occurrence was based on the timing of the significant SST increase (greater than or equal to 0.5 deg C). In the first group, the anomaly increases considerably in the period from January to June, in the second during July to December. Based on this classification and a seasonal rainfall analysis, the following conclusions were made

- A negative SSTA is strongly associated with rainfall deficiency in *Belg*;
- A positive SSTA is mostly associated with normal and above-normal rainfall amounts in *Belg*;
- The Group One type of El Niño is always associated with a severe and widespread meteorological drought in Ethiopia during *Kiremt*. The 1972 and the 1987 El Niño events can be taken as examples;
- The occurrence of Group Two types of El Niño events seems to have relatively less negative effect on *Kiremt* rains, both in its amount and its spatial distribution. The 1982-83 El Niño event can be taken as an example;
- ENSO events may not be the only cause of meteorological drought in Ethiopia. The 1984 and 1985 failure of *Kiremt* in Ethiopia with a warm event of unusual amplitude affected the eastern tropical Atlantic during the relaxation phase of the 1982-83 Pacific ENSO is an example.

In addition, Seleshi et al (2004) described based on correlation and trend analysis of the SST and SOI data that:

- The Ethiopian highland Kiremt rainfall is positively correlated to both the equatorial eastern Pacific sea-level pressure and SOI, and negatively correlated to SST over the tropical eastern Pacific Ocean. Warm SSTs over the South Atlantic Ocean tend to favor enhanced rainfall over the Ethiopian Highlands.

- A cool tropical Indian Ocean has a tendency to be associated with enhanced Kiremt rainfall over the northwest and central Ethiopian highlands and with reduced rainfall conditions over the semi-arid lowlands of northeastern, eastern, southern, and southwestern Ethiopia.

- SSTs over the tropical eastern Pacific Ocean are not significantly correlated with the main rainfall of the semi-arid lowland areas of eastern, southern, southwestern Ethiopia, except at marginal zones in transition to the Ethiopian highlands.

Hence, ENSO information and SSTs of tropical Indian and South Atlantic Ocean are useful in getting information on the cause of rainfall change and meteorological drought and, the investigation of those parameters would help to explain the possible rainfall change in Ethiopia as is done by Seleshi et al (2004).

3 Literature Review

3.1 General

Rainfall is the main source of water that is most vital for human life. It is an essential parameter in hydrology, climatology, agriculture, energy, transportation and recreation. It is also a major factor for planning and management of water resource project and agricultural production. Therefore it is essential to measure rainfall properly to understand the influence of variability on such sectors. Different instruments are used to measure and/or estimate rainfall over a place. These are described as follows:

1. Rain gauges

A rain gauge is a cylindrical funnel with a graduated cylinder used for collecting and measuring rainfall at a point. It is widely used standard measuring device. The measurement is read once every day and this gives a total rainfall over a place during 24 hours of time. The rain gauge has the following advantages and disadvantages (Nurahmed, 1998):

Advantages:

a. It is cheap and easy to maintain and read;

b. Gauge data are available for many years and hence it is possible to do climatologically analysis using long period gauge data; and

c. Comparison between gauge data from different region is possible.

Disadvantages:

a. It measures point data. Thus, even having a high density of gauge network area estimate of rainfall with reasonable accuracy is difficult to achieve. Moreover, it is impractical and not-cost effective to have a dense network that can measure the highly variable spatial distribution of rainfall.

b. Since gauges are read once every day to get real time information they should be located in places where there is easy access for an observer. However, there are remote areas of interest that are difficult to be accessed every day. Therefore, gauge networks can not cover all area of interest to make a real time observation.

c. Source of errors in the reading can easily be occurred due to:

   i. Airflow;
   ii. Unrepresentative orientation and exposure of the gauge;
   iii. Human observation and transmission; and
   iv. Evaporation from within the cylinder; gauge leaks and overflow.

d. Some times there might be time delay in getting the gauge data due to communication problem between the observer and the main center

In addition to the above limitation, the existing meteorological network density of Ethiopia (about 832) doesn't satisfy the World Meteorological Organization (WMO's) recommendations (2399-5428) (Belachew, 2002). Therefore the metrological station network in Ethiopia is sparse by the standards of the WMO's. Thus, the above limitations lead to the use of radar and satellite estimation that augment the rain gauge data.

2. Radar

Radar is used to estimate rainfall over a given area by observing the backscatter of electromagnetic radiation from liquid water drops. Radar has an advantage over rain gauge for providing a spatially continuous image (Nurahmed, 1998).

Advantages of Radar:

a. With Radar real time data acquisition is possible – the data can be viewed every few hours;
b. Radar provides area estimate of rainfall which can not be attained by rain gauge;
c. The estimated rainfall from radar is computerized thus ready for further analysis; and
d. By animating the images it is easy to monitor the development, progress and motion of the rain producing systems.

Disadvantages of Radar:

a. It is expensive and requires sophisticated technical and engineering support;

b. Buildings, nearby weathers, mountains etc. contaminate the radar signal and thereby the rainfall estimate;

c. Low level precipitation may be overlooked by radar signal;

d. Since radar covers a limited area many radar are needed to cover a large area of interest; and

e. Needs calibration with ground measured data

However, satellite is inexpensive, covers more area and also does not require sophisticated technical and engineering support. Therefore, for Africa, use of satellite is more advantageous than radar.

3. Satellite

A Satellite is a spacecraft that orbits the earth and returns images of the earth and the atmosphere back to the receiving station on the ground. Satellites are used to estimate rainfall using radiation signals reflected or emitted from the ground and atmosphere and observed by it. The following are advantages and disadvantages of satellite based area rainfall estimation (Nurahmed, 1998).

Advantages:

a. Real time estimate is possible and once the satellite is in orbit it is inexpensive;

b. Provide a large area coverage;

c. Area estimate is possible; and

d. Animation of the images to observe the development, progress and motion of the weather system is possible.

Disadvantages:

a. Needs calibration with ground measured data;

b. Since the estimates are indirect, contamination (over estimate and/or underestimate) occurs; and

c. Different techniques of rainfall estimations have their own limitations that are to be discussed later.

Since satellite based estimation of rainfall are used to get real time area estimation and minimize the gauge density problem, the use of data from such estimation will be used to understand variation and distribution of rainfall both in space and time. However, the performance of different satellite rainfall estimation method should be checked before using in analysis.

After selecting the best one from the available method of satellite rainfall estimation, the estimation can be used for analysis of rainfall variation and its effect in the agricultural production where rain gauge network is less dense and not accessible at all.

Section 3.2 discuss about basic facts about satellites, methods of satellite based rainfall estimation techniques, their limitation and method of comparison with ground-based estimation of rainfall. Then section 3.3 discuss mainly about Man-Kendall statistical test for rainfall change called trend. And then section 3.4 discuss about agricultural condition and major crops produced in Ethiopia

3.2 Overview of satellite rainfall estimation

3.2.1 Meteorological satellite

Weather satellite is artificial satellite used to gather data on a global basis for improvement of weather information gathering. Information includes cloud cover, storm location, temperature, and heat balance in the earth's atmosphere. They work based on the principle of remote sensing which is the science (and to some extent art) of acquiring information about the earth's surface without actually being in contact with it. This is done by sensing and recording reflected or emitted energy and processing, analyzing, and applying that information.

Satellites have their own path followed by them, which are referred to as orbits. Satellite orbits are matched to the capacity and objective of the sensor(s) they carry. Weather satellites carry passive sensor which measure energy that is naturally available. The sun provides a natural and very convenient source of energy, which is either reflected, as it is for visible wavelengths, or absorbed and then re-emitted, as it is for thermal infrared wavelength. The sensors on the satellite collect detailed information through imaging the target from the electromagnetic waves i.e., visible and thermal infrared.

The first satellite completely dedicated to meteorological purpose was launched on 1 April 1960 and TIROS 1 (Television and Infrared Observational Satellite) was the 22nd successfully launched satellite (Nurahmed, 1998). It was the first satellite that returned an image of the earth with its weather system as a whole. Since then several technological improvements are made and eventually today there are a number of weather satellites.

Two types of satellites are known for the purpose of weather follow up, polar orbiting and geostationary satellites. Polar orbiting satellites are launched into sun-synchronous orbits at an altitude of about 800km (Nurahmed, 1998). The sun-synchronous orbit of the polar orbiting satellite enable them to observe signal at each location with the sun always being in the same place in the sky. The satellite travels northward on one side of the earth and then towards the southern pole on the second half of its orbit.

Polar orbiting satellites have a period of about 100 minutes i.e. they take about 100 minutes to complete an orbit and scan the earth's surface in about 24 hours. The METEOR of the former Soviet Union and the US TIROS are polar orbiting satellites and of which the TIROS (NOAA Series) are the most widely used. They cover each area of the world only once or twice per day. Therefore, images from polar orbiting satellites have low temporal resolution and high spatial resolution.

Geostationary satellites orbit the earth at around 36000km and have a period of 24 hour to complete the orbit (Nurahmed, 1998). Their orbits enable the satellite to remain at the same position in the sky with respect to the ground and watch the same part of the earth with high temporal resolutions. The high temporal resolution of the geostationary satellites enables them to carryout continuous monitoring of the weather. On the other hand, the high orbit of the satellites makes them have low spatial resolutions. There are a number of geostationary satellites dedicated to view particular area of interest in the world.

a. Japanese National Space Development Agency (NASDA) and the Japanese Meteorological Agency launch Geostationary Meteorological Satellite (GMS). It is located at 140^o east. GMS has a spin scan radiometer that provides images of the earth and the atmosphere in visible and infrared wavelength of the electromagnetic spectrum.

b. INSAT is a geostationary satellite launched by India. It is located above 74^o east. It is the first geostationary satellite with no-spinning radiometer; instead their instrument always points towards Earth like those on the low Earth orbiters. The low earth orbiters observe from many angles however, other geostationary satellites observe each point from one angle only. INSAT provides visible and infrared images of the earth and the atmosphere.

c. NOAA launched a series of Geostationary Operational Environmental Satellite (GOES). There are two GOES satellites: GOES-East and GOES-West that are located over 75^o west and 135^o west, respectively.

d. European Space Agency launched METEOSAT. It is located over 0^o latitude and 0^o longitude above the earth surface. Its positions are suitable for watching a continent of Africa. A spin Scan Radiometer is the meteorological instrument on meteosat that enables it to return images of the earth and atmosphere in the Visible (0.4-1.1µm) and Thermal Infra-red (10.5-12.5µm) and Water vapour (5.5-7.1µm). East-west optical scanning is achieved by the rotation of the satellite at the rate of 100rpm, while the north-south optical scanning is done by a scan mirror that moves in 192 µrad steps. Thus, full-disk hemispherical image is obtained from the east-west and north-south optical scanning.

At sub-satellite point the spatial resolution of Meteosat images is 2.5km in the visible channel and 5km in the infrared and water vapour channels. Images of the earth and the atmosphere are taken every half-hour and transmitted to the European Space Operations Centre (Darmstad, Germany). The Centre after registering the images retransmits them back to the satellite and then the satellite again direct the images to Meteosat receivers all over the world.

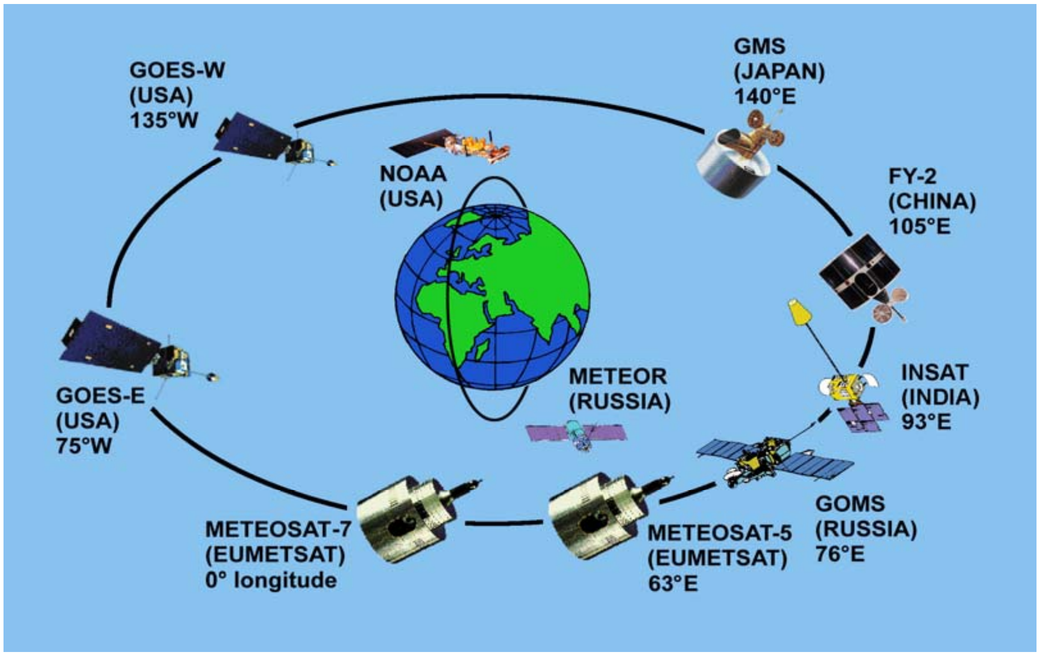

Fig 3-1 Global Satellite Systems

The global satellite system is shown in Fig. 3.1 where METEOR (Russia) and NOAA (USA) are examples of polar orbiting and the others are geostationary satellites.

3.2.2 Rainfall estimation Techniques

The basic method of rainfall estimation is described well by Nurahmed (1998) as described below.

Different methods are available for estimating area rainfall using images of visible (wavelength between 0.4 and 0.7μm) and infrared (wavelength between 10.5 and 12.5μm) electromagnetic radiation from geostationary satellites. The visible channel measures the short wave radiation backscattered by the atmosphere and the earth. This channel gives the albedo of the reflecting body and high brightness implies a highly reflecting cloud. The high cloud brightness in turn is related to the cloud optical thickness and liquid water content. However, this relation is valid only for cloud thickness less than 700m beyond which the relation saturates and there is little change in the cloud albedo. The infrared channel measures thermal radiation emitted by cloud (assumed to be a perfect emitter) and this is related to the temperature of the emitting cloud by the Planck's radiation law. On this approach the height of the cloud is inferred from the temperature of the cloud top that is obtained from satellite infrared observation. Thus, cold cloud is assumed to be deep and rain giving. Therefore, high brightness in the visible channel and low temperature in the infrared channel imply large cloud thickness and high cloud top respectively. These in turn imply greater probability of rain. Therefore, the brightness and / or temperature of precipitating cloud are an indirect measure of rainfall.

Though not yet developed for real time daily operational application there is also a microwave method of rainfall estimation that uses microwave sensors. This technique, unlike the visible and infrared techniques, is a direct way of estimating rainfall.

Several techniques have been developed to estimate rainfall from visible, thermal infrared and microwave radiation images of the satellites. All of the technique use either polar orbiting or geostationary satellite. CPC and TAMSAT are examples of rainfall estimation techniques for Africa that use METEOSAT geostationary satellite.

3.2.3 CPC techniques

The CPC (Climate Prediction Center) technique is a technique developed for estimating rainfall using METEOSAT satellite data, rain gauge data obtained from Global Telecommunication System (GTS), model analysis of wind and relative humidity and orography for the computation of estimates of accumulated rainfall [24]. The rainfall estimate for Africa is derived by the National Oceanic and Atmospheric Administration's (NOAA) Climate prediction Center since 1995.

The CPC technique provides 10-day rainfall estimates throughout Africa at a geographic grid with a 0.1^{o} resolution (Herman, 1997). METEOSAT thermal Infra Red digital data at 5km pixel resolution is accessed every 30 minutes and then reformatted and converted to a geographic grid with a 0.1^{o} resolution. Rain gauge data received every 6 hours via the GTS network are accumulated for each 24 hours and processed for each 10-day period. Rain gauge data are received from approximately 760 stations. And the data are taken to be the true rainfall within 15-km radii of each station.

The first step in the technique is to apply the GOES Precipitation Index (GPI) to all grid squares. GPI is an algorithm developed by Arkin and Meisner [24]. It is developed to estimate accumulated rainfall for ten-day period from convective cloud using cold cloud tops duration over tropical region of a globe (Herman, 1997). In the GPI algorithm, 3mm of precipitation corresponds for each hour that the cloud top temperature is measured to be less than -38^{o}C (235K). In equation form, it can be written as

$$R_{GPI}(mm) = 3 * CCD \qquad [3.1]$$

Where: CCD is cold cloud top duration

A bias adjustment to the GPI estimate is then done empirically using statistical estimation by fitting the GPI estimate to GTS data. This improved GPI algorithm is called CPC technique. However, this estimation still has an over estimation and underestimation biases on cirrus cloud (cloud that is cold but not thick enough to precipitate shown in Fig 3.2) and, orographic precipitation and precipitation from warm clouds respectively. Therefore some modification to the above biases is done using model analysis of wind and relative humidity, and orographic feature. Herman (1997) documented that Precipitation from warm cloud cannot be estimated using a technique such as the GPI algorithm, which relies on the presence of cold convective cloud sources. Over regions in which warm cloud (top temperatures between 275^o-235^{o}K) are present and the low level wind direction is favorable for orographic lifting, the rainfall rate is estimated utilizing a procedure which combines the relative humidity, wind direction and the terrain slope.

3.2.4 TAMSAT technique

The TAMSAT (Tropical Application of Meteorological SATellite) group at the University of Reading developed the technique from the GOES Precipitation Index (GPI) for estimation of Rainfall over Africa. Unlike the CPC techniques, TAMSAT technique is entirely pre-calibrated i.e. it is calibrated against historical rather than contemporaneous gauge data [34].

The TAMSAT rainfall estimation technique uses half-hourly or hourly infrared images from Meteosat satellite. The technique has the following assumptions (Nurahmed, 1998):

a. Convective clouds are the main source of rain;
b. The convective clouds gives out rain if and only if they reached a certain threshold height i.e. if they are deep enough;
c. The threshold height, above which the cloud gives out rain and below which it doesn't, corresponds to certain cloud top temperature and thus it is expressed in terms of the cloud top temperature; and
d. The amount of rainfall over a place is directly proportional to the duration of the convective clouds with the top temperature below the threshold temperature. The duration of time is called Cold Cloud Duration (CCD).

In TAMSAT technique rain gauge values are related to CCD values using the following linear relationship (Nurahmed, 1998):

$$R_{TAM} = a_o + a_1 * CCD \qquad [3.2]$$

$$R_{TAM} = 0 \xrightarrow{when} CCD = 0 \qquad [3.3]$$

Where R_{TAM} is rainfall, CCD is Cold Cloud Duration Value and a_o and a_1 are constants to be determined by comparison of CCD image with rain gauge data.

The values of a_0 and a_1 depend on local climatic conditions and also vary from month to month. Accurate values of a_0 and a_1 are critical in determining reliable rainfall estimates in the TAMSAT approach. Much work is done in determining the values as accurately as possible. Each of the calibration zones has its own monthly value of a_0 and a_1. In this way, differences in rainfall behavior over the continent of Africa and from month to month are described.

Procedures of the Techniques are described by Nurahmed (1998)as:

a. Generate CCD images at different temperature thresholds;
b. Determine an optimum threshold temperature for each calibration zones;

c. Determine calibration parameters a_0 and a_1 for each calibration zone; and then
d. Using the CCD / rainfall relationship formula estimate rainfall

3.2.5 Limitation of CCD products and rainfall estimates

The limitation of CCD products and rainfall estimation techniques is described as follows:

a. The spatial resolution of geostationary satellites is between 5 and 7 km due to the satellite's great distance from the Earth. Individual clouds and rain showers may be much smaller than this. Furthermore, the satellite only `sees' the tops of the cloud, not the rainfall itself. For these reasons the CCD technique cannot hope to pick up the fine detail of rainfall, which may vary over scales as small as 100m.

b. There is significant variation in the threshold temperature from place to place and from month to month. There is also evidence that the threshold for a particular month varies from year to year. This can lead to over-estimation or under-estimation or rainfall estimates. The TAMSAT technique does make some allowances for this variation with the climatic zones, and the monthly calibration values. However, it is likely there is still significant variation within a particular zone. The GPI method of rainfall estimation (used as the first step in the CPC technique) makes no specific allowance for this but does attempt to include rainfall estimates from warmer clouds.

c. The life cycle of a cumulonimbus cloud is shown in Fig 3.2. The CCD image can give a misleading rainfall picture in two cases. Firstly, during the developing stage, the cloud may produce rainfall before the top of the height of the cloud has exceeded the threshold and, secondly when the convective rain-bearing clouds have died down. These are high clouds and are therefore very cold and are composed of ice crystals rather than water droplets. Although they qualify as cold cloud, they do not produce rain.

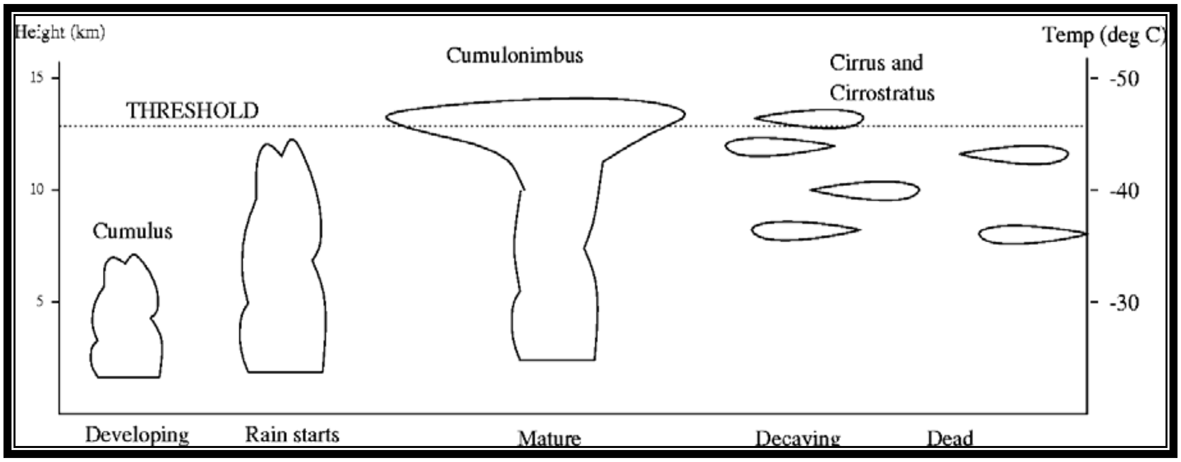

Fig 3-2 The Life Cycle of a Cumulonimbus Cloud

d. The CPC technique makes some attempt to allow for warm cloud rainfall over mountainous regions. However the calibration for this method was made using data from across the whole continent of Africa and only for a short period in 1995. Consequently, it is assumed the rainfall behavior is the same for all mountainous regions in Africa, and at all times during the year. In addition, this does not give good estimates for other types of warm cloud rain such as coastal rain.

e. The relationship between cloud-top temperature and rainfall is only valid for convective rain. Other mesoscale rain systems such as frontal rain have very different cloud structures and rain patterns. This means that in mid-latitudes, CCD images can only give meaningful results when convective systems are identified, e.g. in a summer storm.

Due to the existence of above limitations, rainfall estimated from the above technique should be checked for bias from relatively true estimate of rain fall using gauge stations.

3.2.6 Comparison of satellite rainfall estimate with Gauged rainfall data

Comparison of rainfall estimated from satellite is done usually with rain gauge data because it measures rainfall directly. Comparison is necessary to see the reliability of the technique of rainfall estimation from satellite images and to find evidence (or lack of it) for bias in the satellite estimates.

Rain gauges have the advantage that they measure rain, more or less continuously in time but cover very little of the area. However, satellites don't measure rainfall everywhere in the area at every moment. Therefore direct comparison from the different systems may disagree because of inherent errors in the measurement methods (Bell et al, 2001). Bell et al define this error as error due to sample or sampling error. In addition to the above errors, error can be due to possible algorithmic and instrumental errors in estimating rain rate when rain is observed by satellite. They define this error as retrieval error. Rain gauge also makes errors when measuring rain, depending on the type of apparatus, the environment and the rain itself. They define this error as measurement error.

Bell et al (2002) stated that a bias in the satellite estimate is identified when the difference between the average rain rate measured by satellite and gauge, ΔR, is larger than can be accounted for by the sampling difference of the two systems or by random retrieval and measurements errors. In order to test the presence of bias, it is required to estimate the random error components in the difference, δ^2. The mean squared difference of the averages is a useful measure of the error levels in the difference i.e.

$$\delta^2 = \frac{1}{n}\sum\left(R_s - R_g\right)^2 \qquad [3.4]$$

$$\delta^2 = \delta^2_{samp} + \delta^2_{err,s} + \delta^2_{err,g} \qquad [3.5]$$

Where, R_s is satellite rainfall estimate and R_g is gauge rainfall estimate. Then the true bias will be $\Delta R - \delta$. Because a considerable amount of averaging (large Area and Time) is needed to reduce error variance δ^2 to acceptable levels, the contributions to δ^2 by random retrieval error and measurement error tend to be reduced so that δ^2 dominated by δ^2_{samp}. δ_{sam} is dependent on types of rain , the season , the characteristics of the satellite and its instrument etc (Bell et al, 2001).

Bell et al (2002) stated that there is an optimal averaging time for gauge data when gauge averages are compared to average of satellite rain-rates for a specified area around the gauge in order to reduce comparison error. Their model indicates that for a typical passive microwave instrument bearing satellite providing about 30 visits per month, the optimal averaging area around a single gauge is about that of a 2.5^0 x 2.5^0 box, and time averaging over a substantial part of a year is required to bring sampling error down to the 10% level. The optimal averaging area and time decreases when more gauges are present and as the satellite visit interval becomes shorter. For satellite visits every 3 h (Fig3-3), for example, a single month of averaging might suffice.

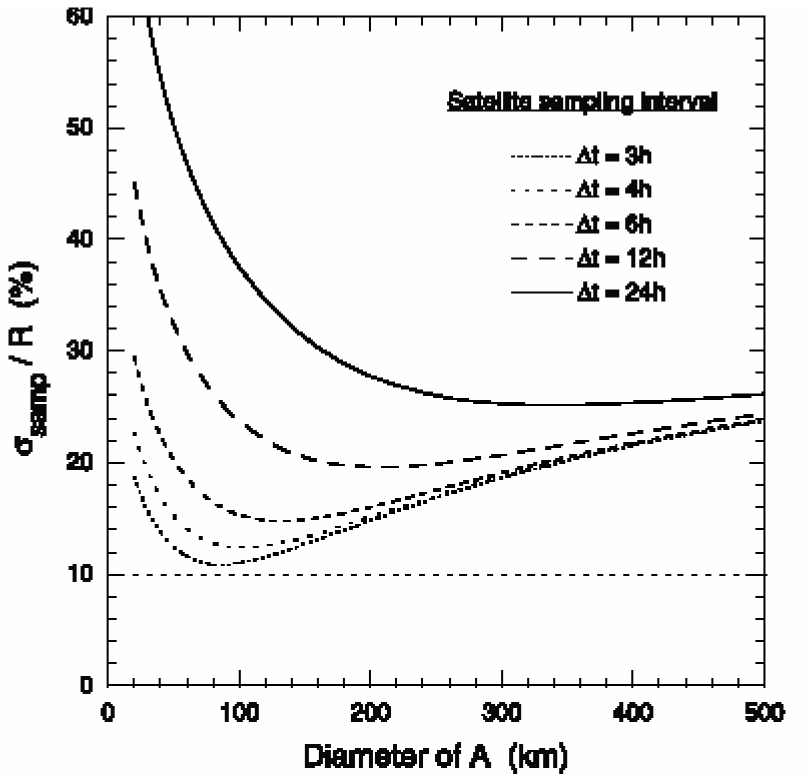

Fig 3-3 Comparison error for Monthly averages (Bell et al, 2002)

Relative sampling error for comparison of monthly averages of data from a single gauge with averages of all satellite estimates during the month for an area A around the gauge is shown in Fig 3.3 by Bell et al (2002). The satellite is assumed to visit at intervals Δt in the figure above. A dashed line indicates error at the 10% level. The figure shows that as the satellite-visiting interval over a single gauge increases the averaging area decreases.

3.3 Overview of Trend Analysis

3.3.1 General

In all region of Ethiopia, the majority of population relies largely on agricultural sector. All food crop production in the country depends on rainfall. Rainfall shows systematic and irregular variation over time. These variations play significant role in adopting farming systems, agricultural planning, crop selection and thus productivity. Characterization of these systematic variations is very helpful in rain-fed agriculture.

Report by FEW's NET on June 21, 2003, for example, showed that rainfall in Ethiopia is becoming increasingly erratic and 'long cycle 'growing region, A and B, shown in Fig 3.4 has experienced a strongly negative rainfall trend since 1972 with adverse consequence for production. It showed that April-September precipitation in the long cycle region reveals a negative trend of 23 mm per year using Collaborative Historical African Rainfall Model (CHARM) data. CHARM combines three sources of information: climatologically aided interpolated (CAI) rainfall grids (monthly/0.5 °), National Centers for Environmental Prediction reanalysis precipitation fields (daily/1.875 °) and orographic enhancement estimates (daily/0.1 °) (Funk et al, 2003).

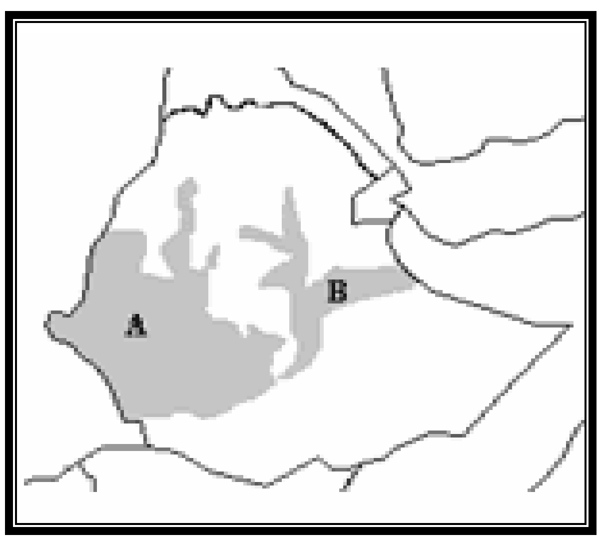

Fig 3-4 Long Cycle Crop Growing Region (FEWs, 2003)

From comparison of the gauge data with the Collaborative Historical African Rainfall Model (CHARM) data with and without its orographic component (i.e., local effect due to mountains) (FEWs, 2003), it was apparent that the orographic enhancement component exaggerated the negative precipitation trends reported in FEW's NET report (June 2003). Hence, the recalculation of precipitation trends in the long cycle region of Ethiopia resulted in -3.1 mm/year.

Detection of such abrupt or gradual changes in hydrologic records is of considerable scientific and practical importance, being fundamental for planning of water resource and related issues. The change in quantity and distribution of annual and seasonal rainfall will directly affect the availability of water and crop production in a region. It is important to know whether there is significant change in rainfall quantity so that this information may be useful for practitioner to improve water resources and agricultural planning.

Analysis of rainfall for agricultural purpose must include information concerning the gradual change (trend), the start, end and length of rainy season, the distribution of rainfall amounts through the year, etc. However, the objective in this thesis work is to identify whether total annual and seasonal rainfall data show significant changes recently in Ethiopia.

3.3.2 Detection of gradual change (Trends)

Trends are one type of systematic changes in rainfall series. Inconsistency (systematic error) and non-homogeneity (changes in nature by humans or by natural disruptive, evolutive or sudden process) are mainly responsible for the over year trends. Long and uninterrupted rainfall data series are required to interpret such changes. These data series could be subjected to statistical techniques to identify significant trend and their slope.

There are parametric and non-parametric test for trends detection (Maidement, 1993). Parametric tests are distribution dependent tests. The power of the tests would be higher if the distributional assumption of data sets is correct. Non-Parametric tests are distribution free tests in which they can be much more powerful than parametric tests if the data distributions depart substantially from the assumed distribution.

One type of parametric test used for assessing the significance of a linear trend is the statistical t-test. The t-test requires a tested series to be normally distributed. If the tested series are not normal, transformation of the data to normal should be implemented before the t-test was applied. The t-statistics for the series with null hypothesis of no trend is give by (Yue et al, 2002(3)):

$$t = \hat{\beta} / s_{\hat{\beta}} \quad [3.6]$$

in which $\hat{\beta}$ and $s_{\hat{\beta}}$ are, respectively, the estimate of slope and its standard deviation.

For sample data without trend, t should fall in the confidence interval

$$\left\{ t_{\frac{\alpha}{2}, n-2}, t_{1-\frac{\alpha}{2}, n-2} \right\}$$

Where: n is total number of data point; α represent the pre-assigned significance level; $t_{\frac{\alpha}{2}, n-2}$ and $t_{1-\frac{\alpha}{2}, n-2}$ are the upper and lower critical values corresponding to the given α for the two-tailed test, respectively.

Two common types of non-parametric tests used for detecting monotonic trend in a time series are Mann-Kendall (MK) and Spearman's rho(SR) test. Yue et al(2002(2)) described that for a given sample data set $\{X_i, i = 1,2,\ldots,n\}$, the null hypothesis H_o of the SR test against trend test is that all the X_i are independent and identically distributed; the alternative hypothesis is that X_i increases or decrease with i, that is, trend exists. The test statistic is given by:

$$D = 1 - \frac{6\sum_{i=1}^{n}\left[R(X_i) - i\right]^2}{n(n^2 - 1)} \quad [3.7]$$

Where: R (X_i) is the rank of i^{th} observation X_i in the sample of size n. Under the null hypothesis, the distribution of D is asymptotically normal with the mean and variance as follows:

$$E(D) = 0$$
$$V(D) = \frac{1}{n-1} \quad [3.8]$$

Using the following standardization,

$$Z_{SR} = \frac{D}{\sqrt{V(D)}} \quad [3.9]$$

The P-value of Z_{SR} can be estimated using the normal CDF

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z} e^{\frac{-r^2}{2}} dt \quad [3.10]$$

For independent sample data without trend the P value should be equal to 0.5. For sample data with a large positive trend the P value should be closer to 1.0, whereas a large negative trend should yield P value closer to 0.0.

Both MK and SR methods are rank based non-parametric tests. However, the MK test has been popularly used to assess the significance of trends in hydrometer-logical time series [39]. The simulation experiments they made have demonstrated that SR test provided results almost identical to those obtained for the MK test. However, the SR test is seldom used in hydro-meteorological trend analysis.

Advantage of the non-parametric statistical test over the parametric test is that the previous are more suitable to non-normally distributed, outlier, censored and missing data, which are frequently encountered in hydrological time series [40]. Moreover, t-test requires transformation of the data to normal if the data is non-normally distributed, which increases the computational procedure.

3.3.3 Mann-Kendall (MK) Test

The method of Mann-Kendall test is well described by Yue et al, 2002 (1) and Yue et al, 2002 (2). According to both articles, it is described below briefly.

MK test is non-parametric test, which tests for a trend in a time series without specifying whether the trend is linear or non-linear. The null hypothesis H_o is that a sample data Y_i, i = 1, 2…n doesn't change as a function of time.

Each value of Y_i, i = 1, 2…n-1 is compared with all subsequent values Y_j, j = i+1, i+2…n and the statistics S of Kendall's tau is defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(Y_j - Y_i\right) \qquad [3.11]$$

Where the Y_j are the sequential data values, n is the length of the data set, and

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & if\theta > 0 \\ 0 & if\theta = 0 \\ -1 & if\theta < 0 \end{cases} \qquad [3.12]$$

Where; $\operatorname{sgn}(\theta) = \operatorname{sgn}\left(Y_j - Y_i\right)$

This statistics represents the number of positive differences minus the number of negative differences for all the difference considered.

Mann and Kendall (Yue et al, 2002(1)) have documented that when n ≥ 8, the statistics S is approximately normally distributed with the mean and the variance as follows:

$$E(S) = 0 \qquad [3.13]$$

$$V(S) = \left[\frac{n(n-1)(2n+5) - \sum_{i=1}^{n} e_i i(i-1)(2i+5)}{18} \right] \qquad [3.14]$$

Where: e_i is the number of ties of extent i.

The standardized test statistics Z is computed by:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\operatorname{var}(S)}} & S < 0 \end{cases} \qquad [3.15]$$

The standardized MK test statistics Z follows the standard normal distribution with mean of zero and variance of one.

The P-value (probability value, p) of the MK statistic S of sample data can be estimated using the normal CDF as

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z} e^{\frac{-r^2}{2}} dt \qquad [3.16]$$

For independent sample data without trend the P value should be equal to 0.5. For sample data with a large positive trend the P value should be closer to 1.0, whereas a large negative trend should yield P value closer to 0.0.

The slope of a trend is estimated using the Theil-Sen approach (Yue et al, 2002(1)), and it is estimated as follows:

$$b = median\left(\frac{Y_j - Y_l}{j - l}\right) \quad \forall l < j \qquad [3.17]$$

Where b is the estimate of the slope of the trend and X_l is the l^{th} observation. The slope determined by the Theil-Sen approach (TSA) is a robust estimate of the magnitude of a trend. The TSA approach has been popularly employed for identifying the slope of trends in hydrological time series (Yue et al, 2002 (1)).

3.3.4 Power of MK test

The power of a test is the probability of correctly rejecting the null hypothesis when it is false. When sampling from a population that represents the case where the null hypothesis is false, the power can be estimated by;

$$power = \frac{N_{rej}}{N} \qquad [3.18]$$

Where: N is the total number of simulation experiments

N_{reg} is the number of experiments that fall in the critical region

Yue et al (2002(2)) conducted Monte Carlo simulation to observe the power of the MK test. The result obtained from the simulation is summarized as follows:

I. For a fixed significance level α, the power of a test is increasing function of the absolute slope

II. For a fixed slope of the trend, increasing the significance level also increase the power

III. The power of the test is an increasing function of both the absolute slope and the sample size

IV. For a fixed slope, the power of a test is a decreasing function of the coefficient of variation of a time series

V. In case of no trend, the power of the test is independent of distribution type of time series. However, in the case some trend exists, the power of the test is dependent on the distribution type

In addition Yue et al (2002(1)) showed that, the MK test requires a time series to be serially independent. The existence of serial correlation in time series will affect the ability of the test to correctly assess the significance of trends. They showed that the existence of positive serial correlation increases the type I error i.e. increase tendency to reject the null hypothesis of no trend while it is true. In contrast negative serial correlation underestimates the probability of detecting trends.

The most common approach to remove the influence of serial correlation is pre-whitening the series (Burn et al, 2002). The pre-whitening is accomplished through:

$$Y_{pi} = Y_{i+1} - rY_i \qquad [3.19]$$

Where: Y_{pi} is the pre-whitened series value

Y_i is original time series

r is estimated serial correlation coefficient

Yue et al, 2002(1) investigated that pre-whitening approach does remove the AR (1) component, but it also removes part of the magnitude (slope) of the trend compared with the true one, and hence leads to an acceptance of the null hypothesis of no trend while the null hypothesis of no trend might be false.

In order to detect a significant trend in a time series with significant serial correlation, a modified pre-whitening procedure, termed Trend –Free Pre-Whitening (TFPW) was proposed by Yue et al (2002(1)):

a. The slope b of a trend in a sample data is estimated by TSA. If the slope is almost equal to zero, then it is not necessary to continue to conduct trend analysis. If it is different from zero, then it is assumed to be linear, and the sample data are detrended by

$$Y_i^{'} = Y_i - T_i = Y_i - bi \qquad [3.20]$$

b. The lag-1 serial correlation coefficient r_1 of the detrended series $Y_i^{'}$ is computed and then the AR (1) is removed from the $Y_i^{'}$ by

$$X_i' = Y_i' - r_1 Y_{i-1}' \qquad [3.21]$$

This pre-whitening procedure after de-trending the series is referred to as the trend-free pre-whitening (TFPW) procedure. The residual series after applying the TFPW procedure should be an independent series.

c. The identified series T_i and the residual $X_i^{'}$ are blended by

$$X_i = X_i' + T_i \qquad [3.22]$$

It is evident that the blended series X_i could preserve the true trend and is no longer influenced by the effects of autocorrelation.

d. The MK test is applied to the blended series to assess the significance of the trend

Yue et al (2002(1)) noted that the above procedure assumes that a hydrological time series can be represented by a linear trend (T_i = bi) and an AR(1) component with noise. They have two reasons for only taking these simplest processes into account. First, much of the existing literature investigating the possibility of change has assumed it to be gradual and monotonic. Second, most of the hydrological time series have relatively weak serial correlation and their stochastic behavior can therefore be approximated by an AR (1) process.

3.4 Over view of crop production in Ethiopia

3.4.1 Agriculture in Ethiopia

Ethiopian's economy is predominantly agrarian and the majority of the population in the country is engaged in agriculture. It is the single biggest employer with 70.4% of the economically active population engaged in the sector (CSA, 1999/2000). Accordingly, it contributes a considerable portion to the Gross Domestic Product (GDP). Agricultural share in GDP is quite high averaging about 53% during 1980/81-1990/91 period and 51.2% during 1991/1992-1997/98 period (Degefe, 1999/2000).

Ethiopian agriculture is predominantly characterized by traditional methods of farming with very little change in farming practice over the past few centuries. The continuous use of such farming practice over a long period of time with little or no soil conservation measures has significantly eroded the fertility of the soil and has made agricultural outputs highly susceptible to minor climate change.

Degefe (1999/2000) explained that effective agricultural production requires the availability and effective utilization of factors of production such as land, labor, capital and knowledge. Considering the per capital arable land availability in the country[4] and the number of people employed in agriculture, lack of land and labor resources couldn't be the main factors explaining the poor performance of Ethiopian agriculture although their inefficient utilization certainly is.

Among the major factors behind the poor performance of Ethiopian agriculture according to Degefe (1999/2000) are diminishing farm size and subsistence farming, soil degradation, inadequate and variable rainfall, tenure insecurity, weak agriculture research base and extension system, lack of financial system, imperfect agriculture markets and poor infrastructure.

Ethiopian farming largely produces only enough food for the peasant holders and their family for consumption, leaving little to sell. Crops are the major production and sources of food in the country since most of the population depends on them for protein and carbohydrates

[4] According to the most recent World Bank development report (1991-2000), Ethiopia has 0.2 hectares per capita while Egypt has 0.05 and Japan has 0.03 with much higher production and productivity than Ethiopia.

(energy) due to high cost of animal products. Therefore, all famines that occurred in Ethiopia were attributed to crop failure. The major problem of crop production in Ethiopia is the low productivity due to lack of integrated disease and insect pests control, heavily dependence on the rain-fed agriculture and shortage of technique for proper conservation and utilization of water for full and supplemental irrigation at critical stage of crops. These severely affect the productivity and production of crops in addition to the factors mentioned in the previous paragraph.

3.4.2 Crops in Ethiopia

The diverse climate of the country and the multiple utilizations of crops have promoted the vast majority of agricultural holders to grow various temporal and permanent crops. Temporary crops are crops that are grown in less than a year's time, sometimes only a few months, with an objective to sow or replant again for additional production following the current harvest (CSA, 2001/2002). Continuously grown crops planted in rotation are also considered temporary crop since each is harvested and destroyed by ploughing in preparation for each successive crop. Cereals, Pulses, oilseeds, vegetables and Root crops are included in temporary crops. Permanent crops are crops that are grown and occupy land for a long period of time, not requiring replanting for several years after each harvest (CSA, 2001/2002). All fruit tress (i.e. orange, mandarins, banana, etc.) and tree crops (i.e. coffee, tea, etc.) are considered permanent crops.

In Ethiopia, the crops have two agricultural seasons that coincide with the two rainy seasons and play a significant role in the performance of rain-fed agriculture, Belg and Meher. Meher season refers to long rainy season, which normally occurs from June to September, while Belg season refers to small rainy season, which normally occurs from February to May (CSA, 2001/2002). The Belg season is very important for the production of Belg crops in Southern Tigrai region; North -West Shoa, Arsi, Bale, East and West Hararghie zones of Oromia region; North Shoa, North and South Wollo zones of Amhara region; and Hadiya, North Omo and Kembata Alaba Tembaro (KAT) zones of SNNPR (Mersha, 1999). Although the contribution of Belg cropping season accounts for 5 to 10 % of the country's overall crop production, it covers from 25 to 60 % of the food need of the area mentioned above (Mersha, 1999).

CSA (2001/2002) reported that, in most cases during Belg period, long maturing crops are planted and their harvest can extend to December or January. And, short maturing crops are planted during Belg period and harvested in June or July. Belg seasons crops were defined as any crops that are harvested during the months of March to August, while those crops that are harvested during September to February are considered as main (Meher) season crops (CSA. 2001/2002). The Meher season contributes 90-95 % to the national crop production. All part of Ethiopia except southern and southeastern parts of the country is influenced by the Meher season. Fig 3.5 shows the period of sowing and harvest for cereals crops in Ethiopia.

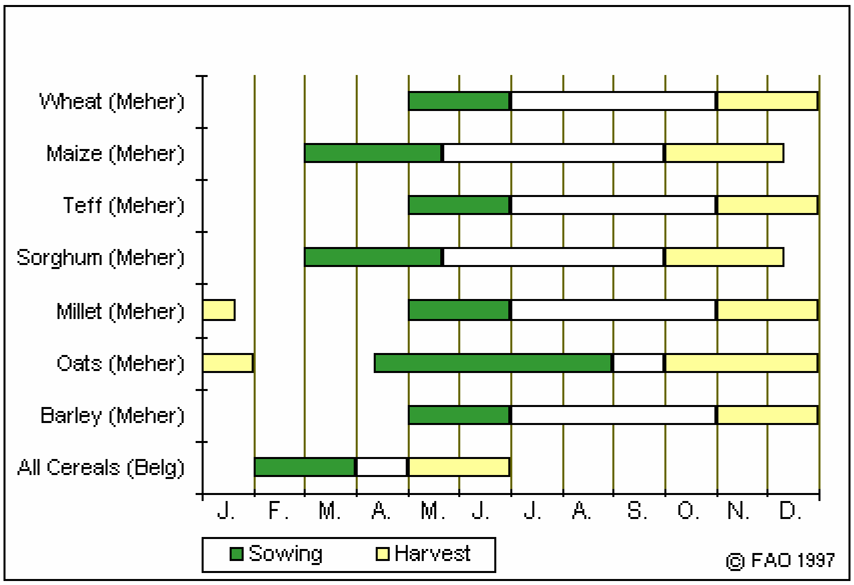

Fig 3-5 Crop Calendar of Ethiopia (FAO)

In the Ethiopian agricultural systems, cereals are the most extensively grown crops in terms of the magnitude of the area under crops and volumes crop production. About 80% of the country's crops area and 77% of the crop production are contributed by cereals (CSA. 2001/2002). In the cereal category Teff, maize, Sorghum, wheat and Barely are the main food crops in the country.

CSA (2001/2002) reported that about 23% of the country's land under crops was planted to Teff and 14% of the crop production was attributed to this crop with an average yield of about nine quintals per hectare. Maize was grown on 17% of the crop land and contributing about one quarter of the cereal crop production with an average yield of 25 quintals per hectare, which is the highest yield of all cereal crops in the country. Moreover, sorghum (the third principal crop), wheat, and barely were grown on 14%, 13% and 10% of crop land and contributing about 14%, 13% and 8% of the total crop production, respectively.

All crops in the cereal category are planted in all the regions. Tigray region contribution to the country in terms of area and production is summed up at about seven percent each. Because of a high population density and low rainfall, Tigray is traditionally a food deficient region (FAO/WFP, 2002).

In the ten zones of Amhara , two, North wollo and Weghamra, are less favorably situated, with lower rainfall, thin soils and sloping topography; therefore, yields at some 25-30% of the main production zones of Awi, West Gojam and East Gojam are normally expected. The remaining five zones generally produce harvests somewhere between the two extremes. Generally, Amhara region contribution to the country's total in terms of area and production of cereals is about 35% and 31% (FAO/WFP, 2002), respectively.

Oromia region contributes to the country about 46% and 51% of country's total area and production of Cereals, respectively. The most productive zones in the region are the zones of Arsi, West Shoa and East Shoa, which regularly produce 50% of the regional and 25% of the national cereal harvests (FAO/WFP, 2002).

Benishangul-Gumuz region (2% area and 2% production), SNNPR (9% area and 8% production of cereals) and Afar (0.13% area and 0.09% production) contribute to the country. Afar region is an arid area with very little rain fed crop production potential (FAO/WFP, 2002).

3.4.3 Major crops and their response to water stress

Major crops in Ethiopia in terms of area of land coverage and contribution to the country's production are Teff, Maize, Sorghum, Wheat and Barely. They are produced using rainfall as source of water supply. Defining the crop water requirement during its various stages of growth and development in terms of potential evapo-transpiration and comparing these requirements with the water available at the time can obtain the effect of rainfall on the crops.

When water supply (i.e. rainfall) doesn't meet crop water requirement, crops vary in their response to water deficient. In some crops there is an increase in water utilization efficiency (amount of harvested yield produced by the crop per unit of water evapo-transpired) whereas for other crops it decreases with increase in water deficient (Doorenobs, 1979).

When water deficiency occurs during a particular part of the total growing period of a crop, the yield response to water deficient can vary greatly depending on how sensitive the crop is at that growing period. In general, crops are more sensitive to water deficient during emergence, flowering and early yield formation than they are during early (vegetative, after establishment) and late growing periods (ripening) (Doorenobs, 1979).

However, the response of yield to water cannot be considered in isolation from all other agronomic factors, such as fertilizers, plant density and crop protection, because these factors also determine the extent to which actual yield approaches maximum yield (Doorenobs, 1979).

In the following paragraph, it is tried to discuss major crops growing period, water requirement and water stress condition in Ethiopia based on documents of Ethiopian Agricultural Research Organization (EARO) and FAO Irrigation and Drainage papers (Doorenobs, 1979).

1. Teff

Teff is used only in Ethiopia as a staple food although its presence as a cultivated forage grass or a naturally occurring grass is reported in Kenya, Uganda and Pakistan. It is cereal grain with high nutrient content particularly protein (11%) which is higher than in any other cereals found in the country. The grain is also rich in minerals such as iron, Potassium, calcium and phosphorous. The great advantage of the grain is that it can be stored for many years in the traditional storehouse for many years without being damaged by insects and that represents a very suitable safe guard against famine.

The plant performs better at altitudes of 1700 to 2400m and in areas where the rainfall reaches an annual average of 1000mm during the growing period. In addition, for better productivity, sowing can take place from the second weak of July to the third weak of July for light soil and it is more advisable to sow later generally during the last two weeks of the month of July, even though the time of sowing varies according to the type of soil and the appearance of the big rains. IAR also recommend that the growth period is 107 to 120 days from the time of germination.

Once well established, it is a very drought resistant plant capable of maturing a crop on very little rain. The crop coefficient relating water requirement to reference evapo-transpiration during its growing period in Abbay basin is:

Table 3-1 Crop coefficient of Tef during its Growing Period in Abbay Basin

Month	June	July	August	September
K_c	0.3	0.7	1.1	0.7

2. Wheat

Wheat is an important crop in the highland of Ethiopia. It is very sensitive to drought and it is recommended to avoid growing in dry areas. Wheat production is affected by factors mentioned for barely.

The most suitable areas for wheat production are those with an average annual rainfall of 1200mm with 600mm well distributed during the growth period. For high yield water requirements are 450 to 650 mm depending on climate and length of growing period. The crop coefficient (K_c) relating water requirement to reference evapo-transpiration in Abbay basin is:

Table 3-2 Crop coefficient of Wheat during its Growing period in Abbay Basin

Month	June	July	August	Sep	October
K_c	0.8	1.1	1.1	1.05	0.25

For better yield, sowing time is the end of June or the early days of July. And the growing period for different verities are 115-135 days.

Growing stages of Wheat according to FAO are classified as establishment (10-15 days), vegetative (10-30 days), flowering (15-20 days), yield formation (30-35 days) and ripening

(10-15 days) (Doorenobs, 1979). Slight water deficient in the vegetative period may have little effect on crop development or may even somewhat hasten maturation. The flowering period is most sensitive to water deficient. Water deficient during the yield formation period results in reduced grain weight and, during the ripening period has a slight effect on yield.

3. Barely

Barely is a crop very well known in Ethiopia since ancient times. It is mainly a highland crop found at altitudes ranging from 2000 to 3000m above sea level in the country. The actual type of production is characterized by low productivity of the crop. An average of 8-10 quintal per hectare is the yield most commonly obtained by the farmers. The factors influencing barely production have been investigated over many years and are being identified. They can be summarized as follows:

- Lack of proper management, recommended techniques and care within the actual peasants, farming system
- Poor quality planting materials, and to a lesser extent frost, water logging, diseases and pests affects the yield of the crop in many areas of the country

The plant gives the best results in areas where an annual average rainfall of 1000 to 2000mm with 650 to 700mm well distributed during the main growth per period. In addition, for better yield, sowing should take place soon after the big rains have started which is usually during June or the early days of July. And most varieties mature in 4 to 5 months of time.

Barely will tolerate wide variation in rainfall, and has a lower water demand per unit of dry matter (518) while wheat needs 542-557, 304 for sorghum and 350 for maize. The crop factor (K_c) relating water requirement to reference evapo-transpiration (ET_o) in Abbay Basin during their growing period is:

Table 3-3 Crop coefficient of Barely during its Growing Period in Abbay Basin

Month	June	July	August	September	October
K_c	0.82	1.1	1.1	0.45	0.25

4. Maize

Maize is an introduced crop to Ethiopia and it has been expanding widely in the recent years because of the very favorable conditions found in large areas of the country. Successfully, it can be grown in a wide range of altitude ranging from lowland areas below 1000m up to 1800m above sea level. And it can be grown preferably in areas where the annual rainfall reaches an average of 800mm equally distributed over the whole growing period.

A major conclusion of research findings from many experiments in EARO concluded on maize during a number of years in Ethiopia is that yield is generally influenced more by the date of sowing than any other factor. Sowing should take place the first two weeks of May or as early as possible at the onset of the big rains. In addition, the growth period is 4 to 5 months even if it depends on the variety planted.

For maximum production a medium maturity grain crop requires between 500 and 800 mm of water. The crop factor (K_c) relating water requirement to reference evapo-transpiration (ET_o) in Abbay Basin during their growing period is:

Table 3-4 Crop coefficient of Maize during its Growing Period in Abbay Basin

Month	May	June	July	August	September	October
K_c	0.4	0.65	0.85	1.1	0.8	0.3

Growing stages of grain maize according to FAO are classified as establishment (15-25 days), vegetative (25-40 days), flowering (15-20 days), yield formation (35-45 days) and ripening (10-15) [16]. Maize appears relatively tolerant to water shortage during the vegetative and ripening periods. Greatest decrease in grain yields is caused by water deficient during the flowering period. Water deficient during the yield formation period may also lead to reduced yield due to a reduction in grain size. However, water deficient during ripening period has little effect on grain yield.

4 Data collection and preparation

4.1 Gauged rainfall data

From currently available meteorological stations about 832 in numbers (Belchew, 2002), for the purpose of this thesis work, 51 rain gauge stations have been selected and monthly rainfall has been collected from the NMSA. Their spatial coverage in the country is distributed as shown in Fig 4.1; Detail information of the stations is given in Appendix- A.

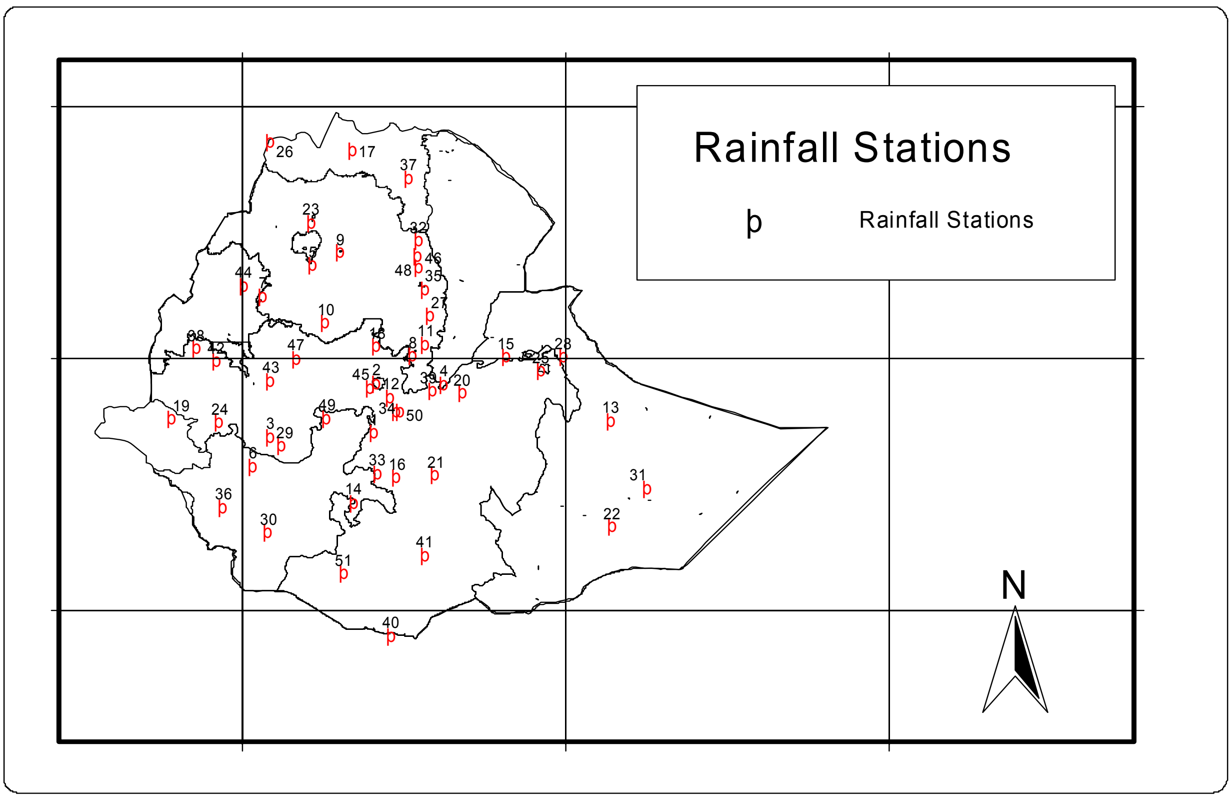

Fig 4-1 Gauged Stations Collected from NMSA

For comparison of satellite estimate with the gauge data, stations having continuous record for the period of 1996-2002 are used. The period is used for the simple reason that satellite estimates are available in this time period. Stations used for this objective are shown in Fig 4.2.

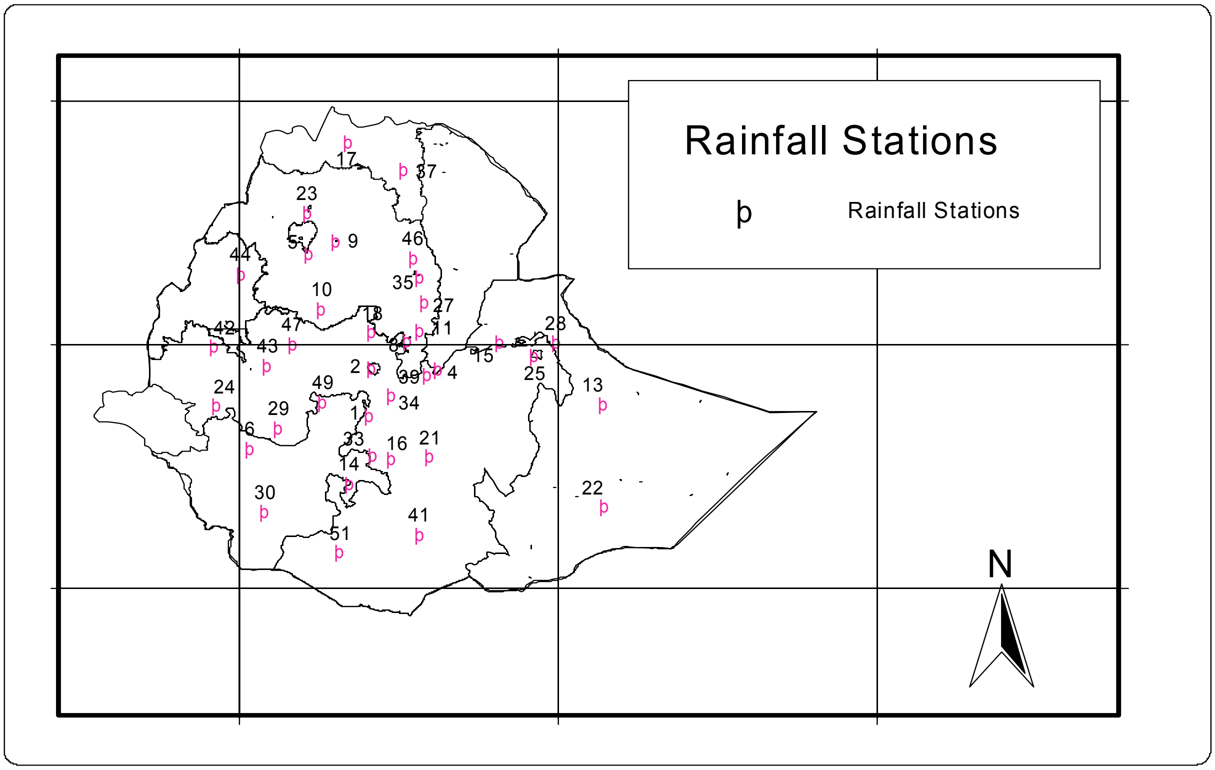

Fig 4-2 Gauge Stations Used in the Comparison of Satellite Estimate with Gauged Data

For the study of rainfall variation (trend detection) in annual and seasonal basis in recent years in Ethiopia, 10 stations are selected and used in the analysis which are shown on Fig.4.3, which have less number of missing data and which have continuous record compared to the other station. The record period 1973-2002 are taken as the common period where statistical test is applied to detect and measure trend. This 30 year period is selected to see change of rainfall variation recently in the country.

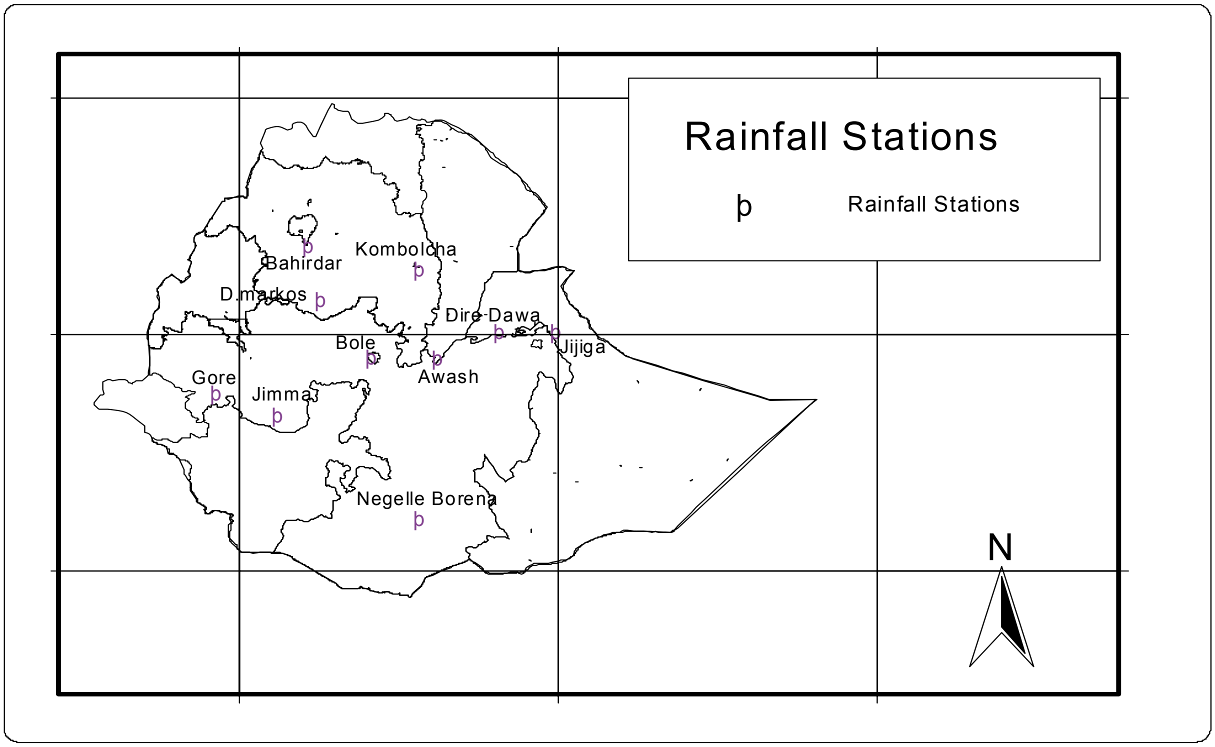

Fig 4-3 Gauged Stations Used in Trend Detection

4.2 Satellite rainfall data

NOAA produced two data sets from satellite, the old version Rainfall Estimate 1.0 (RFE 1.0) and new version Rainfall Estimate 2.0 (RFE 2.0). The old version rainfall estimation was operational from 1995 through 2000. RFE 1.0 used an interpolation method to combine METEOSAT and Global Telecommunication System (GTS) data, and included warm cloud information for the decadal estimates as described in section 3.2.3.

As of January 1, 2001, new version of rainfall estimation has been implemented by NOAA's climate prediction center. The new version rainfall estimation RFE 2.0 uses additional two new satellites rainfall estimation instruments called Special Sensor Microwave/Imager (SSM/I) on board Defense Meteorological Satellite Program satellites, and the Advanced Microwave Sounding Unit (AMSU) on board NOAA satellites, while continuing the use of cold cloud duration and station rainfall data. SSM/I rainfall estimates are acquired at 6-hr intervals while AMSU rainfall estimates are available every 12 hours. RFE 2.0 obtains the final daily rainfall estimation using a two part merging process, then sums daily totals to produce decadal estimates. All satellite data are first combined using the maximum likelihood estimation method, and then GTS station data are used to remove bias.

A 10-day rainfall estimate is prepared operationally at the Climate Prediction Center for the USAID/FEWS Program. Cold cloud duration, computed bias, and the resulting rainfall estimates (prepared with and without the dot product/relative humidity analysis) are stored as grid files in eight bit integer words, for both compactness and compatibility with personal computers (Herman, 1997).

Precipitation estimates are produced on the 1st, 11th, and 21st day of each month (Herman, 1997). It is available on ADDS's (African Data Dissemination Service) server with two type's format, BIL and WinDisp. WinDisp format images can be displayed on map and image display analysis software called WinDisp. However, BIL format image, with the BLW and HDR files that accompany each BIL image contain the necessary spatial reference information, can be displayed on Arc View GIS, which is used as a tool for the analysis of rainfall image in this thesis work.

The Department of Civil Engineering of AAU provided satellite estimated rainfall data from 1995 to 2002. It is available in 10-days in WinDisp format for east Africa with the spatial information given in Table 4.1. WinDisp format should be changed to BIL format to manipulate and process the satellite data of rainfall using Arc View GIS.

Table 4-1 The Spatial Reference Information for The Two Formats, BIL And Windisp (ADDS[5])

COORDINATE SYSTEM DESCRIPTION (for all spatial extents):	
Projection	ALBERS (WinDisp projection 8, Albers Equal Area Conic)
Units	METERS
Spheroid	CLARKE1866
1st standard parallel (dms)	-19 00 0.000
2nd standard parallel (dms)	21 00 0.000
Central meridian (dms)	20 00 0.000
Latitude of projection's origin	1 00 0.000
False easting (meters)	0
False northing (meters)	0
Pixel size (for all spatial extents):	
X-direction	8000 m
Y-direction	8000m
Data value parameters for WinDisp format (for all spatial extents):	
Lower Limit	0
Upper Limit	255
Missing value	0
Value slope	0.004016
Value Intercept	-0.004016
Value Decimal Places	2
Spatial parameters for East Africa window	
NROWS	540
NCOLS	490
Image coordinates (center of pixel) (x,y):	
Upper left (UL)	-572000, 2652000
Upper right (UR)	3340000, 2652000
Lower left (LL)	-5720000, -1660000
Lower right (LR)	3340000, -1660000
Additional WinDisp header information:	
IMAGE TYPE	200, User Defined
X CENTER	72.0
YCENTER	331.0

[5] African Data Dissemination Service web site

For example, Fig 4.4 shows the image of rainfall in WinDisp format for January 2nd decade, 1996. This format was converted in to BIL format for the decade to display the image in Arc View GIS so that the data processing will be ease. The process of changing WinDisp format to BIL includes:

- WinDisp format image is available with filename followed by an extension (i.e., '*.IMG') for each decade rainfall image. This filing system is changed to '*.BIL' without changing the name of the file but its extension.
- Header files were prepared for each decade rainfall image using similar filename of the image, but another extension i.e., '*.hdr'. The header file contains the spatial information of the image in Table 4.1 of spatial parameters for East Africa window and Image coordinates (center of pixel) (x, y).
- The two files, the image and the header files, saved together in the same folder to display the image in Arc View GIS.

Similar procedure is applied for every decadal satellite data. Then, rainfall image for Ethiopia is extracted from BIL format image and, the three-decade for each month was added together to get monthly rainfall image. Fig 4.5 is an image of rainfall for January 1996 in BIL format obtained by the above process.

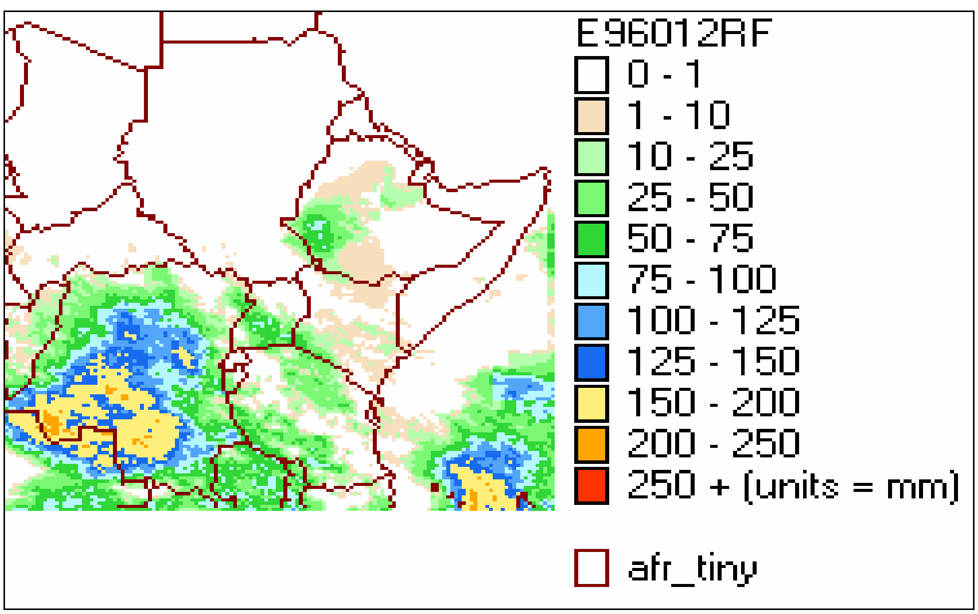

Fig 4-4 Satellite Rainfall Image of 1996 2nd Decadal Of January in Windisp Format in East Africa

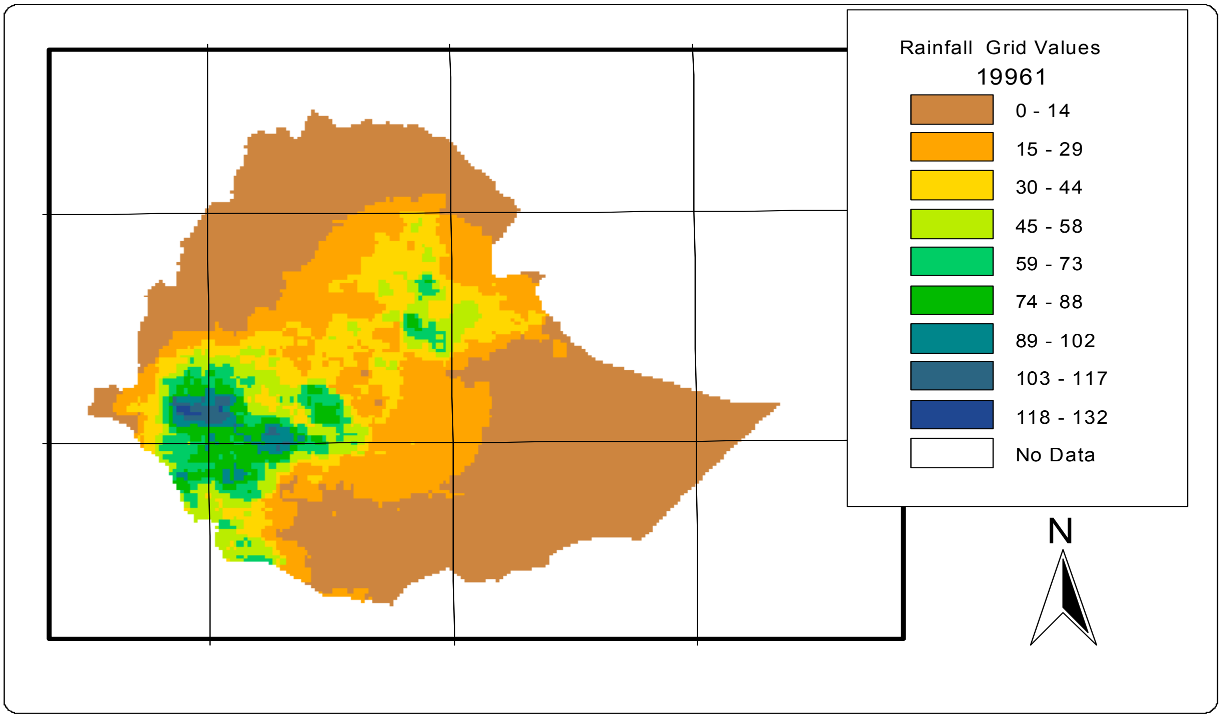

Fig 4-5 Satellite Image of Rainfall in BIL Format for January, 1996

4.3 Crop data

The Central Statistical Authority (CSA) has been conducting agricultural sample surveys on annual basis since 1980/81(1973E.C.) to meet some of the statistical data needs of planner and policy makers. As a result, data on area, production and yield of major crops such as cereals, pulses and oil seeds have been produced at country, regional and zonal levels for both Meher and Belg seasons on a yearly basis. The CSA has been concerned about the quality of the data right from the conception of the agricultural census. It has made every effort to maintain the data quality by lending more attention to those aspects of the census that affect the quality of the data (CSA, 2001/2002).

The survey was interrupted in 1992/93 (1985E.C.) and 1993/1994 (1986E.C.) because during these two years the CSA was fully engaged in undertaking the preparatory activities for the 1994 Population and Housing Census. However, crop assessment for 1993/1994 was conducted in a different way. A committee was formed comprising members from Ministry of Planning and Economic Development (MoPED), Ministry of Agriculture (MOA) and the

Central Statistical Authority, chaired by MoPED. Similarly, in 2002/2003, the survey was interrupted due to census of Agriculture on 2001/20002 in Ethiopia.

Even though CSA has collected production data since 1980/81, CSA library provides production data from 1986/87 only. The production data since then is reported at different regional level, since the country has been in different systems of administration. For example, table 4.1 shows how the data for area, production and yield of major crops are available since 1986/87 for Gojam region. Similar situation exist for other part of the country.

Three farming categories are identified in the country for the sample survey; rural private holdings, urban private holdings and commercial farms. However, CSA has reported usually data that correspond to rural private holdings in most of its yearly report. Nowadays, the survey has included the other categories. To accomplish census on those categories, CSA have Enumeration Areas (EAs), which are locality that is most of the cases equal to a farmers association in geographical area, and usually consist of 150-200 households. Accordingly most of the information on crop area and yield was elicited from the holders through interviews and the remaining information was obtained by physically measuring the data items of interest from EAs.

Table 4-2 Administration Level Where Production Data is Available for Gojam Region

Year	Gojam Area where production is available
1986/1687	AT each Awraja Level
1987/1988	AT each Awraja Level
1988/1989	East Gojam, West Gojam, Metekel
1989/1990	East Gojam, West Gojam, Metekel
1990/1991	East Gojam, West Gojam, Metekel
1991/1992	East Gojam, West Gojam, Metekel
1992/1993	Not available
1993/1994	East Gojam, West Gojam
1994/1995	Awi, East Gojam, West Gojam
1995/1996	Awi+East Gojam+West Gojam
1996/1997	Awi + East Gojam + West Gojam
1997/1998	Awi , East Gojam , West Gojam
1998/1999	Awi, East Gojam, West Gojam
1999/2000	Awi, East Gojam, West Gojam
2000/2001	Awi, East Gojam, West Gojam
2001/2002	Awi, East Gojam, West Gojam
2002/2003	Not available
2003/2004	Awi, East Gojam, west Gojam

To study the relationship of rainfall and production in this thesis work, production data is collected only for rural private holdings. And since, among major crops, cereals are by far the most dominant among the field crops, accounting for 88.3% and 83.2 of the total production and cultivated area, respectively for the period 1980 to 1996 (Degefe, 1999/2000), the data collection include only Cereal production of Teff, Barely, Wheat, Maize and Sorghum in selected study areas. Since Amhara and Oromia regions contribution to the country's production is large as stated in section 3.4.2, the study areas include

1. Awi, West and East Gojam zone merged together as the first study area;
2. South wolo, Oromia and North Shoa as the second;
3. West and East Welega as the third;
4. Jima and Ilubabor as the fourth study area
5. North and West Shoa as the fifth study area

Fig 4.6 and Fig 4.7 shows the study areas in both Amhara and Oromia region.

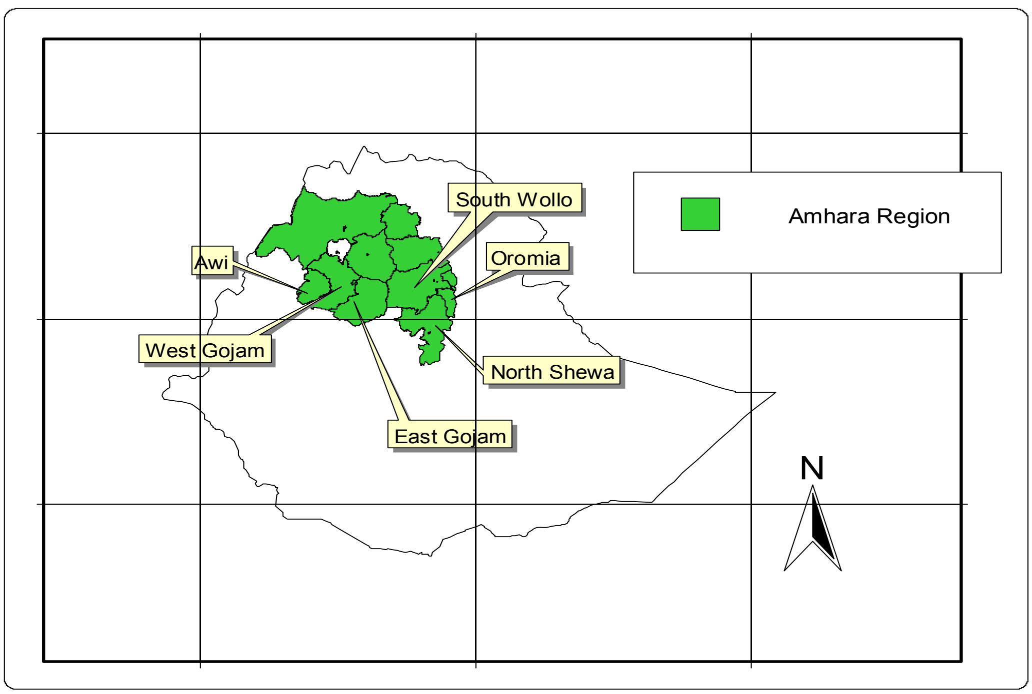

Fig 4-6 Study Area in Amhara Region

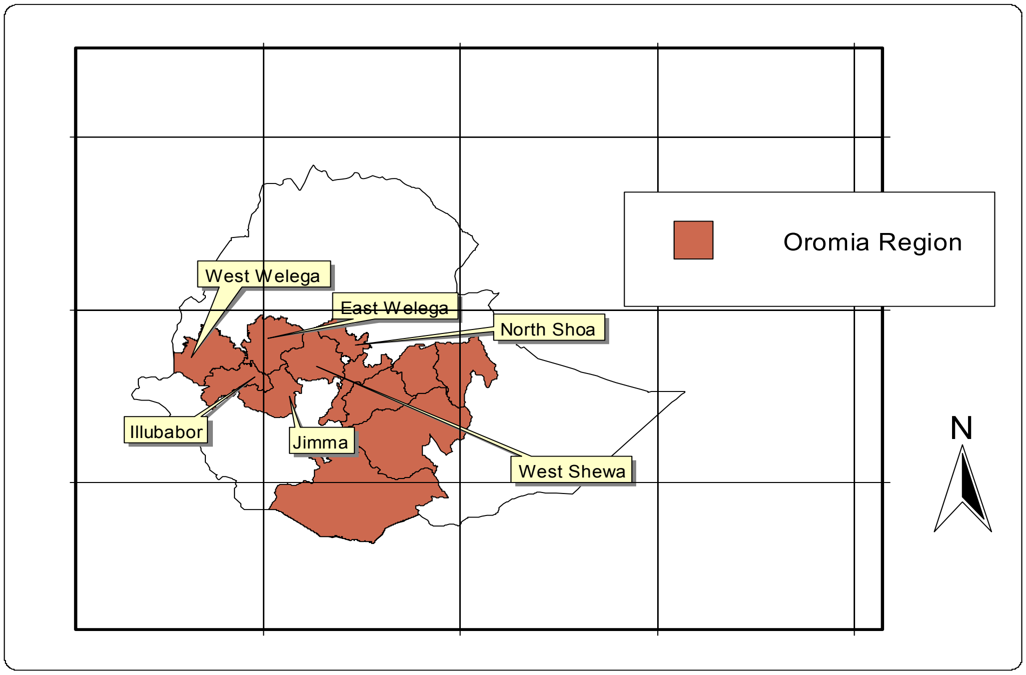

Fig 4-7 Study area in Oromia region

Each zone in the study areas is combined together to form five different single areas. This is because production data for 1995/96 and 1996/1997 were reported to the level of study areas considered.

In this thesis work, cereals data of Teff, Barely, Wheat, Maize and Sorghum for Meher season are collected from a yearly report of CSA on Area, Production and Yield of crops of private holding over the period 1994/95 – 2001/2002 for the study areas. In the analysis, only Teff, Barely, Wheat and Maize are considered (Shown in Appendix G) since they are available continuously in the study areas. And the period of analysis is selected for the simple reason that CSA follows the same level of administration area for reporting the data since 1994/1995 as shown in Table 4.2.

In addition to the above data, for comparison of water requirement of Teff, Barely, Wheat and Maize with rainfall in their growing period, data of crop water requirement and their growing period in the study areas are required. There were problem of finding these data. However, for stations of Bahir Dar, Debre Markos, Nekemt, Pawe and Nejo station monthly average potential evapo-transpiration is obtained from Abbay master plan.

5 Methodology

5.1 Comparison of satellite data with gauged data

The study area for comparing the two data systems covers the whole part of Ethiopia except Afar and Gambella for which no observable rainfall data is collected. The performance of satellite rainfall estimate from NOAA is compared directly to rain gauge rainfall data using around 37 rain gauge stations as shown in Fig 4.2.

Comparison is made assuming that monthly station data is taken to be actual rain in 8km by 8km grid. The assumption of true rain in 8km by 8km is better than the assumption made by WMO GTS data that station rain gauge totals are taken to be the true rainfall within 15-km radii of each station. Then, satellite monthly average rainfall data over pixel size of 8km by 8km given by NOAA is compared directly with it. This is with the assumption that comparison error in comparing a single gage within 8x8 km^2 box with satellite average estimate is small since Bell et al. (2002) showed in Fig 3.3 that as the satellite visiting interval over a single gauge increases the averaging area decreases. METEOSAT satellite visit interval is 30 minutes.

The performance of monthly satellite rainfall estimates with rain gauge, visually, can be studied applying time series plot. And simple linear regression can be applied to see how well the two estimates are correlated for the stations.

Arc View GIS 3.2a has been used for processing and analyzing of the spatial satellite data as shown in Fig 5.1. It creates an output table and chart, which contain all of the summery statistics computed for each station as shown in Fig 5.2. The summery statistics include area, minimum, maximum, range, mean, standard deviation, sum, variety, majority, minority, and median in each grid. The important statistics for the thesis work is mean.

This process is applied for each month in the period of 1996-2002 and the resulting table is exported to Excel. The mean, representing average monthly satellite rainfall in the grid, is picked for each station to compare with the actual monthly gauged value.

The satellite rainfall estimate was regressed with the gauged rainfall estimate to assess how well the two fields are correlated for each station in Fig 4.2. Correlation statistics, statistical t-test and root mean squared error were extracted for each station and recorded in table. Moreover, graphical representation of the difference between the gauged value, which is taken as true estimate and the satellite estimate were made to identify overestimation or underestimation in the estimate.

A statistical t-test is performed to determine the significance of correlation between the two estimates. The null hypothesis H_0 ($\rho = 0$), which states that there is no linear relation between two data set is rejected if

$$T \le t_{n-2,\frac{\alpha}{2}} \textbf{ Or } T \ge t_{n-2,1-\frac{\alpha}{2}} \qquad [5.1]$$

$$\text{Where: } T = r\left[\frac{(n-2)}{(1-r^2)}\right]^{0.5} \qquad [5.2]$$

n = number of data points

r = correlation coefficient of sample data

ρ = correlation coefficient of population data

T has a t-distribution with n-2 degree of freedom. For different value of α, the critical t value can be read from t-distribution Table.

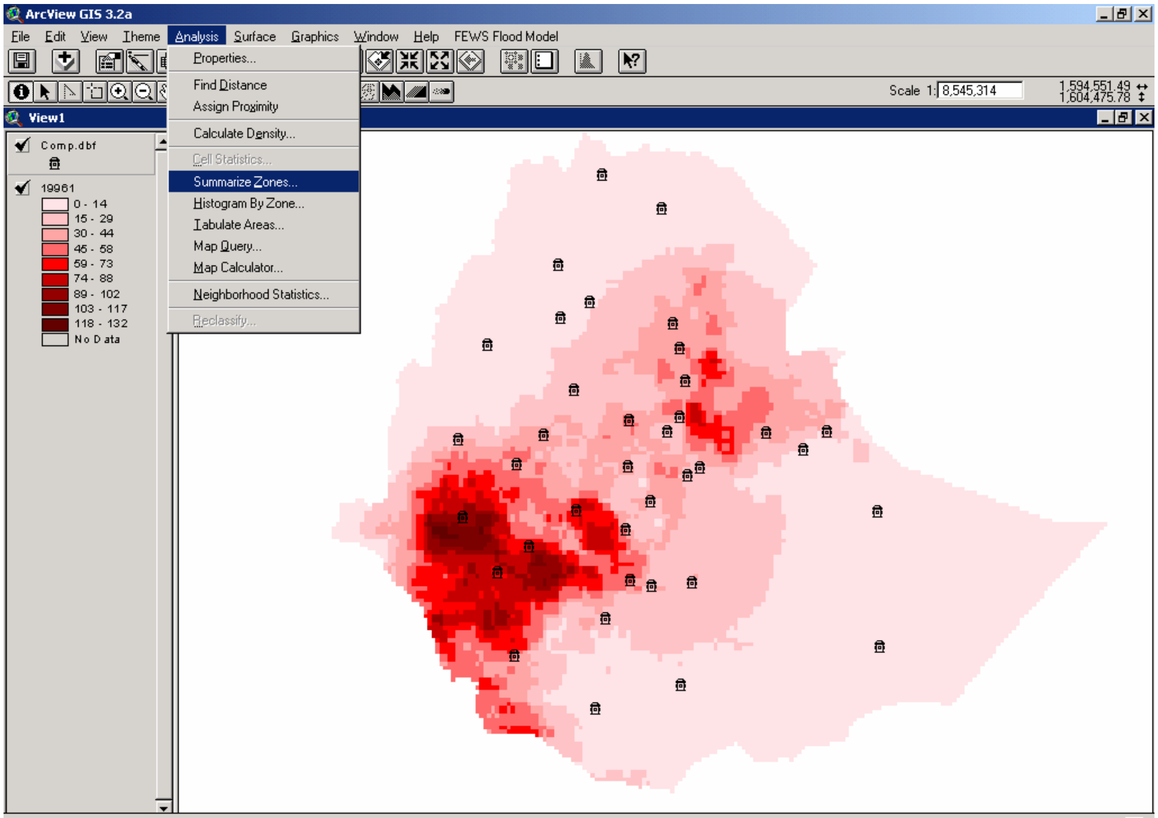

Fig 5-1 Summarizing Satellite rainfall estimate image for the stations on January 1996

Stats of 19961 Within Zones of Comp.dbf

Station	Zone-code	Count	Area	Min	Max	Range	Mean	Std	Sum	Variety	Majority	Minority
AdameTulu	1	1	64000000.000	43	43	0	43.0000	0.0000	43.0000	1	43	43
Addis Ababa	2	1	64000000.000	30	30	0	30.0000	0.0000	30.0000	1	30	30
Bahir Dar	4	1	64000000.000	6	6	0	6.0000	0.0000	6.0000	1	6	6
Bonga	5	1	64000000.000	87	87	0	87.0000	0.0000	87.0000	1	87	87
Debre Tabore	7	1	64000000.000	14	14	0	14.0000	0.0000	14.0000	1	14	14
Debre Markos	8	1	64000000.000	28	28	0	28.0000	0.0000	28.0000	1	28	28
Debre Sina	9	1	64000000.000	27	27	0	27.0000	0.0000	27.0000	1	27	27
Dega Habour	10	1	64000000.000	5	5	0	5.0000	0.0000	5.0000	1	5	5
Dilla	11	1	64000000.000	19	19	0	19.0000	0.0000	19.0000	1	19	19
Dire Dawa	12	1	64000000.000	30	30	0	30.0000	0.0000	30.0000	1	30	30
Dodola	13	1	64000000.000	27	27	0	27.0000	0.0000	27.0000	1	27	27
Endeselassie	14	1	64000000.000	0	0	0	0.0000	0.0000	0.0000	1	0	0
Fiche	15	1	64000000.000	47	47	0	47.0000	0.0000	47.0000	1	47	47
Goba	16	1	64000000.000	23	23	0	23.0000	0.0000	23.0000	1	23	23
Gode	17	1	64000000.000	4	4	0	4.0000	0.0000	4.0000	1	4	4
Gonder	18	1	64000000.000	0	0	0	0.0000	0.0000	0.0000	1	0	0
Gore	19	1	64000000.000	95	95	0	95.0000	0.0000	95.0000	1	95	95
Harar	20	1	64000000.000	14	14	0	14.0000	0.0000	14.0000	1	14	14
Jara	21	1	64000000.000	36	36	0	36.0000	0.0000	36.0000	1	36	36
Jijiga	22	1	64000000.000	18	18	0	18.0000	0.0000	18.0000	1	18	18
Jimma	23	1	64000000.000	79	79	0	79.0000	0.0000	79.0000	1	79	79
Jinka	24	1	64000000.000	39	39	0	39.0000	0.0000	39.0000	1	39	39
Koffle	25	1	64000000.000	50	50	0	50.0000	0.0000	50.0000	1	50	50
Koka Dam	26	1	64000000.000	24	24	0	24.0000	0.0000	24.0000	1	24	24
Kombolcha	27	1	64000000.000	51	51	0	51.0000	0.0000	51.0000	1	51	51
Mekele	28	1	64000000.000	4	4	0	4.0000	0.0000	4.0000	1	4	4
Metehara	29	1	64000000.000	19	19	0	19.0000	0.0000	19.0000	1	19	19
Negele Borena	30	1	64000000.000	8	8	0	8.0000	0.0000	8.0000	1	8	8
Nedjo	31	1	64000000.000	34	34	0	34.0000	0.0000	34.0000	1	34	34
Nekemte	32	1	64000000.000	39	39	0	39.0000	0.0000	39.0000	1	39	39
Pawe	33	1	64000000.000	1	1	0	1.0000	0.0000	1.0000	1	1	1
Sirinka	34	1	64000000.000	36	36	0	36.0000	0.0000	36.0000	1	36	36
Shambu	35	1	64000000.000	36	36	0	36.0000	0.0000	36.0000	1	36	36
Wolkite	36	1	64000000.000	69	69	0	69.0000	0.0000	69.0000	1	69	69
Yabello	37	1	64000000.000	6	6	0	6.0000	0.0000	6.0000	1	6	6

Fig 5-2 Table resulted from summarization of satellite image for the stations on January 1996

5.2 Rainfall Trend Analysis in Ethiopia

In this study, the trend of rainfall at station level is investigated in a time period of 1973-2002. Mann-Kendall statistical test described in section 3.3.3 is performed to assess the significance of trend in this period for annual and seasonal (‘Kiremt’[6] and ‘Belg’[7]) rainfall totals of 10 stations in Ethiopia shown in Fig 4.3.

The procedure used for the statistical test of Mann-Kendall in this thesis work is:

a. The rainfall stations (shown in Fig 4.1) and their record are investigated to select the rainfall stations (shown in Fig 4.3) that have long and rather complete records. Here ten stations having 30 years record length with best complete records are selected.

   Among the stations, Gore station has monthly missing data for continuous two complete years (1991 and 1992), and Negelle Borena and Jijiga have monthly missing data of randomly distributed in the study period. In these stations, missed months are estimated from nearby stations using simple average method. Estimation is required since the sample data is modeled by AR(1) in step d to remove serial coefficient as described in section 3.3.4. The other seven stations have rather complete record in the study period.
b. Compute all possible annual slopes betewen years for each station using Equation 3.17 and record the slopes of each pair. Sort the slopes in ascending order and take the median estimate.
c. If the slope, b, is different from zero, then it is assumed to be linear, and the sample data are de-trended by Equation 3.20.
d. The lag one serial correlation coefficient r_1 is computed with its upper and lower limits of the confidence interval at the significance level of 0.10 of the two tailed test. If the sample data are not significantly serially correlated, MK test can be applied without need of correction for the effect of serial dependence on the test. Otherwise, use equation 3.21 to remove the serial dependence.

   To judge if observed sample data and TFPW data are serially correlated, the significance of the lag-1 serial correlation coefficient at the significance level $\alpha = 0.10$ of the two tailed test is assessed using the following approximation [40]:

[6] ‘Kiremt’ is defined by months June to September
[7] ‘Belg’ is defined by months February to May

$$\frac{-1-1.645\sqrt{n-2}}{n-1} \leq r_1 \leq \frac{-1+1.645\sqrt{n-2}}{n-2}$$

e. The results of step c and d blended together and MK test is applied on the blended series.

f. For each station of result of step e: Compute the sign of all possible differences within the set of rainfall values , as $\text{sgn}(X_j - X_i)$, as shown in Equation 3.11.

g. Convert the positive $\text{sgn}(X_j - X_i)$ to +1, negative $\text{sgn}(X_j - X_i)$ to -1, and 0 results to no differnce (i.e., there is a tie) as of Equation 3.12. Then add the results for the number of years and call that S as of equation 3.11.

h. Compute the variance of S using Equation 3.14. In the equation e_i is the number of ties of extent i. For example, in the data set 5, 5, 6, 7, 8, 8, 8, 10, 10, 11, 12, 12, the tie values are as follows:

$$e_1 = 3 \quad \textit{three untied values } (6,7,11)$$
$$e_2 = 3 \quad \textit{three ties of extent two } (5,10,12)$$
$$e_3 = 1 \quad \textit{one ties of extent three } (8)$$

and for all higher values of i , $e_i = 0$

i. Compute the standard test statistic Z from Equation 3.15.

j. Compute the P-value of the statistics Z from Equation 3.16 to consider the null hypothesis is valid or not. For sample data with a large positive trend the P value should be closer to 1.0, whereas a large negative trend should yield P value closer to 0.0.

The above procedure is prepared on Ms-Excel worksheet and the computation is finished on the worksheet.

5.3 Rainfall effect on production of cereals

Simple linear regression is applied between area rainfall estimated from gauged data and production over the study areas. The area estimates of rainfall on those five study areas are obtained by summarizing for each study area based on grid value of Ethiopia, which is obtained by Inverse Distance Weight (IDW) of stations on Fig 4.1. IDW gives values to each cell in the output grid by weighting the value of each station by the distance that station is from the cell being analyzed and then averaging the values. Arc View GIS has a menu called Surface which contains a command called Interpolate grid with a method of IDW to obtain grid map of rainfall.

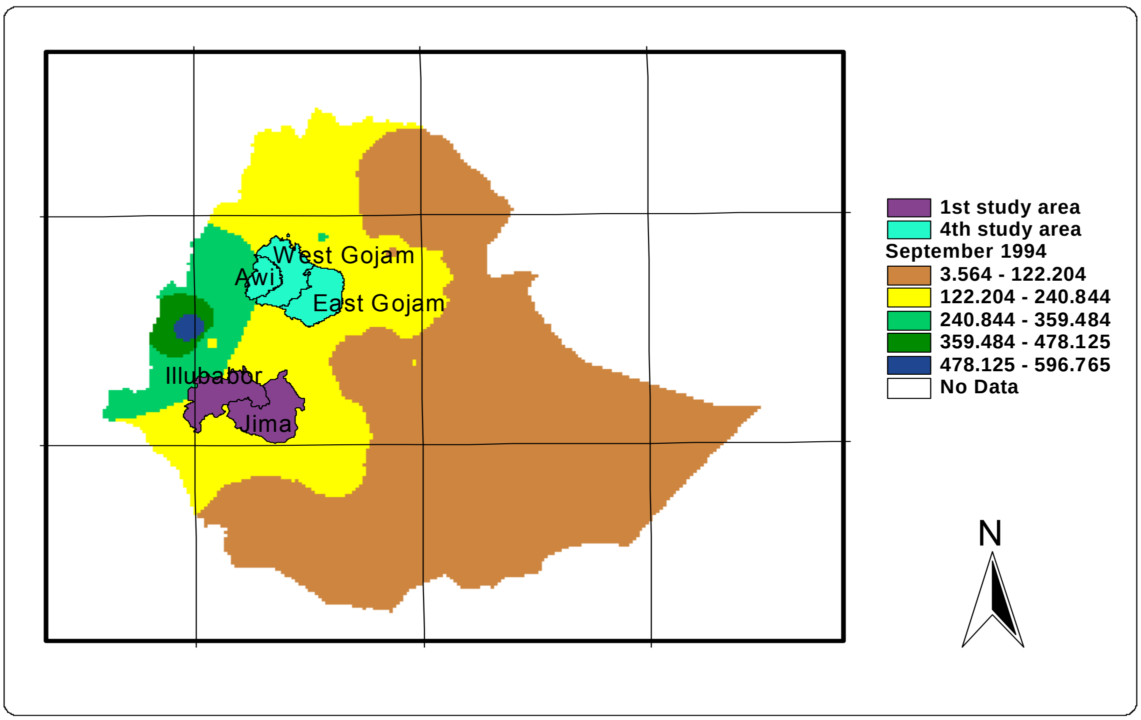

Fig 5-3 Grid values of rainfall for September 1994 with 1st and 4th study areas

For example, the area rainfall on September 1994 for the 1st(Awi, West Gojam & East Gojam zones) and 4th 4th (Jima & Illubabor zones) study areas is obtained by overlying the study area on a grid map of Ethiopia, as shown in Fig 5.3, and then summarizing the statistical values of rainfall for the study areas based on the grid value of Ethiopia. Table 5.1 shows the result of summarization of statistics. And the mean value is the important variable in the analysis of this thesis work. In the analysis, mean of the mean values are taken i.e, mean of

190.22 mm, 185.37mm, and 235.43mm is 203.67mm and mean of 172.75mm and 208.81mm is 190.78mm, for the 1st (Awi, West Gojam & East Gojam zones) and 4th (Jima & Illubabor zones) study areas, respectively. Similar procedure is applied for all months in the analysis period for the five study areas.

Table 5-1 Statistics of September 1994 within 1st and 4th Study Areas

Zone	Zone-code	Count	Area	Min	Max	Range	Mean	Std	Sum
West Gojam	1	203	1.3E+10	146.05	237.73	91.67	190.22	21.96	38614.93
East Gojam	9	222	1.42E+10	144.02	217.78	73.75	185.37	17.81	41153.20
Awi	10	100	6.4E+09	202.90	272.67	69.78	235.43	17.10	23543.17
Jima	4	289	1.85E+10	137.41	213.32	75.91	172.75	10.82	49924.75
Illubabor	5	255	1.63E+10	171.47	265.95	94.48	208.81	20.90	53246.73

Then, Simple linear regression analysis is then made between the production and area rainfall on the study areas. The correlation coefficient of the analysis would explain how strong the relationship between total annual and seasonal rainfall and production. A statistical t-test is performed to determine the significance of correlation between the two estimates as described in section 5.1.

6 Result and Discussion

6.1 Performance of satellite based rainfall estimate

6.1.1 Correlation and Difference between the two estimate

The average value for monthly satellite estimate, which represent the 8km by 8km grid and the corresponding gauged average rainfall within the grid were taken to test the reliability of the satellite estimate. Time series plot of satellite rainfall estimate and observed gauge rainfall estimate for five stations are shown in Appendix B.

The graph of time series plot showed that the satellite estimates show the same trend of monthly distribution within the year of each station in the country and similarly the spatial distribution of rainfall noticed by the station in the country is also indicated by the satellite estimate. This shows clearly that the satellite estimate is able to show the rainfall condition in the country. However, the plots show that in most of rainy months, the gauged estimate is higher than the satellite estimate. This underestimation by the satellite can be due to the fact that the CPC technique is designed to estimate rainfall from convective clouds only, yet in Ethiopia the effect of orography on rainfall is significant.

A simple regression between satellite rainfall estimate and rain gauged rainfall in the period 1996-2002 is shown in Table 6.1 below. It shows the regression equation, correlation coefficient, the statistical t-test for testing significance of correlation R and RMSE (root mean squared error) between the two estimates.

Table 6-1 The Result Of Correlation And RMSE Between Satellite Estimate and Gauged Estimate

Id	Station	No of Data points	Equation	R	Elevation	T	RMSE
1	AdameTulu	75	Y = 0.4874x + 20.458	0.57	1880	6.00	61.83
2	Addis Ababa	82	Y = 0.8639x + 33.248	0.85	2410	14.34	51.78
4	Awash	80	Y = 0.6334x + 17.34	0.76	915	10.38	42.88
5	Bahir Dar	82	Y = 1.1301x + 1.3614	0.89	1770	17.89	70.16
6	Bonga	82	Y = 0.6313x + 61.917	0.71	1725	11.19	62.31
8	Debre Birhan	82	Y = 1.0985x - 3.367	0.87	2750	15.92	54.11
9	Debre Tabore	82	Y = 1.2563x + 20.452	0.88	2690	16.37	86.21
10	Debre Markos	82	Y = 0.8639x + 33.248	0.81	2450	12.19	70.48

Id	Station	No of Data points	Equation	R	Elevation	T	RMSE
11	Debre Sina	78	Y = 1.6913x + 74.505	0.66	2000	7.57	216.03
13	Dega Habour	82	Y = 0.7854x + 6.4239	0.72	1070	9.31	30.62
14	Dilla	82	Y = 0.9223x + 21.658	0.71	1560	8.94	59.73
15	Dire Dawa	82	Y = 0.76x + 17.35	0.78	1210	9.12	40.86
16	Dodola	72	Y = 0.2813x + 65.234	0.50	1680	4.70	77.82
17	Endeselassie	82	Y = 0.9679x + 15.392	0.88	1913	16.57	52.78
18	Fiche	82	Y = 1.2266x + 1.0446	0.89	2800	17.89	64.01
21	Goba	70	Y = 0.8039x + 46.835	0.55	2710	5.40	62.49
22	Gode	78	Y = 0.7408x + 56.99	0.74	275	9.64	32.53
23	Gonder	74	Y = 1.1913x + 10.261	0.87	2270	14.70	81.90
24	Gore	82	Y = 0.9844x + 44.002	0.85	2024	14.71	74.27
25	Harar	77	Y = 0.6037x + 23.396	0.64	1856	7.22	42.27
27	Jara	70	Y = 1.3493x + 12.062	0.79	1600	10.53	113.36
28	Jigiga	70	Y = 0.5338x + 19.382	0.63	1840	6.73	45.44
29	Jima	82	Y = 0.8126x + 43.62	0.71	1820	9.12	70.84
30	Jinka	82	Y = 0.7408x + 56.99	0.59	1430	6.56	70.11
33	Koffle	82	Y = 0.6618x + 44.589	0.54	2680	5.72	64.84
34	Koka Dam	79	Y = 1.191x - 3.2258	0.79	1943	11.21	87.46
35	Kombolcha	72	Y = 1.0179x + 17.808	0.93	1900	21.64	43.88
37	Mekele	82	Y = 0.7906x + 3.7155	0.86	2210	15.09	48.99
39	Metehara	80	Y = 0.6024x + 7.4729	0.82	930	12.65	40.36
41	Negele Borena	82	Y = 0.9132x + 7.1036	0.81	1440	12.35	36.49
42	Nedjo	82	Y = 0.8731x + 26.246	0.79	1800	11.67	73.88
43	Nekemte	82	Y = 1.2877x + 23.651	0.90	2240	18.47	97.20
44	Pawe	82	Y = 0.9439x + 30.243	0.79	1050	11.67	93.21
46	Sirinka	82	Y = 0.91x + 38.272	0.82	2000	12.81	68.61
47	Shambu	82	Y = 0.947x + 22.128	0.86	2400	15.07	62.13
49	Wolkite	82	Y = 1.0441x + 6.6866	0.77	1860	10.79	69.38
51	Yabello	82	Y = 0.8481x + 2.4338	0.78	1740	11.19	35.17

Table 6.1 reveals that all stations have significant correlation between the two values since T value shown in column 6 is greater than the critical t equal to 1.99 for significance level of 0.05 and 58 data points. In average the correlation coefficient between satellite estimate and gauged estimate in the country is 0.77. In Fig 6.1, it is tried to summarize how linear correlation coefficient looks like for the country as whole interpolating the values of column 5 of table 6.1 using Arc View GIS. The map shows that the North and Northwestern part of the

country is correlated above average value of 0.77. The Southern, Southwestern and Southeastern part of the country is correlated below average value of 0.77.

From Table 6.1, the RMSE shows how the satellite estimates deviate from the gauged estimates, which are considered as the true rainfall value in the grid. In average, satellite estimate deviates from the true estimate by 66.0mm. Fig 6.2 describes that RMSE is above average in the Northwestern and Southwestern part of the country where rainfall amount is large. In the other hand RMSE is below average in the southern, southeastern and eastern part of the country where rainfall amount is small.

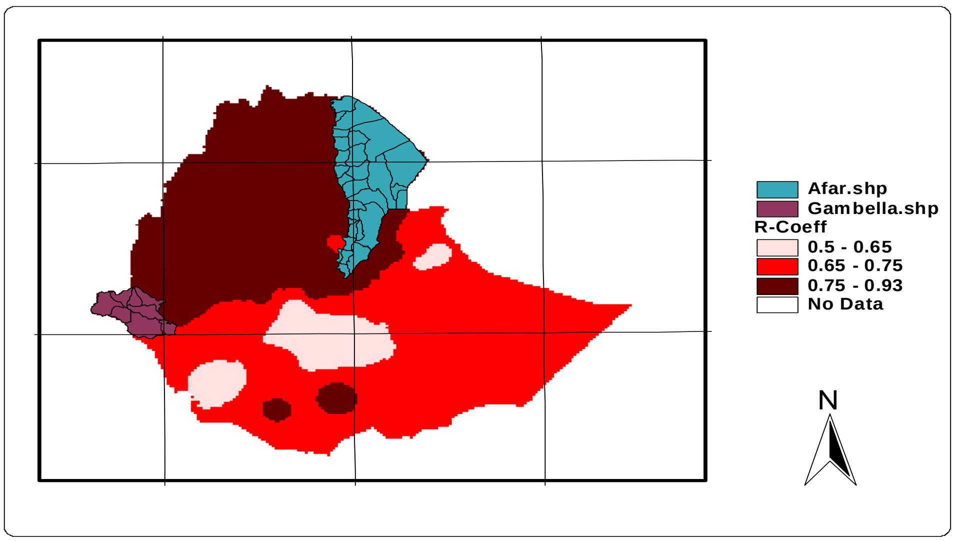

Fig 6-1 Map of Correlation Coefficient R

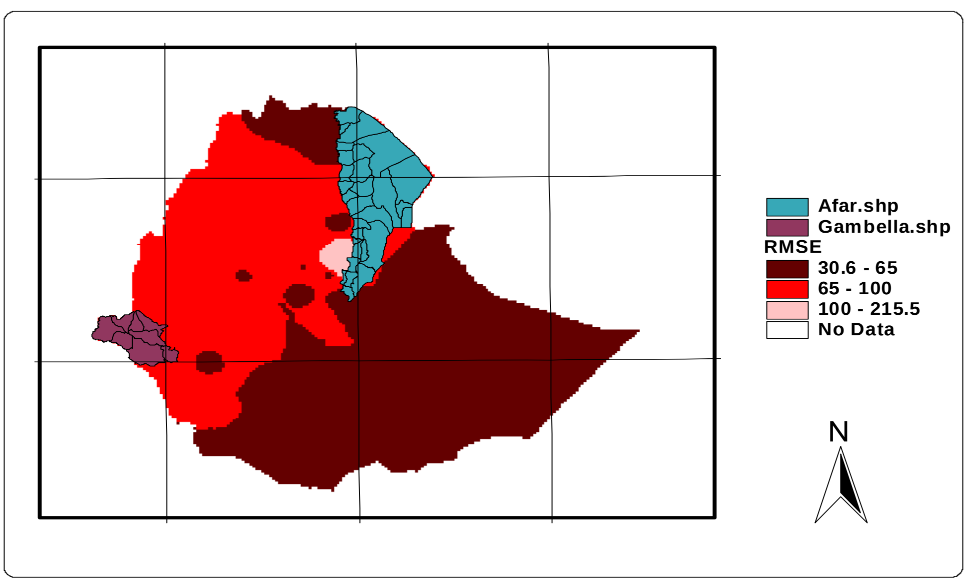

Fig 6-2 Map of root mean squared error (RMSE)

Appendix C shows graphically the difference between satellites based estimate and gauged estimate in the grid in which stations are found. The difference in most of the stations shows that the number of months during rainy seasons underestimated by the satellite is larger than the overestimation. Moreover, the difference between the two estimates increases as the year increases. For example, on 1996, in most of the station the difference is below the RMSE value. However, as the year increases, the difference between two estimates is above the RMSE value. This may be related with the limitation of the CPC technique discussed in section 3.1.6 of part d.

6.1.2 Estimating missing data using satellite estimate

From the map of correlation shown in Fig 6.1, it is seen that in most part of the region there is significant correlation. To check that this relationship is helpful in estimating missed data in the rain gauge estimation, an experiment is made to estimate rainfall for all months in 2000-2002 periods, considering those years are missed years and simple linear regression equation from 1996 to 1999 is used as model to estimate the missed data. RMSE is calculated between the estimated value by the model and the actual observed value obtained from the station in the period of analysis. Table 6.2 below shows stations used for the experiment and their corresponding RMSE.

On average there is deviation of 68.13mm between the actual gauge rainfall estimate and the estimate made from regression equation using satellite estimate as input value. As shown in Appendix D, estimated rainfall from the model and actual observed rainfall are plotted together. The plots show that when the gauge was not measuring rain, the model was estimating some rain. In addition, during peak rainy periods, the difference between the two values increases.

Table 6-2Experiment on estimation of missing data

Station	Model used	RMSE (mm)
N.Borena	Y = 0.9153x + 2.6196	46.24
Metehara	Y = 0.8533x - 1.2612	41.58
D.Dawa	Y = 0.859x + 8.929	41.47
Gode	Y = 1.0031x + 6.6337	25.26
Dega H.	Y = 0.7423x + 2.9533	33.85
Pawe	Y = 0.9514x + 14.551	107.07
Shambu	Y = 0.8827x + 17.418	79.43
D.Birhan	Y = 1.2482x - 10.869	80.98
Addis A.	Y = 1.0219x + 12.709	75.86
Mekele	Y = 1.2256x - 1.982	95.97
BahirDar	Y = 1.0329x + 4.2262	90.77
Gonder	Y = 1.1968x + 4.1483	103.49
Kombolcha	Y = 1.0651x + 6.093	67.08
Koka Dam	Y = 1.191x - 3.2258	117.07
Jima	Y = 0.9082x + 32.623	77.95
Yabello	Y = 0.9222x - 2.0595	30.41
Harar	Y = 0.6639x + 14.764	42.70
Gore	Y = 1.0422x + 28.764	69.24
	Average	68.13

Table 6.2 shows that stations N. Borena, Gode, Dega Habour, Metehara, Dire Dawa, Harar, and Yabelo found in Eastern, Southern and Southeastern part of the country, the error made by the estimation is small, whereas stations Gore, Jima, Bahir Dar, Addis Ababa, Mekele,etc found in Central, Southwestern and Northern part of the country, the error is above average RMSE value, 68mm. With better calibration of the technique, the method could estimate missing rainfall data, especially in the Eastern, Southern and Southeastern part of the country.

6.2 Changes in Rainfall Totals

Studies of recent changes by Seleshi et al (2004) over Ethiopian rainfall have shown that the annual and the June-September total rainfalls for the eastern (Jijiga, 137mm/decade), southern (Negele, 119mm/decade) and southwestern (Gore, 257mm/decade) stations show a significant decline since about 1982. The non-parametric Mann-Kendall test has been used in the study. However, the effect of autocorrelation on the method was not considered in the study. For example, a study made on detection of trends in annual extreme rainfall in Canada by Adamowski et al (2003) showed that stations containing significant autocorrelation were pre-whitened. Yue et al, 2002(1) proved that significant autocorrelation in the sample data misleads the result of the test. Hence, in this thesis work, the effect of autocorrelation is taken into consideration.

For a normally distributed random series, its skew-ness and kurtosis should be equal to 0. It is evident from Table 6.3, column 5 and 6, the data are positively skewed and the relative peaked-ness is large for some stations. Most of the data could not be represented by normal distribution. As a result, the choice for Mann-Kendall statistical test from t-test could be appropriate.

Column 4 of Table 6.3 calculates the coefficient of variation (CV) of the data at stations. This provides a measure of year-to-year variation in the data series. NMSA (1996) documented that CV less than 0.20 is less variable, CV between 0.20 and 0.30 is moderately variable and CV greater than 0.30 is highly variable. The Belg rain in all stations shows that there is high variability since CV is greater than 0.30. Jima, Gore, D.Markos, Addis Ababa and Kombolcha stations have less variability in the annual and Kiremt rainfall. The other station in annual and Kiremt rainfall show moderate variation.

The lag-1 serial correlation coefficient (ρ_1) and it's upper and lower limits for confidence interval at the significance level of 0.10 of the two-tailed test for the original and TFPW data are presented in columns 7 up to 10 of Table 6.3. The table shows that N.Borena (Annual & Kiremt), Jijiga (Annual & Kiremt), Bahir Dar (Annual & Kiremt), Gore (Kiremt), and Dire Dewa (Annual) are significant serially correlated at the significance level of 0.10. Therefore, Trend free pre-whitening procedure should be followed to the series to remove the effect of serial correlation on MK test. As it is shown in column 8, the TFPW procedure made the series independent and serially uncorrelated. However, the remaining stations and Belg rainfall series over all stations are not significantly correlated. Hence, MK test is applied directly to the rainfall total series.

The magnitude of the Mann-Kendall statistics S, the standardized normal variate Z and P-value are given in columns 10, 11 and 12, respectively of table 6.3. When S and Z values are positive, these indicate an upward trend, negative values indicate downward trend in the rainfall series. At a significance level of $\alpha = 0.05$, Z value is used to measure the significance of the trend. P-value in column 12 indicates that significant downward trend is seen at N.Borena[8] (Annual,-11.11mm/year and Sep-Nov,-3.25mm/year), Gore (Kiremt-7.7mm/year and Annual-12.2mm/year) and Jijiga (Kiremt-5.8mm/year) stations. Belg total rainfall doesn't show significant trend in any of the stations. These results are similar to the result of study made by Seleshi et al. (2004). The slope of trend on stations, which show significant trend, is determined by the Theil-Sen approach (TSA) approach. And it is shown in column 13 of table 6.3.

As it is shown in section 2.3.3, Seleshi et al (2004) reported that a persistent increase in December-February sea-level pressure over the tropical eastern pacific ocean and persistent warming of the South Atlantic Ocean over the period approximately from 1986 to 2002 correspond to a persistent decline in the annual rainfall at Jijiga, Negele-Borena and Gore.

Gore and Jima are found in the same rainfall regime called Monomodal of b_1 as shown in Fig 2.2. Cross-correlation of annual rainfall between the two stations in the period of 1973-2002 is around 0.36, which is low. Though they are in the same rainfall regime, the correlation shows that they may not be subjected to the same climatic change influence. However, number of other stations near to Gore and Jima (for example, Gambela, Bonga) should be checked for trend, and their correlation to SSTs and SOI data should be investigated so that conclusion on rainfall trend at regional (field) level will be easy.

[8] Main rainfall season for the station is March to May while second rainfall season is September to November.

Table 6-3 Statistical Properties and Result of Mann-Kendall Test for 10 Selected Stations

1	2	3	4	5	6	7	8	For α = 0.10		11	12	13	14
Station	Seasons	No Years	CV[9]	Skew-ness	Kurtosis	ρ1 raw data	ρ1 after TFPW	Upper	Lower	S	Z	P	Slope (mm/year)
Dire Dawa	Annual	30	0.24	0.21	-0.09	0.352	0.178	0.27	-0.33	75	1.32	0.91	
	Kiremt	30	0.35	0.46	-0.39	0.006		0.27	-0.33	61	1.07	0.86	
	Belg	30	0.46	0.63	0.60	0.23		0.27	-0.33	5	0.07	0.53	
Bole	Annual	30	0.17	1.22	1.96	-0.32		0.27	-0.33	-59	-1.03	0.15	
	Kiremt	30	0.20	0.12	3.36	-0.28		0.27	-0.33	-55	-0.96	0.17	
	Belg	30	0.39	0.08	-0.88	-0.11		0.27	-0.33	11	0.18	0.57	
D. Markos	Annual	30	0.11	0.41	0.50	-0.09		0.27	-0.33	61	1.07	0.86	
	Kiremt	30	0.11	0.10	-1.05	-0.09		0.27	-0.33	33	0.57	0.72	
	Belg	30	0.37	0.60	0.03	-0.015		0.27	-0.33	-19	-0.32	0.37	
Jima	Annual	30	0.13	0.36	-0.26	0.16		0.27	-0.33	101	1.78	0.96	
	Kiremt	30	0.15	0.25	0.69	0.046		0.27	-0.33	17	0.29	0.61	
	Belg	30	0.20	0.09	0.30	-0.283		0.27	-0.33	7	0.11	0.54	
Bahirdar	Annual	30	0.22	0.00	3.11	0.46	-0.03	0.27	-0.33	-33	-0.57	0.28	
	Kiremt	30	0.23	-0.27	1.41	0.37	0.06	0.27	-0.33	-45	-0.79	0.22	
	Belg	30	0.69	1.27	1.91	-0.027		0.27	-0.33	-13	-0.23	0.41	
Awash	Annual	30	0.24	-0.32	-0.19	-0.059		0.27	-0.33	33	0.57	0.716	
	Kiremt	30	0.25	0.15	1.21	-0.179		0.27	-0.33	71	1.25	0.89	
	Belg	30	0.48	1.15	1.88	0.199		0.27	-0.33	-33	-0.57	0.28	
N. Borena	Annual	30	0.28	0.70	1.27	0.56	0.092	0.27	-0.33	-215	-3.818	7E-05	-11.11
	Sep-Nov	30	0.43	0.72	0.63	0.38	0.003	0.27	-0.33	-117	-2.07	0.019	-3.255
	Mar-May	30	0.42	0.72	1.50	0.24		0.27	-0.33	-107	-1.89	0.029	
Kombolcha	Annual	30	0.16	-0.65	0.30	0.15		0.27	-0.33	109	1.93	0.97	
	Kiremt	30	0.24	-0.18	-0.06	0.09		0.27	-0.33	79	1.39	0.92	
	Belg	30	0.39	0.23	0.33	-0.043		0.27	-0.33	3	0.04	0.51	
Gore	Annual	30	0.13	0.93	1.56	0.04		0.27	-0.33	-125	-2.21	0.013	-12.19
	Kiremt	30	0.12	0.26	-0.30	0.41	0.14	0.27	-0.33	-125	-2.21	0.013	-7.75
	Belg	30	0.63	0.21	-0.54	0.11		0.27	-0.33	-53	-0.93	0.18	
Jijiga	Annual	30	0.39	3.14	12.21	0.34	-0.02	0.27	-0.33	-107	-1.89	0.029	
	Kiremt	30	0.45	2.02	4.06	0.6	-0.002	0.27	-0.33	-159	-2.82	0.0024	-5.87
	Belg	30	0.52	1.80	4.51	-0.019		0.27	-0.33	-67	-1.18	0.12	

[9] Coefficient of variation

Similarly, Jijiga and Dire Dawa stations are found in the same rainfall regimes of Bimodal type-1 as shown in Fig 2.2. And their annual rainfall cross-correlation is around 0.02, which is almost zero. Therefore, the work requires number of other stations, which are found around Jijiga and Dire Dawa to generalize trend at regional level. As well, stations near to Negele-Borena (Yabelo, Moyale, etc) should be investigated for trend to make similar conclusion.

Moreover, 3-year moving averages of annual rainfall over Dire-Dawa, D/Markos and Jijiga stations (Fig 6.3, 6.4 and 6.50) tend to show cyclicity component of rainfall about average value, which should be checked, in further studies. In contrast, Jima and Addis Ababa stations (Fig 6.6 and 6.7) show weak cycle about the average value. This cyclic component may lead to wrong conclusion of trend detection if the period of analysis includes incomplete part of the cycle.

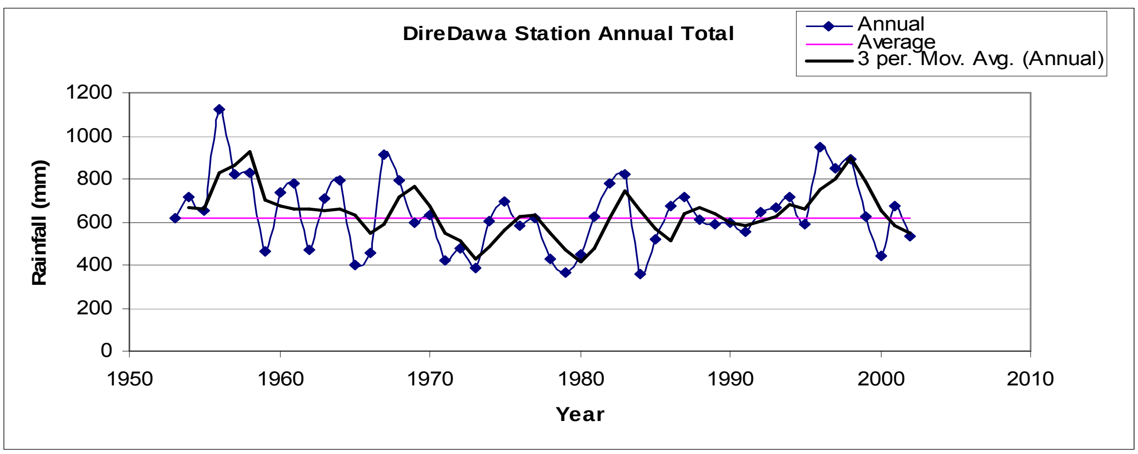

Fig 6-3 Three Year Moving Average Plot of Annual Rainfall for Dire-Dawa Station

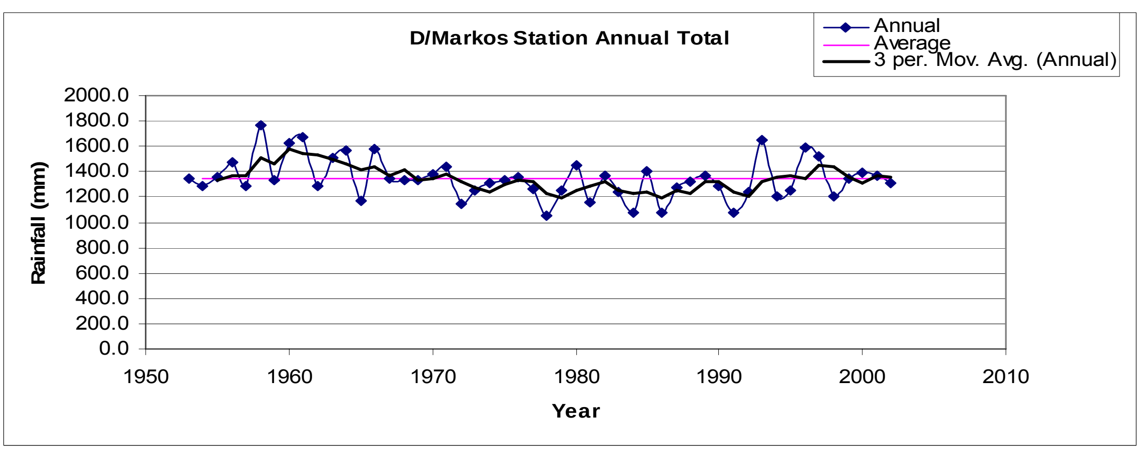

Fig 6-4 Three Year Moving Average Plot of Annual Rainfall for Debre-Markos Station

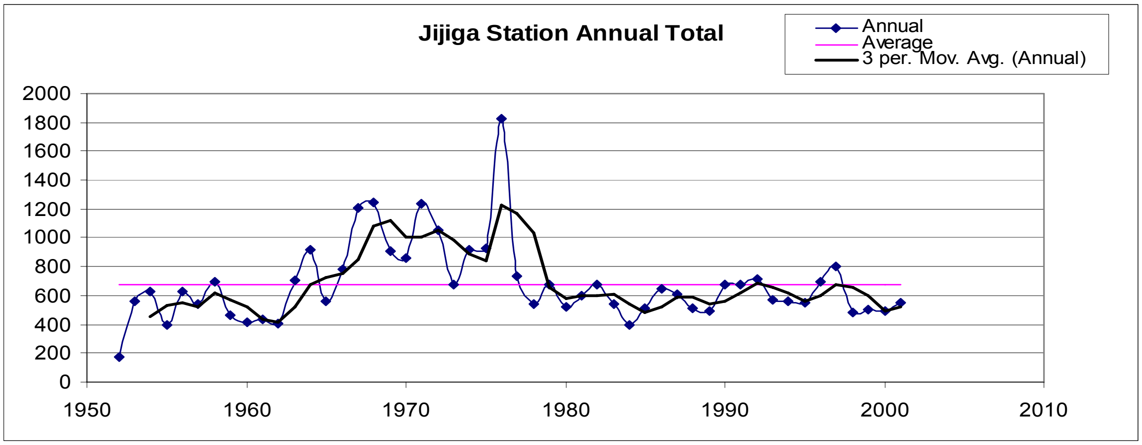

Fig 6-5 Three Year Moving Average Plot of Annual Rainfall for Jijiga Station

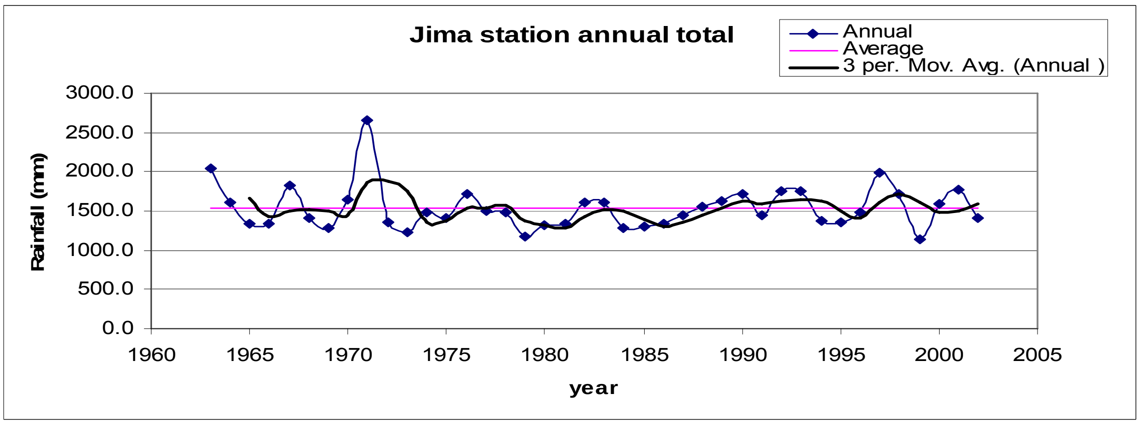

Fig 6-6 Three Year Moving Average Plot of Annual Rainfall for Jima Station

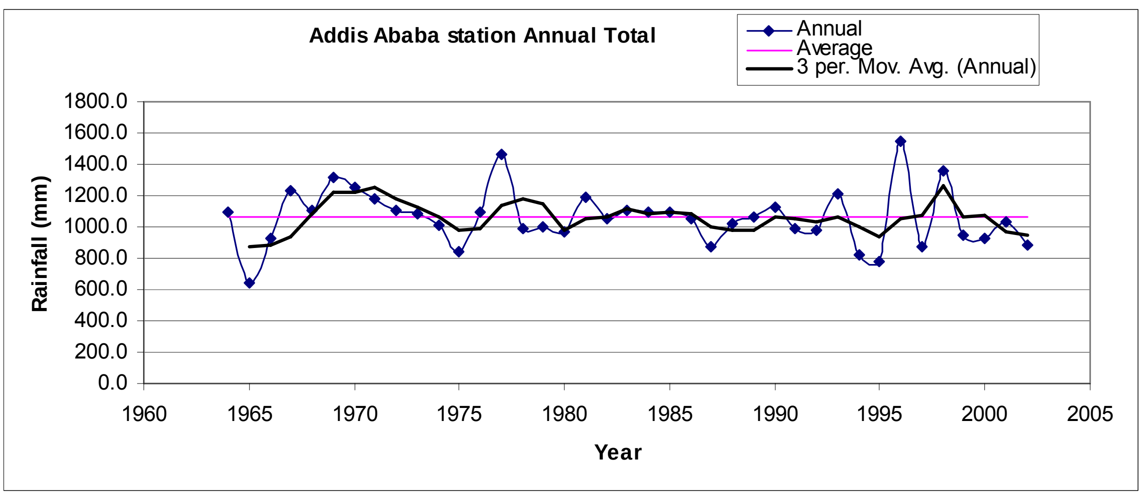

Fig 6-7 Three Year Moving Average Plot of Annual Rainfall for Addis Ababa Station

Study made by Mersha (2002) on rainfall cyclicity over selected stations in Ethiopia also shows that there appears to be cyclic tendency in the annual rainfall data. Gode, Dire Dawa, Negelle, and Debre Zeit stations show a clear cyclic pattern and are under 52, 52, 36 and 46 years rainfall cycle. Over Kombolcha, Gonder and Jima stations the cyclic trend are not strong and are under 48, 46 and 46 years of rainfall cyclic respectively.

Therefore, it is necessary to check the effect of this cyclic component on trend detection. Moreover, more number of stations should be checked for cyclicity and trend to generalize at the regional level.

6.3 Relationship between rainfall and cereal production in Ethiopia

The result of correlation from linear regression between rainfalls totals (Annual and Seasonal) and cereal Meher production on the study areas of Fig 4.6 and Fig 4.7 in the 1994-2001 periods is shown in Fig 6.8, Fig 6.9 and Fig 6.10. The rainfall is area estimate from interpolation of gauged data for the study area as described in section 5.3 and the rainfall seasons for the study area are classified as Meher season (June-September) and Belg seasons (February-May).

The analysis considers annual, main season (Kiremt) and Belg season rainfall. Belg rainfall is taken in to the analysis since it supports crop production offering the opportunity and encouragement for early land preparation for the main (Meher) season [18]. Moreover, FEWS NET reported that the national Meher yield and production correlate well with April-may rainfall in the long cycle crop growing region of Ethiopia [20].

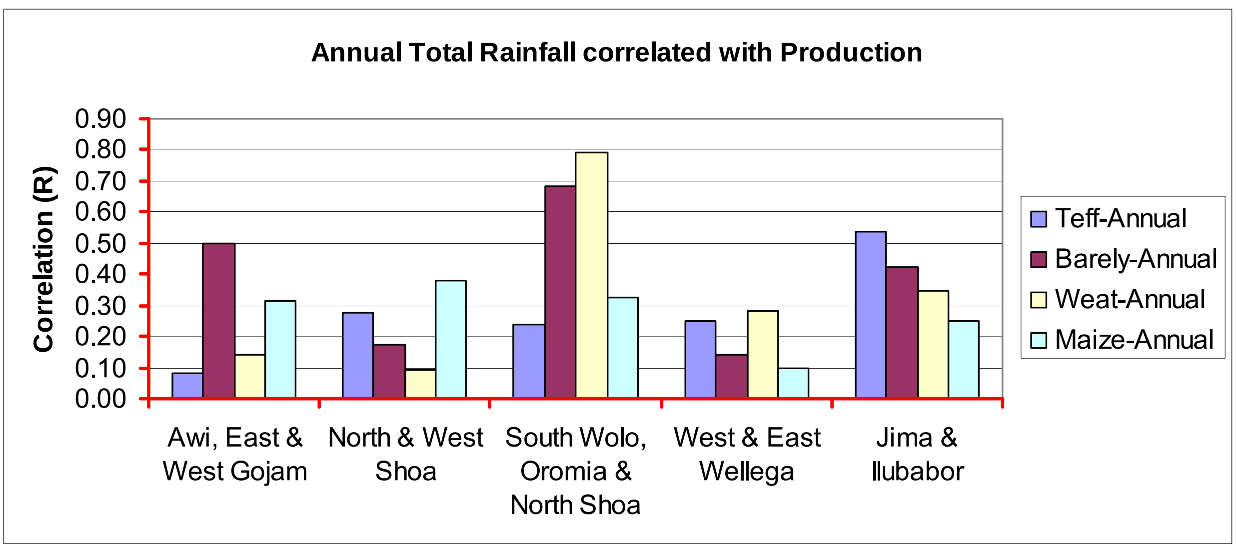

Fig 6-8 Correlation of Total Annual Rainfall with Cereal Meher Production

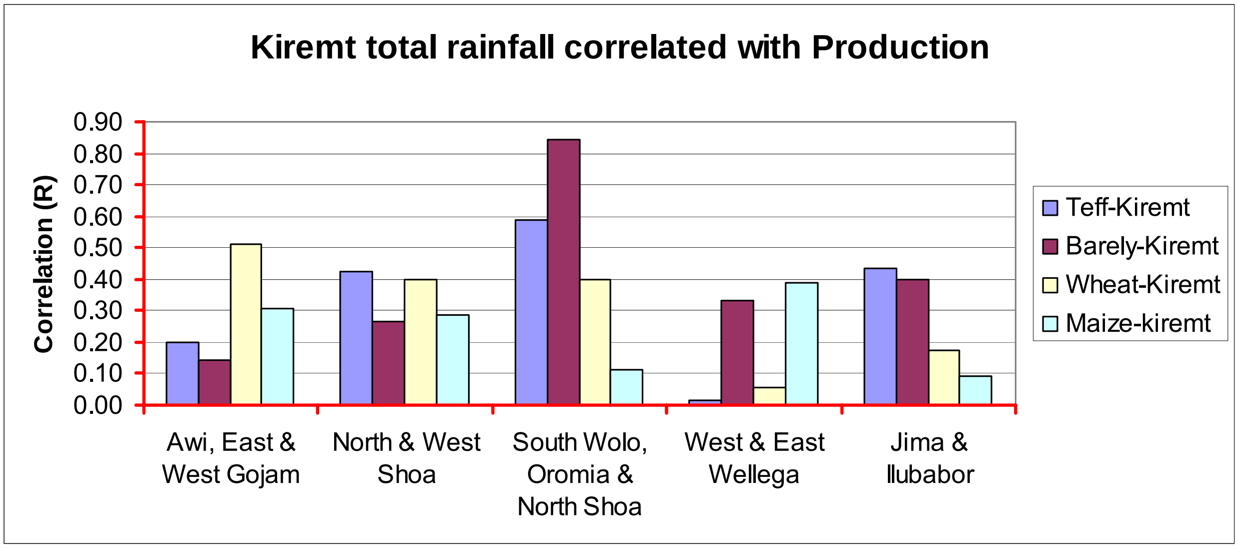

Fig 6-9 Correlation of Total Kiremt Rainfall with Cereal Meher Production

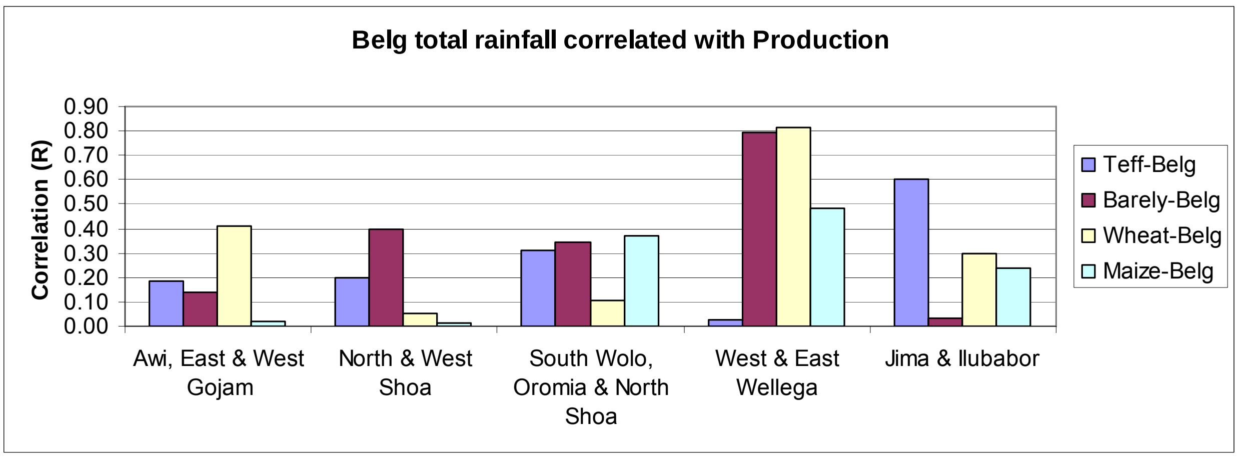

Fig 6-10 Correlation of Total Belg Rainfall with Cereal Meher Production

To check the significance of correlation between the two variables, t-test is performed using equation 5.1 and 5.2. For a sample size of 8 and α-level equal to 0.5, the critical t value is given as 2.45 in t-distribution table. The T value from Equation 5.2 for each study area is given in table below.

Table 6-4 T value to check significance of correlation

	1st	2nd	3rd	4th	5th
Teff-Annual	0.19	0.60	0.64	1.57	0.70
Teff-Kiremt	0.50	1.79	0.04	1.19	1.15
Teff-Belg	0.46	0.79	0.06	1.85	0.50
Barely-Annual	1.41	2.31	0.35	1.15	0.43
Barely-Kiremt	0.35	**3.83**	0.86	1.07	0.67
Barely-Belg	0.35	0.90	**3.20**	0.08	1.07
Wheat-Annual	0.35	**3.20**	0.72	0.90	0.23
Wheat-Kiremt	1.45	1.07	0.13	0.43	1.07
Wheat-Belg	1.11	0.26	**3.41**	0.77	0.13
Maize-Annual	0.81	0.84	0.24	0.63	1.00
Maize-Kiremt	0.79	0.28	1.03	0.23	0.73
Maize-Belg	0.05	0.99	1.36	0.59	0.02

Note: 1st is Awi, West and East Gojam zones, 2nd is South Wolo, oromia and North Shoa Zones, 3rd is West and East Welega Zones, 4th is Jima and Ilubabor Zones, and 5th is North and East Shoa Zones

Figures 6.8, 6.9, 6.10 and Table 6.4 show that there is only significant correlation in the 2nd (South Wolo, Oromia and Nort Shoa zone) and 3rd (West and East Wellega zones) study areas for Barely and wheat production. Bold values indicate situations where both variables have significant correlation. For most of the situations, the two variables don't show strong correlation.

As stated in the previous sections, Ethiopian agriculture is mainly dependent on rainfall. However, the above result shows that there is no significant correlation between productions and, annual and seasonal rainfall. This can be due to shortage of analysis period to include drought years and consideration of rainfall isolating from all other agronomic factors such as growing period, radiation, temperature, pests, diseases, etc. However, the result may imply that the total annual and seasonal rainfall amount may not be indicative for the failure of production but the distribution of amount of rainfall during crop growing period is important.

To compare water requirement of crops during its various stages with the water supply i.e., rainfall, available at the time, the response of crops to water stress should be understood. The yield response to water deficiency during part of total growing period varies depending on how sensitive the crop at that growing period. However, crops are generally more sensitive to water deficient during emergence, flowering and early yield formation [16]. Therefore, it would be preferable to see how rainfall distribution looks like during these crops growing period.

To do this, crop growing periods and their crop water requirement should be known in the study areas. These data couldn't be found in each study areas. However, Appendix F tries to compare observed monthly rainfall and mean monthly crop water requirements of Teff, Maize, Barely and Wheat for selected stations during their growing in 1994-2001. Average potential evapo-transpirations (PET) of the crops are obtained for the selected stations from the Abbay basin Master Plan. PET is changed to crop water requirement using crop coefficient factor give in table 3.1, 3.2, 3.3, and 3.4. Appendix F shows observed monthly rainfall is greater than the crop water requirements during the growing months of June, July, August and September in all stations except for Bahir Dar station (1995). In addition, during October on 1994, 1995, & 1996, Bahir Dar and Debre Markos station show that the crop water requirement is greater than the observed rainfall. These situations may decrease the grain yield of the crops.

Since the above analysis isn't adequate to conclude, it is recommended to extend this study to more number of stations and to get a better view of relationship of rainfall and production it is good to subdivide the growing season in to different stages (emergence, vegetative, flowering, yield formation and ripening stages), estimate the water requirement in each of the stage and then compare the water requirement against observed rainfall during the stages.

In addition, variation of total annual and seasonal rainfall alone may not be considered as a factor for the failure of production on the study areas. Other agricultural inputs (fertilizers, improved seeds, etc) and other factors for failure of production (late onset of rainfall, pests, etc) should be studied together to see the effect of rainfall on agriculture in Ethiopia. Moreover, the analysis period should include drought years, which occur in the country, and the study area should be relatively smaller than area used in this thesis work.

7 Conclusion and Recommendation

7.1 Conclusions

From the comparison of monthly satellite estimate with gauged data, the following points are concluded:

I. The result of correlation between monthly satellites estimate from NOAA and gauged rainfall reveal that there is a significant correlation between the two estimates with an average correlation coefficient of 0.77 for 37 number of gauge station used in the country. The Northern and Northwestern part of the country have above average correlation coefficient and the Southern, Southwestern, and Southeastern part of the country have correlation coefficient below average.

II. In addition, the root mean squared errors (RMSE) between the two variable for 37 gauge station show that the Eastern (Harer, Jijiga, D.Dawa stations), Southern (Yabello, N.Borena stations) and Southeastern (Gode, Dega Habour stations) part of Ethiopia have below average (66mm) error whereas Northwestern (Gonder, Debre Tabore stations) and Southwestern (Jima, Gore, Jinka stations) part of the country have above average error.

III. From experiment made on estimating missed monthly gauged data using satellite estimate, it is found that in average there is deviation of 68mm between the estimated and the actual rainfall. Eastern (Harer, Jijiga, D.Dawa stations), Southern (N.Borena , Yabello stations) and Southeastern (Gode station) have error less than 68mm between the two variables whereas Central (Addis A., D.Birhan stations), Southwestern (Jima) and Northern (Mekele,Bahirdar) part of the country, the error is above average RMSE value, 68mm.

IV. The CPC technique, generally, shows underestimation on the country. This can be due to the fact that the technique is designed to estimate rainfall from convective clouds. However, in Ethiopia, rain from warm clouds especially at high altitudes (Koffle and Debre Tabour Stations) is significant. Moreover, the difference between satellite estimates and observed gauged rainfall, i.e. R_s-R_g, increases from 1996 to 2000

(Appendix-c). This can be due to the fact that the calibration for CPC method for warm cloud rainfall over mountainous regions was made using data from across the whole continent of Africa and only for a short period in 1995 [32]. Therefore, with more comprehensive calibration, the method could produce useful estimate.

In the work of identifying any change on total annual and seasonal rainfall within recent years in the country using 10 stations, the result leads to the following conclusion.

I. Belg rainfall totals in the country don't show any significant change (trend).

II. Kiremt rainfall totals show significant change at Gore and Jijiga station. Sep-Nov rainfall total shows significant change at N.Borena.

III. Annual rainfall totals also show significant change at Gore and N. Borena station.

And finally, the thesis work on the relationship of rainfall and production reveal that

I. Total annual rainfall doesn't show correlation with production of cereals of Teff, Barely, Wheat and Maize in the study areas except for annual rainfall with Wheat production in the 2rd study area (South wolo, Oromia and North Shoa Zones).

II. Total Kiremt rainfall also doesn't show correlation with production of cereals of Teff, Barely, Wheat and Maize in the study areas except for Kiremt rainfall with Barely production in the 2rd study area (South wolo, Oromia and North Shoa Zones).

III. Total Belg rainfall doesn't also show correlation with production of cereals of Teff, Barely, Wheat and Maize in the study areas except for Belg rainfall with Barely and Wheat production in the 3rd study area (West & East Welega).

IV. Appendix F shows observed monthly rainfall is greater than the crop water requirements during the growing months in all selected stations in the analysis period except for Bahir Dar station on 1994 (October), 1995 (growing months), & 1996 (October) and Debre Markos station during October on 1994, 1995 and 1996.

V. Generally, the effect of rainfall on production cannot be considered in isolation from other factors like fertilizer, seed varieties, pests, change of other meteorological variables like temperature, etc. It is better to compare available rainfall with the water requirement of crops during their growing period in the study areas to understand rainfall effect on production. However, this is not well studied here due to the difficulty of obtaining crop water requirement during their growing period.

7.2 Recommendations

The following points are recommended to future work:

I. CPC rainfall estimation technique generally shows underestimation and its correlation with some gauged data (Dodola, Goba, Koffele stations, etc) is, though it is significant, relatively small. Therefore, with a better calibration of the method using more gauge data, the method could produce a better estimate.

II. Similar study should be done with other satellite rainfall estimation technique like TAMSAT to use the best in the country.

III. Here, annual and seasonal rainfall totals are studied using only 10 gauge stations. To generalize trend of rainfall at regional level and to increase the spatial coverage, it is recommended to extend this study by including more number of stations.

IV. In addition, the moving average plot and research made by Mersha(2002) show that there appears to be cyclic tendency in annual rainfall. The cyclicity of rainfall should be checked on more number of stations and its effect on detection of rainfall trend should be studied.

V. No significant correlation exists between production and, total annual and seasonal rainfall in the study. However, the study was made using short data in the period of 1994-2001. Therefore, with long analysis period and smaller study area, the analysis should be done. Along with rainfall, other agronomic factor should be dealt. In addition, subdividing the growing season of crops in to different stages and estimating the water requirement during these stages, comparison can be made between water requirement and supplied water (rainfall) to see clearly the relationship.

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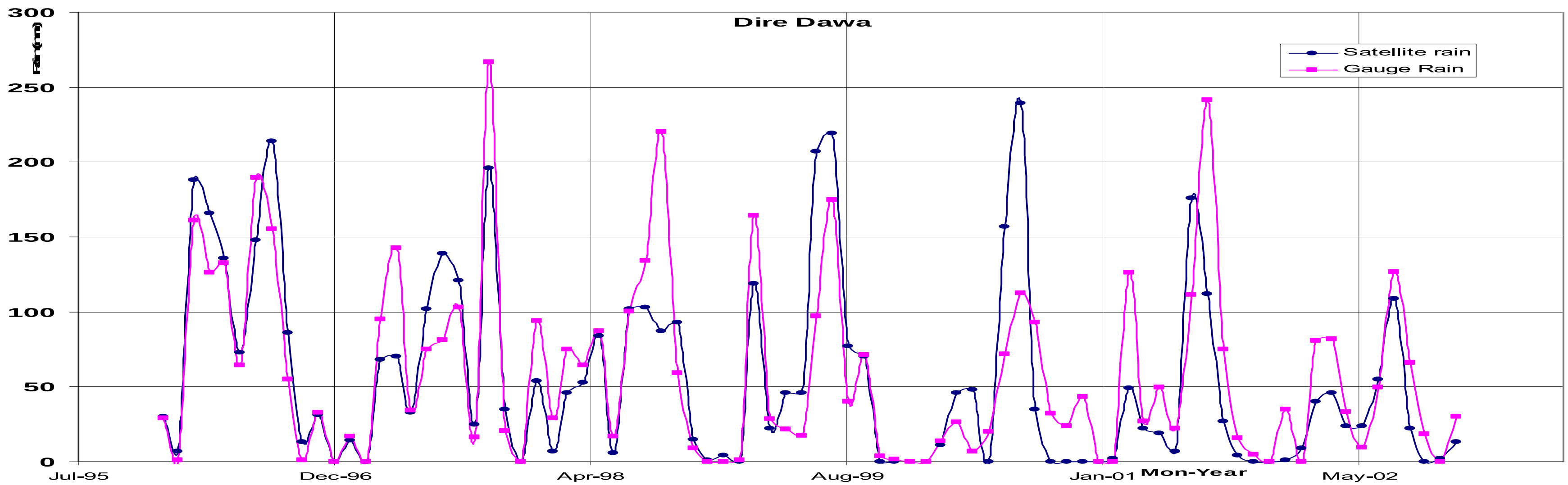
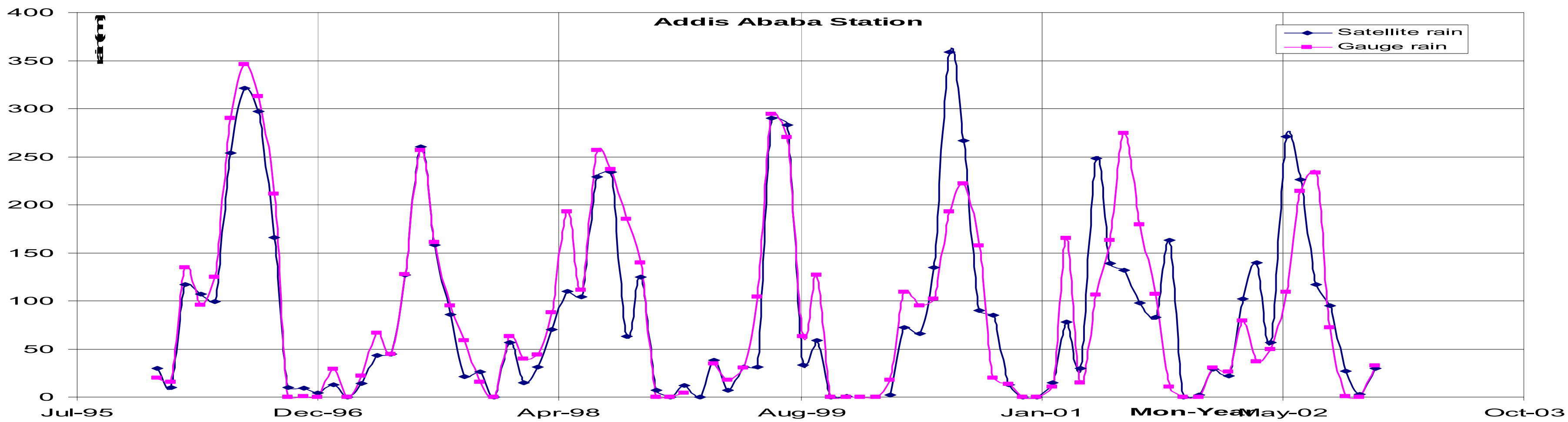
Appendix A Description of Rain Gauge Stations

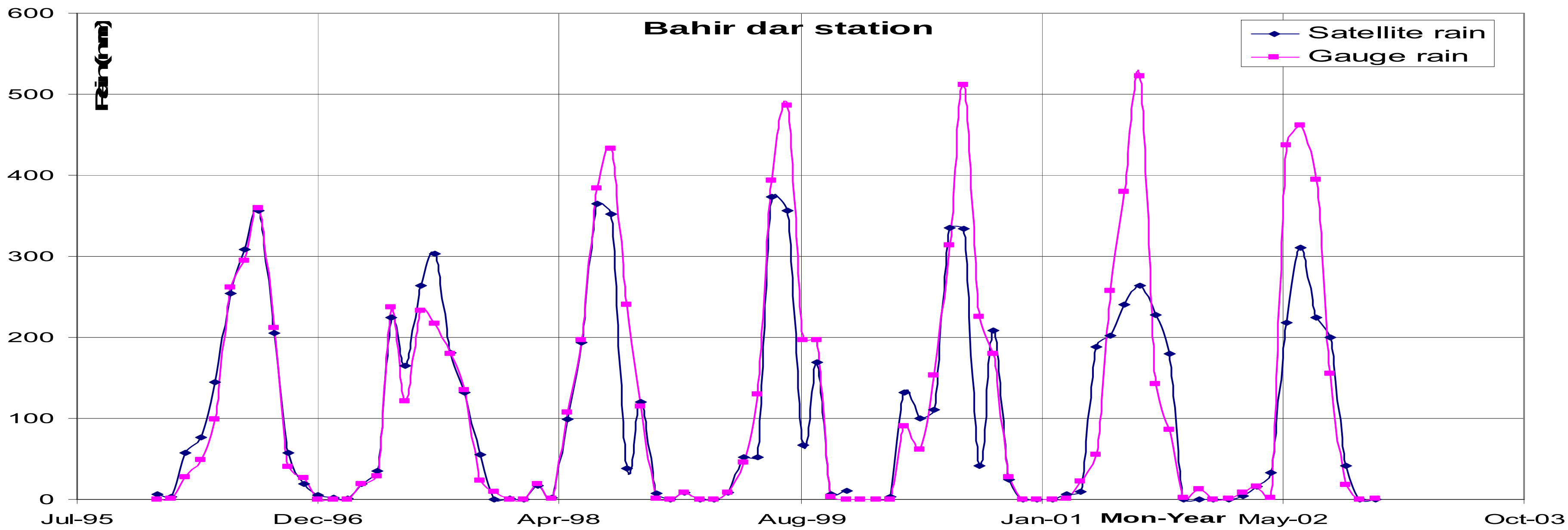
ID	Station Name	Region	Latitude (Decimal degree)	Longitude (Decimal degree)	Elevation (M a.s.l)	Beging Year
1	Adame Tulu	Shoa	7.95	38.70	1880	1958
2	Addis ababa	Shoa	9.03	38.75	2410	1963
3	Agaro	Keffa	7.85	36.60	2030	1953
4	Awash	Shoa	9.00	40.13	915	1952
5	Bahir Dar	Gojjam	11.60	37.45	1770	1970
6	Bonga	Keffa	7.22	36.23	1725	1953
7	Chagni	Gojjam	10.92	36.43	1725	1984
8	Debre Birhan	Shoa	9.63	39.50	2750	1954
9	Debre Tabore	Gonder	11.88	38.03	2690	1951
10	Debre marcos	Gojjam	10.35	37.72	2450	1953
11	Debre sina	Shoa	9.88	39.75	2000	1962
12	Debre zeit	Shoa	8.73	39.03	1900	1951
13	Dega Habour	Harrargie	8.22	43.55	1070	1954
14	Dilla	Sidamo	6.42	38.30	1560	1954
15	Dire Dawa	Harrargie	9.60	41.42	1210	1952
16	Dodola	Bale	6.98	39.18	1680	1988
17	Endeselassie	Tigray	14.10	38.27	1913	1961
18	Fiche	Shoa	9.83	38.77	2800	1954
19	Gambela	Ilubabor	8.25	34.58	480	1956
20	Gelemso	Harrargie	8.82	40.52	1820	1969
21	Goba	Bale	7.02	39.97	2710	1962
22	Gode	Harrargie	5.90	43.58	275	1966
23	Gonder	Gonder	12.53	37.43	2270	1952
24	Gore	ILUBABOR	8.17	35.55	2024	1951
25	Harar	Harrargie	9.30	42.12	1856	1969
26	Homora	Gonder	14.28	36.58	760	1968
27	Jara	Shoa	10.50	39.85	1600	1962
28	Jigiga	Harrargie	9.60	42.58	1840	1952
29	Jimma	Keffa	7.67	36.83	1820	1952
30	Jinka	Gamo Gofa	5.78	36.55	1430	1983
31	Kebridehar	Harrargie	6.73	44.30	545	1959
32	Kobo	Wollo	12.13	39.63	1470	1976

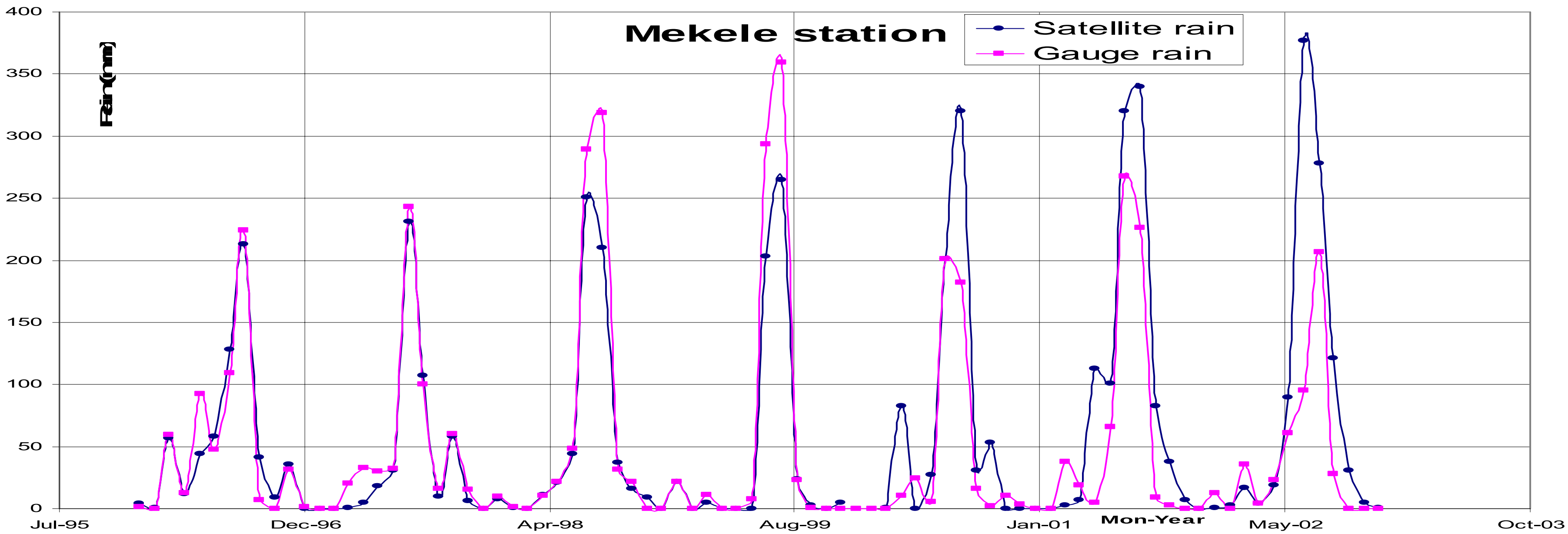
ID	Station Name	Region	Latitude (Decimal degree)	Longitude (Decimal degree)	Elevation (M a.s.l)	Beging Year
33	Koffle	Arssi	7.07	38.78	2680	1961
34	Koka Dam	Shoa	8.42	39.17	1595	1943
35	combolcha	Wollo	11.07	39.75	1900	1952
36	Maji	Keffa	6.33	35.63	2316	1954
37	Mekele	Tigray	13.50	39.42	2210	1959
38	Mendi	Wellega	9.78	35.08	1650	1955
39	Metehar	Shoa	8.87	39.90	930	1984
40	Moyale	Sidamo	3.52	39.07	1110	1978
41	Negele Borena	Sidamo	5.28	39.75	1440	1952
42	Nedjo	Wellega	9.50	35.48	1800	1952
43	Nekemt	Wellega	9.08	36.60	2080	1971
44	Pawe	Gojjam	11.15	36.05	1050	1987
45	Sebeta	Shoa	8.93	38.63	2240	1962
46	Sirinka	Wollo	11.55	39.62	2000	1966
47	Shambu	Wellega	9.57	37.12	2400	1969
48	Woldia	Wollo	11.82	39.60	1960	1954
49	Wolkite	Shoa	8.27	37.75	1860	1954
50	Wonji	Shoa	8.42	39.25	1540	1951
51	Yabelo	Sidamo	4.88	38.10	1740	1957

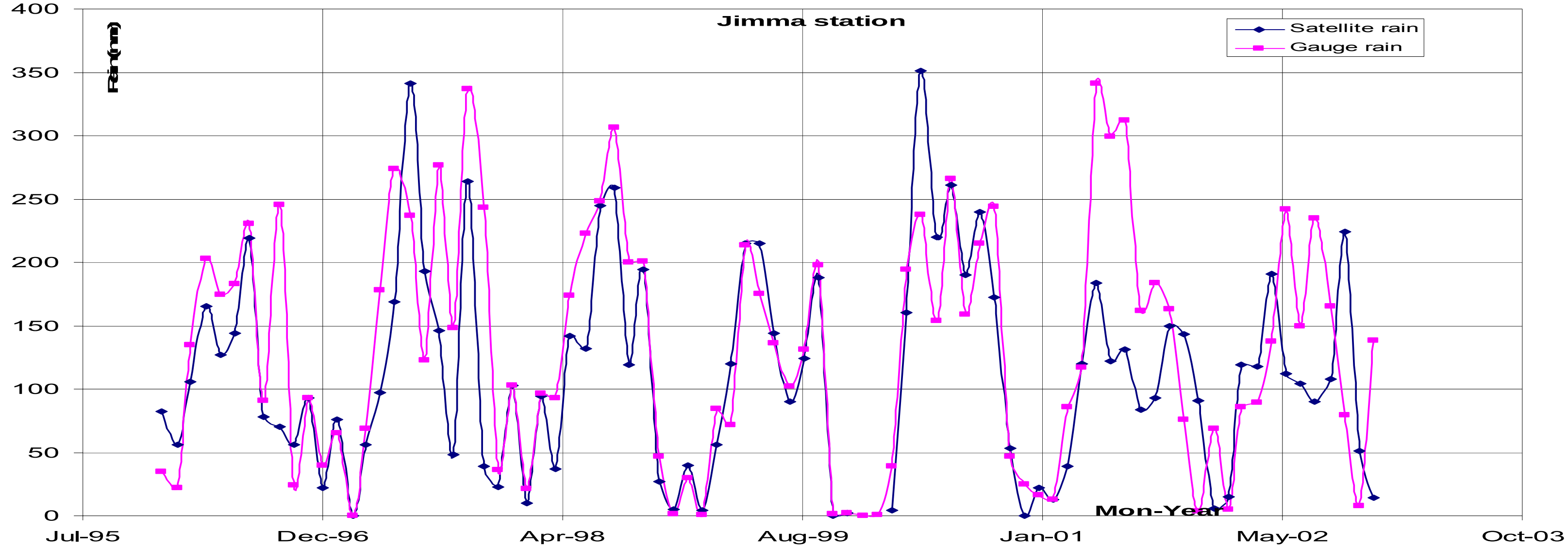
Appendix B Time Series Plot of Satellite Estimate & Gauged Rainfall for Selected Stations

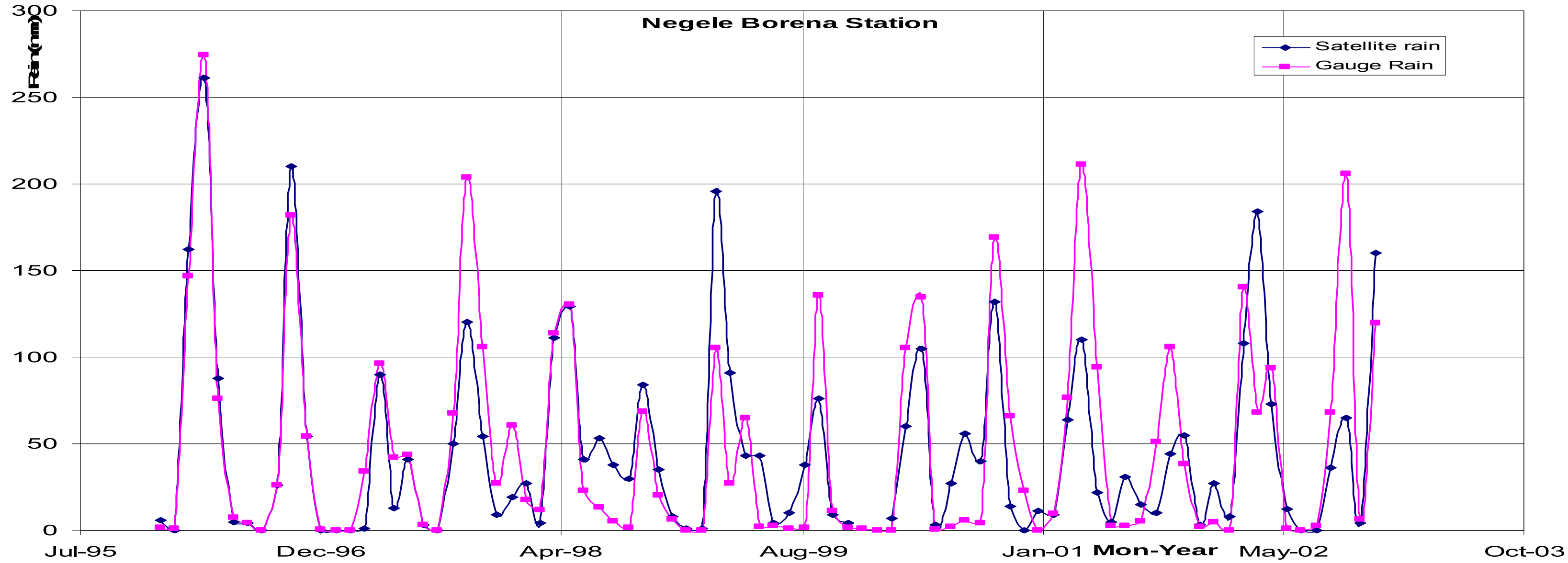


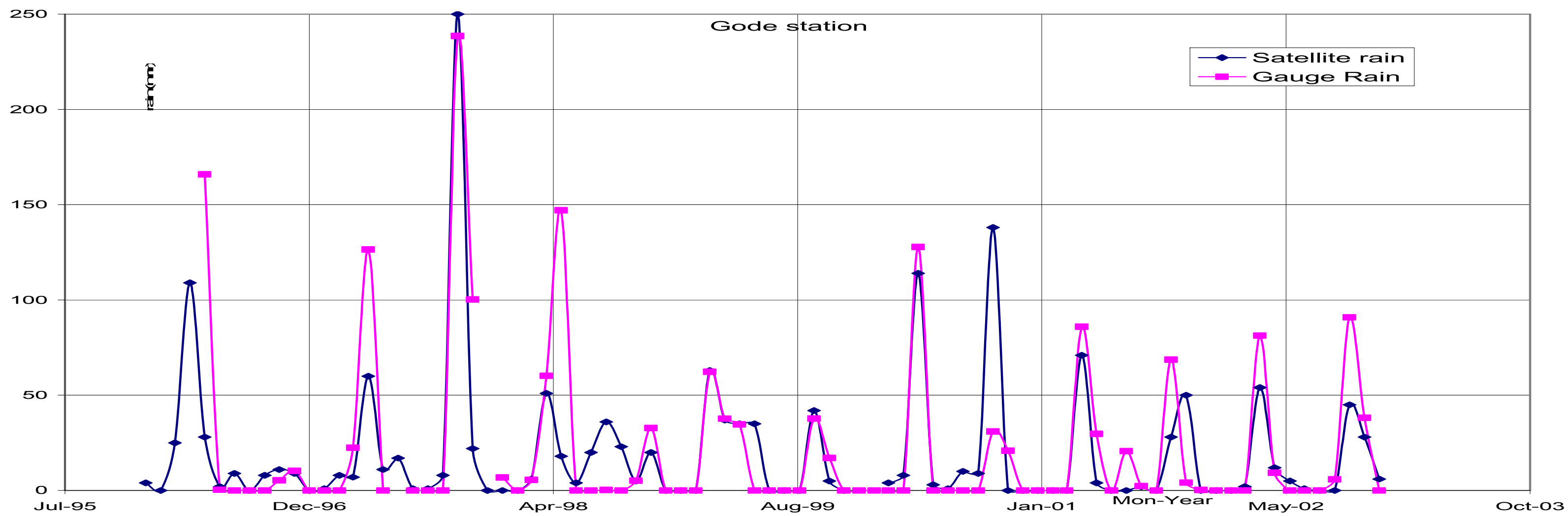


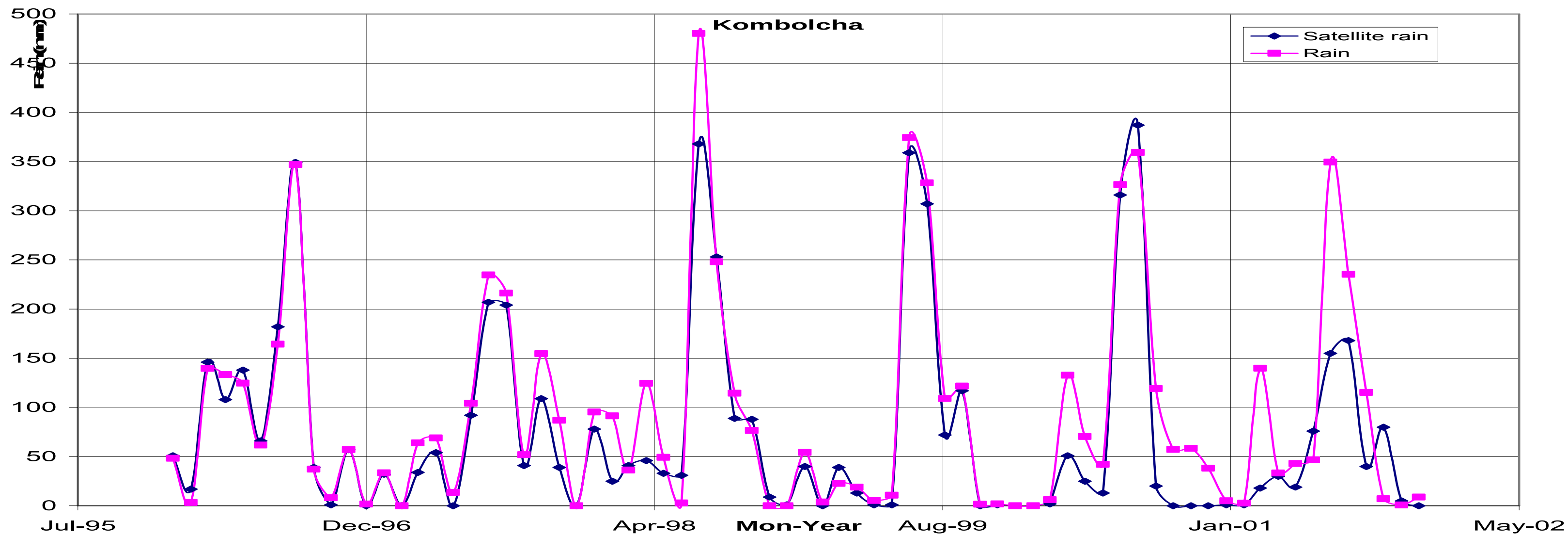

Bahir dar station
Satellite rain
Gauge rain
Rain(mm)
600
500
400
300
200
100
0
Jul-95
Dec-96
Apr-98
Aug-99
Jan-01
Mon-Year
May-02
Oct-03

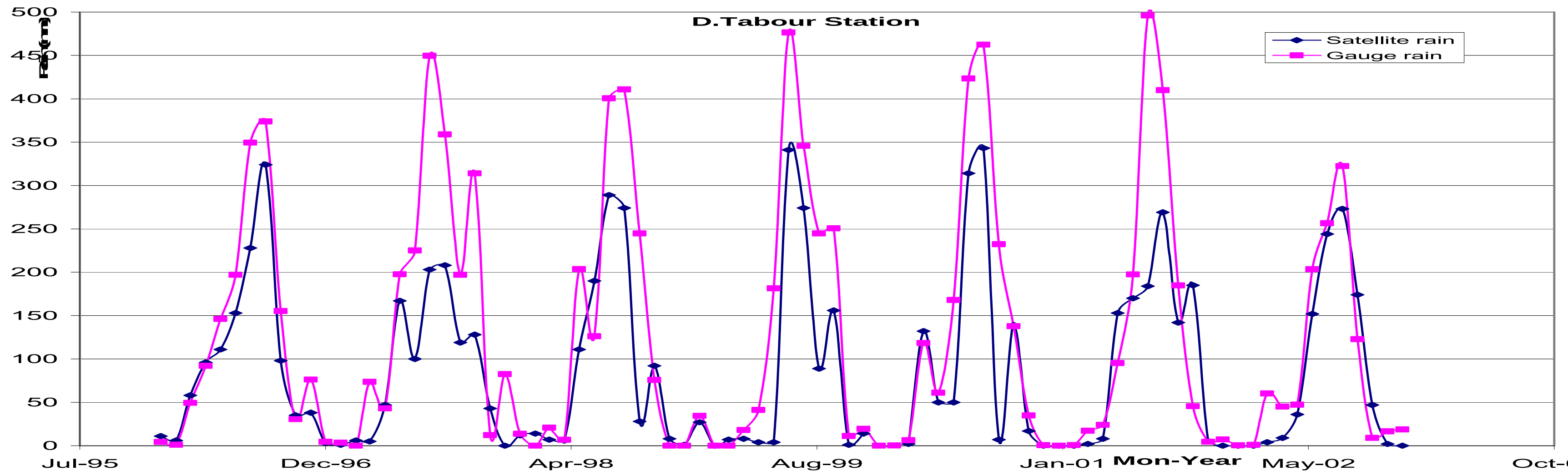

Mekele station
Satellite rain
Gauge rain
Rain(mm)
400
350
300
250
200
150
100
50
0
Jul-95
Dec-96
Apr-98
Aug-99
Jan-01
Mon-Year
May-02
Oct-03

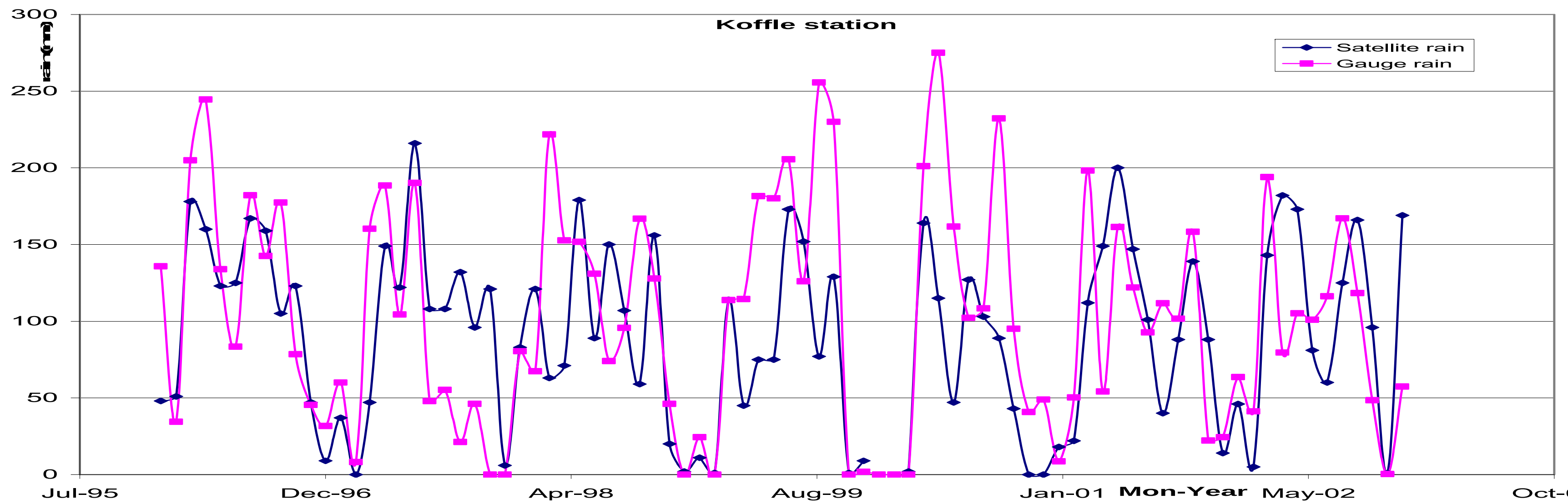

Jimma station
Satellite rain
Gauge rain
Rain(mm)
Mon-Year
400
350
300
250
200
150
100
50
0
Jul-95
Dec-96
Apr-98
Aug-99
Jan-01
May-02
Oct-03


Negele Borena Station
Satellite rain
Gauge Rain
Rain(mm)
Mon-Year
300
250
200
150
100
50
0
Jul-95
Dec-96
Apr-98
Aug-99
Jan-01
May-02
Oct-03

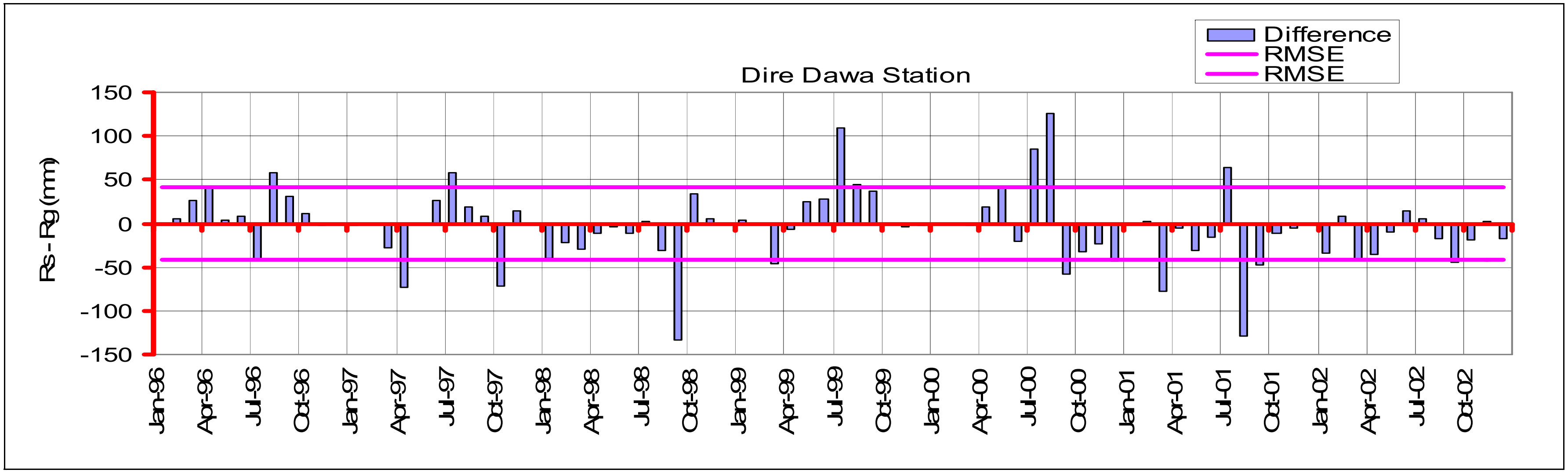

Gode station
Satellite rain
Gauge Rain
rain(mm)
250
200
150
100
50
0
Jul-95
Dec-96
Apr-98
Aug-99
Jan-01
Mon-Year
May-02
Oct-03

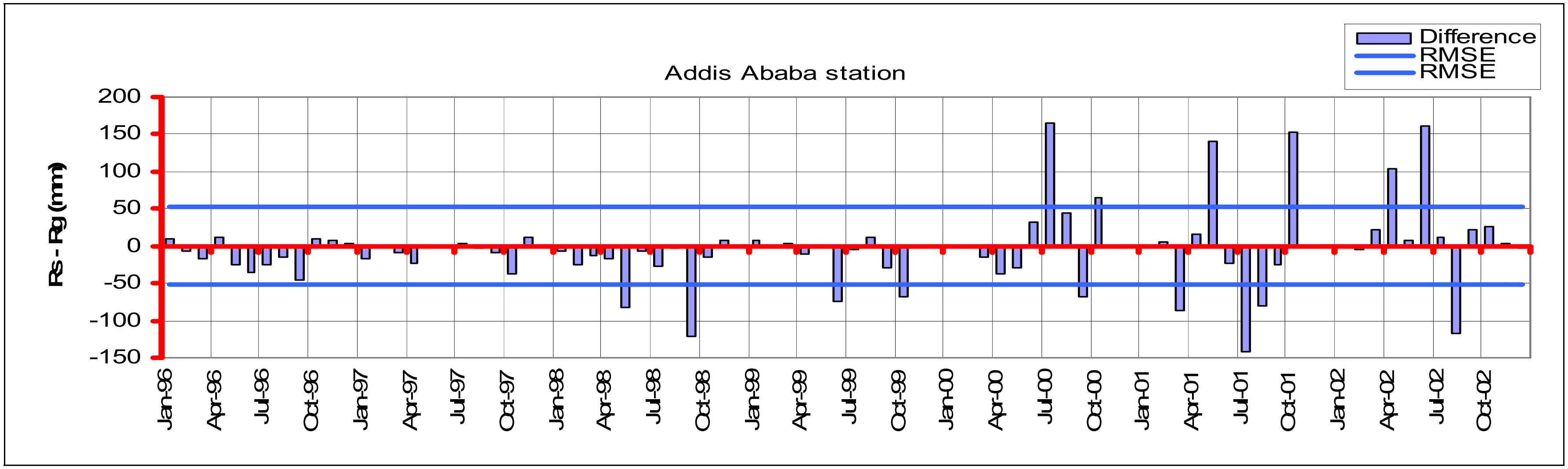

Kombolcha
Satellite rain
Rain
Rain(mm)
500
450
400
350
300
250
200
150
100
50
0
Jul-95
Dec-96
Apr-98
Mon-Year
Aug-99
Jan-01
May-02

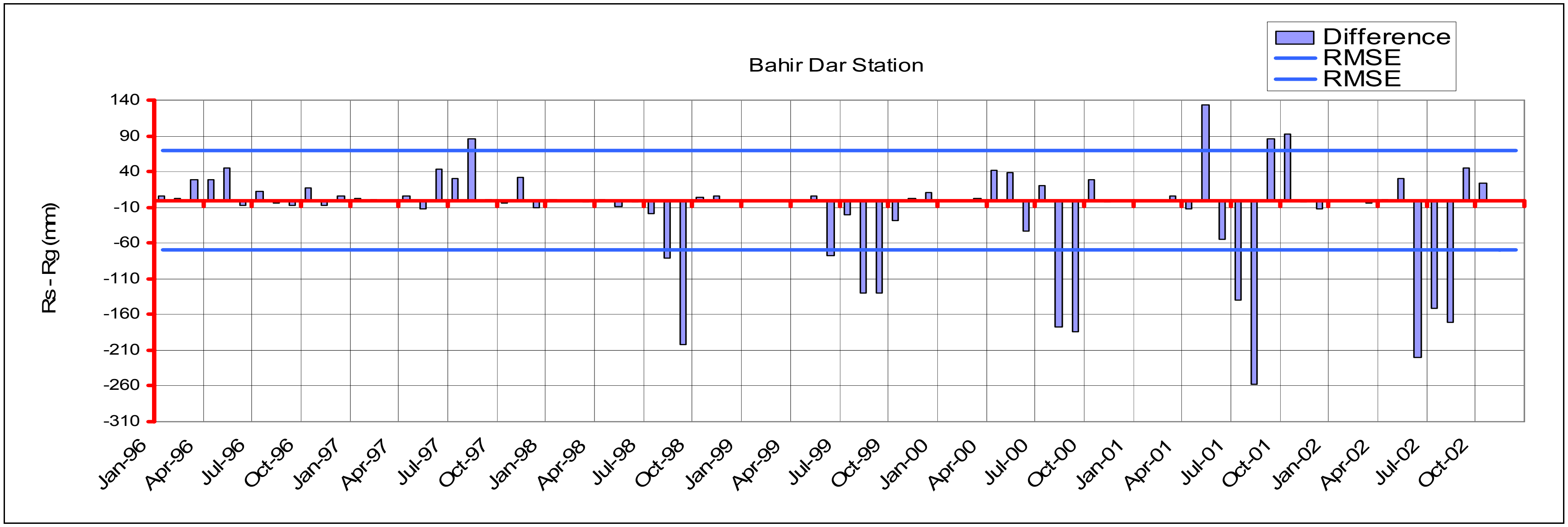

D.Tabour Station
Satellite rain
Gauge rain
500
450
400
350
300
250
200
150
100
50
0
Jul-95
Dec-96
Apr-98
Aug-99
Jan-01
Mon-Year
May-02

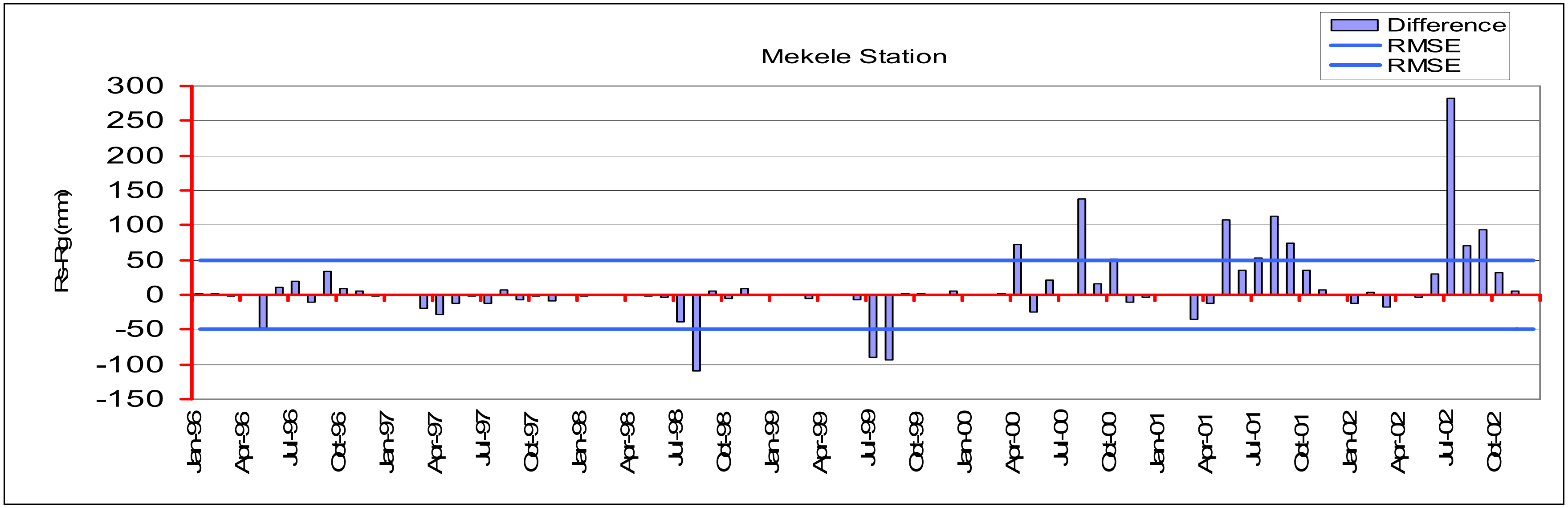

Koffle station
Satellite rain
Gauge rain
300
250
200
150
100
50
0
Jul-95
Dec-96
Apr-98
Aug-99
Jan-01
Mon-Year
May-02

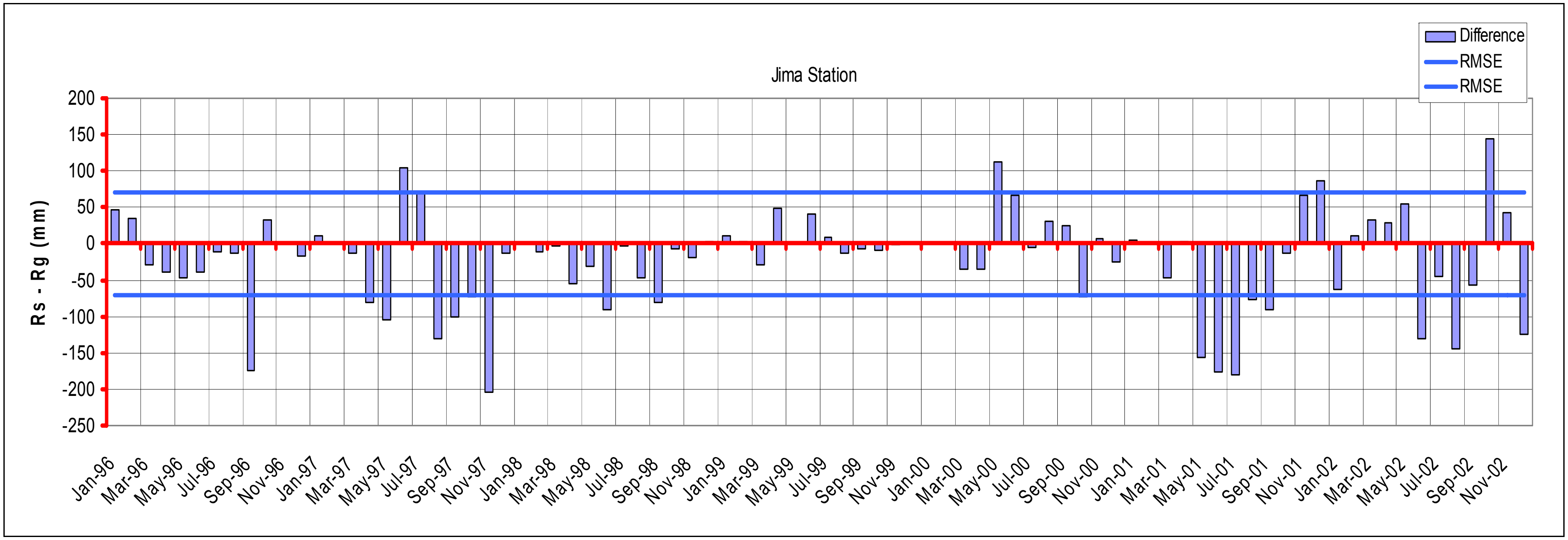
Appendix C Difference between Satellite Estimated and Gauged Rainfall for Selected Stations

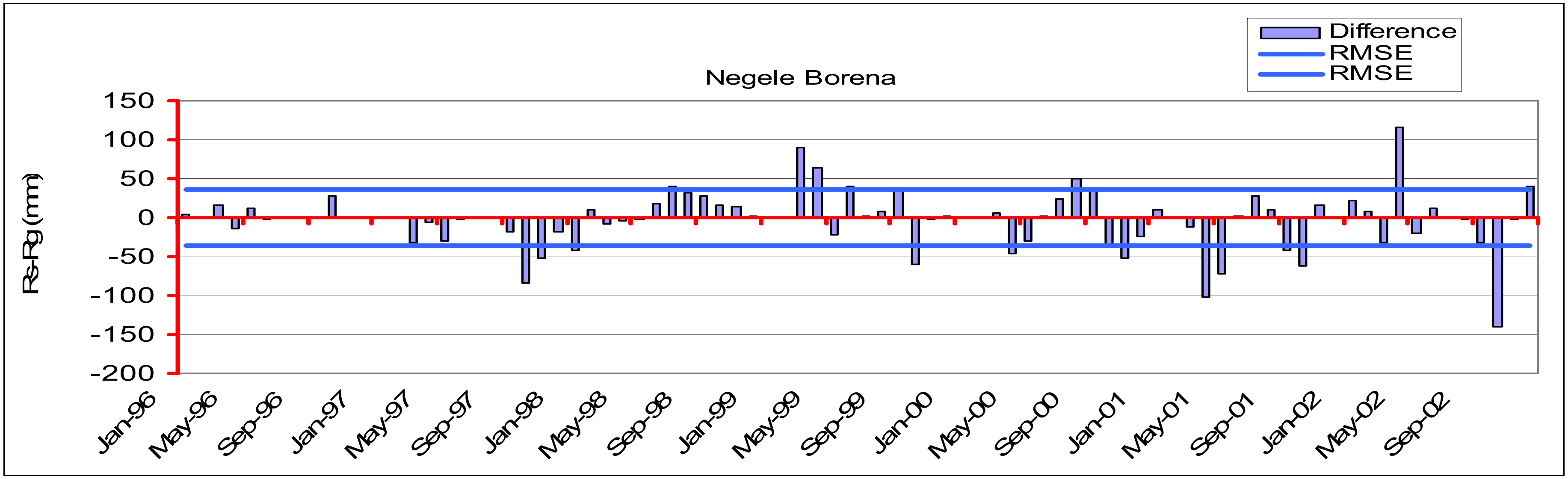


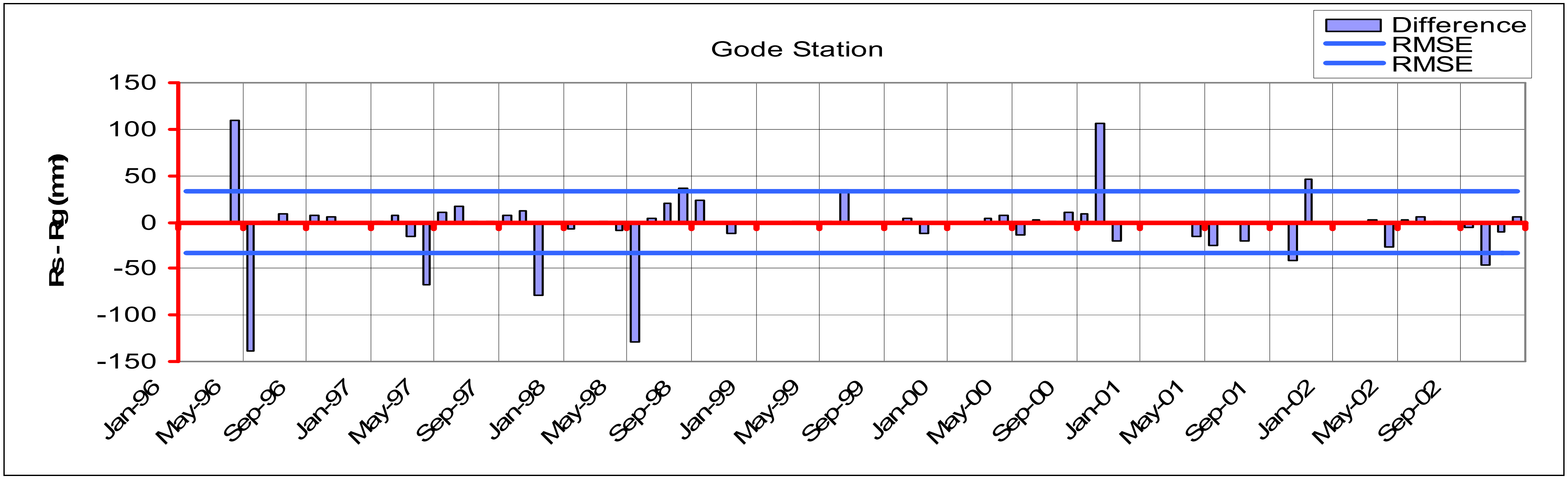


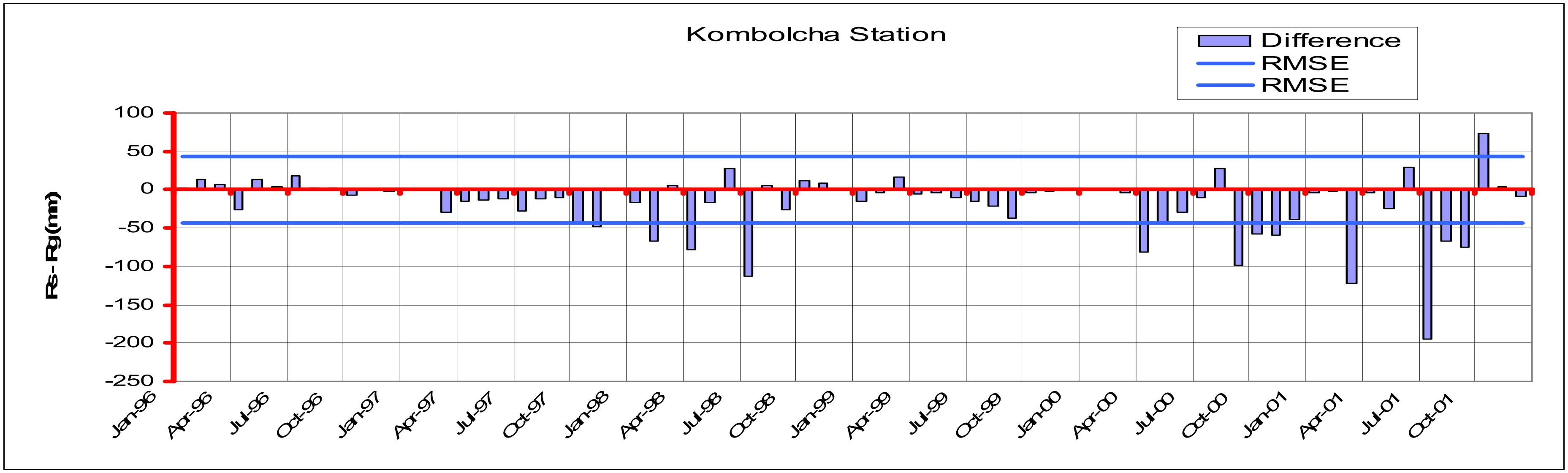

Bahir Dar Station
Difference
RMSE
RMSE
Rs - Rg (mm)
140
90
40
-10
-60
-110
-160
-210
-260
-310
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02

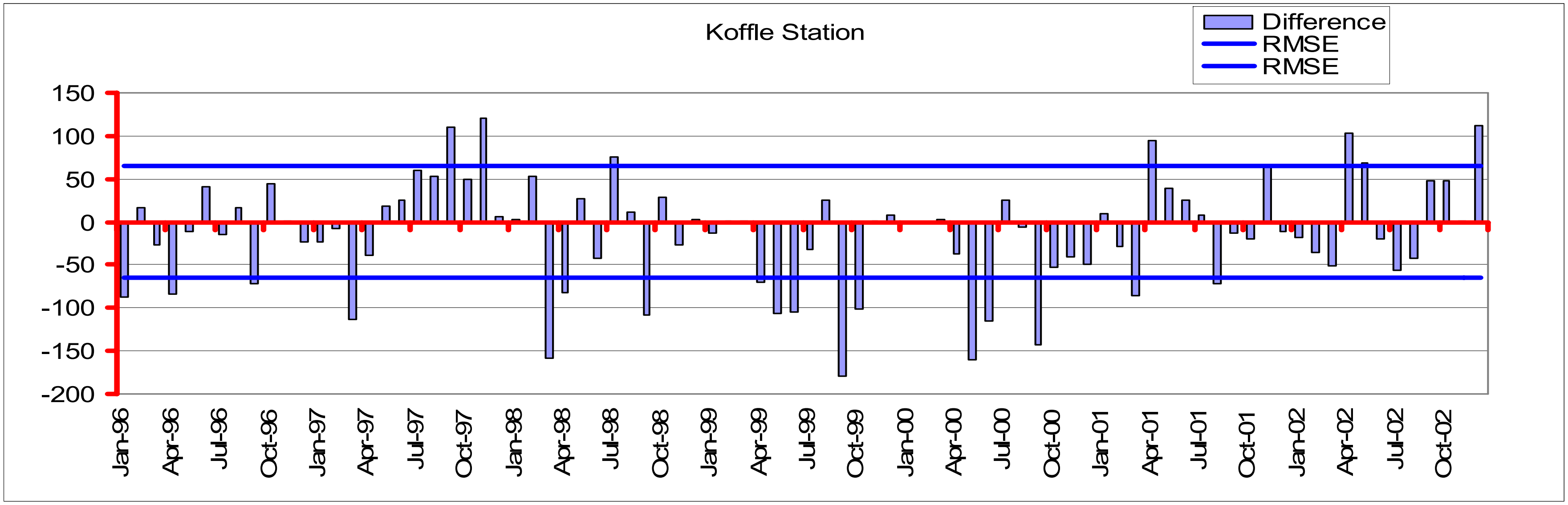

Mekele Station
Difference
RMSE
RMSE
Rs-Rg(mm)
300
250
200
150
100
50
0
-50
-100
-150
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02

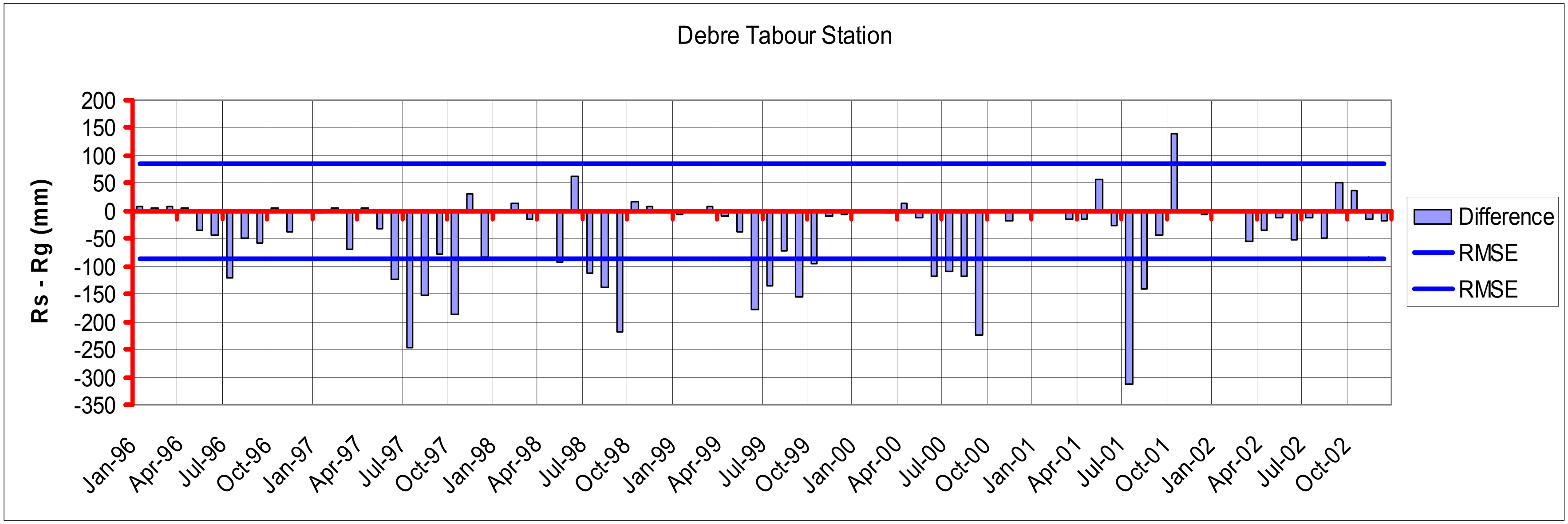

Jima Station
Difference
RMSE
RMSE
Rs - Rg (mm)
200
150
100
50
0
-50
-100
-150
-200
-250
Jan-96 Mar-96 May-96 Jul-96 Sep-96 Nov-96 Jan-97 Mar-97 May-97 Jul-97 Sep-97 Nov-97 Jan-98 Mar-98 May-98 Jul-98 Sep-98 Nov-98 Jan-99 Mar-99 May-99 Jul-99 Sep-99 Nov-99 Jan-00 Mar-00 May-00 Jul-00 Sep-00 Nov-00 Jan-01 Mar-01 May-01 Jul-01 Sep-01 Nov-01 Jan-02 Mar-02 May-02 Jul-02 Sep-02 Nov-02


Negele Borena
Difference
RMSE
RMSE
Rs-Rg (mm)
150
100
50
0
-50
-100
-150
-200
Jan-96 May-96 Sep-96 Jan-97 May-97 Sep-97 Jan-98 May-98 Sep-98 Jan-99 May-99 Sep-99 Jan-00 May-00 Sep-00 Jan-01 May-01 Sep-01 Jan-02 May-02 Sep-02

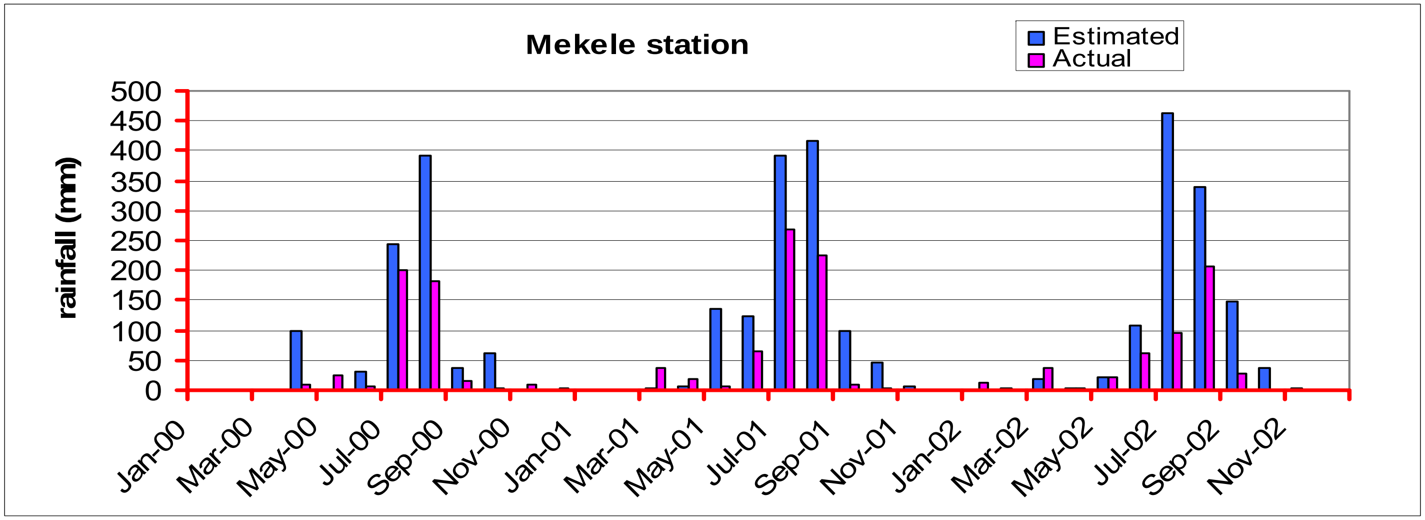

Gode Station
Difference
RMSE
RMSE
Rs - Rg (mm)
150
100
50
0
-50
-100
-150
Jan-96
May-96
Sep-96
Jan-97
May-97
Sep-97
Jan-98
May-98
Sep-98
Jan-99
May-99
Sep-99
Jan-00
May-00
Sep-00
Jan-01
May-01
Sep-01
Jan-02
May-02
Sep-02

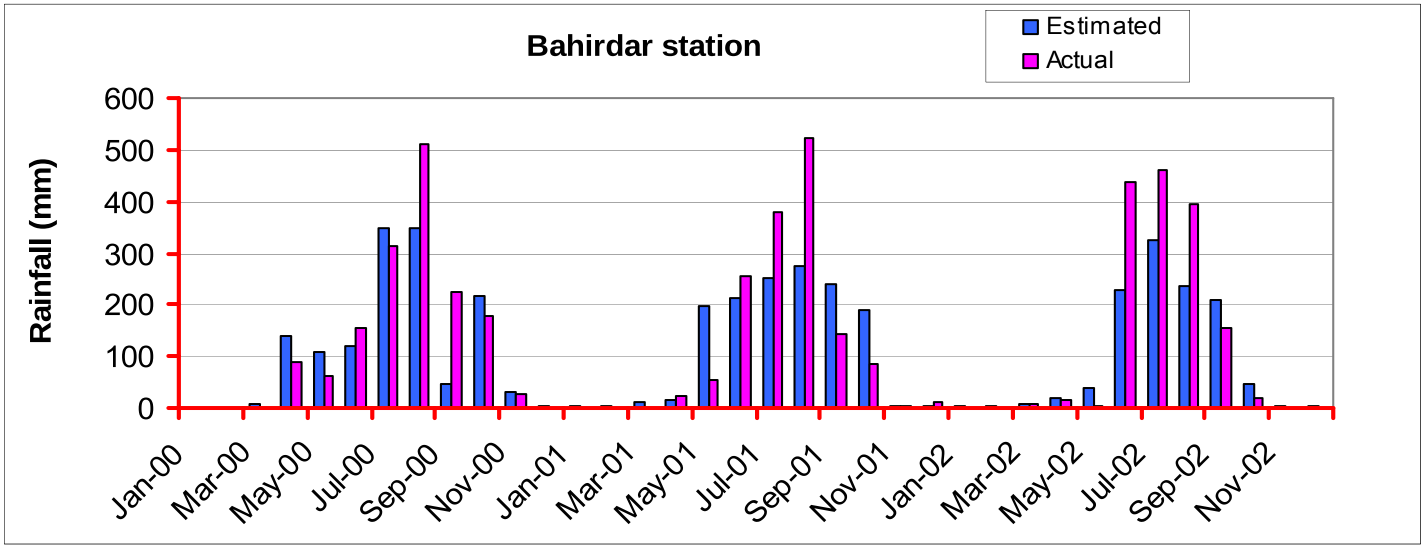

Kombolcha Station
Difference
RMSE
RMSE
Rs - Rg(mm)
100
50
0
-50
-100
-150
-200
-250
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01

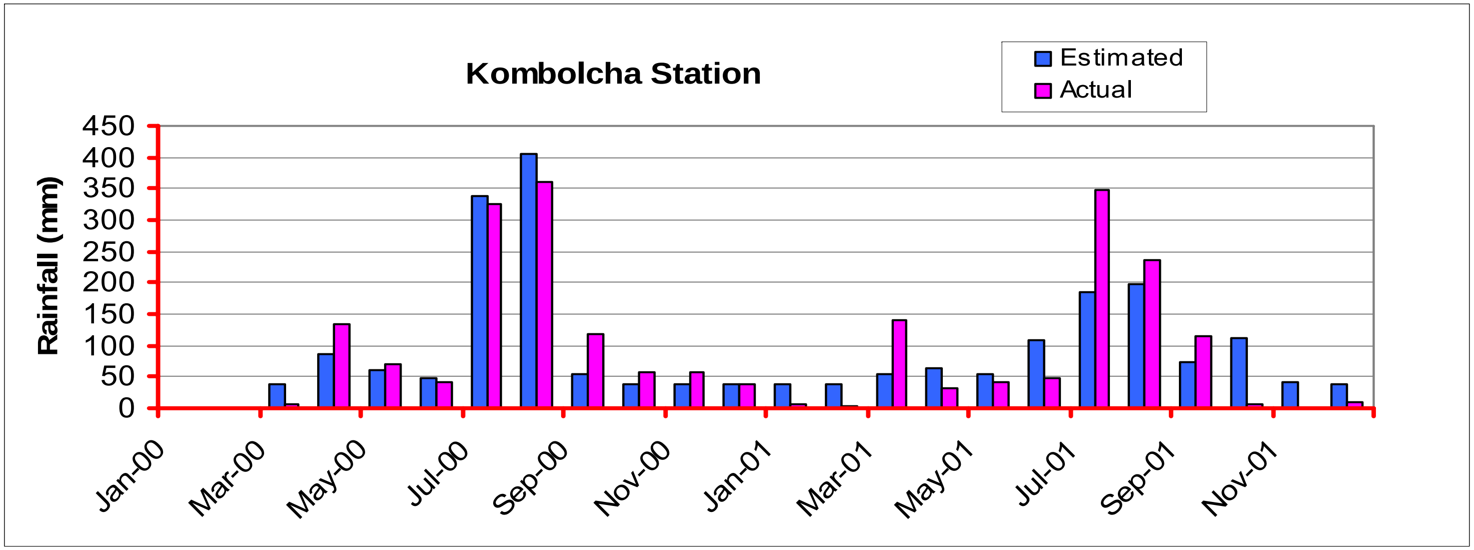

Koffle Station
Difference
RMSE
RMSE
150
100
50
0
-50
-100
-150
-200
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02

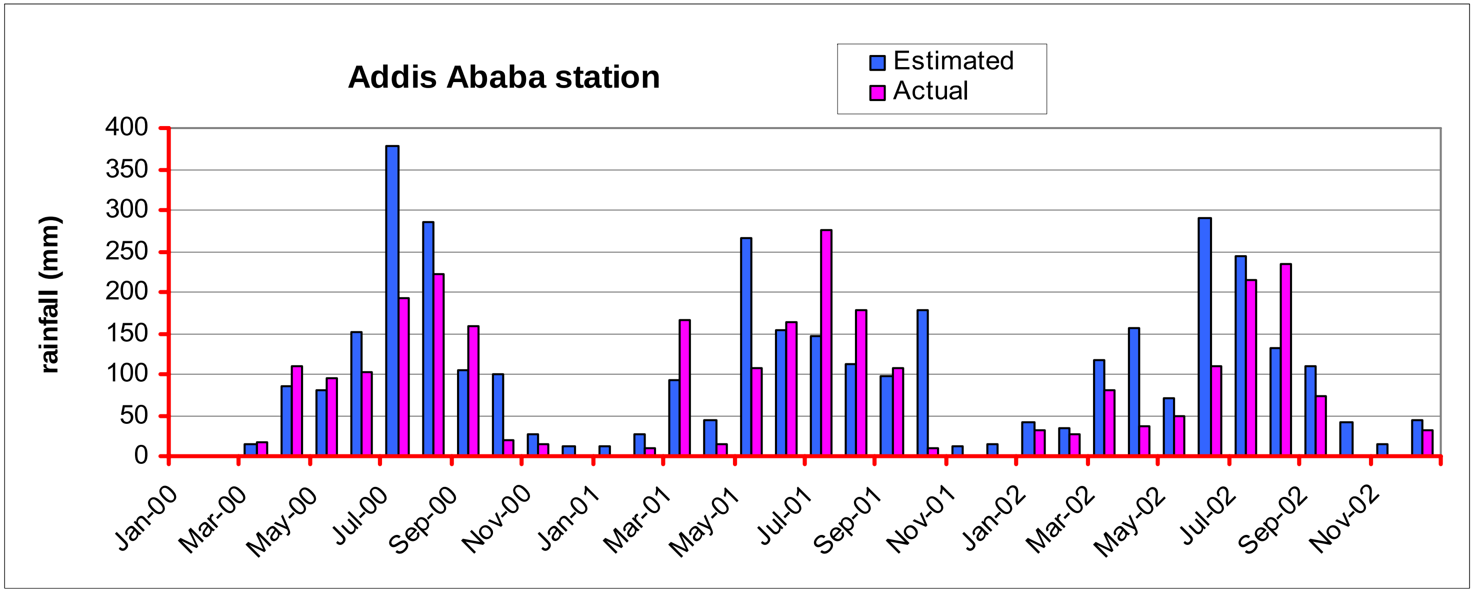

Debre Tabour Station
Rs - Rg (mm)
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
Difference
RMSE
RMSE
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02

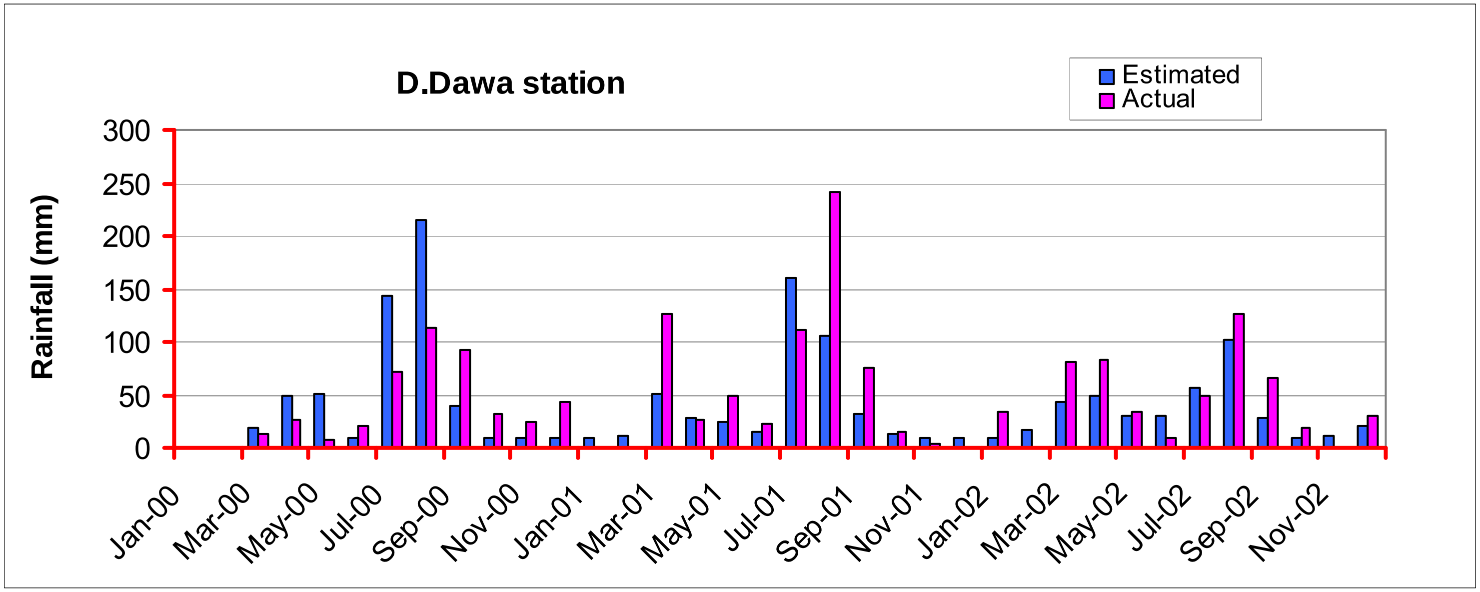
Appendix D Satellite Estimates of Missing Months and Actual rainfall for Selected Stations

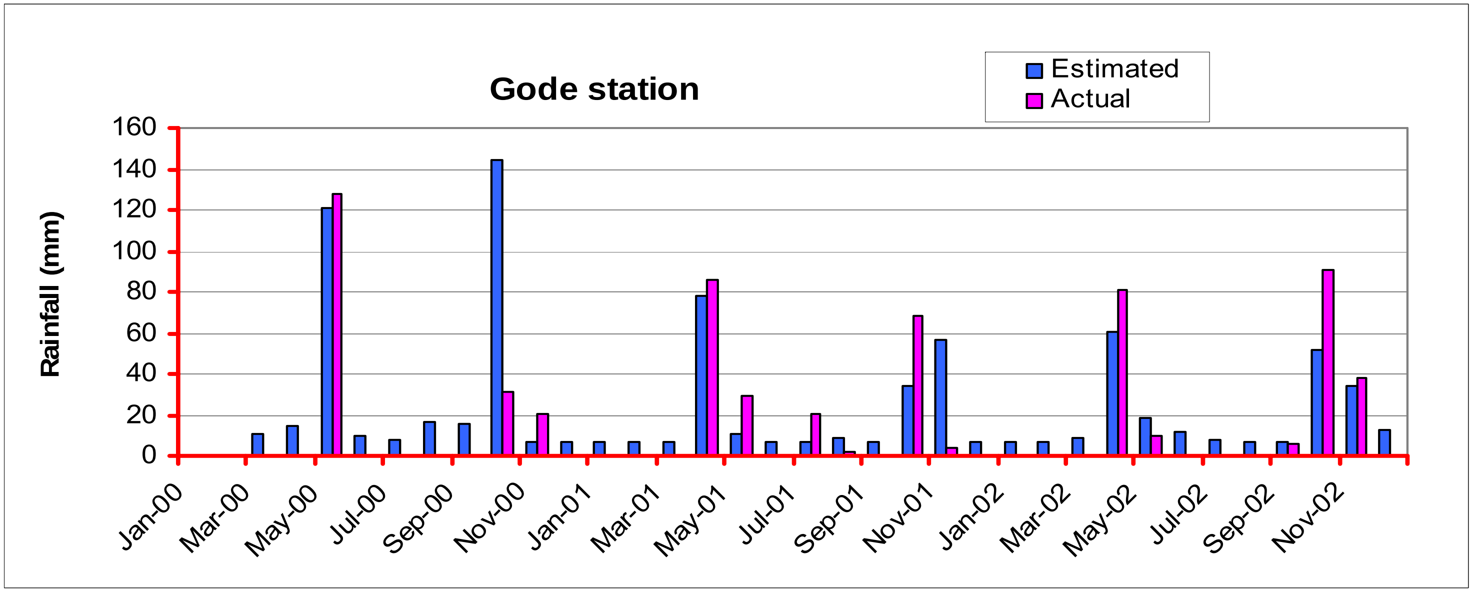


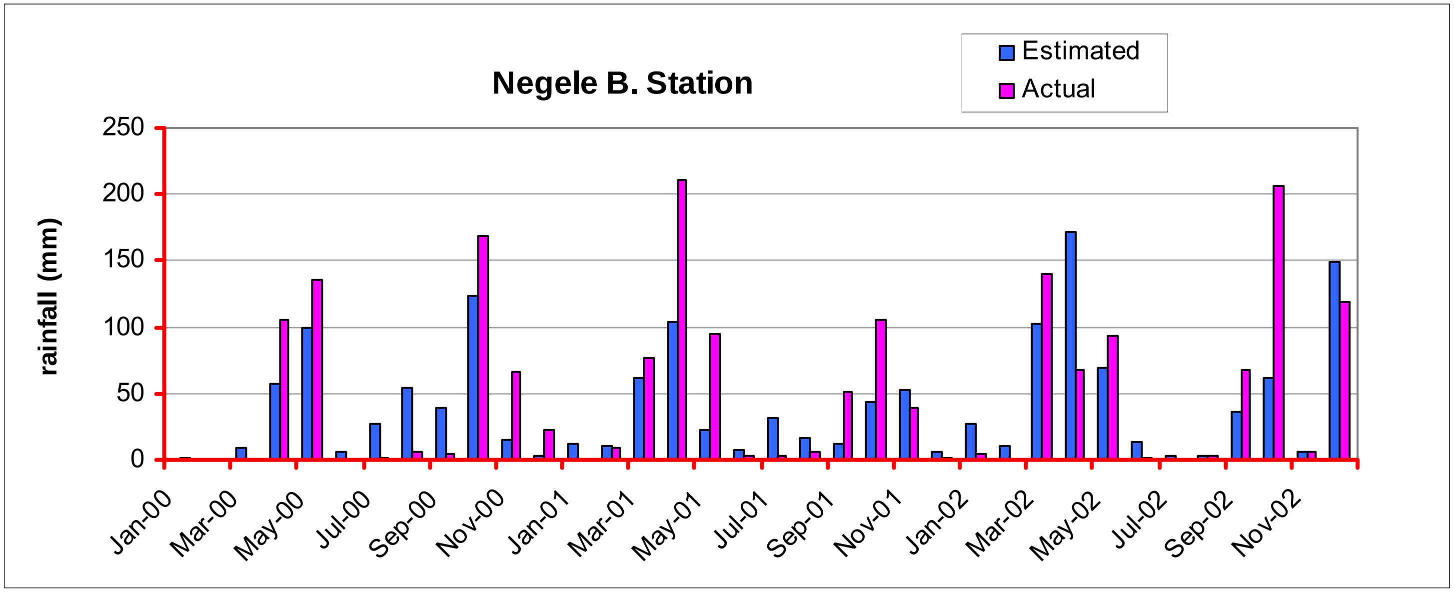


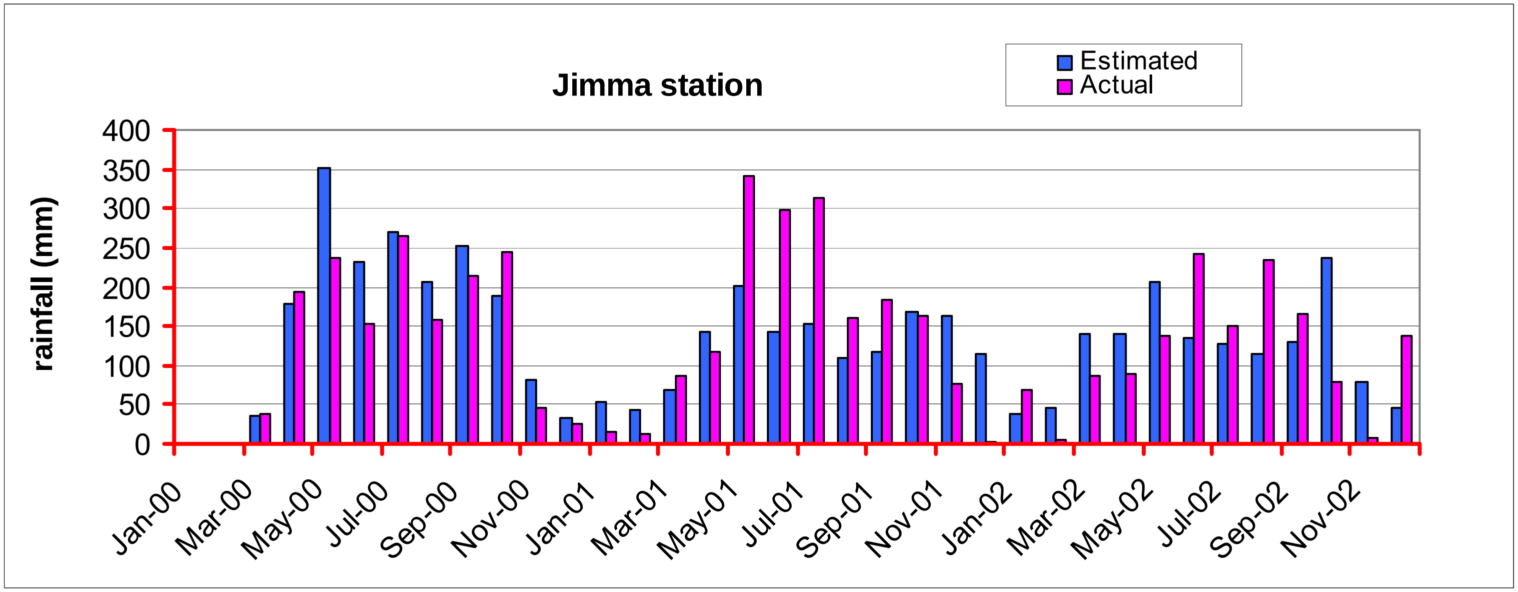

Kombolcha Station
Estimated
Actual
Rainfall (mm)
450
400
350
300
250
200
150
100
50
0
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01


Addis Ababa station
Estimated
Actual
rainfall (mm)
400
350
300
250
200
150
100
50
0
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02

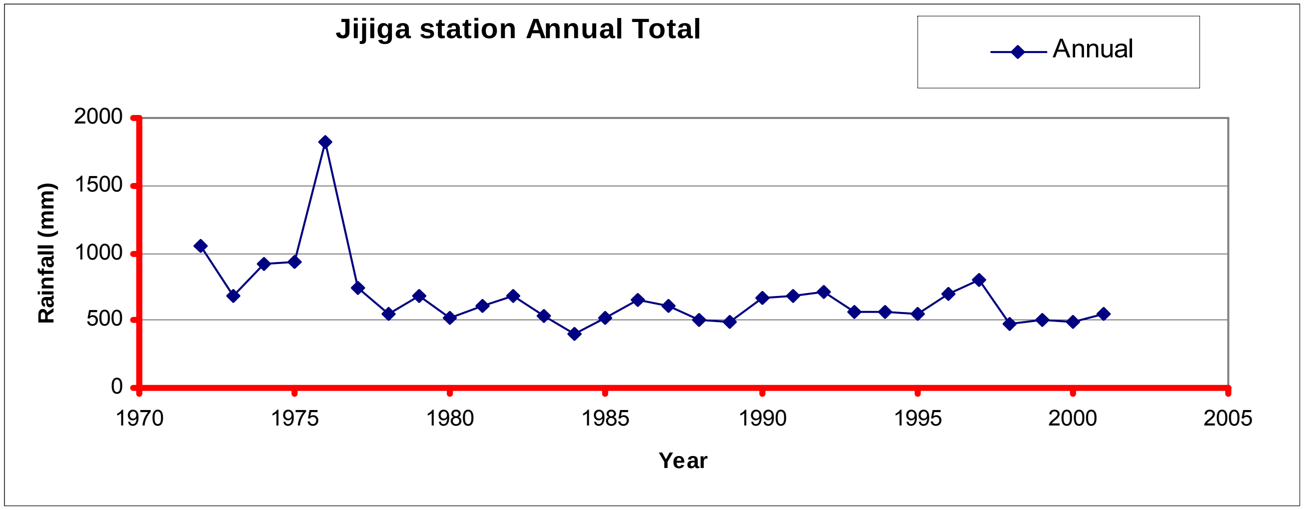

D.Dawa station
Estimated
Actual
Rainfall (mm)
300
250
200
150
100
50
0
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02

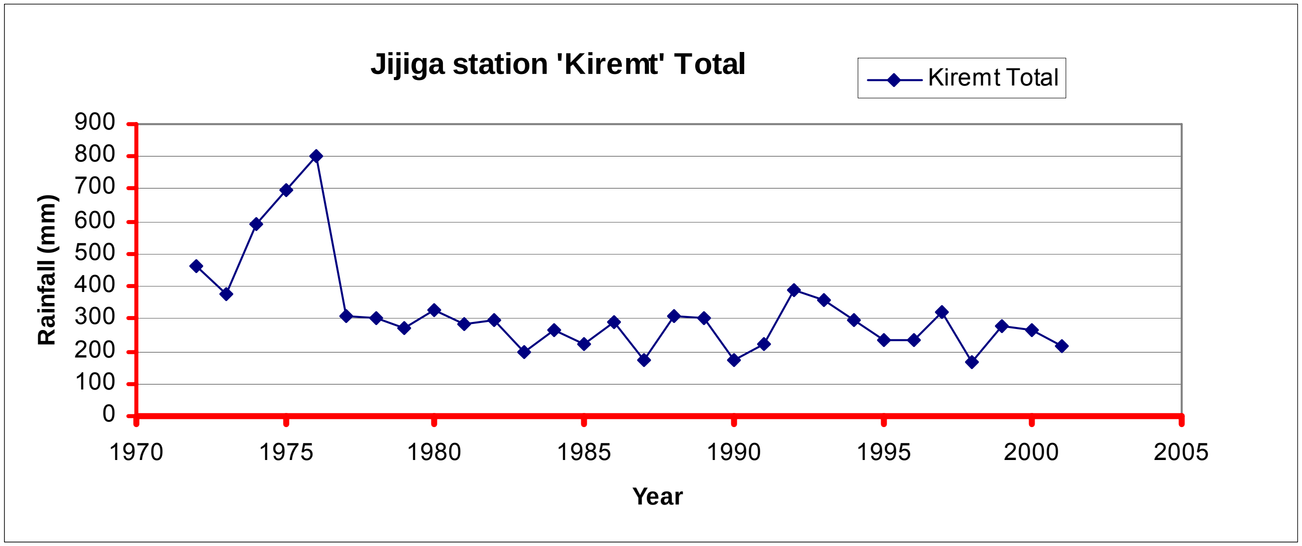

Gode station
Estimated
Actual
Rainfall (mm)
160
140
120
100
80
60
40
20
0
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02

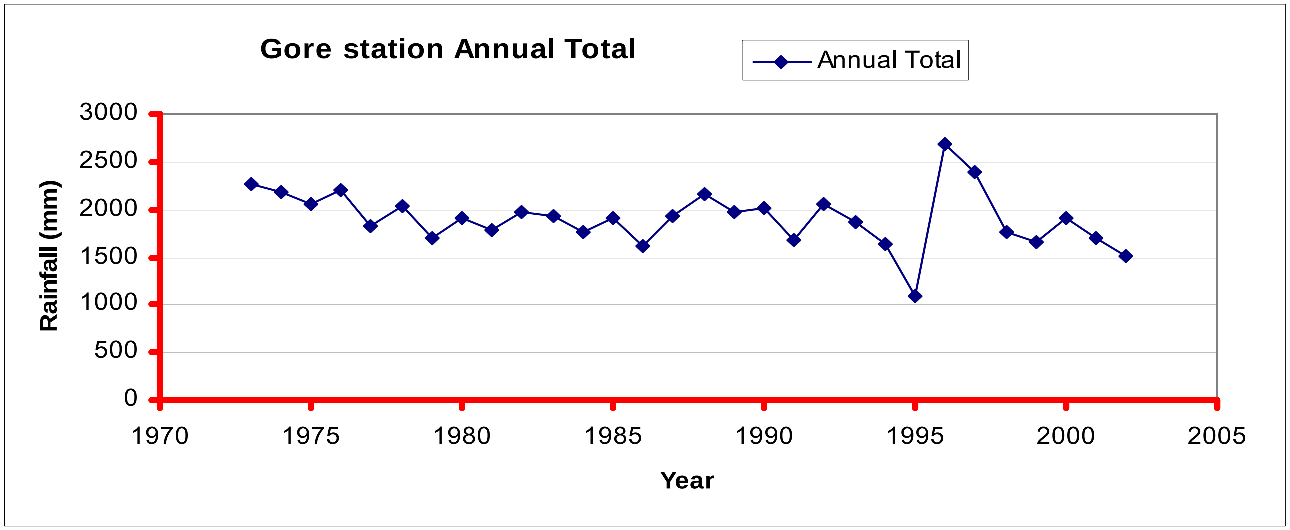

Negele B. Station
Estimated
Actual
rainfall (mm)
250
200
150
100
50
0
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02

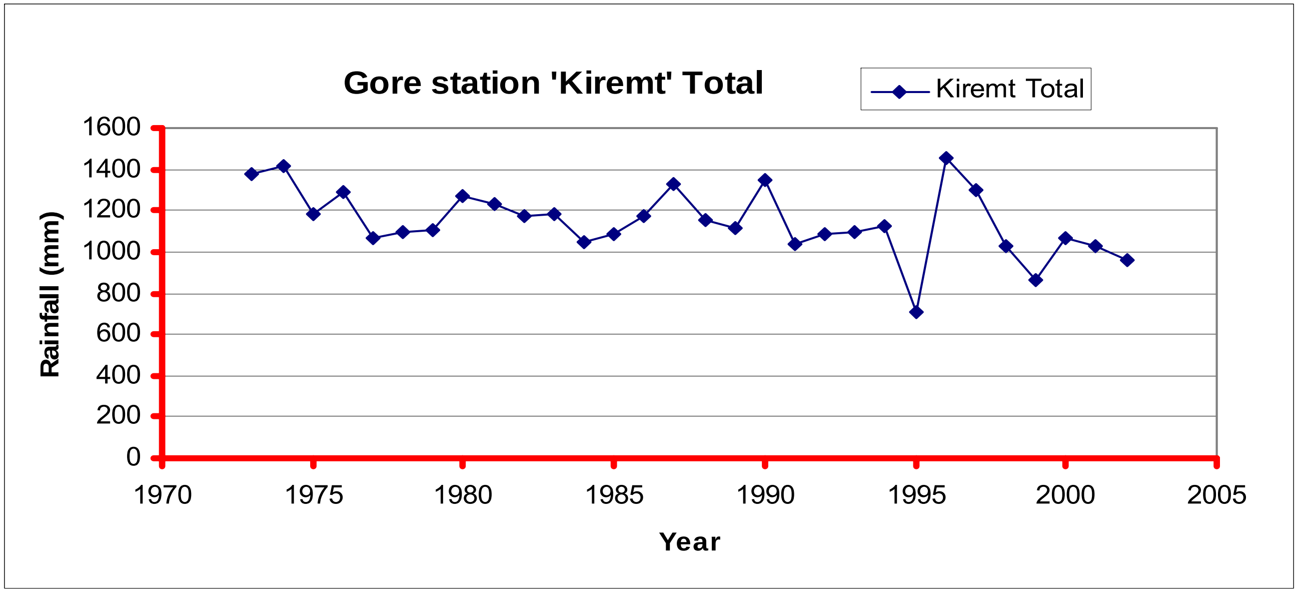

Jimma station
Estimated
Actual
rainfall (mm)
400
350
300
250
200
150
100
50
0
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02

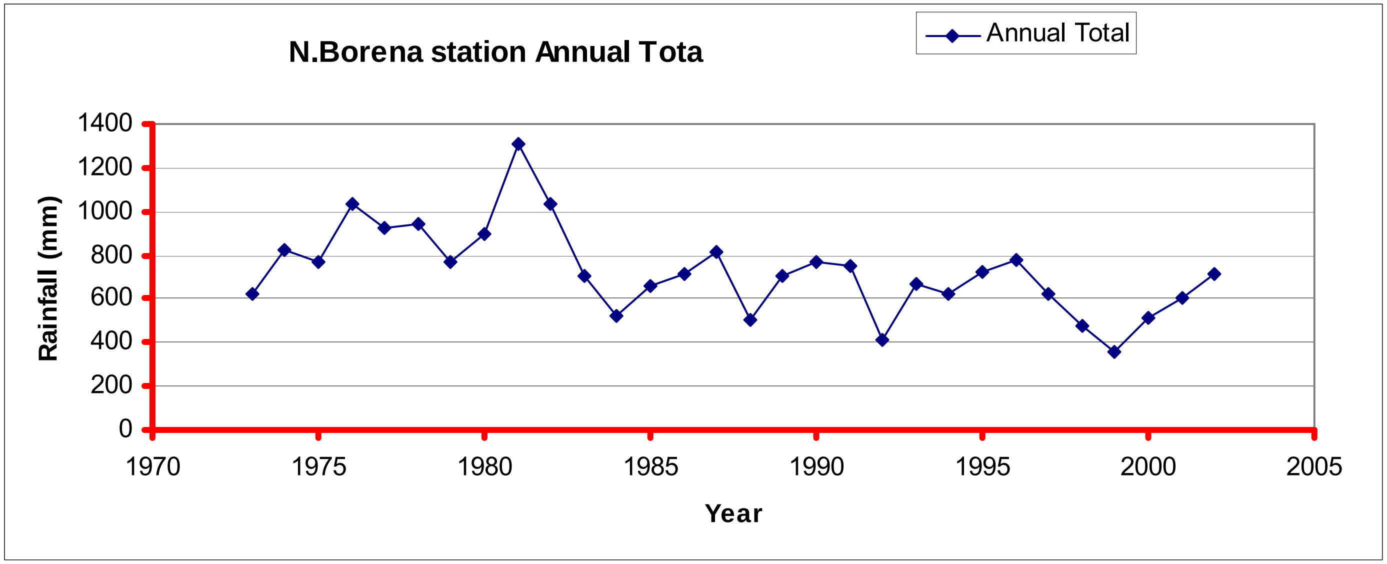
Appendix E Time series plot of Annual and seasonal rainfall Totals

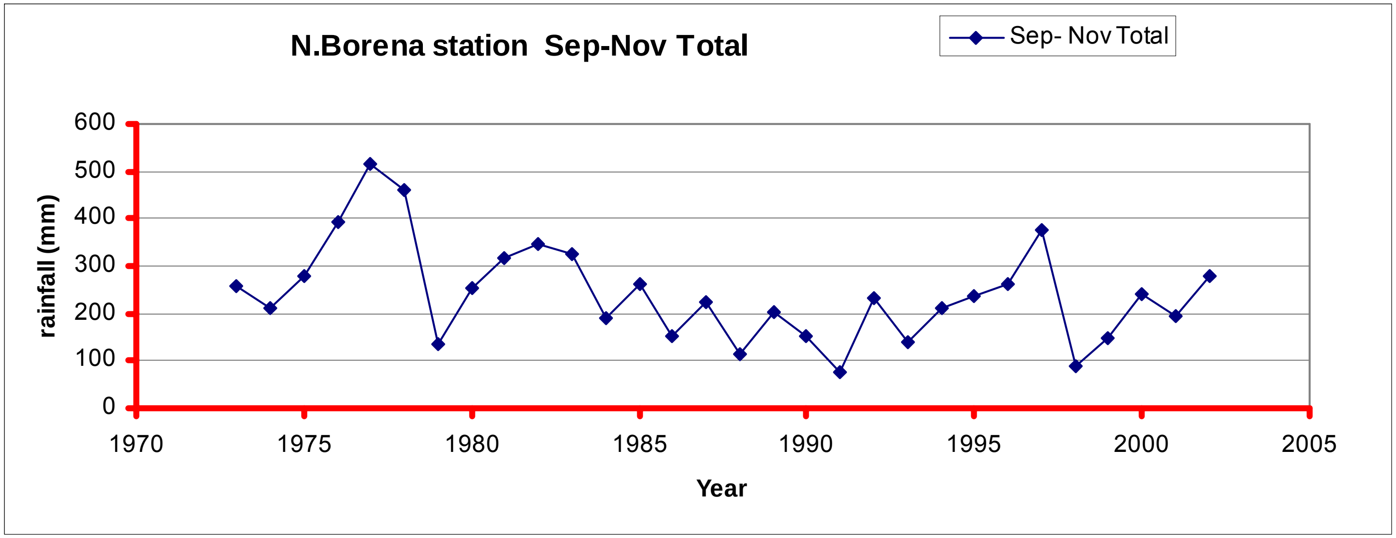


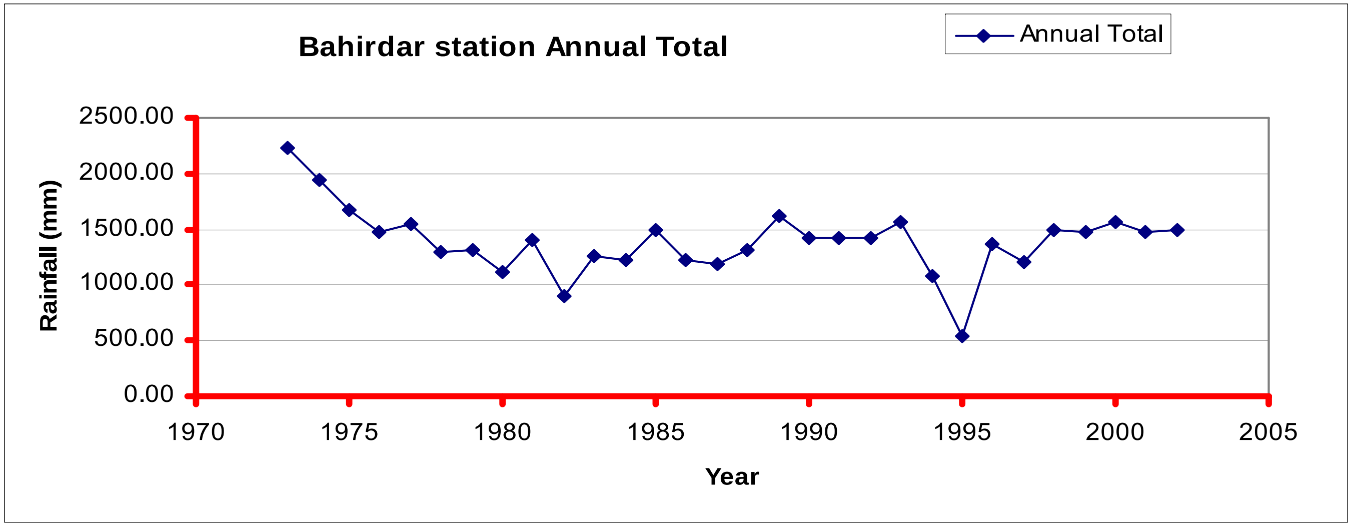


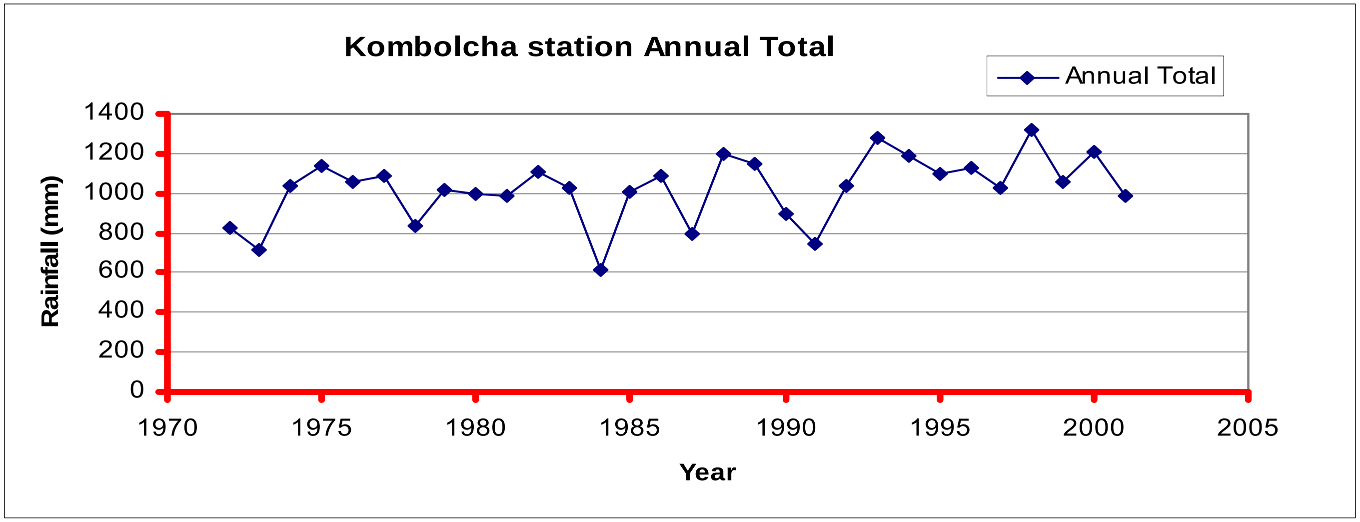

Gore station Annual Total
Annual Total
Rainfall (mm)
3000
2500
2000
1500
1000
500
0
1970
1975
1980
1985
1990
1995
2000
2005
Year

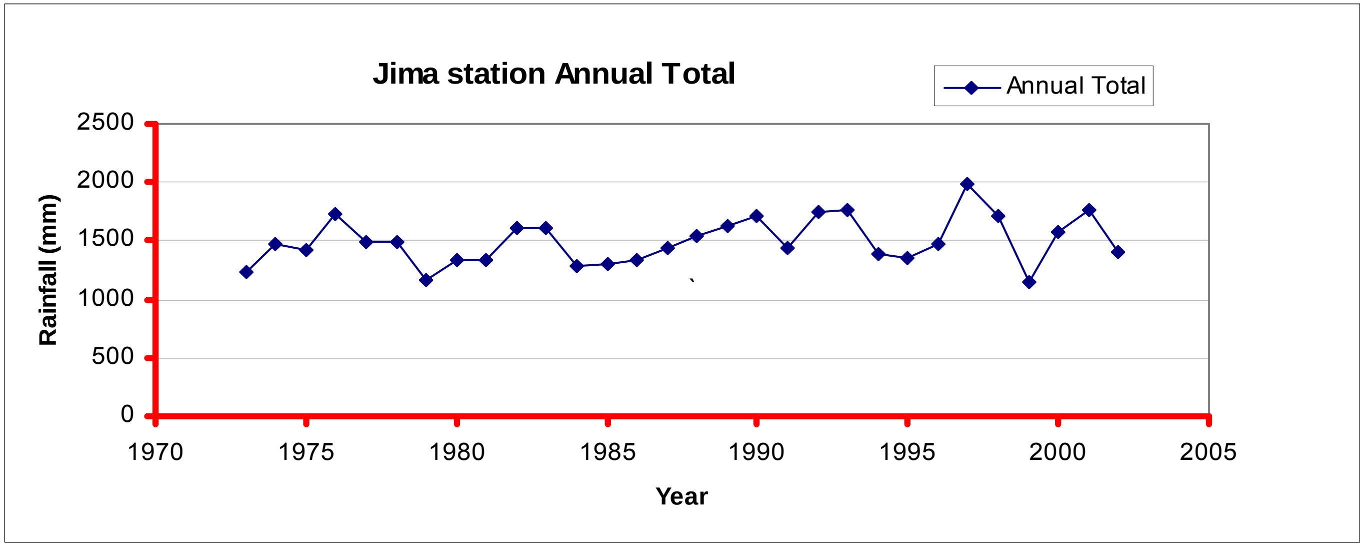

Gore station 'Kiremt' Total
Kiremt Total
Rainfall (mm)
1600
1400
1200
1000
800
600
400
200
0
1970
1975
1980
1985
1990
1995
2000
2005
Year

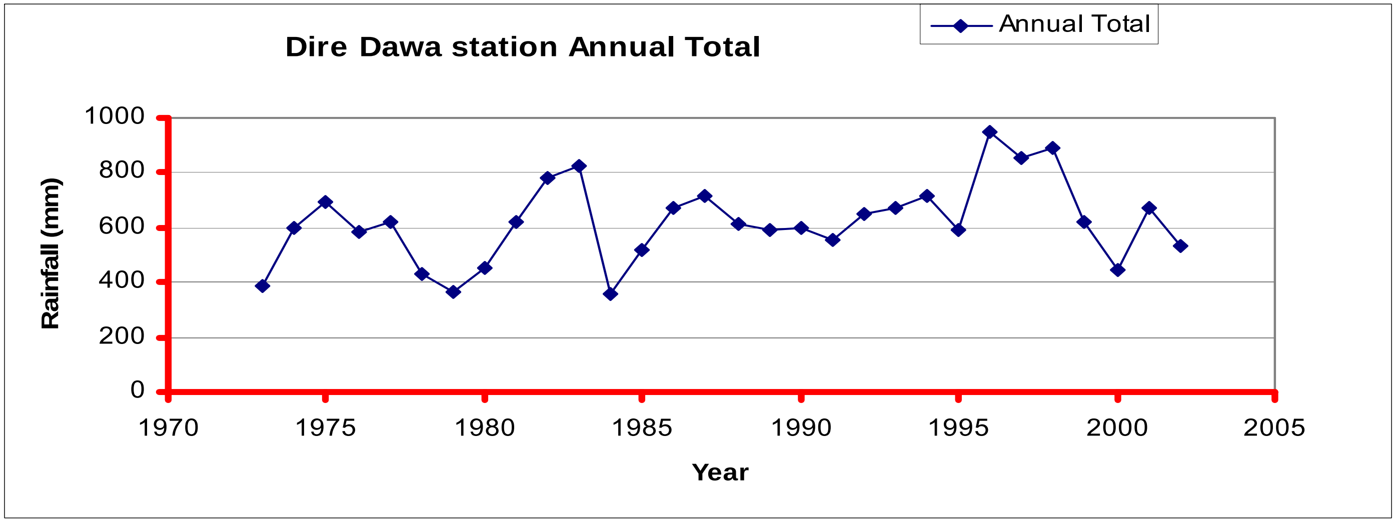

N.Borena station Annual Tota
Annual Total
Rainfall (mm)
1400
1200
1000
800
600
400
200
0
1970
1975
1980
1985
1990
1995
2000
2005
Year


N.Borena station Sep-Nov Total
Sep- Nov Total
rainfall (mm)
600
500
400
300
200
100
0
1970
1975
1980
1985
1990
1995
2000
2005
Year

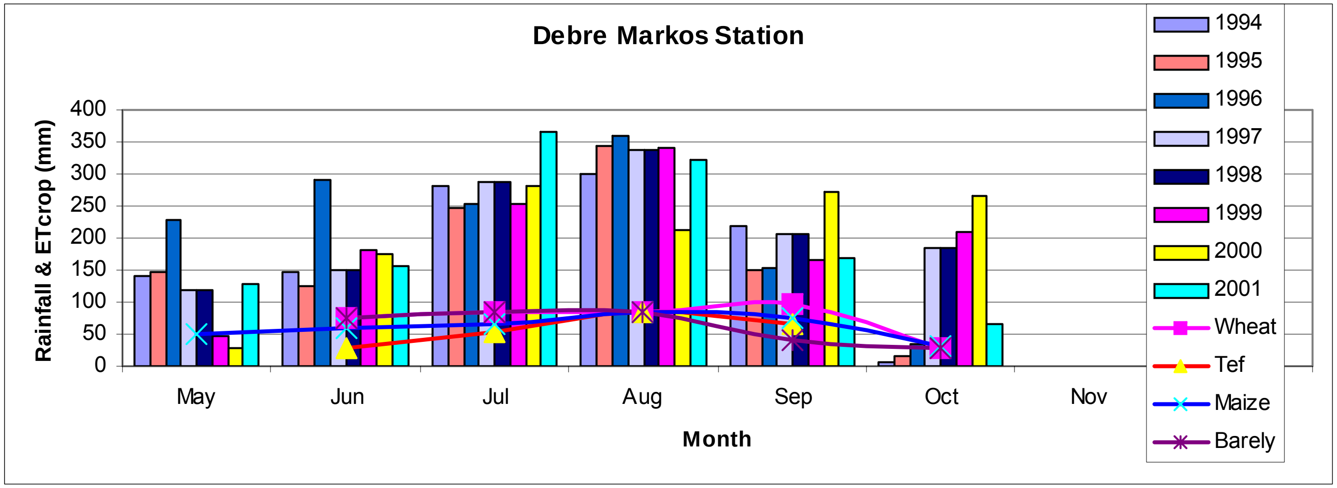

Bahirdar station Annual Total
Annual Total
2500.00
2000.00
1500.00
1000.00
500.00
0.00
Rainfall (mm)
1970
1975
1980
1985
1990
1995
2000
2005
Year

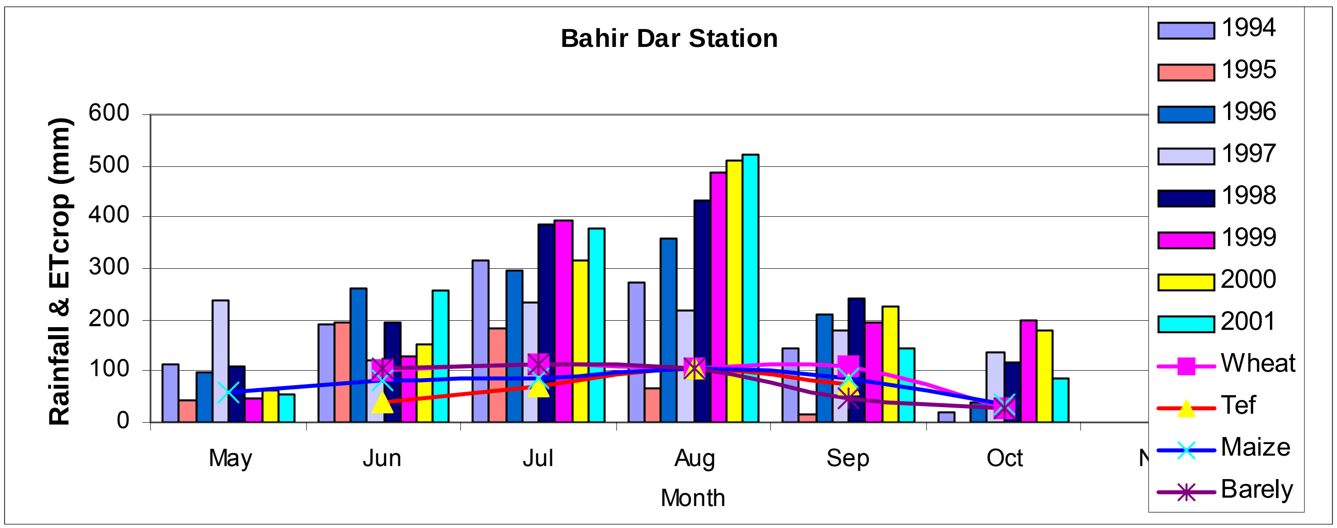

Kombolcha station Annual Total
Annual Total
1400
1200
1000
800
600
400
200
0
Rainfall (mm)
1970
1975
1980
1985
1990
1995
2000
2005
Year

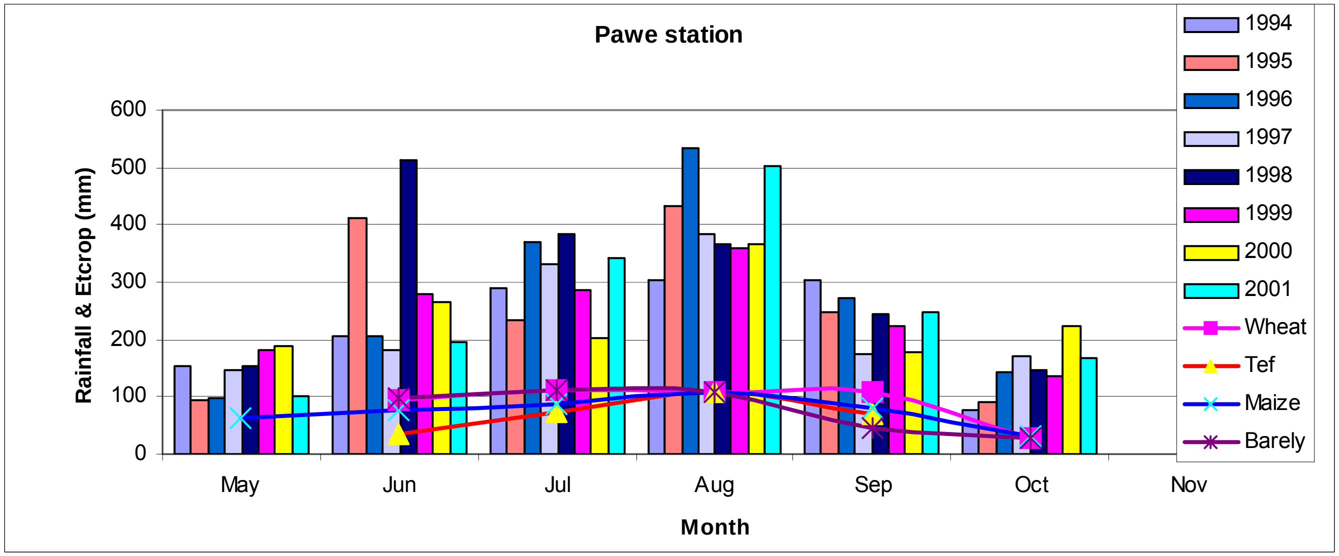

Jima station Annual Total
Annual Total
2500
2000
1500
1000
500
0
Rainfall (mm)
1970
1975
1980
1985
1990
1995
2000
2005
Year

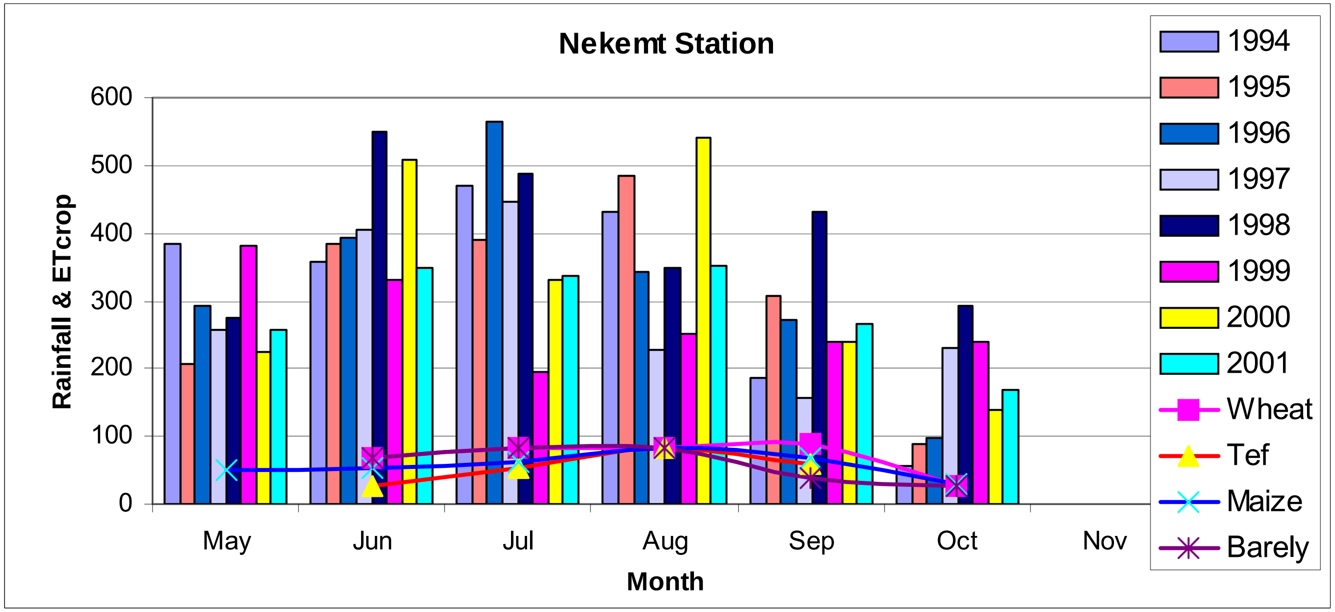

Dire Dawa station Annual Total
Annual Total
1000
800
600
400
200
0
Rainfall (mm)
1970
1975
1980
1985
1990
1995
2000
2005
Year

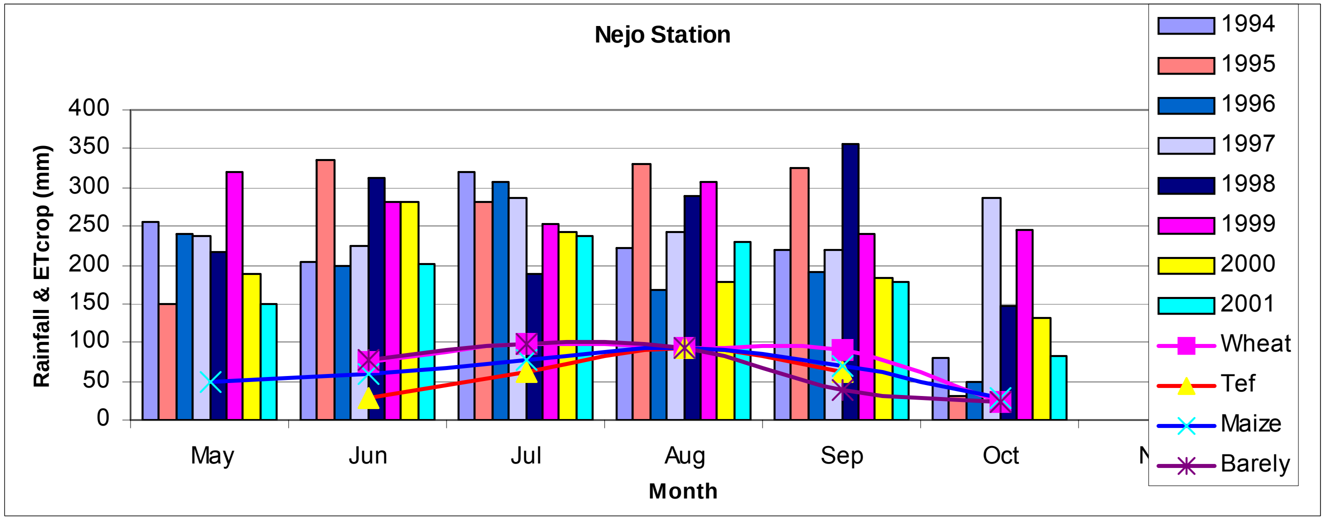
Appendix F Water Requirement and available Rainfall during Crops Growing period for Selected Stations






Pawe station
600
500
400
300
200
100
0
Rainfall & Etcrop (mm)
May
Jun
Jul
Aug
Sep
Oct
Nov
Month
1994
1995
1996
1997
1998
1999
2000
2001
Wheat
Tef
Maize
Barely


Nekemt Station
600
500
400
300
200
100
0
Rainfall & ETcrop
May
Jun
Jul
Aug
Sep
Oct
Nov
Month
1994
1995
1996
1997
1998
1999
2000
2001
Wheat
Tef
Maize
Barely


Nejo Station
400
350
300
250
200
150
100
50
0
Rainfall & ETcrop (mm)
May
Jun
Jul
Aug
Sep
Oct
Month
1994
1995
1996
1997
1998
1999
2000
2001
Wheat
Tef
Maize
Barely

Appendix G Production Data Used in the Study Areas

Production Data used in the First study area (Awi, West Gojam & East Gojam Zones)					
Year	Cereals	Teff	Barely	Wheat	Maize
1994	Area[10] (,000)	340.07	119.19	75.32	131.81
	Production[11] (,000)	2902.19	907.97	932.76	1898.14
	Yield (Qui/Hec)	8.53	7.62	12.38	14.40
1995	Area (,000)	399.40	84.04	66.17	171.32
	Production (,000)	3365.91	813.20	699.65	4219.42
	Yield (Qui/Hec)	8.43	9.68	10.57	24.63
1996	Area (,000)	394.60	70.02	64.16	194.05
	Production (,000)	3665.76	761.82	668.43	3805.95
	Yield (Qui/Hec)	9.29	10.88	10.42	19.61
1997	Area (,000)	311.98	68.47	47.30	146.69
	Production (,000)	2551.61	657.36	504.83	2857.69
	Yield (Qui/Hec)	8.18	9.60	10.67	19.48
1998	Area (,000)	363.49	82.64	67.14	181.76
	Production (,000)	3315.72	640.91	752.31	3686.04
	Yield (Qui/Hec)	9.12	7.76	11.21	20.28
1999	Area (,000)	383.13	71.92	68.29	192.78
	Production (,000)	3360.65	572.19	778.17	3711.46
	Yield (Qui/Hec)	8.77	7.96	11.40	19.25
2000	Area (,000)	318.87	83.81	81.97	240.14
	Production (,000)	2645.00	756.91	1138.30	4823.39
	Yield (Qui/Hec)	8.29	9.03	13.89	20.09
2001	Area (,000)	323.26	83.44	79.86	194.71
	Production (,000)	3267.51	944.22	1226.19	4920.59
	Yield (Qui/Hec)	10.11	11.32	15.35	25.27

[10] area of land is given in Hectare
[11] production is given in Quintals

Production Data used in the Second study area (South Wolo, Oromia, & North Shoa Zones)					
Year	Cereals	Teff	Barely	Wheat	Maize
1994	Area (,000)	168.77	65.52	78.20	23.60
	Production (,000)	1085.37	693.28	1106.01	376.69
	Yield (Qui/Hec)	6.43	10.58	14.14	15.96
1995	Area (,000)	156.28	80.57	116.31	42.59
	Production (,000)	1309.25	851.87	1081.04	614.20
	Yield (Qui/Hec)	8.38	10.57	9.29	14.42
1996	Area (,000)	167.08	64.45	82.69	40.21
	Production (,000)	1251.17	813.08	859.85	603.02
	Yield (Qui/Hec)	7.49	12.62	10.40	15.00
1997	Area (,000)	162.70	54.32	64.20	4.55
	Production (,000)	1197.61	639.97	834.02	99.38
	Yield (Qui/Hec)	7.36	11.78	12.99	21.84
1998	Area (,000)	261.51	47.15	87.09	212.65
	Production (,000)	1679.33	364.72	978.99	357.73
	Yield (Qui/Hec)	6.42	7.74	11.24	1.68
1999	Area (,000)	222.84	53.46	57.34	36.14
	Production (,000)	1880.05	446.65	710.88	518.05
	Yield (Qui/Hec)	8.44	8.35	12.40	14.33
2000	Area (,000)	239.90	64.66	119.91	42.65
	Production (,000)	2160.49	666.20	1187.21	535.61
	Yield (Qui/Hec)	9.01	10.30	9.90	12.56
2001	Area (,000)	185.05	125.78	125.44	35.29
	Production (,000)	1557.21	1062.33	1453.43	382.69
	Yield (Qui/Hec)	8.41	8.45	11.59	10.84

Production Data used in the Third study area (West & East Welega Zones)					
Year	Cereals	Teff	Barely	Wheat	Maize
1994	Area (,000)	140.98	21.56	17.84	151.18
	Production (,000)	747.83	158.87	203.62	2128.16
	Yield (Qui/Hec)	5.30	7.37	11.41	14.08
1995	Area (,000)	163.16	28.44	28.07	177.15
	Production (,000)	1710.92		266.51	3633.69
	Yield (Qui/Hec)	10.49	0.00	9.49	20.51
1996	Area (,000)	171.05	24.09	34.17	166.41
	Production (,000)	1159.30	42.76	189.68	3153.05
	Yield (Qui/Hec)	6.78	1.78	5.55	18.95
1997	Area (,000)	164.04	18.07	23.86	169.64
	Production (,000)	977.64	154.07	315.79	2860.45
	Yield (Qui/Hec)	5.96	8.53	13.24	16.86
1998	Area (,000)	178.30	17.82	30.25	187.87
	Production (,000)	1134.20	164.63	434.32	3803.95
	Yield (Qui/Hec)	6.36	9.24	14.36	20.25
1999	Area (,000)	164.64	18.77	21.24	208.47
	Production (,000)	1200.10	190.31	331.42	4725.06
	Yield (Qui/Hec)	7.29	10.14	15.60	22.67
2000	Area (,000)	159.34	22.25	24.19	219.31
	Production (,000)	1097.60	247.02	350.82	4768.41
	Yield (Qui/Hec)	6.89	11.10	14.50	21.74
2001	Area (,000)	120.53	22.54	26.81	184.76
	Production (,000)	1048.86	207.54	385.64	4076.89
	Yield (Qui/Hec)	8.70	9.21	14.38	22.07

Production Data used in the Fourt study area (Jima & Ilubabor Zones)					
Year	Cereal	Teff	Barely	Wheat	Maize
1994	Area (,000)	124.85	24.01	14.47	122.75
	Production (,000)	628.35	287.74	177.85	2050.20
	Yield (Qui/Hec)	5.03	11.98	12.29	16.70
1995	Area (,000)	148.40	17.55	11.89	168.90
	Production (,000)	1241.63	179.73	159.44	3599.41
	Yield (Qui/Hec)	8.37	10.24	13.41	21.31
1996	Area (,000)	173.28	15.49	9.40	177.29
	Production (,000)	1720.78	187.78	117.99	3112.49
	Yield (Qui/Hec)	9.93	12.12	12.55	17.56
1997	Area (,000)	152.19	12.12	14.76	114.52
	Production (,000)	1150.45	93.43	118.09	2061.53
	Yield (Qui/Hec)	7.56	7.71	8.00	18.00
1998	Area (,000)	163.38	10.96	12.81	141.53
	Production (,000)	1099.31	82.48	107.28	2714.17
	Yield (Qui/Hec)	6.73	7.53	8.37	19.18
1999	Area (,000)	164.72	14.13	14.13	155.28
	Production (,000)	1087.08	120.79	136.38	3021.72
	Yield (Qui/Hec)	6.60	8.55	9.65	19.46
2000	Area (,000)	159.00	21.76	26.31	194.14
	Production (,000)	1006.52	156.58	266.17	4411.03
	Yield (Qui/Hec)	6.33	7.20	10.12	22.72
2001	Area (,000)	133.86	25.58	31.58	207.79
	Production (,000)	1221.41	248.00	383.75	4098.38
	Yield (Qui/Hec)	9.12	9.69	12.15	19.72

Production Data used in the Fifth study area (North & West Shoa Zones)					
Year	Cereal	Teff	Barely	Wheat	Maize
1994	Area (,000)	278.10	136.89	112.91	43.08
	Production (,000)	2153.12	1218.23	1768.47	856.40
	Yield (Qui/Hec)	7.74	8.90	15.66	19.88
1995	Area (,000)	307.63	163.56	139.59	43.85
	Production (,000)	3127.65	1757.63	1716.57	891.57
	Yield (Qui/Hec)	10.17	10.75	12.30	20.33
1996	Area (,000)	324.27	141.72	127.76	38.52
	Production (,000)	3268.51	1291.02	1873.72	726.35
	Yield (Qui/Hec)	10.08	9.11	14.67	18.86
1997	Area (,000)	249.25	97.89	118.18	37.88
	Production (,000)	2231.39	1285.34	1541.82	666.97
	Yield (Qui/Hec)	8.95	13.13	13.05	17.61
1998	Area (,000)	310.38	128.20	178.19	46.78
	Production (,000)	2683.18	1088.20	1770.81	1022.95
	Yield (Qui/Hec)	8.64	8.49	9.94	21.87
1999	Area (,000)	326.23	117.39	155.75	48.77
	Production (,000)	3113.51	1025.95	1657.86	1042.67
	Yield (Qui/Hec)	9.54	8.74	10.64	21.38
2000	Area (,000)	327.74	135.07	171.55	57.50
	Production (,000)	3152.51	1550.56	2161.46	1212.85
	Yield (Qui/Hec)	9.62	11.48	12.60	21.09
2001	Area (,000)	291.07	147.41	124.70	83.24
	Production (,000)	2981.12	1457.80	1727.70	2121.59
	Yield (Qui/Hec)	10.24	9.89	13.85	25.49