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The Role of Reservoirs in Drought Mitigation in Ethiopia, Awash River Basin

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Preface

This thesis work with a topic "The Role of Reservoirs in Drought Mitigation in Ethiopia, Awash River Basin" is submitted as a requirement for partial fulfillment of Master of Science degree in Hydropower Development course 2014-2016, to the department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

The work mainly involves assessment of drought characteristics of the Awash valley on a sub basin level followed by analysis of climate change impact on the risk of drought in the future period. Drought Index Calculator software, R programming language and ARC view are used during the analysis. It also involves assessment of water resource management options using WEAP model to reduce the impact of drought on people, livestock and economic development of the basin.

The work was started on January 15th, 2016 and finalized on June 10th, 2016 under the supervision of Professor Knut Alfredsen and Tor Haakon Bakken. This work is purely for academic purpose and doesn't mean to oppose or harm any individual, group or organization. I here witness that as the work is mine and all sources of information are referenced.

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Acknowledgment

Beside to my work, I would like to express my deepest gratitude to my supervisors, Professor Knut Alfredsen and Tor Haakon Bakken, for their continuous guidance, assistance and motivation provided throughout the study. Special thanks also goes to Abebe Girmay for his assistant and support during the work.

My deepest gratitude shall also goes to Norwegian government for providing me this chance along with the financial support. Special thanks as well to academic and administration staffs of NTNU for their consistent service during my two year stay in Norway.

I would also like to extend my gratitude to my parents for their endless blessings and encouragements. Finally, I would like to thank all my classmates and friends for their encouragements and advice to complete my study on time.

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Abstract

Drought is weather related natural hazard that can affect a particular region or entire country. It affects the lives of people, livestock, and economic development of a given region or country. In Ethiopia it is becoming a recurrent phenomenon which usually is caused due to lack of precipitation for an extended period. This extended lack of precipitation causes water shortage of different demand sectors of a given community. As majority of the food production in Ethiopia is dependent on rain-fed agriculture the impact is much worse. It often turns into famine and food crisis. Hence, This thesis work aims in analysing drought and its mitigation measures in Awash river basin. Detail drought assessment is performed on a sub basin level. Standardized precipitation index and standardized stream flow index are used to characterize meteorological and hydrological droughts of the basin respectively. A good relationship is found between meteorological and hydrological droughts based on shorter time scale of drought index calculation. Drought severity maps are developed using Arc view to have an over view of drought affected areas. The lower and middle Awash are found to be hit by extreme and severe drought in a higher percentage. A drought of moderate and mild severity is common across the basin.

Impact of climate change on drought severity in the future is also analysed. The impact is analysed by downscaling historical and future climate data of three RCP scenarios of Moh hadely and MPI climate models by using Arc map and R-programming language. A total of 54 index points are downscaled with in the catchment and average values are used when more than two index points are downscaled per sub basin. It is found that drought severity due to climate change will increase in the future in the upper and middle part of the basin. In the lower part almost same type of drought is found but this is uncertain due to the fact that the correlation of downscaled climate data and observed data is found to be very weak. A WEAP model is also used to analyse the role of reservoirs and integrated water resource management to mitigate drought. A set of future scenarios are tested to identify efficient management options to minimize water deficiency.

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List of Abbreviations

Below is description of abbreviations used through out the report.

ETB Ethiopian Birr
ITCZ Inter-Tropical Convergence Zone
Gwh Giga Wat Hour
ha Hectares
Drinc Drought Index Calculator
PET Potential Evapotranpiration
SPI Standardized Precipitation Index
SPEI Standardized Precipitation Evapotranspiration Index
SDI Standardized Streamflow Drought Index
FAO Food and Agriculture Organization of the United Nations.
WEAP Water Evaluation and Planning tool
DSM Demand Side Management
mm Millimeter
RCP Representative Concentration Pathway
Moh hadely Met Office Hadely Centre, UK
MPI Max Planck Institute of Meteorology, Hamburg, Germany

1. Introduction

Ethiopia is again hit by a severe drought. Historically droughts have caused the death of millions of people, big losses in agriculture and power production which represents a big risk to economic development and introduces enormous personal tragedies. Droughts can be categorized as climatic droughts, agricultural and hydrological droughts, where the first category is described by changes in climatic conditions. Agricultural drought is beside the climatic conditions also determined by the agricultural management and planning, causing shortfall in the crop production. Hydrological drought happens when the available water in rivers, lakes, reservoirs, and ground water aquifers is lower than a certain statistical threshold. Construction and sound operation of reservoirs can hence reduce the risk of hydrological drought.

In the last decades Ethiopia has started an extensive development of water resources, which includes constructing of several dams and reservoirs. Reservoirs are also key-stones in the infrastructure and prerequisite in water-stressed areas to secure adequate water services to a large range of sectors and are used for the purpose of securing irrigation demand, drinking water supply, flood control, navigation and Hydro power production and more. The national storage capacity has increased rapidly and this would potentially make the country more prepared and less vulnerable against drought, but this depends on where the reservoirs are located, how they are operated and for what they are used for. This masters thesis aims at studying the role of reservoirs in mitigating hydrological droughts in Ethiopia, Awash river basin as case study.

1.1. Drought History

Ethiopia has a long history of drought and famine. In total of 39 recorded events and shortage of food have been identified. Most events have been concentrated in the central and Northern highlands, stretching from Northern Shewa to Wollo and Tigray and in the crescent of low-lying agro-pastoral lands ranging from wollo in the North, through Hararghe and Bale, to Sidamo and Gamo Gofa on the south.

Table 1.1 on page 2 shows list of recorded drought and famine crises taken from a book by Degefu (1987).

Date	Region affected	"Triggers" and severity
1836-37	Northern Provinces	A holocaust of drought, famine, cattle disease, epidemic, and cholera.
1888-92	The whole Ethiopia	One of the most serious droughts in Ethiopia Known as "Kifu Ken" (Harsh days). 90% of cattle perished, 1/3 of population death
1895-96	Ethiopia	Minor drought, loss of livestock and human lives
1899-1900	Ethiopia	Drought deduced from levels of lake Rudolf and Low Nile floods
1913-14	Northern Ethiopia	Lowest Nile floods since 1965, grain prices said to have risen thirty-fold
1920-22	Ethiopia	Moderate Drought
1932-34	Ethiopia	Deduced from low level of Lake Rudolf
1953	Tigray and Wollo	Severity unrecorded
1957-58	Tigray and Wollo	Rain failure in 1957, Locusts and epidemic in 1958
1962-63	Western Ethiopia	Very severe
1964-66	Tigray and Wollo	Undocumented; said to be worse than in 1973/74
1971-75	Ethiopia	Sequence of rain failure; estimated 250 thousands dead and 50 percent of livestock lost in Tigray and Wollo
1978-79	Southern Ethiopia	Failure of Belg rains
1982	Northern Ethiopia	Late Meher rains
1984-85	Ethiopia	Sequential rain failure; 8 million people affected, estimated 1 million dead and much livestock loss
1987-88	Ethiopia	Drought of undocumented severity in peripheral regions
1990-92	Northern, Eastern and southwestern Ethiopia	Rain failure and regional conflicts estimated 4 million people suffering food shortage

Table 1.1.: List of Drought and Famine crises in Ethiopia

Historical droughts have happened either due to total failure of rainfall or early or too late inadequate rainfall during the short rainy season or low rainfall intensity and short duration. As most of the agriculture development is based on rain-fed small land holder farmers the effect of shortfall in rain is very critical and millions of peoples have lost their lives so far. The number of peoples affected by drought in Ethiopia can be seen in figure 1.1 on page 3 Flintan and Tamrat (2002). It can be seen that the number of affected peoples is increasing from one drought year to another.

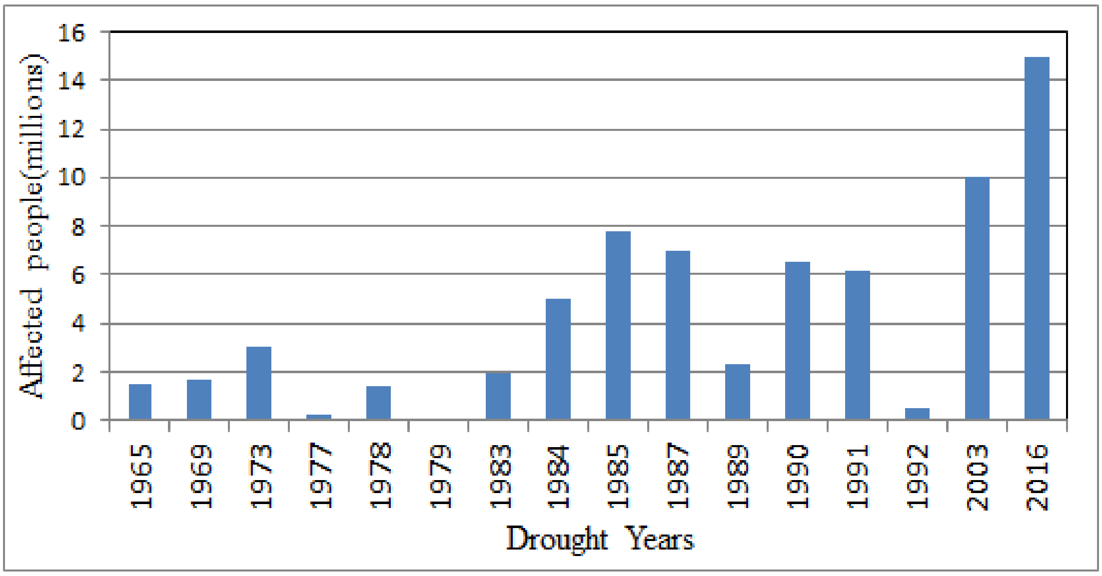

Figure 1.1.: Drought history in Ethiopia (Fiona Flintan and Imeru Tamrat 2002)

1.2. Study Objectives and Limitations

Main objective of these study is to analyse the role of storage reservoirs in drought mitigation so that to set recommendations for early drought warning and propose alternative water resource management options in order to reduce the risk and impacts of drought in Awash basin. In particular it aims in analysing the characteristics and relationships of different types of droughts, and impacts of climate change on drought severity and occurrence in order to understand how it has been trending in the past, and how it will change in the future time. It also aims in analysing the impact of drought on people, livestock, agriculture and economic development of the Awash valley society.

Specifically it also identifies parts or places of the basin where extreme or severe drought occurrences are high so as any structural drought mitigation measures can be proposed in higher priorities. The structural measures can be development of storage reservoirs or any water diversion structure or water transfer system.

In this study accessibility of reliable meteorological and hydrological data was the main limitation. For drought assessment an already processed areal meteorological data from a WEAP model is used due to the lack of enough time series of station data. Infact it is also chosen to be consistent with the WEAP model data base and application to propose effective drought mitigation measures. Only three stream flow gauging stations which are very far apart to each other were accessible during the study. Due to lack of neighbouring gauging stations consistency of the data is not checked. It all depends on the WEAP model developed for the basin by FAO.

Another limitation in this study was the absence of observed water withdrawals for hydropower, irrigation and other demand sectors of a given reservoir. Hence detail optimization of efficient water resource allocation for different purposes is not performed as intended.

1.3. Study area

Awash river basin is part of the great rift valley of Ethiopia. It originates from the central highlands west of Addis Ababa in Ginchi town and terminates in the afar triangle in a salty lake called Abbe in the border of Djibouti. It covers a total land mass area of approximately 116,000km2. It is a home for around 15 million peoples. The total length of the course is around 1200km. Based on Location, altitude, climate, topography, agricultural development, physical and socio-economic factors the Awash valley is divided in to three distinct zones namely Upper valley, middle valley and Lower valley.

In this thesis work the Awash valley is studied in 21 sub-basins as can be seen in figure 1.2 on page 5. Area of each sub basins can be seen in figure 1.3 on page 5. The eastern catchment is the biggest sub basin which accounts for around 40% of the total basin area. It expands from the middle part down to the Lower part of the basin with its tributary joining at the main river outlet. The smallest sub basin (Ataye) is located in the Lower part which accounts 1.03% of the total area.

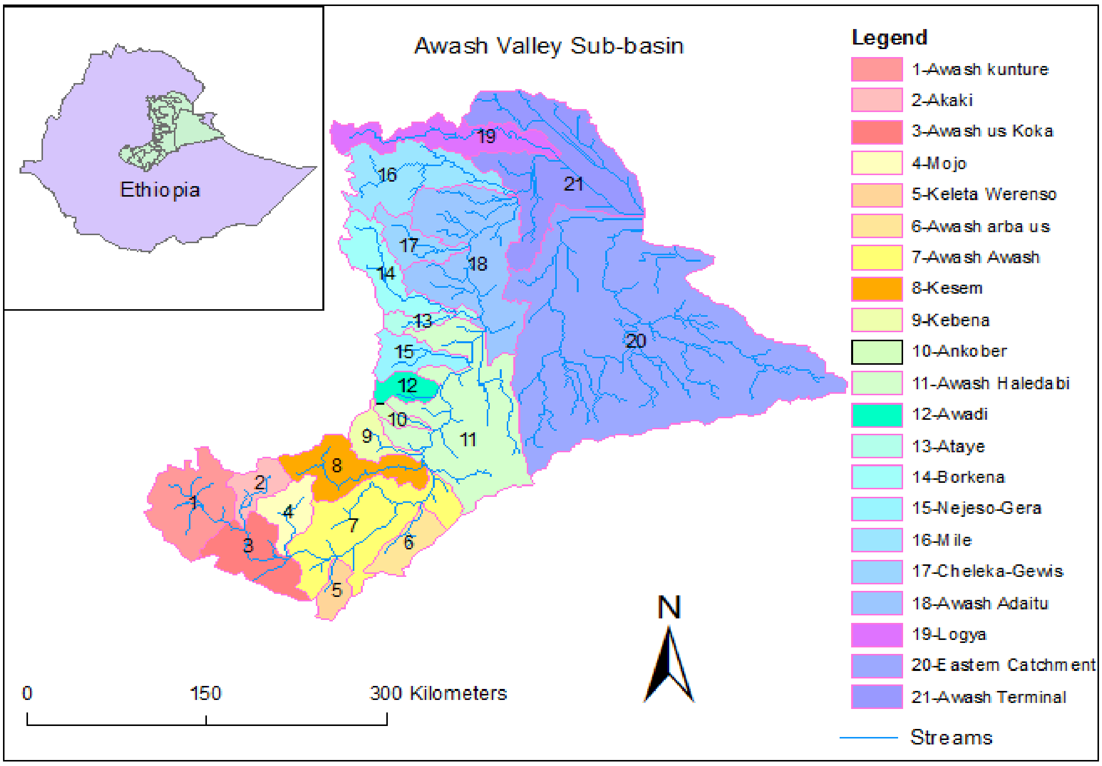

Figure 1.2.: Awash Valley sub-basin

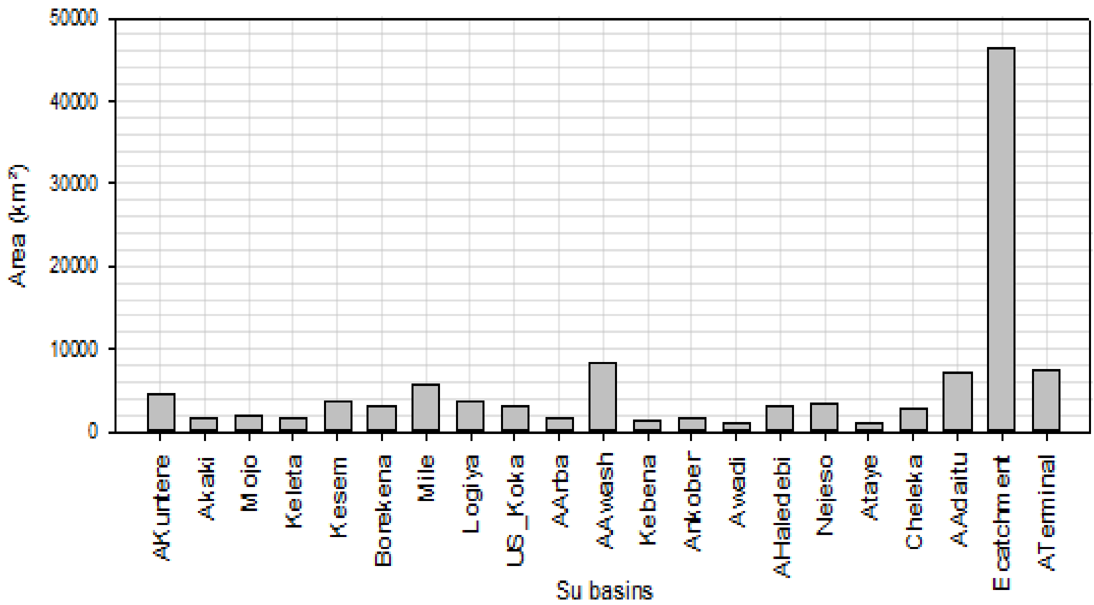

Figure 1.3.: Area of Awash river sub basin

1.4. Drought Impacts In Awash Valley

Drought is a recurrent phenomenon in the Awash valley. In 1973/74 a devastating drought has happened where a severe loss of both human and livestock was recorded. Harbeson and Beshah (1974), estimated the loss between one-fourth to one-third or more of the livestock and human population. According to Toulmin (1985) this drought event reduced cattle population by 90%, camels by 30%, sheep by 50%, goats by 30% and the Afar population by about 25 to 30%. Bondestam (1974) also indicated a loss of about 25-30% of the Afar population during the drought event of 1973/74.

From a survey of 83 households carried out by Said (1994) the size of human and livestock loss during the drought of 1973/74 and 1983/1984 was estimated as shown in table 1.2 on page 6.

year	Human loss	Cattle loss	Camel loss	Sheep & Goats loss
1973/74	90	2,321	251	3,158
1983/84	13	792	84	1,327

Table 1.2.: Human and Livestock loss during two drought events from 83 selected households

During drought events conflict between ethnic groups is a common phenomenon as a result of migration for water resource and grazing competition. Data collected by Said (1994) indicated the number of animals raided and human killed by different ethnic groups from a sample of 94 Afar households in the year 1981/82 to 1991/92 is shown in table 1.3 on page 7. The indirect effect of drought is also a reason for the death of human lives and livestock. If there were well managed storage facility in their vicinity, at least such numbers of lives could have been saved in every drought events.

In the middle Awash armed confrontation between state farm guards and pastorals is a common incident during drought events which ends up with heavy casualties and damage of crops. From the year 1982/83 to 1989/90 an estimated value of 9.25 million ETB. was lost due to the damage of crops by Afar herds Said (1994). The development of irrigation schemes in the upper Awash also triggers for the drought impact in the lower Awash. The drought impacts are severe in the middle and lower part. The weather in the middle and lower awash is warmer and dryer compared to the upper valley as a result the impact is worse. Hence, Integrated water resource management is an important aspect to alleviate the impact. The possibility of using water resource developments as a multipurpose is very high. As the basin is prone to drought, it is also affected by intense flooding. This happens usually after a severe or extreme drought. Risk management is a far better option than crisis management.

Raider	Afar Killed	Camel raided	Cattle raided	Sheep & Goats raided
Issa	70	353	937	313
Kereyu	4	2	27	30
Ittu	-	10	33	-
Argoba	12	-	81	-
Total	86	367	1078	343

Table 1.3.: Number of Afar killed and animals raided by different ethnic groups from 94 sample households from 1981/82 to 1991/92

1.5. List of Used Literature

Many articles and publications of the Awash basin are used during the study. Most of them are listed in the reference with all necessary items. During calculation of drought index a publication made by Tigkas et al. (2015) is used as a main material of reference of theories and procedures of drought assessment. A WEAP user guide developed by Sieber and Purkey (2007) is also used as a main reference of theories and procedures in building of alternative scenarios for water resource management during drought.

1.6. Structure of The Report

This report contains six chapters in total. In this chapter the background and objective of the study, and description of the study area are presented briefly as can be seen in the previous sub topics. In chapter 2 beginning on page 9, description of Awash basin climate, data used and existing hydraulic infrastructures is given. Potential of future water resource development is also included. The rest of the chapters contains description theory, analysis method, result and discussion of the findings. In chapter 3 beginning in page 19, drought assessment is done. The assessment method, result and discussion is included. Chapter 4 beginning in page 37 contains report of climate change impact on drought severity and occurrence. Detail analysis result and discussion is also included. Chapter 5 starting from page 55 is composed of theory of water resource management for drought mitigation using WEAP model and assessment of alternative scenarios for effective reduction of water scarcity in the basin.

The last chapter is conclusion of the whole study. It contains summary of findings. It also includes recommendation on how to mitigate drought and manage its risk. After all the chapters references and appendices are also included in good order.

2. Climatic and Hydrological Data

The climate of Awash is influenced by a low pressure convergence called Inter-Tropical Convergence Zone (ITCZ).This zone marks the convergence of dry tropical easterlies and the moist equatorial westerlies. The annual migration of the ITCZ gives a seasonal rainfall distribution across the basin. In March it advances across the basin from south giving spring rains. In June and July the rainfall reaches its most northerly location beyond the basin which then gives the heavy summer rain. It then returns southwards during August to October, restoring the drier easterly air streams which prevails until the cycle repeats itself in March Halcrow (1989). Due to this cycle rainfall distribution is mainly occurring in two different seasons, spring and summer.

Mean annual temperature ranges from 20.8°c in the upper Awash to 29°c in the lower part. Highest mean monthly temperature occurs in June as high as 23.8°c and 33.6°c in the upper and lower Awash respectively. As a result the potential evapotranspiration (PET) is very high. At the Upper Awash the mean annual PET is as high as twice the mean annual rainfall, with average monthly rainfall exceeding PET only in July and August. In the lower Awash the mean annual potential evapotranspiration (PET) may exceed ten times the mean annual rainfall Belete Berhanu (2013a). The climate pattern indicates that the Awash basin is prone to water scarcity.

2.1. Rainfall Data

Major rains occur from July to August and minor rains occur in March and April. The distribution of rainfall across the basin is highly erratic. High rainfall is observed in the upper Awash on the highlands reaching up to 1600mm, where as a relatively low rainfall is inhibited in the lower part as low as 160mm Edossa et al. (2010). Annual average monthly precipitation of sample sub basins is given in figure 2.1 on page 10. It shows the variation in precipitation between the upper, middle and lower part of the basin. The main variation occurs during the rainy season that is July to September. Considerable variation is also observed from April to June and from September to October. The pattern between middle and lower part is almost similar. In the middle and lower Awash more rains are exhibited in April and May than in June. Almost similar pattern is observed in all parts of the basin at the start and end of a year.

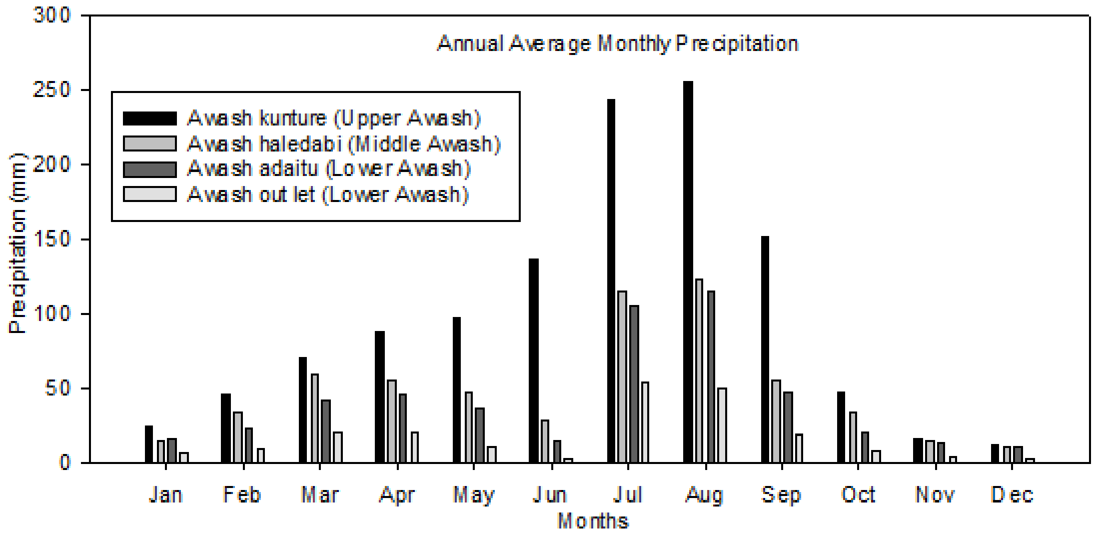

Figure 2.1.: Annual average monthly precipitation of sample sub basins

Rainfall distribution and amount also varies from year to year which causes a drought of different magnitude across the basin in a given year while flood prevails in another year. Hence drought analysis is performed on a sub basin level across the basin. To perform this analysis monthly areal rainfall of 21 sub basins is used from a WEAP model developed by FAO. The data covers a total of 38 year starting from 1970 to 2008. Due to the lack of data the year 2008 is assumed as a current year of analysis. The quality of the data is checked by using double mass curve analysis of neighbouring sub basins. First the areal precipitation values of each sub basin are tabulated in chronological order and their respective cumulative values are estimated. The mean of the accumulated precipitation value is the pattern used to test the consistency Langbein and Iseri (1960). Double-mass plot of sub basins on the upper Awash gives a fairly straight line refer figure 2.2 on page 11 which shows the data of neighbouring sub basins is consistent.

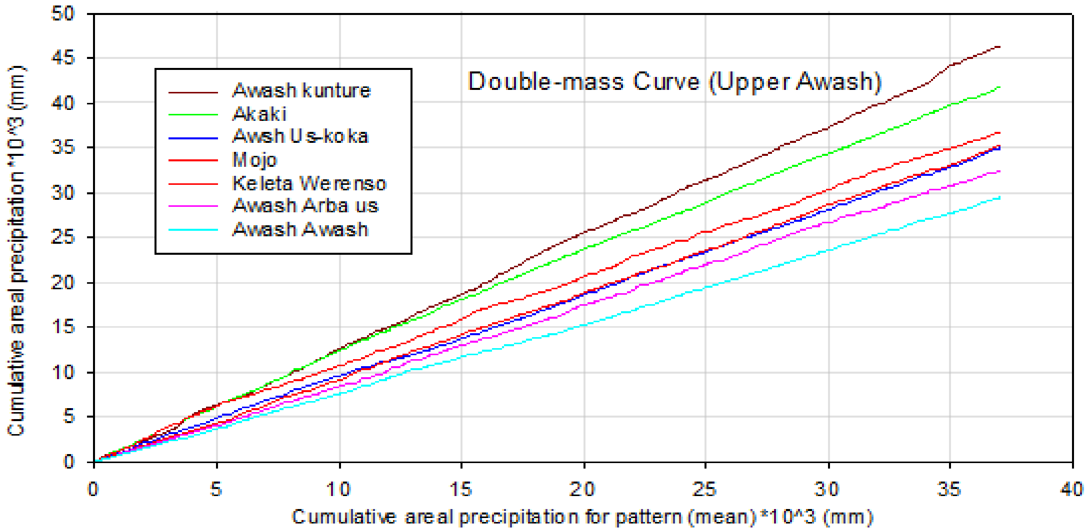

Figure 2.2.: Double-mass curve of sub-basins in the upper Awash

Same analysis is performed in the middle and lower Awash to check the consistency of the data. Double mass plot in the middle Awash gives a fairly straight line as in the upper Awash which can be seen in figure 2.3 on page 11 indicating consistent data.

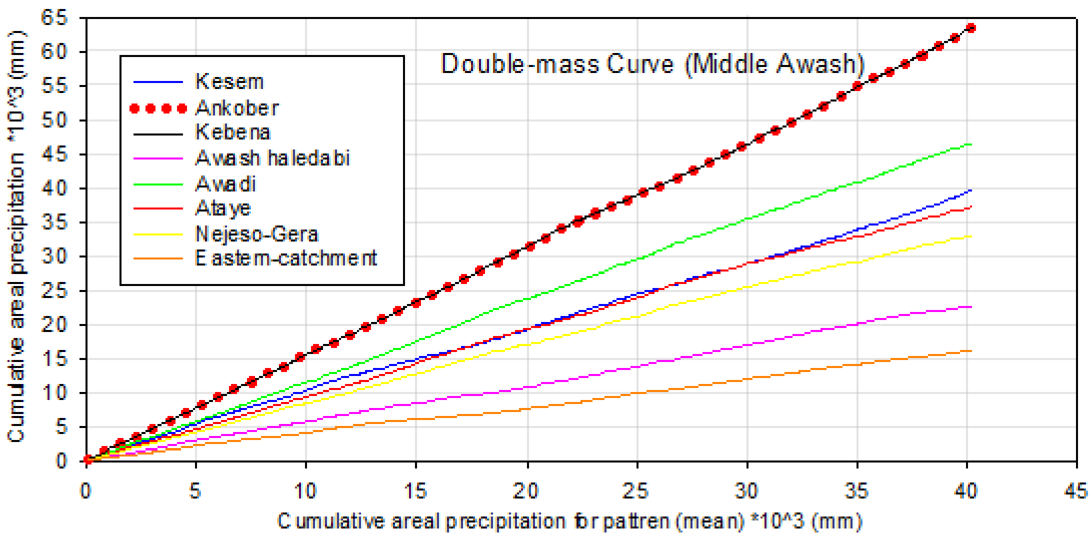

Figure 2.3.: Double-mass curve of sub-basins in the middle Awash

A similar double mass plot of sub basins in the lower Awash indicates a consistent data of precipitation as can be seen in figure 2.4 on page 12. Hence no adjustment of precipitation is needed in all cases.

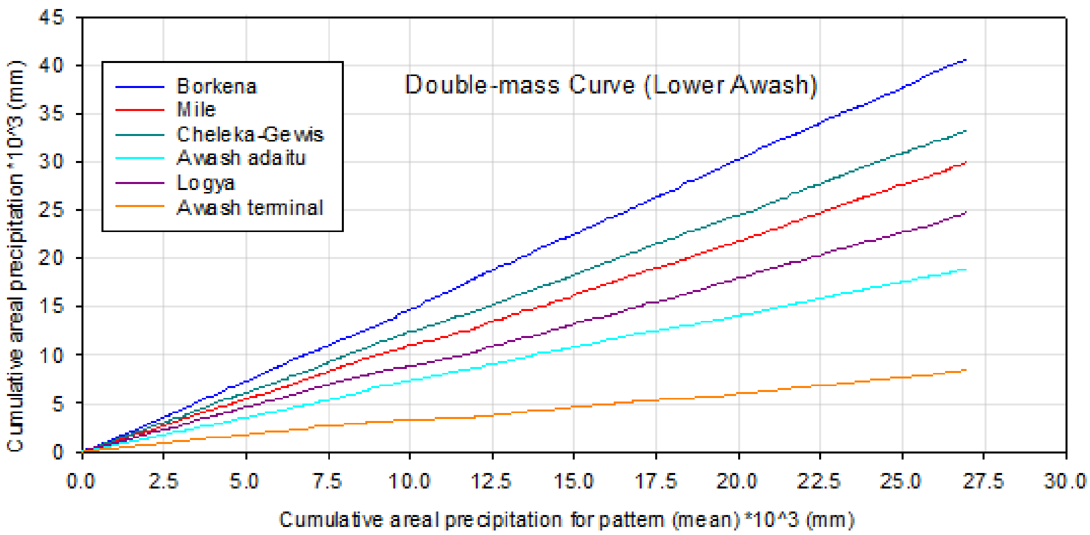

Figure 2.4.: Double-mass curve of sub-basins in the lower Awash

2.2. Temperature data

A monthly time series of temperature of 38 years from 1970 – 2008 is taken from a WEAP model for each sub basin. Monthly temperature of Awash basin is found to be highly correlated with elevation (Belete Brhanu and Semu Ayalew, 2013).

2.3. Stream Flow Data

Despite the existence of gauging stations in the tributaries and main river of Awash, there is no a well monitored and supervised measurement system. Even though there are automatic measurement gauges, many of them are non-functional. Hence manual staff gauge reading is a common practice. This is done by local peoples with less attractive payment. During harsh conditions such as in hot days the reader may not be able to go. During high rainfall period it is also difficult to come out and take measurement. Automatic gauges must be well established and monitored in such big water basin with plenty of water resource schemes. In this work monthly data of 38 years from three gauging stations taken from a WEAP model developed by FAO is utilized. Since these gauging stations are located far apart to each other there was no chance of checking the data consistency. Summary of time series of sample flow data can be referred in figure 2.5 on page 13.

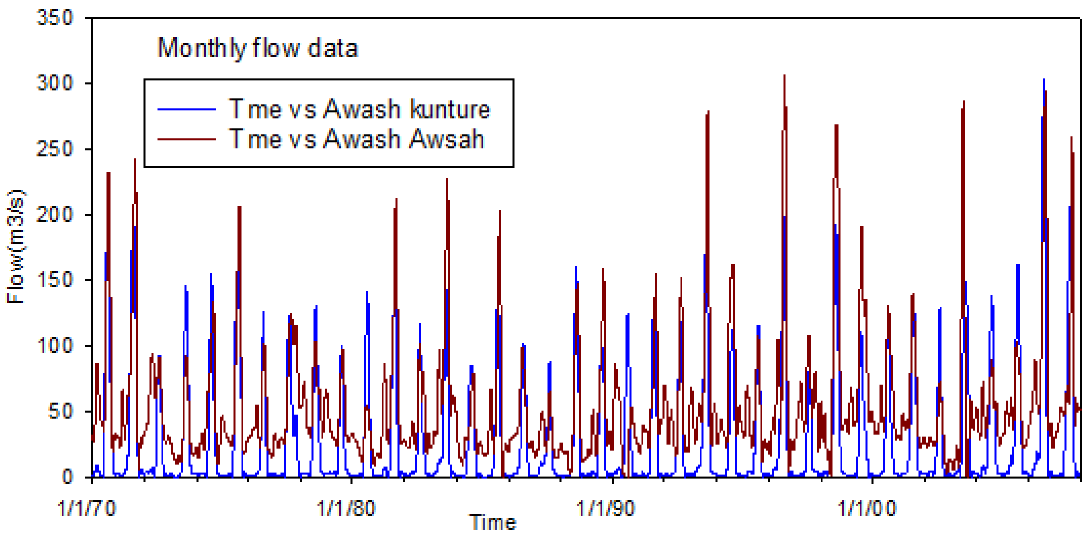

Figure 2.5.: Time series of stream flow of Awash knture and Awash Awash gauging stations

2.4. Hydraulic Infrastructure

Three main reservoirs are built so far in Awash basin namely Koka, Kesem and Tendaho excluding reservoirs build for Adis Ababa city drinking water supply on small streams close to the city. Their location along with gauging stations can be seen in figure 2.6 on page 14. The rainfall gauges located in this map are stations used to estimate the areal rainfall of each sub basin during a WEAP model development of the basin. It must be clear that due the lack of point precipitation areal precipitation is used in this study as explained in the previous section refer sub topic 2.1 on page 9. The two reservoirs Koka and Tendaho are built on the main river Awash where as Kesem reservoir is built on one of the tributaries to the main river that is River Kesem. Koka and Kesem reservoirs are located on the upper and middle part of Awash respectively where as Tendaho is located in the lower part of the basin. Even though the eastern catchment is big catchment, no schemes are developed yet.

2.4.1. Koka Reservoir

Koka dam is located in south-central Ethiopia in the upper part of Awash basin with a storage capacity of 1,071 million cubic meter. It is hydropower reservoir which comes in to operation since 1960. But during drought periods the plant doesn't produce enough power due to shortage of water. During the current drought (2015/16) it was reported that koka hydropower plant is among the plants failed to produce the power needed.

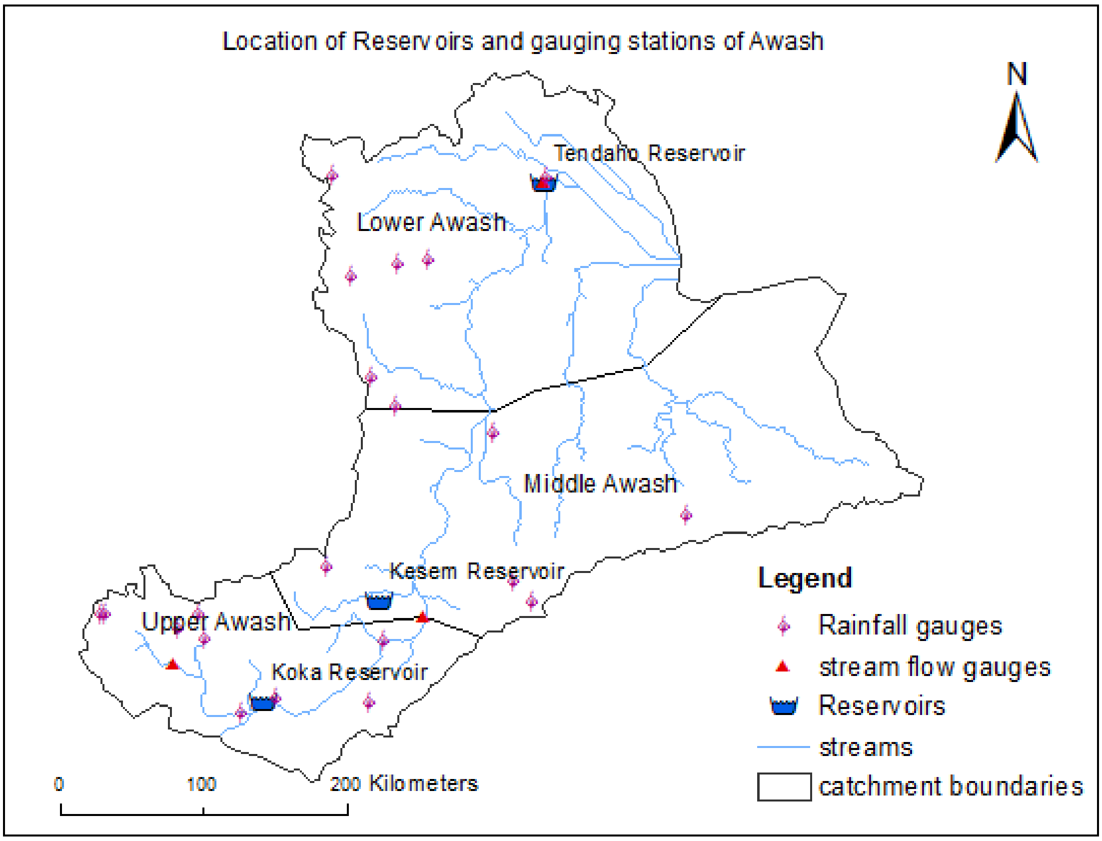

Figure 2.6.: Location of Reservoirs and gauging stations

The volume elevation curve of the reservoir can be referred in figure 2.7 on page 15. From the figure It can be seen that the maximum capacity of the reservoir 1,071 million cubic meter is reached at $1590.4m$ elevation above mean sea level. The inflow to the reservoir covers a catchment area of $11,250km^2$.

The main purpose of the reservoir is power production but irrigation scheme is also common practice on the downstream. It is also used as flood protection downstream of the reservoir. It is a long serving dam but still it is expected to meet some of the current power demands. Even though it is an old power plant it can be used as a multi purpose dam for longer periods in the future as it is located at the upstream of the basin where plenty of demand sectors in the downstream need to be met. If a proper and efficient operation are implemented it can be a life saver during extreme or severe drought periods. But to meet all these purposes in the future maintenance has to be done. As it is old the active storage capacity is reducing due to accumulation of sediments. As a result its power production capacity as well will reduce significantly in the near future.

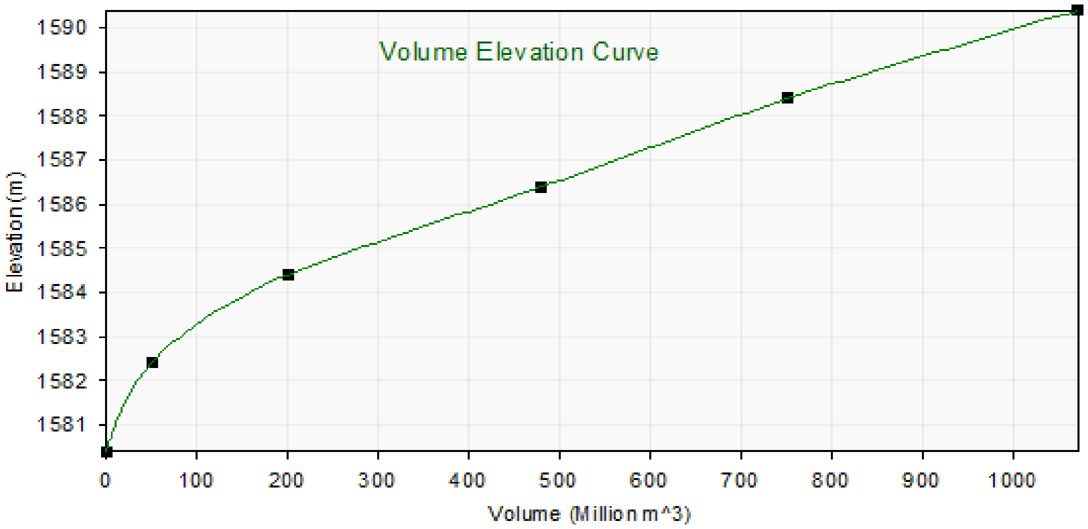

Figure 2.7.: Volume elevation curve of Koka reservoir

2.4.2. Kesem Reservoir

Kesem reservoir is located 237km away to North east of Addis Ababa in the Afar regional state that is in the middle part of the Awash basin. It has a storage capacity of 500 million cubic meters which can irrigate 20,000 hectares of farm land. Volume elevation curve of the reservoir can be seen in figure 2.8 on page 16. Its location is strategic for both the middle and lower part of the basin. If proper transfer systems are implemented it can be used to reduce risk of water scarcity.

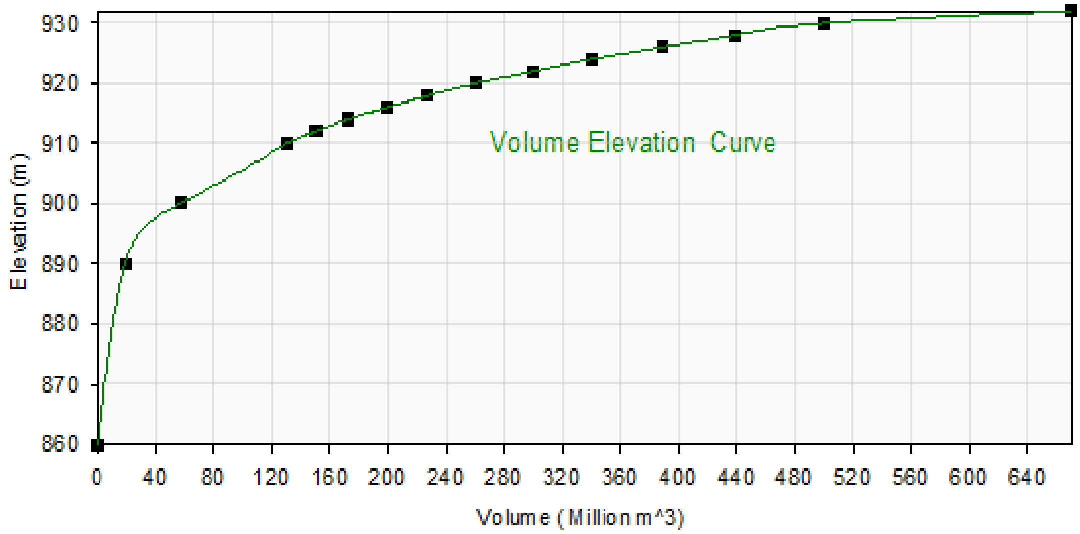

Figure 2.8.: Volume elevation curve of Kesem reservoir

2.4.3. Tendaho Reservoir

It is located in eastern Afar region in the lower part of the Awash river basin. It is a multipurpose reservoir mainly used for irrigation. It has a storage capacity of 2,017 million cubic meter with irrigation potential of 60,000 hectares. Volume elevation curve of Tendaho reservoir is given in figure 2.9 on page 16.

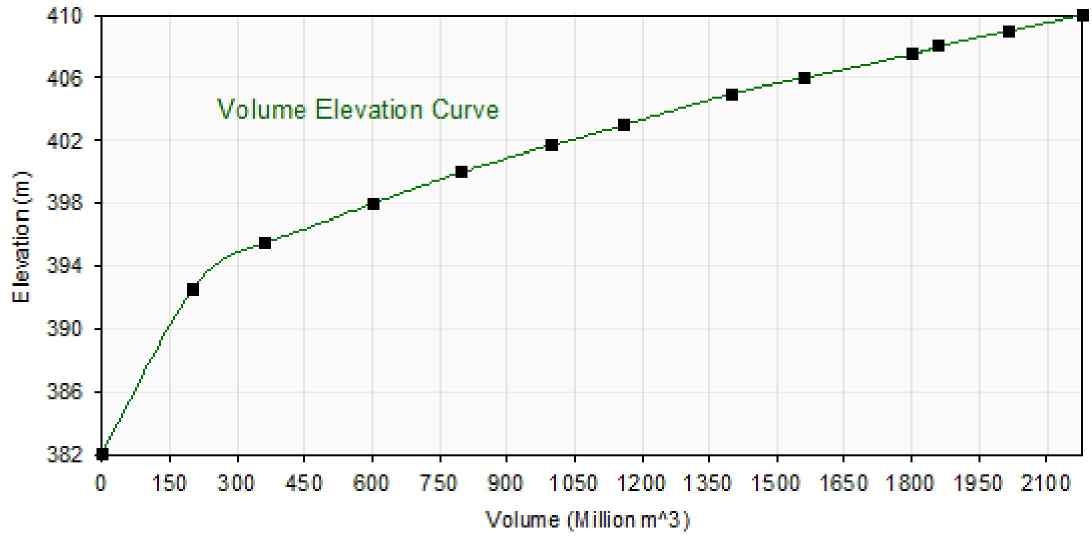

Figure 2.9.: Volume elevation curve of Tendaho reservoir

Apart from the primary purposes these reservoirs are expected to mitigate drought and flood hazard. But it has been observed that the Awash basin is hit by drought of various magnitude. In the next chapter drought characteristics is analysed across the basin based on historical observed data.

2.5. Water Resource Development Potential

Compared to other basins in Ethiopia Awash basin is the most utilized and researched river basin due to its irrigation potential, water resource and strategic location. According to Awulachew et al. (2007) this basin has a total of 37 irrigation sites and out of which 5 are small scale, 18 are medium scale, and 14 are large scale sites. Irrigation potential of the basin is summarized in table 2.1 on page 17.

Irrigation scale	Small scale	Medium scale	Large scale	Total
Area (hectares)	30,556	24,500	79,065	134,121

Table 2.1.: Irrigation potential of the awash basin Awulachew et al. (2007)

According to Belete Berhanu (2013b) the irrigation potential of the basin is around 206,000 ha (about 4.67% of the total irrigation potential of the country). Assessment of this potential only considered gravity system of irrigation with land slope not exceeding 5%. Only 65% of this potential is identified by Awulachew et al. (2007). The hydropower potential of the basin is estimated to be 5,589 Gwh per year Belete Berhanu (2013b). Only 17.8% of this potential is developed so far. This shows the basin has a good irrigation and hydropower potential.

In general with increasing urbanization and high population growth in the basin other demand sectors are possibly to grow fast. Hence, in the future drinking water supply projects and industrial demands has to be given priorities as the other big water resource development projects.

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3. Drought Assessment

Drought is a weather related natural hazard that can affect a particular region or entire country. It has an impact on people, livestock, food production, hydropower production and economic development. It can occur in all types of climate. Hence, drought has to be well studied and assessed to understand its characteristics Drought assessment is conventionally based on drought indices for the identification of drought characteristics such as its duration, severity, frequency and areal extent. Drought indices are used to characterize drought and to compute its statistical properties. They provide temporal and spatial variation of historical droughts and hence current conditions can be set from historical perspective. They are very valuable indicators for decision makers with a measurement of the abnormality of recent weather for a region Wilhite (2000). They are also very helpful as they can communicate to the wider audience easily comprehensible information regarding the severity of drought episodes Tsakiris et al. (2007). They are computed mainly based on meteorological and hydrological data.

Conventionally, droughts are characterized based on the determinant studied and are usually classified as meteorological (precipitation, potential evapotranspiration), hydrological (stream flow) and agricultural (soil moisture) or combination of the above, Dracup et al. (1980). Similar classification can be found by Wilhite and Glantz (1985), where four categories are adopted; Meteorological drought, hydrological drought, agricultural drought and socio-economic drought. Initially, meteorological drought is caused by the lack of precipitation possibly in combination with high evapotranspiration. This drought will in turn causes lack of soil moisture which is called agricultural drought which affects crops and vegetation. Precipitation deficit may also cause the streamflow drought defined by low streamflow values Vrochidou et al. (2013). Socioeconomic drought is related with supply and demand of economic goods. It occurs when the demand for an economic good exceed the supply as a result of shortfall in water supply.

In this work the software package named Drinc (Drought Index Calculator) developed at the Centre of Natural Hazards and Proactive Planning and the Laboratory of Reclamation Works and Water Resources Management of the National Technical University of Athens was used to calculate drought indices Tigkas et al. (2015). Three drought indices named the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) and Standardized Streamflow drought Index (SDI) were calculated based on available meteorological and hydrological data of Awash River basin.

3.1. Standardized Precipitation Index (SPI)

The standardized precipitation index is used for the analysis of meteorological drought. The long term precipitation record for a desired period is fitted to a probability distribution function, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero Edwards et al. (1997). Positive SPI value Indicate greater than median precipitation and negative values indicate less than median precipitation.

Thom (1958) found the gamma distribution function to fit well to climatological precipitation time series. The gamma distribution is defined by its frequency or probability density function.

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{(\alpha-1)} e^{(-x/\beta)}, for x > 0 \tag{3.1}$$

In which α and β are the shape and scale parameters respectively, x is the precipitation amount and $\Gamma(\alpha)$ is the gamma function. Parameters alpha and beta of the gamma probability distribution function are estimated for each sub basin and for each time scale of interest (3, 6, 9, 12 month etc.). Maximum likelihood estimation of Alpha and Beta are:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right), \beta = \frac{\bar{x}}{\alpha}, where, A = \ln \bar{x} - \frac{\sum \ln(x)}{n} \tag{3.2}$$

And n is the number of observations. The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month and time scale for the location in question. Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zero values, the cumulative probability becomes:

$$H(x) = q + (1 - q)G(x) \tag{3.3}$$

where q is the probability of zero precipitation and G(x) is the cumulative probability of the incomplete gamma function. If m is the number of zeroes in a precipitation time series, then q can be estimated by m/n. The cumulative probability H(x), is then transformed to the standard normal random variable z with mean zero and variance of one Abramowitz and Stegun (1964), which is the value of SPI.

According to SPI, a drought event occurs when the index continuously reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, intensity for each month that the event continues. Drought magnitude is the positive sum of the SPI for each month during the drought event. Classification of drought condition is given in table 3.1 on page 21.

SPI values	Classification
≥ 2.0	Extremely wet
$[1.5 - 2.0)$	Very wet
$[1.0 - 1.5)$	Moderately wet
$(-1.0 - 1.0)$	Near normal
$[-1.0 - -1.5)$	Moderately dry
$[-1.5 - -2.0)$	Severely dry
≤ -2.0	Extremely dry

Table 3.1.: Classification of drought according to SPI

SPI values of each sub basin was computed for each month and each hydrological year on different time scale based on their respective areal precipitation. A 3 month SPI for September of a particular year utilizes precipitation total of July to September of the available previous years and a 6 month SPI for September utilizes precipitation totals of May to September. Likewise, the 12 month SPI for September utilizes precipitation totals of October to September. SPI values for Awash Kunture based on 12 month time scale for September month is shown in figure 3.1 on page 22 for illustrative purpose. The result shows a near normal drought condition for most of the time in awash kunture sub basin. The drought conditions are represented in different colors for better visualization. green color indicates extreme wet condition while the red one indicates severe drought condition. Near normal condition of drought is represented by grey color. Two extreme wet conditions are observed while no extreme drought condition is observed. In this sub basin one severe drought event is observed during the famous drought and famine period in Ethiopia that is 1984/1985.

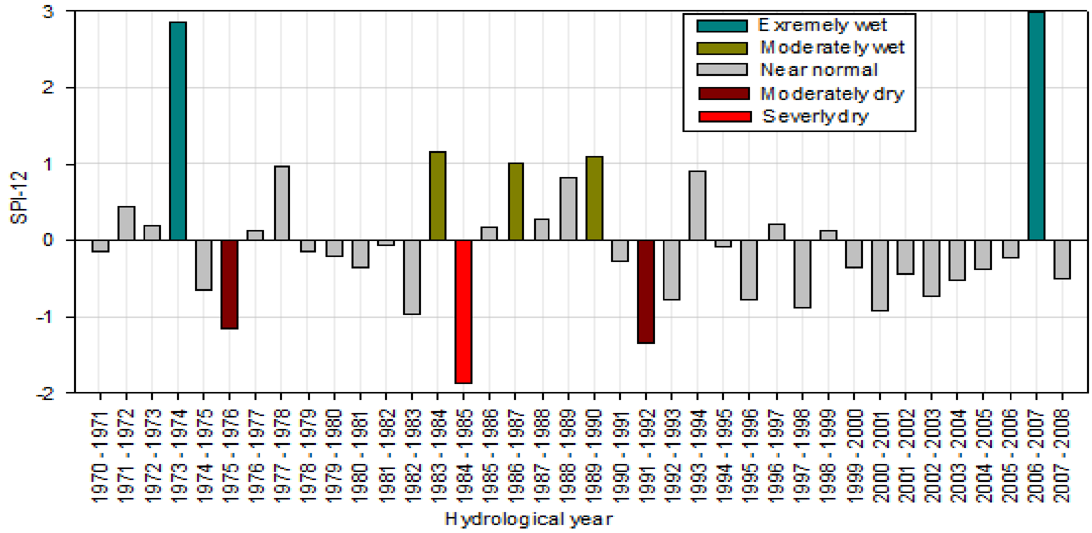

Figure 3.1.: Meteorological drought condition of awash kunture based on 12 month SPI for September

3.1.1. Temporal Variation of Meteorological Drought

A 3-month SPI is used to assess the effect of drought on agricultural production. It reflects a short and medium-term soil moisture condition. A 12-month SPI reflects long-term precipitation patterns and is effective in assessment of drought impact on reservoir and water body. SPI based on 6-month time scale shows a medium term precipitation trend. It can be associated with anomalous stream flow and storage reservoir. Time series of SPI is estimated for each sub basin on 3, 6 and 12 month time scale. Result values of SPI for awash kunture sub basin is shown in figure 3.2 on page 23. The result shows a single event of precipitation on shorter time scale index is more visible than on longer time scale index during drought periods. Longer duration of drought event is observed on longer time scale, conversely, a shorter duration of drought is observed on shorter time scale but with more number of drought occurrences.

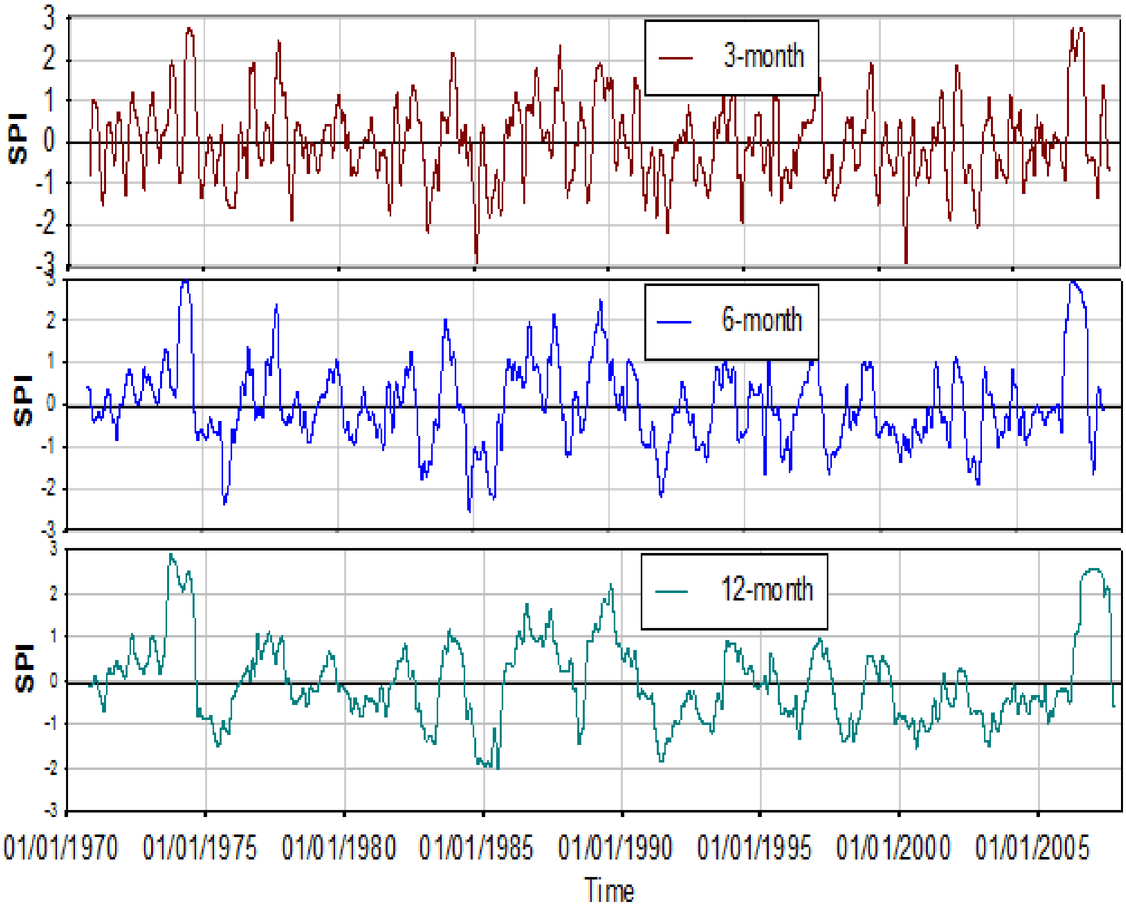

Figure 3.2.: SPI time series for Awash Kunture based on 3, 6 and 12 month time scale

Temporal variation of drought at the end of a rainy season is investigated. The reason is that in dry areas precipitation event is normally limited to certain period. Hence, the drought event that will happen in the rainy season is the main concern for planning and mitigation purpose to minimize the impact. In the Awash valley the main rainy season is on July, August and September months. So time series of drought index at the end of rainy season that is September in this case is analysed. Awash Kunture from upper, Awash haledabi from middle and Awash adaitu from lower awash were selected to illustrate the temporal variation of drought for September on 3, 6 and 12 month time scale across the basin and summary of the result is shown in figure 3.3 on page 24. In Awash Adaitu sub basin which is located in the lower part, two extreme drought events have happened. One is during the known famine event in Ethiopia in 1984/85 which left millions of people and livestock in danger. This event is revealed by SPI in all considered time scale. The second extreme drought event has happened in 1991/92 which is also a known drought period in Awash valley. In the middle Awash one extreme drought event has happened, while no extreme event in the upper Awash as expected. Hence the SPI index is able to reflect the actual drought events happened so far, refer the marked years in figure 3.3 on page 24.

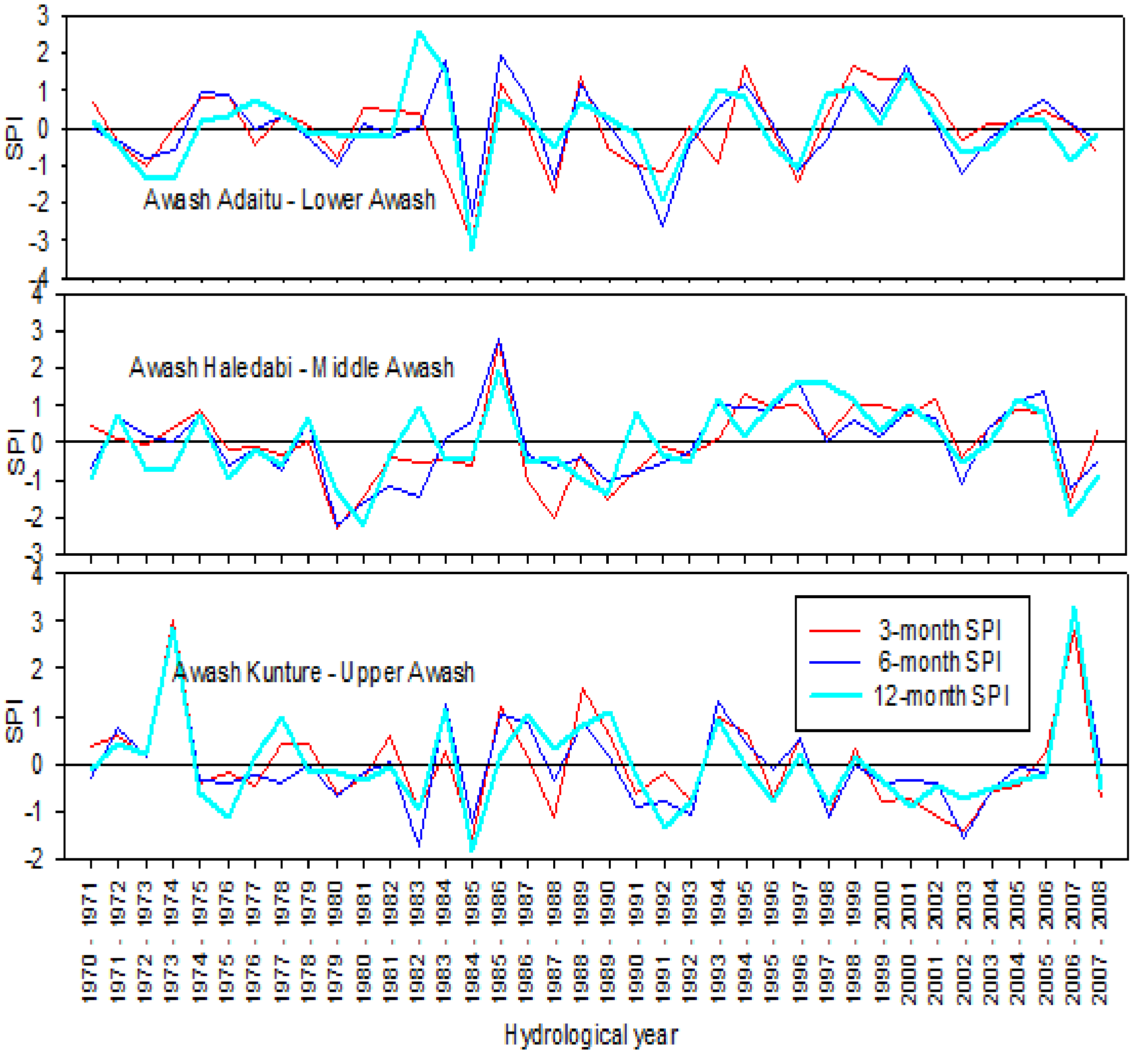

Figure 3.3.: SPI time series of September on 3, 6 and 12 month time scale

3.1.2. Relative Frequency of Meteorological Drought Events

Drought occurrence in the awash valley is analysed for each sub basin for September on 12 month time scale. It is based on the percentage occurrence of each event in each category with respect to the total number of observations, 38 years in this case. The aim is to identify areas hit by frequent drought of different severity level. Summary of the percentage of drought occurrence for each sub basin is given in table 3.2 on page 25. Extreme drought event occurrence is mostly happening in the middle and lower Awash valley where as mild and severe drought event is common phenomenon on the upper Awash.

Id	Sub basin	Extremely dry(%)	Severely dry(%)	Moderately dry(%)	Mild dry(%)	Mild & above(%)
1	Awash kunture	0.00	2.63	5.26	52.63	60.53
2	Akaki	0.00	5.26	10.53	34.21	50.00
3	Mojo	2.63	5.26	7.89	31.58	47.37
4	Awash US-koka	0.00	2.63	10.53	44.74	57.89
5	Keleta werenso	2.63	2.63	15.79	26.32	47.37
6	Awash Arba us	2.63	0.00	13.16	36.84	52.63
7	Awash awash	5.26	5.26	5.26	26.32	42.11
8	Kesem	0.00	2.63	15.79	42.11	60.53
9	Kebena	2.63	5.26	2.63	44.74	55.26
10	Ankober	2.63	5.26	2.63	44.74	55.26
11	Awash haledabi	2.63	2.63	5.26	44.74	55.26
12	Awadi	2.63	2.63	5.26	52.63	63.16
13	Ataye	2.63	0.00	7.89	50.00	60.53
14	Borkena	2.63	7.89	2.63	42.11	55.26
15	Nejeso-gera	2.63	2.63	5.26	50.00	60.53
16	Mile	5.26	2.63	5.26	26.32	39.47
17	Cheleka-gewis	5.26	2.63	5.26	26.32	39.47
18	Awash adaitu	2.63	2.63	7.89	34.21	47.37
19	Logiya	5.26	0.00	10.53	23.68	39.47
20	Eastern catchment	2.63	2.63	10.53	36.84	52.63
21	A.terminal	2.63	0.00	10.53	39.47	52.63

Table 3.2.: Percentage of drought occurrence in each sub basin for September

The spatial drought occurrence on each sub basin for September is mapped using ARC view to have an overview of the drought event in the basin. The map shows the percentage of a given drought category that has happened in each sub basin. Figure 3.4 on page 26 shows occurrence of extreme and severe drought across the basin. It can be seen that extreme droughts are occurring in higher percentage in the lower, middle and the lower part of the upper Awash, downstream of Koka reservoir. It can be also seen that as there is no occurrence of extreme drought in the the upstream part of the upper Awash that is in the highlands of the basin. Similar result is seen for severe drought except in the Awash terminal that very low severe drought is observed. Relatively the middle Awash is facing middle percentage of extreme and severe drought occurrence.

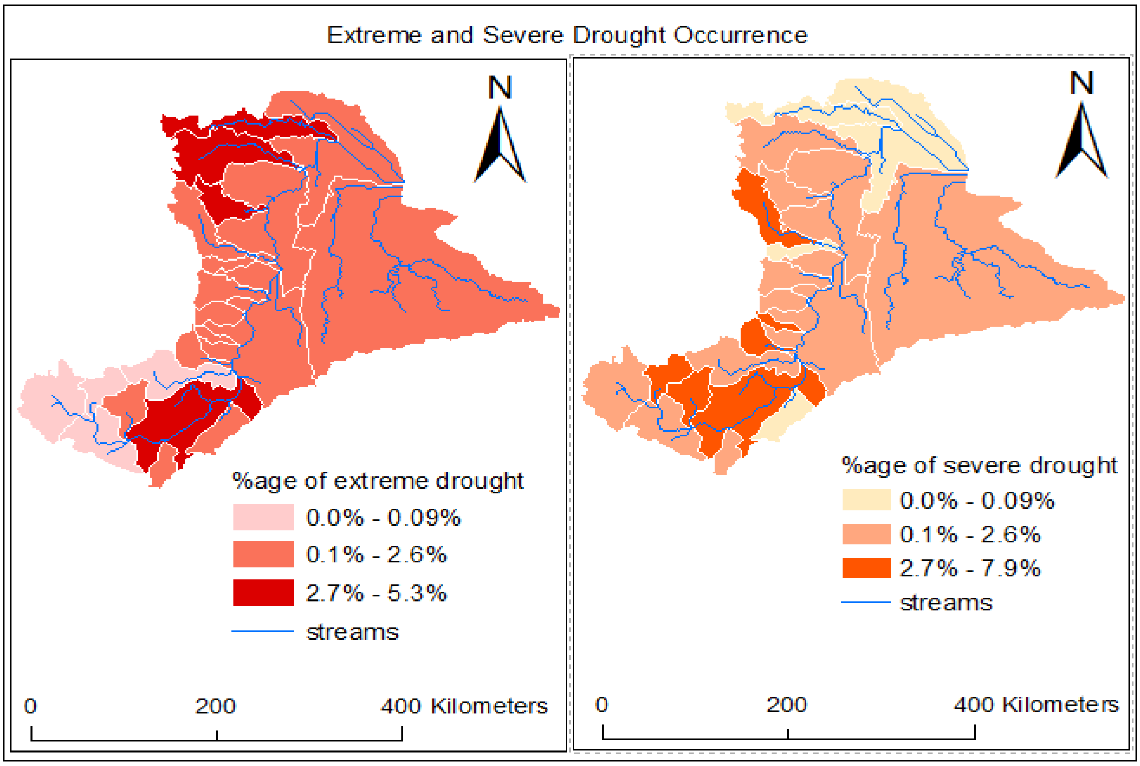

Figure 3.4.: Extreme and severe drought occurrence over view of Awash basin

Moderate and mild drought occurrences are also mapped in the same way as the extreme and severe droughts. The result shows higher percentage of moderate droughts in all over the Eastern catchment, Logiya and Awash terminal sub basins. Higher percentage of moderate drought is also observed in some sub basins of the upper Awash refer figure 3.5 on page 27. Mild drought occurs in higher percentage in almost all sub basins except in some basins of the upper and lower Awash.

Hence, one can quickly identify drought affected areas across the basin during any decision making process related to drought mitigation.

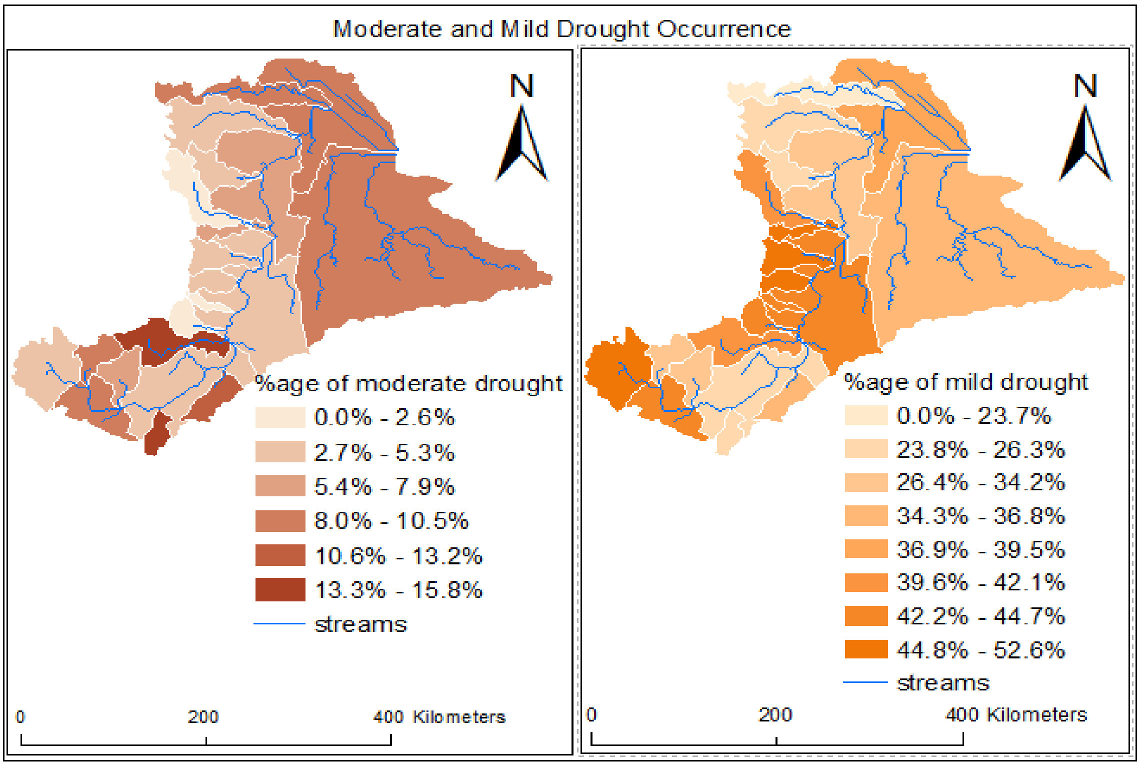

Figure 3.5.: Moderate and Mild drought occurrence over view of Awash basin

The duration of drought events and their frequency is also analysed for each sub basin. A duration of five consecutive year drought event out of the analysis period (1970−2008) is observed once in Awash terminal and Eastern catchment sub basins as expected. Drought event with one year duration is a common phenomenon in all sub basins happening 3 to 8 times out of the analysis period. In most of the sub basin a two year drought event is also common which happens one to three times. Summary of the consecutive drought event frequency and their duration is presented in figure 3.6 on page 28. This analysis is very important in identifying areas hit by consecutive drought events so as to decide necessary mitigation measures.

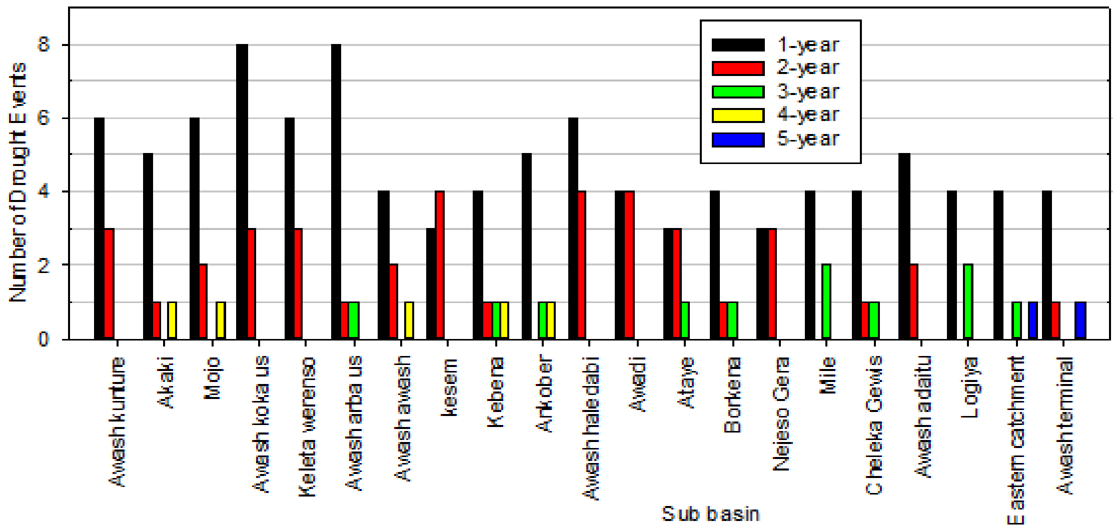

Figure 3.6.: Duration of consecutive drought years of each sub basin of Awash

3.2. Standardized Precipitation Evapotranspiration Index (SPEI)

The basic principle behind SPEI is same as SPI except it uses temperature time series as input in addition to precipitation time series. Temperature is used to compute the potential evapotranspiration, and then a simple water balance computation is performed to account the temperature effect over drought intensity. Same classification of drought condition is used as SPI refer table 3.1 on page 21. In some sub basins of the lower awash higher evapotranspiration than precipitation is observed in all month of given year which gives several zero values of net precipitation. Analysis of drought index with several zero values doesn't give reasonable value but it can be concluded that those areas are extreme drought prone areas. For homogeneity of the analysis across the basin the SPI is used as main meteorological drought index for further analysis. In the upper and middle awash the SPEI index result was very similar as SPI result except some variation in the index values. A comparison of the two indices can be seen in figure 3.7 on page 29. The result shows a drought condition of severely dry in SPI is observed as extremely dry in SPEI as expected. Likewise, the wetness intensity is also reduced in SPEI. But in near normal condition the changes are not significant.

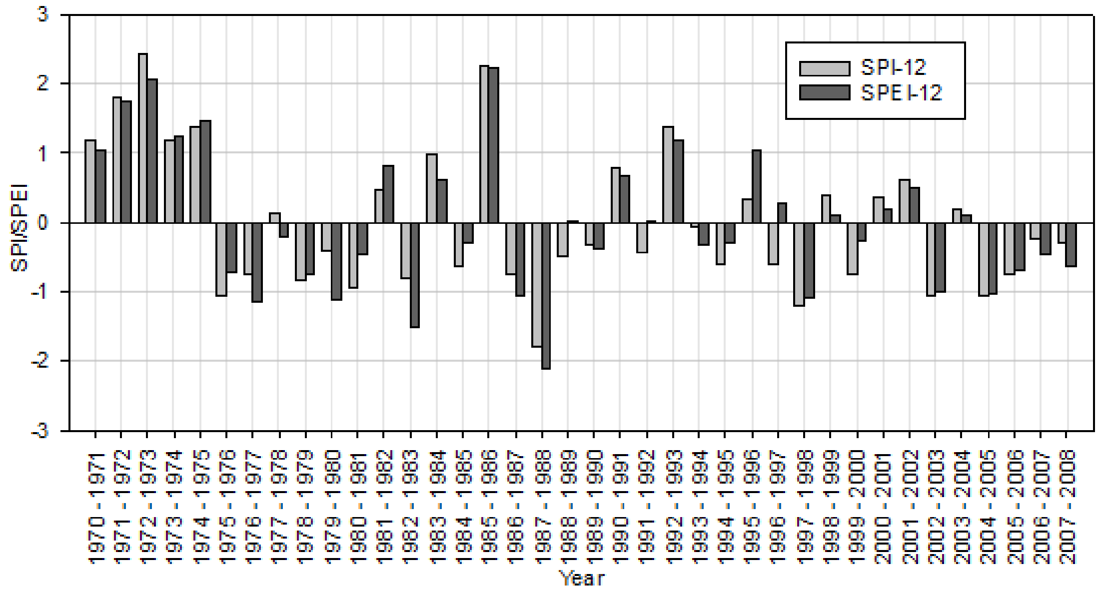

Figure 3.7.: Comparison of SPI and SPEI for Awash US Koka sub basin on 12 month time scale

3.3. Standardized Streamflow Drought Index (SDI)

SDI is used for the analysis of hydrological drought by using stream flow time series as an input. According to Nalbantis (2008), if a time series of monthly stream flow volumes Q_{ij} is available, in which i denotes the hydrological year and j the month with in the hydrological year (j = 1 for October and j=12 for September), $V_{i,k}$ can be obtained based on the equation:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j}, i = 1, 2, ...j = 1, 2, ..., 12, k = 1, 2, 3, 4 \tag{3.4}$$

In which $V_{i,k}$ is the cumulative stream flow volume for the i_{th} hydrological year and k_{th} reference period, k = 1 for October-December, k = 2 for October-March, k = 3 for October-June and k = 4 for October-September. Based on the cumulative stream flow volumes v_{ik}, the stream flow drought index (SDI) is defined for each reference period k of the i_{th} hydrological year as follows:

$$SDI_{i,k} = \frac{V_{i,k} - \bar{V}_k}{S_k}, i = 1, 2, ..., k = 1, 2, 3, 4 \tag{3.5}$$

In which V_k and S_k are respectively the mean and standard deviation of cumulative stream flow volumes of the reference period k as these are estimated over a long period of time.According to Nalbantis and Tsakiris (2009), classes of hydrological drought are defined for SDI in identical way to those used in the meteorological drought indices SPI. Hydrological drought conditions along with their definition of states with the aid of SDI is given in table 3.3 on page 30.

State	Description	Criterion
0	Non-drought	$SDI \geq 0.0$
1	Mild drought	$-1.0 \leq SDI < 0.0$
2	Moderate drought	$-1.5 \leq SDI < -1.0$
3	Severe drought	$-2.0 \leq SDI < -1.5$
4	Extreme drought	$SDI < -2.0$

Table 3.3.: Definition of states of hydrological drought with the aid of SDI

SDI of three gauging stations namely Awash kunture, Awash Awash and Awash Tendaho is computed using Drinc software on different time scale.

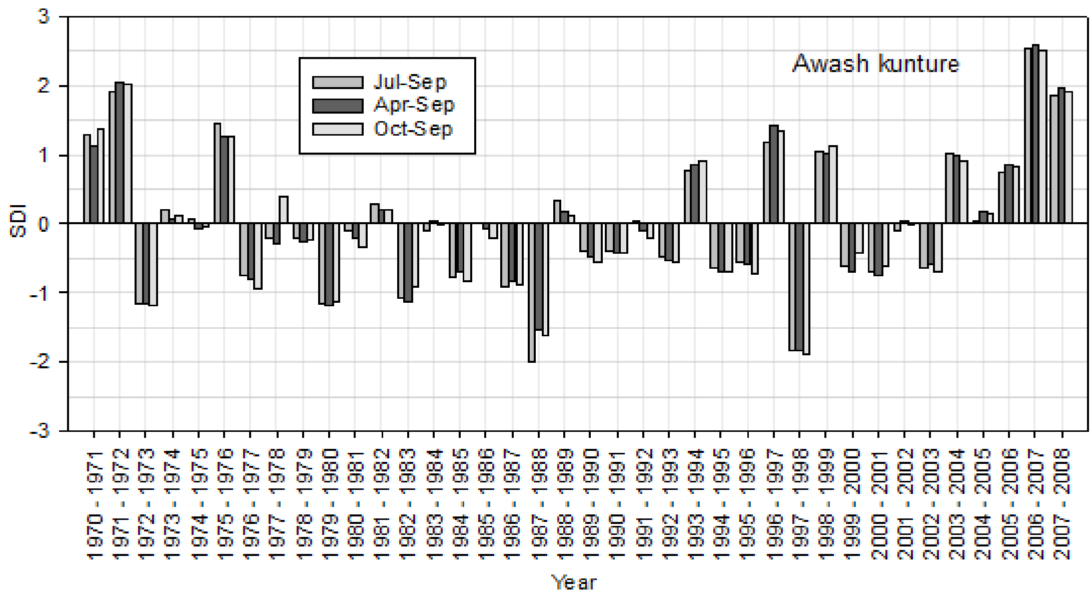

Figure 3.8.: SDI of Awash kunture gauging station

In Awash kunture sub basin two severe hydrological drought events in 1987/88 and 1997/98 are observed in all the considered time scale as can be seen in figure 3.8 on page 30. In those periods a moderate meteorological drought events are observed which is revealed in the stream flow index on down stream of the sub basin catchment. Extreme drought event is not observed in this station as expected. A similar trend of stream flow index is observed for all the considered time interval except some variation in the severity level. This is due to a reason that in upper Awash spring rainfall is a common phenomenon followed by heavy rainfall in summer.

A different trend of stream flow index is observed at Awash Awash gauging station which is located at the lower part of the upper Awash valley compared to the index at the most Upper part of the valley at Awash kunture gauging station. A considerable variation of drought severity is seen on different time scale which gives a different state of hydrological drought. This is due to the water uptake for irrigation and koka reservoir in the upstream of the gauging station. So there will be a different pattern of irrigation water use during dry and wet period. The out flow from Koka reservoir as well will have an effect on the amount of downstream flow.

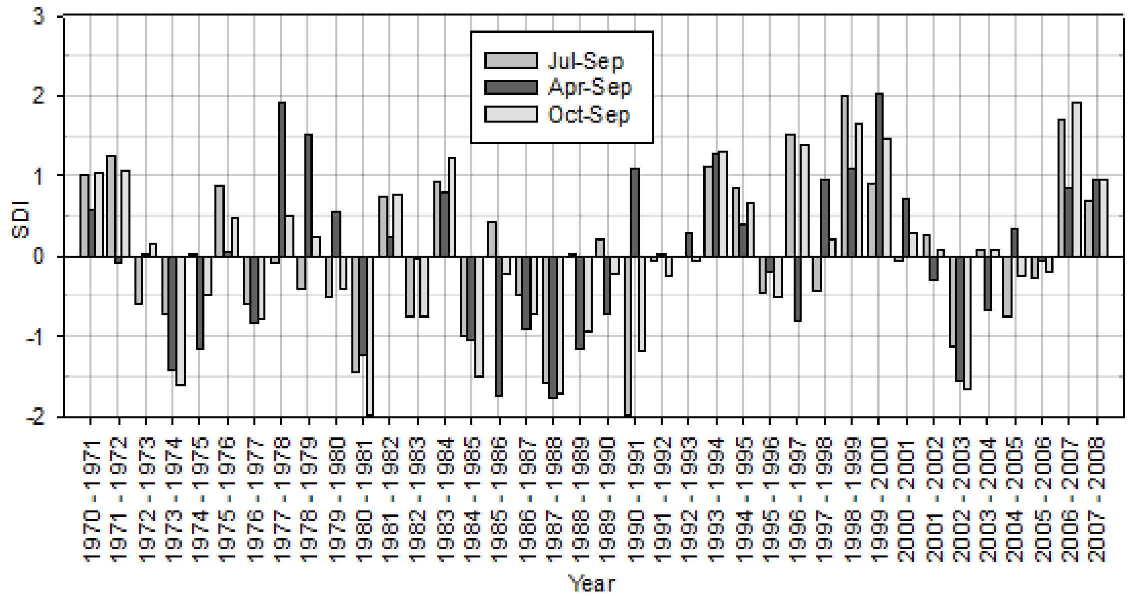

Figure 3.9.: SDI of Awash awash gauging station

The major drought event that happened in awash in 1973/74, 1984/85 and 2002/03 are revealed in this gauging station in all the considered time scale as can be seen in figure 3.9 on page 31. Mild and Moderate drought has happened for index period of Jul-Sep and Apr-Sep respectively. While, a severe hydrological drought is observed in annual basis index. This is due to the reason that a dry period where water consumption for different purposes is high is included in the annual index. In 1990/91 severe and moderate drought has happened for index values of Jul-Sep and Oct-Sep, but a non drought condition for Apr-Sep.

3.4. Relationship of Meteorological and Hydrological Droughts

The main cause of drought is lack of precipitation over a large area for a considerable period of time and usually called as meteorological drought. This lack of water propagates through the hydrological cycle and gives rise to soil moisture, ground water and stream flow reduction. Due to reduction in ground water recharge and stream flow hydrological drought will develop. But this development happens after the onset of meteorological droughts. Hence, hydrological droughts are out of phase or lag of the occurrence of meteorological droughts Wilhite (1997).

A relationship is analysed by using SPI time series of Awash kunture sub basin and a time series of SDI of a gauging station at the out let of the sub basin catchment. Drought characteristics such as the onset time, end time, magnitude and duration is estimated for the sub basin and the gauging station. Magnitude of drought is estimated by taking positive sum of the SPI or SDI values of each drought pulses.

$$DM = \sum_{j=1}^{x} SPI_{ij} \tag{3.6}$$

where DM is drought magnitude, j starts with the first month of drought and continues till the end of drought month x for any of the i time scale. From regression analysis of the drought characteristics a good correlation is found between the duration of meteorological and hydrological droughts based on one and two month time scale of drought index. Correlation based on one month time scale gives $R^2 = 0.792$ with a time lag of 0 month to 4 month. It takes on average of two months to see shortage of stream flow at the gauging station due to the deficit of precipitation of Awash kunture catchment. The result of the analysis based on one month time scale is given in figure 3.10 on page 33. Hence, this relationship between the two drought types can be used to forecast hydrological droughts ahead of rainfall shortage. Decision makers and water managers can use it for proper allocation of available water for different purposes.

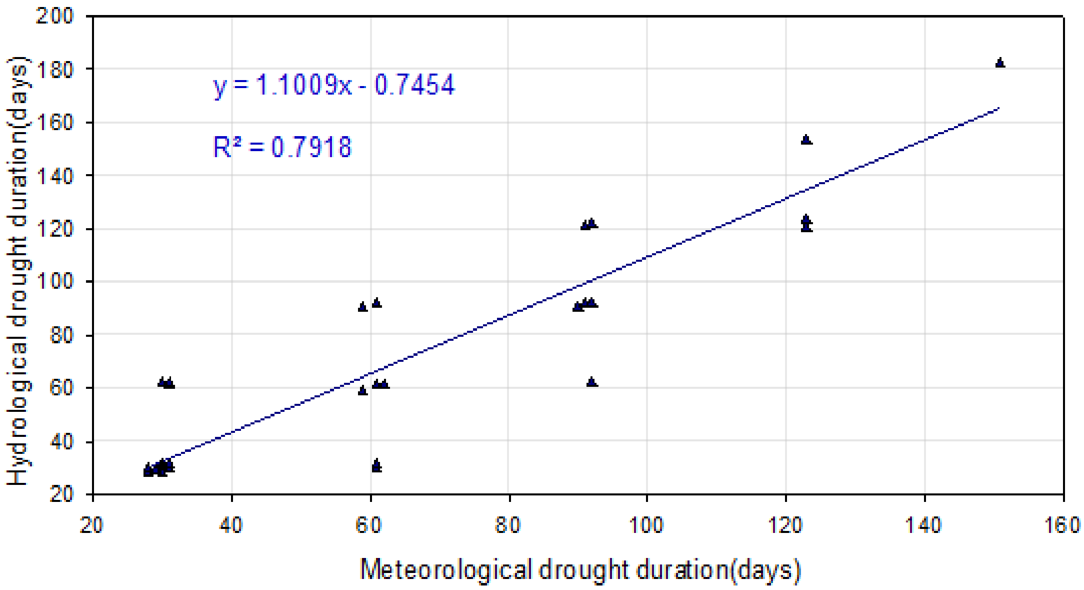

Figure 3.10.: Relationship of meteorological and hydrological drought events duration based on one month time scale

Analysis based on two month time scale gives better correlation ($R^2 = 0.811$) of linear relationship and can be referred to figure 3.11 on page 34 with a time lag of zero to 5 months. Zero month lag time shows that it takes some days it could be 10 days or 20 days to see a hydrological drought due to rain failure in the upstream catchment. Since a monthly data is used, the exact days can not be known for zero month lag time. This zero lag time is reasonable as the used catchment area is very small (4% of total area) compared to the total area of the basin. Edossa et al. (2010) found a similar result with $R^2 = 0.87$ based on 2 month time scale and average time lag of seven months of hydrological drought. The reason why in the current analysis gives a shorter time lag is that the considered catchment area is smaller (4% of total basin catchment) than the area used by Edossa (25% of total basin catchment). As a result, a less time lag of hydrological drought is found in the current analysis.

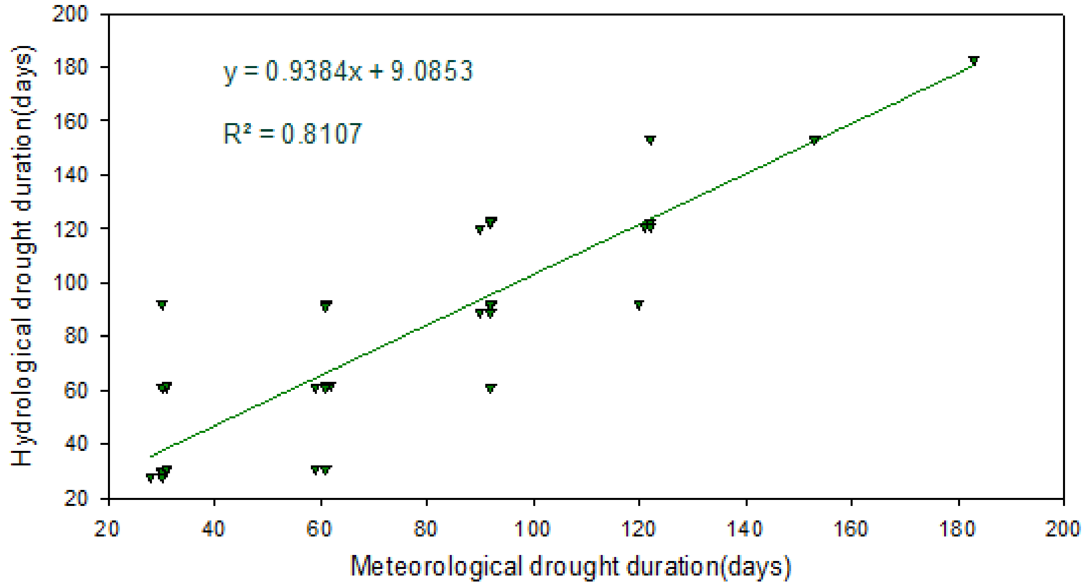

Figure 3.11.: Relationship of meteorological and hydrological drought events duration based on two month time scale

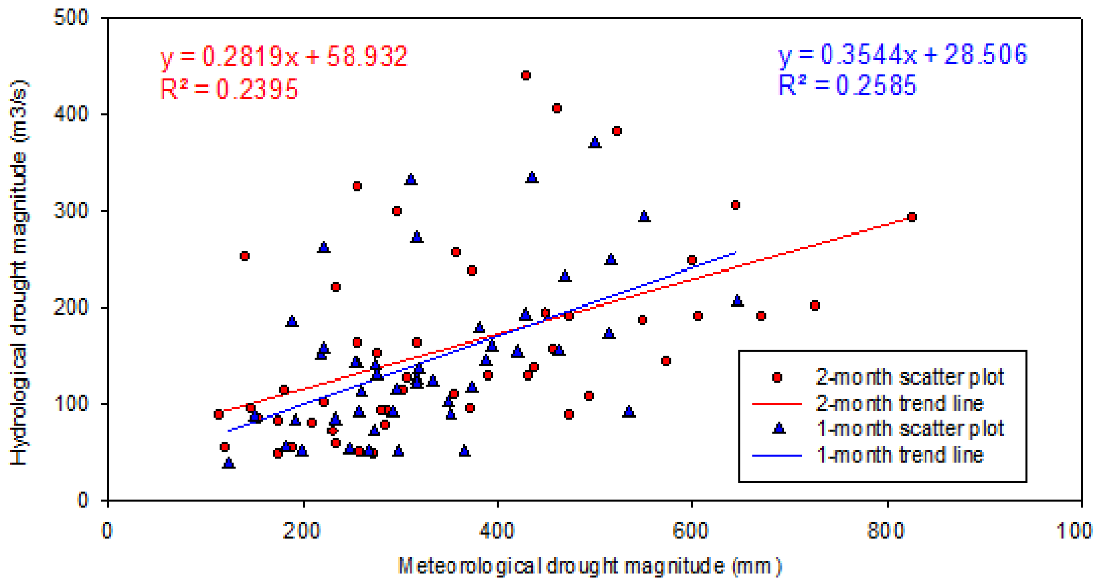

Figure 3.12.: Regression analysis between magnitudes of meteorological and hydrological droughts

Regression analysis using drought magnitude is also performed based on one and two month time scale. The result gives a linear relationship as the drought durations but a weak correlation is observed as shown in figure 3.12 on page 34. This weak correlation could be due to the effect of land use change and irrigation practices upstream of the gauging station. In general establishing relationship between meteorological and hydrological droughts is very helpful in estimating stream flow deficit ahead of rainfall shortage. A better demand side water management can be implemented in each demand sites if such forecasting techniques are available. Intensity of the drought events is also analysed to find the severity level by taking the ratio of drought magnitude and its duration, but the relationship result between meteorological and hydrological intensities doesn't give any meaningful combination. Detail calculation performed to see how the two drought types characteristics are related is summarized in appendix A on page 79.

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4. Impact of Climate Change

Studies indicate that climate change will and is having negative impact on the environment, development, health, agriculture and water resource development. It can cause a long term impact which creates drought, Ice melting and sea level rise. On the other hand it may bring short term impacts such as intense rainfall and flooding Mishra and Singh (2010). Hence drought is amongst the hazards that can be triggered by global warming. In Ethiopia drought is becoming a more recurrent and dangerous phenomenon. It has already affected millions of people so far. As it has been presented in the introduction chapter, the Awash valley is also affected with frequent droughts and floods. Analysis of future climate change impact is performed in the Awash valley by using global climate models. Climate data of Awash basin was down scaled and processed with the help of R-programming language and Arc-GIS. A total of 54 index points were downscaled with in the Awash catchment. The points are shown in figure 4.1 on page 37.

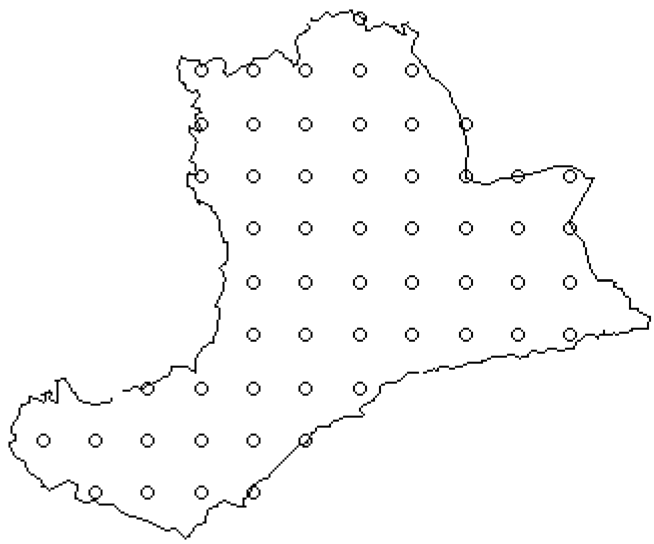

Figure 4.1.: Downscaled index points of Awash catchment

The down scaled points contain time series data of precipitation and temperature. It consists of historical data of 30 years covering from 1970 to 2000 and future data from 2041 to 2100. Two future climate phases are considered, from 2041 to 2070 and from 2071 to 2100. Moh hadely and MPI climate models with three emission scenarios are used. Three representative concentration pathways (RCPs) emission scenarios are also considered. These are low emission scenario (RCP2.6), medium emission scenario (RCP4.5) and high emission scenario (RCP8.5). Precipitation and temperature data is down scaled for each scenario and each period.

4.1. Downscaled Precipitation Data

Historical and future precipitation data is downscaled using both Moh hadely and MPI climate model. Average value is taken if more than one index are downscaled in a single sub basin. Three sub basins are selected namely Awash kunture from upper , Awash haledabi from middle and Awash adaitu from lower part to present the analysis results in the coming sub topics. These three sub basins are assumed to be representative of the basins through out the analysis. As each of them are located in the heart of the three parts (Upper, Middle and Lower) of the Awash they can represent the variation and similarity across the basin. Comparison between downscaled and observed precipitation data is done and a good correlation is found in the upper part where as poor correlation is observed in the middle and lower part by using both climate models. The correlation result is summarized in table 4.1 on page 38. The correlation value is reducing from upper part down to the lower part.

R^2	Awash kunture	Awash haledabi	Awash adaitu
Moh hadely	0.68	0.52	0.22
MPI	0.76	0.48	0.12

Table 4.1.: Correlation value (R^2) between downscaled and observed montly precipitation data ($1971 - 2000$) of Awash basin

Despite the weak correlation between observed and downscaled monthly precipitation data in the middle and lower part of the basin a good correlation is found when it is tested with annual average monthly precipitation as can be seen in table 4.2 on page 40. The result shows strong correlation in the upper and middle Awash and good correlation in the lower part. The weak correlation on monthly data basis won't affect the analysis too much as long as the annual average monthly precipitation is used to estimate the future precipitation data of the basin.

Comparison between downscaled and observed annual average monthly precipitation is shown in figure 4.2 on page 39. It shows how well the data in the upper and middle part are fitted. It is plotted by using both climate models and the displays are almost similar. In both cases it is shown that the fitting in the lower Awash is not as good as in the upper and middle part. Hence it is reasonable to use either of these climate models to determine the future climate change effect on drought severity and occurrence in Awash river basin.

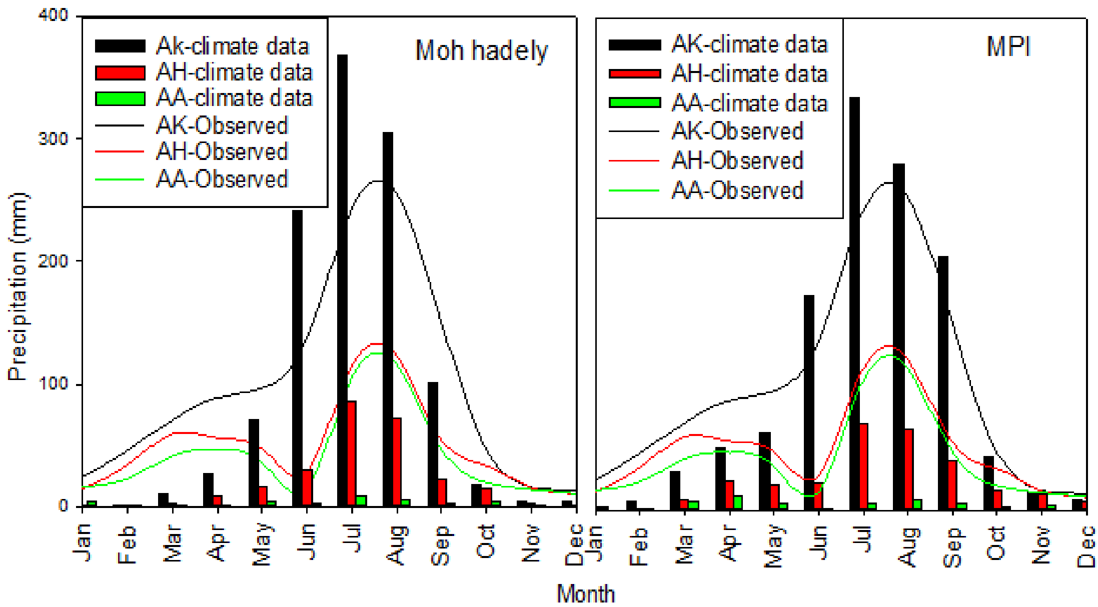

Figure 4.2.: Comparison of observed and downscaled historical climate data (1971-2000) for Moh hadely and MPI models of RCP85 emission scenario; AK-Awash kunture (Upper Awash), AH-Awash haledabi (Middle Awash), AA-Awash adaitu (Lower Awash)

Using the future and historical precipitation data, changes in precipitation can be estimated for each month. These delta values can be imposed on observed historical data to estimate the data for the next 30 to 80 years for each RCPs scenarios. These should not be used as forecasts or absolute bounds but it still provides important information for decision making in climate change research Van Vuuren et al. (2011).

R^2	Awash kunture	Awash haledabi	Awash adaitu
Moh hadely	0.93	0.87	0.67
MPI	0.97	0.90	0.55

Table 4.2.: Correlation value (R^2) between downscaled and observed annual average monthly precipitation data ($1971 - 2000$) of Awash basin

4.2. Precipitation Changes

Percentage of delta values has been estimated for each phases and scenarios using formula 4.1 on page 40 by utilizing the downscaled data for both climate models.

$$Delta(\%) = \frac{Future - Historical}{Historical} * 100 \tag{4.1}$$

This has been done for the selected sub basins across the basin. In the upper Awash a slight change of precipitation is observed in all scenarios of Moh hadely climate model in the main rainy season, July to September for the years 2041-2070 refer figure 4.3 on page 40. Huge raise in precipitation is observed in January for RCP26 and RCP85 but a small reduction for RCP45.

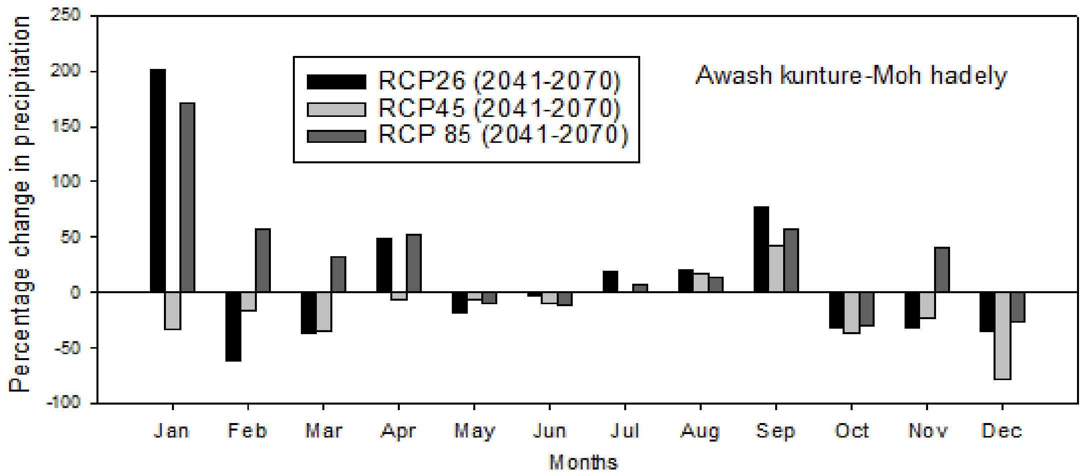

Figure 4.3.: Percentage change in precipitation of Awash kunture (upper Awash) for the year 2041-2070 for each scenario of Moh hadely model.

In the middle awash a considerable reduction in precipitation is revealed in almost all months except in April, November and December for all the scenarios in the Moh hadely model for the year 2041 to 2070 refer figure 4.4 on page 41.

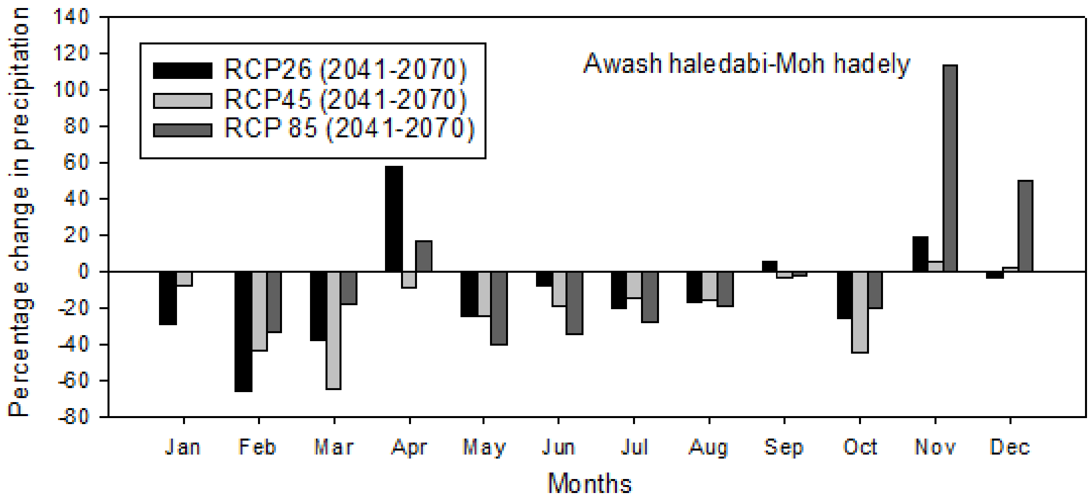

Figure 4.4.: Percentage change in precipitation of Awash haledabi (middle Awash) for the year 2041-2070 for each scenario of Moh hadely model

In the lower Awash by the year 2041-2070 an increase in precipitation is observed in April, July and August and decrease in the rest of the months in Moh hadely model refer figure 4.5 on page 41. From Moh hadely climate model for the year 2041-2070 it can be seen that for most of the months in the middle and lower Awash precipitation will be reduced while no clear trend is observed in the upper awash.

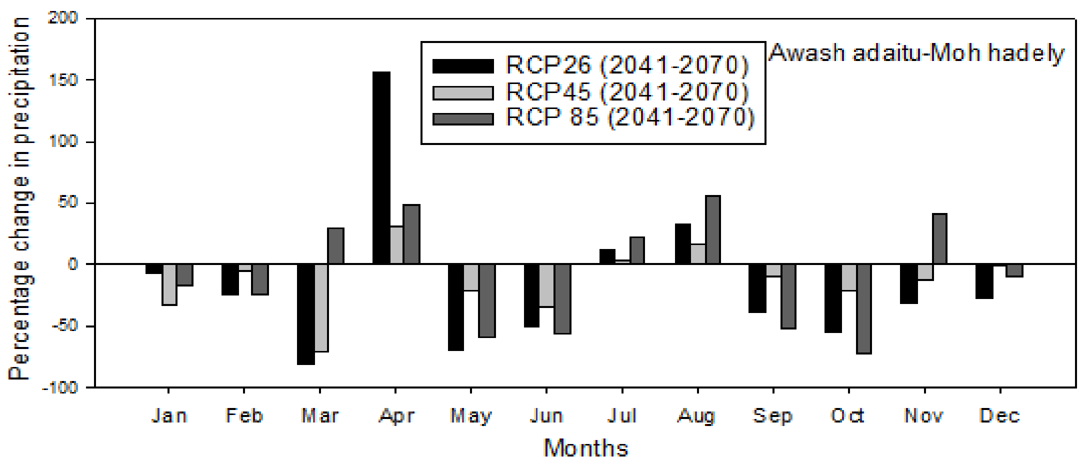

Figure 4.5.: Percentage change in precipitation of Awash adaitu (lower Awash) for the year 2041-2070 for each scenario of Moh hadely model

In the MPI climate model a different change in precipitation is observed for the same period (2041-2070). For instance in the upper Awash a considerable reduction is observed in March, May and June refer 4.6 on page 42. A small reduction and increment is observed in July and August to September respectively. Increment is also observed in October and November. Same percentage change in precipitation is observed in RCP45 and RCP85 emission scenarios. In few months RCP26 emission scenario is giving higher changes than the other RCPs (45 and 85). In most of the months it is giving smaller changes compared to RCP45 and RCP85 as expected.

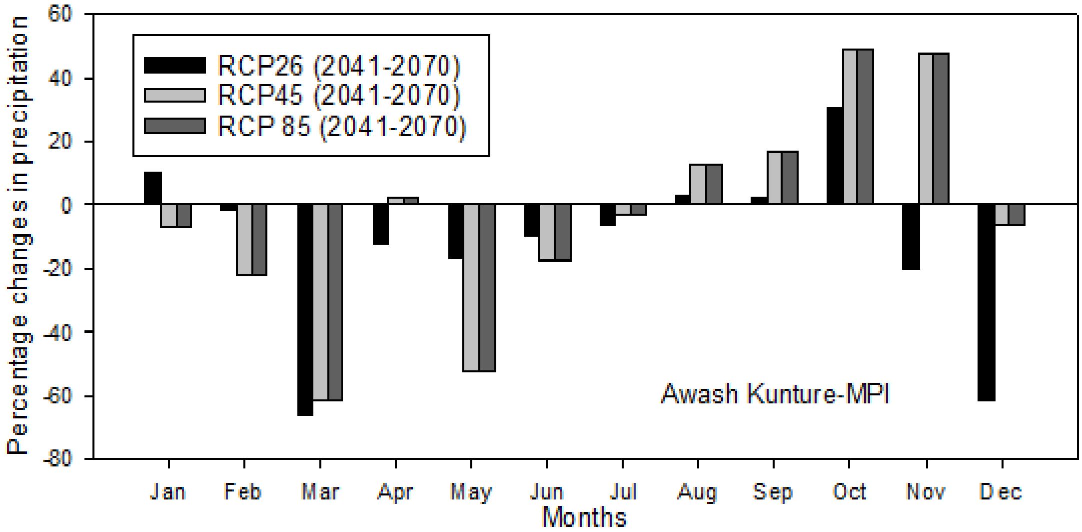

Figure 4.6.: Percentage change in precipitation of Awash kunture (upper Awash) for the year 2041-2070 for each scenario of MPI model

In the middle Awash huge precipitation increase is observed in October and November while a small reduction is seen in August and September. In almost all of the months RCP26 is giving smaller changes compared to RCP45 and RCP85. Considerable reduction is also observed from March to May and in July refer figure 4.7 on page 43.

In the lower Awash a slight increase is seen from August to September and huge increase from October to November refer figure 4.8 on page 43. Precipitation changes for the year 2071-2100 are enclosed in appendix B on page 83 for both models and each scenarios of the three representative sub basins.

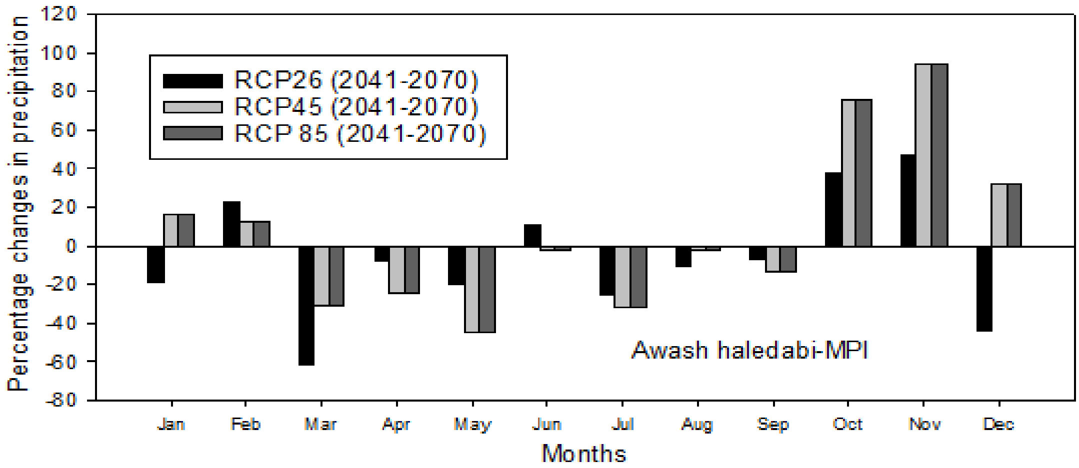

Figure 4.7.: Percentage change in precipitation of Awash haledabi (middle Awash) for the year 2041-2070 for each scenario of MPI model

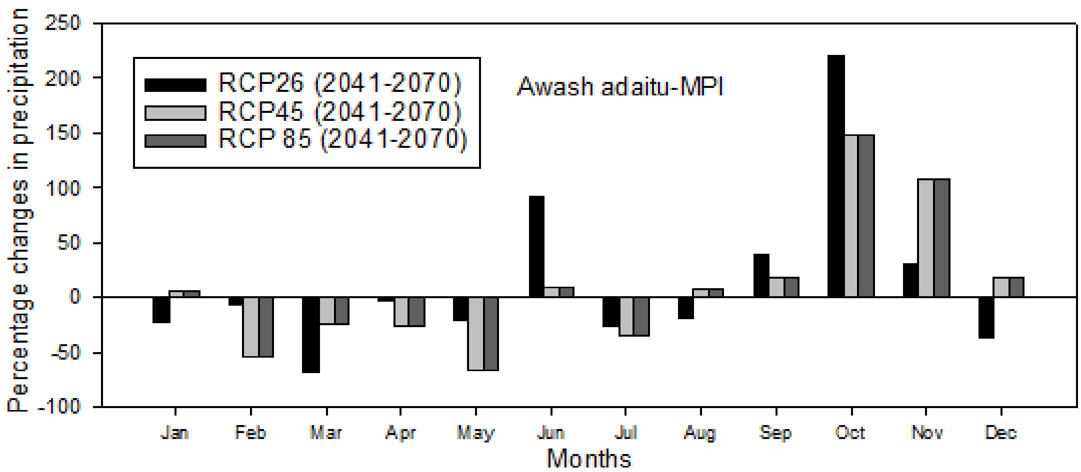

Figure 4.8.: Percentage change in precipitation of Awash adaitu (lower Awash) for the year 2041-2070 for each scenario of MPI model

4.2.1. Comparison of Precipitation Changes of RCPs Scenario

The RCP26 is emission path way that lead to very low green house gas concentration levels. It is a peak and decline scenario where emissions of air pollutants are reduced substantially over time Van Vuuren et al. (2011). RCP45 is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing level Clarke et al. (2009). RCP85 is characterized by increasing greenhouse gas emissions over time, representative of scenarios that lead to high greenhouse gas concentration levels Riahi et al. (2007). Hence from the above definitions a higher and lower change of precipitation is expected from RCP85 and RCP26 respectively. The result shows a higher changes in RCP85 in most of the months in both climate models as expected refer a sample figure 4.9 on page 44. In few months of the analysis RCP26 shows a higher change than the other RCPs.

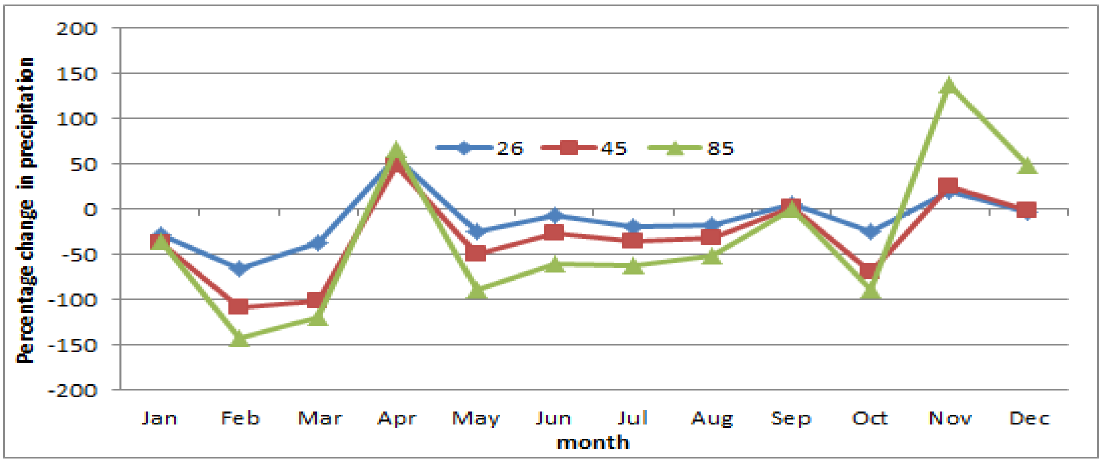

Figure 4.9.: Percentage change in precipitation of Awash haledabi (middle Awash) for the year 2041-2070 for each RCP scenarioS of MPI model

4.3. Future Precipitation Estimates

Using observed data and percentage changes, future precipitation is estimated using both climate models. Simple arithmetic formula as given below is used. Delta can be positive or negative depending on the findings from the downscaled data. Hence, the factor will be greater than one and less than one for positive and negative delta values respectively.

$$Future(mm) = \left(1 + \frac{Delta\%}{100}\right) Observed(mm) \quad (4.2)$$

In the Moh hadely model it is found that future annual average monthly precipitation is higher than its corresponding observed data for most of the months in the future period (2041-2070). A result in the upper Awash indicates increment of annual average monthly precipitation in all months except from October to December for each scenario. It can be seen in figure 4.10 on page 45. This can be confirmed from the percentage change presented in figure 4.3 on page 40. Almost Same result is found for 2071 – 2100 period refer figure 4.11 on page 45.

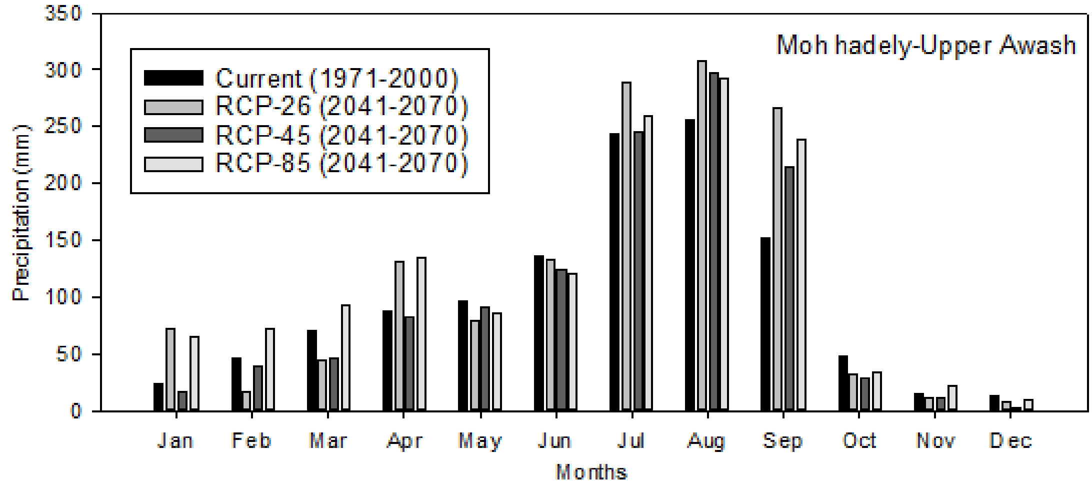

Figure 4.10.: Estimated future annual average monthly precipitation of Awash kunture (Upper Awash) for each RCP scenario of Moh hadely climate model of future period (2041-2070)

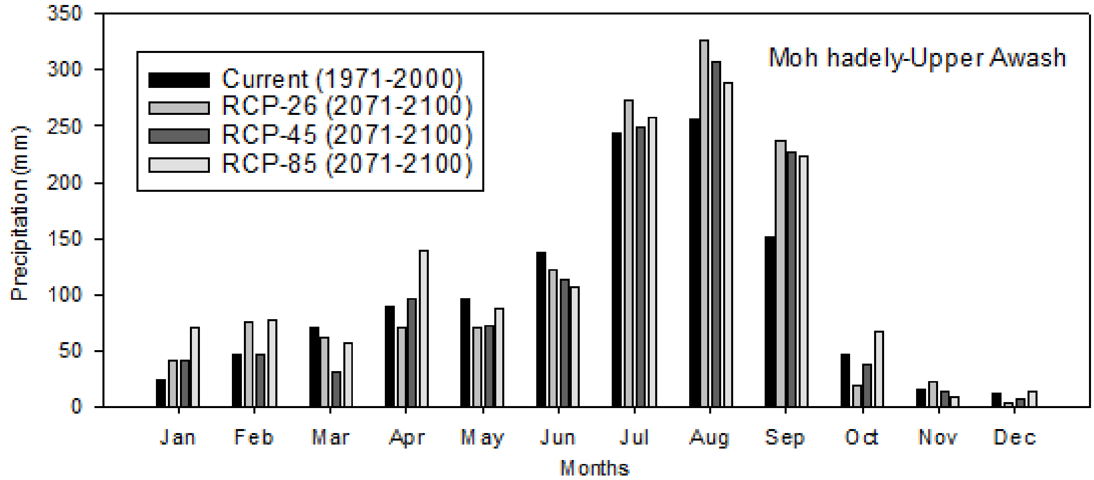

Figure 4.11.: Estimated future annual average monthly precipitation of Awash kunture (Upper Awash) for each RCP scenario of Moh hadely climate model of future period (2071-2100)

Estimated values in the middle Awash shows a reduced annual average monthly precipitation compared to the current value for most of the months in each RCP scenarios.

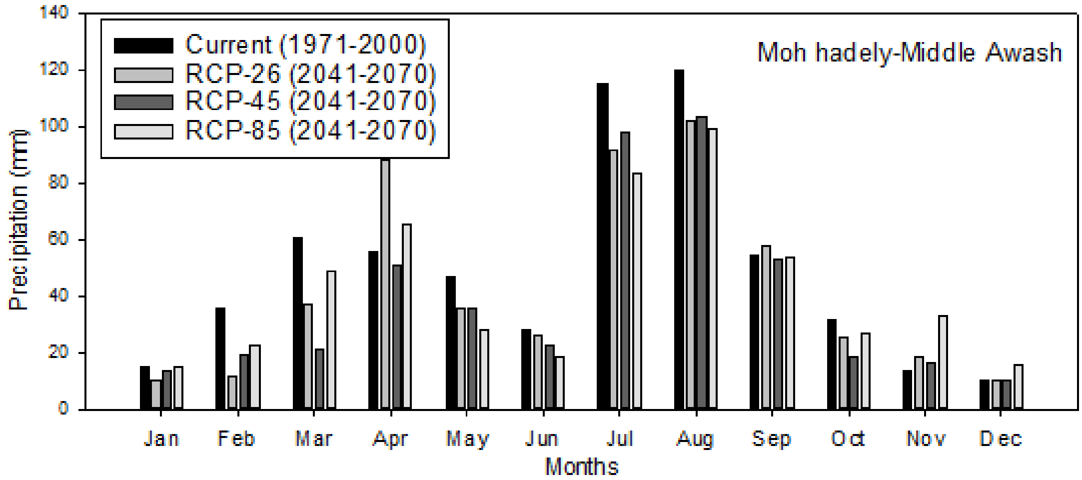

Figure 4.12.: Estimated future annual average monthly precipitation of Awash haledabi (Upper Awash) for each RCP scenario of Moh hadely climate model of future period (2041-2070)

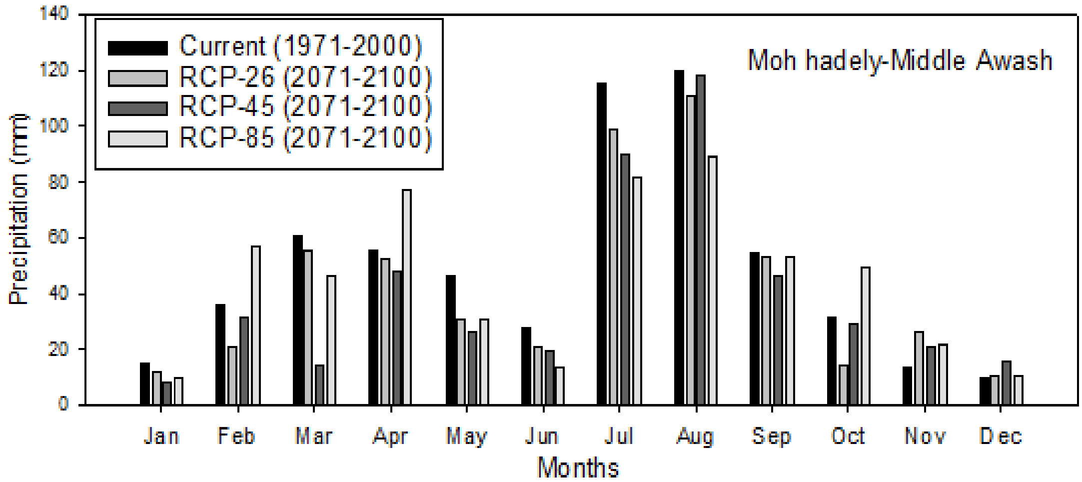

Figure 4.13.: Estimated future annual average monthly precipitation of Awash haledabi (Upper Awash) for each RCP scenario of Moh hadely climate model of future period (2071-2100)

In the period 2041-2071 of Moh hadely climate model a considerable reduction is observed in July and August. Reduction is also observed in February, May and June refer fig 4.12 on page 46. The precipitation values are much lower compared to the upper awash value as expected. Results for the period 2071-2100 can be seen in figure 4.13 on page 46. A slight changes are found in most of the months compared to the current value for each RCP scenarios.

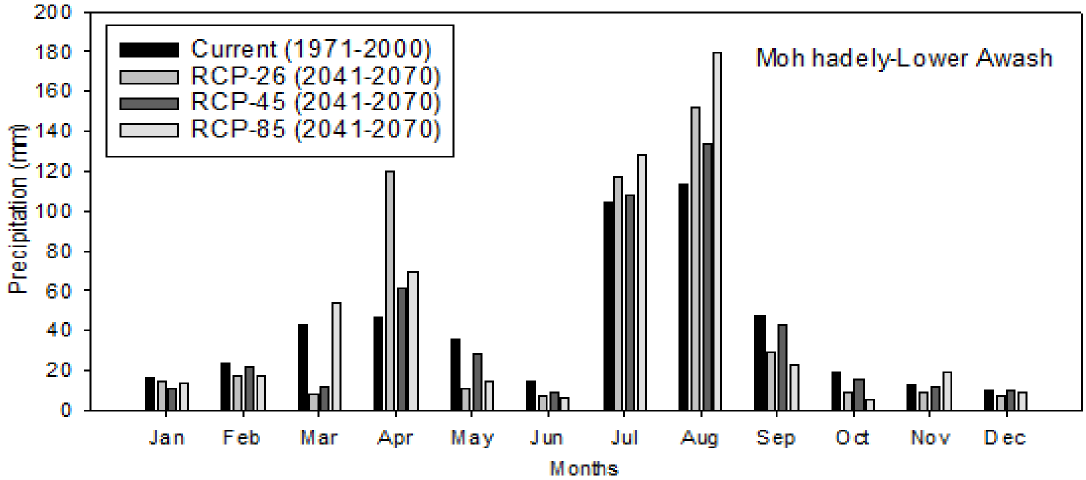

Figure 4.14.: Estimated future annual average monthly precipitation of Awash adaitu (Lower Awash) for each RCP scenario of Moh hadely climate model of future period (2041-2070)

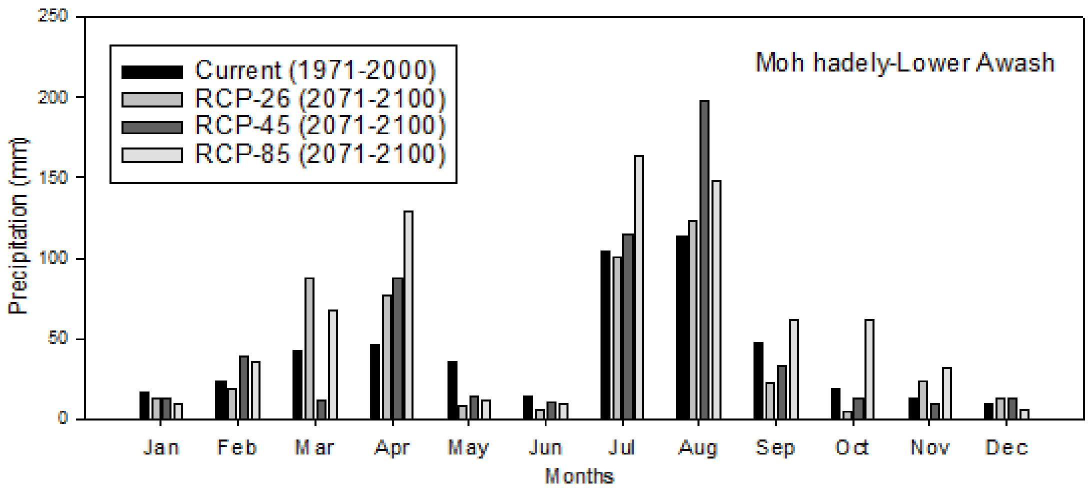

Figure 4.15.: Estimated future annual average monthly precipitation of Awash adaitu (Lower Awash) for each RCP scenario of Moh hadely climate model of future period (2071-2100)

Same estimation in the lower Awash is performed to see the trend and variation of future precipitation compared to the current scenario (Observed data). In both future periods the annual average monthly precipitation is higher than the current period in each RCP scenarios for most of the months. Results are given in figure 4.14 on page 47 for 2041-2070 and figure 4.15 on page 47 for 2071-2100.

In general the estimated future annual average monthly precipitation is following the trend that has been seen in the precipitation changes. So mostly it is found that precipitation is raising in the lower Awash while reducing in the upper and middle part due to climate change. But this doesn't mean that drought risk is reduced in the lower part. A wet year can turn preceding or succeeding dry years in to normal. Even though, there are changes in precipitation the trend is almost similar compared to the past trends in precipitation.

The same analysis using the MPI climate model shows a slightly lesser changes in each RCP scenarios compared to Moh hadely model. The result of each scenario are almost the same. Not much variation is observed between RCP scenarios. Estimated result summary is included in appendix C on page 85, D on page 86 and E on page 87 for upper, middle and Lower part of the basin respectively for both future periods.

4.4. Future Drought

Based on future data estimated by imposing the changes in precipitation, standardized precipitation index of the representative sub basins is calculated in the same fashion as the drought assessment done in the last chapter refer chapter 3 on page 19. This is done for both climate models and each RCP scenario. The main purpose of this analysis is to see if the future change in climate is going to increase or reduce the risk of drought. The analysis is done in two phases of the future time. The first phase is for the year 2041-2070 and the second phase is the year from 2071-2100.
Future drought analysis result in the upper Awash based on 12 month time scale for September is given in figure 4.16 on page 49. The result shows a slightly higher drought magnitude in RCP85 than the other RCPs. Compared to the historical drought given in figure 3.3 on page 24 more drought risk is observed in the future analysis. One extreme drought is observed in the future (2041-2070) in the three RCPs where there was no such drought occurrence in the past. This particular analysis shows how the rain fed agriculture in the upper awash will be affected by the future drought. The upper Awash is usually not affected by extreme drought as the middle and lower part. Moderate droughts do occur in the upper Awash

both in the past and future in a higher rate than other drought categories.

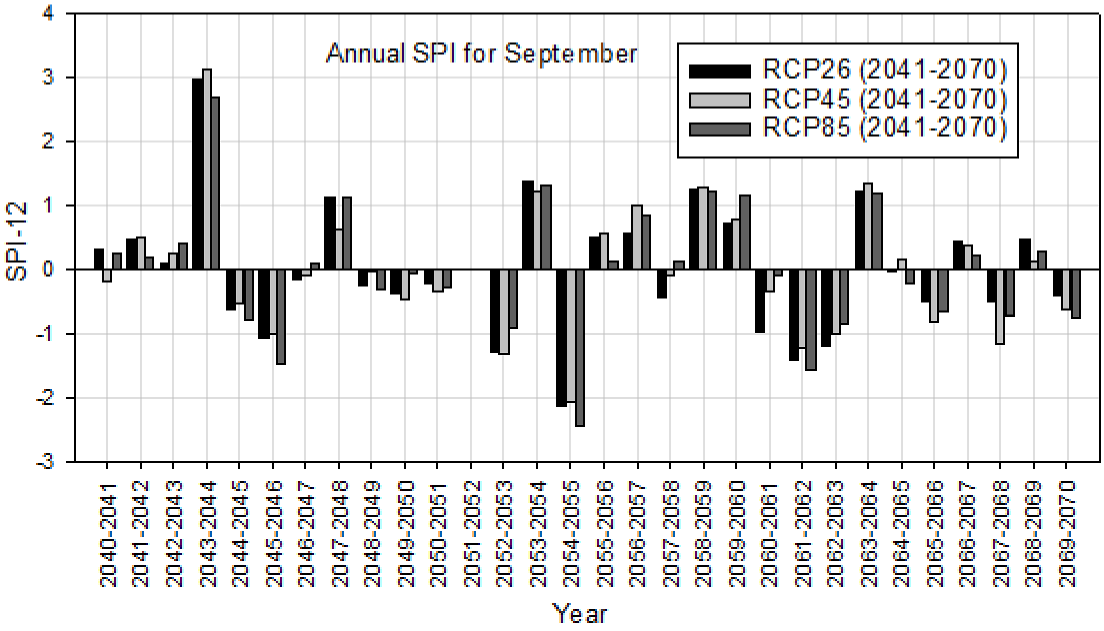

Figure 4.16.: Annual future drought (2041-2070) of Awash kunture (Upper Awash) based on Moh hadely climate model

4.4.1. Comparison of Historical and Future Droughts

Comparisons between historical droughts and future droughts is performed for each selected sub basins. Comparison is also done between the occurrence of drought categories. Three drought categories namely extreme, severe, and moderate and above droughts are selected to see the changes through time.

Future drought analysis based on precipitation in the upper Awash shows more drought occurrence compared to the historical droughts. Analysis result of Awash kunture (Upper Awash) based on 12 month time scale of the RCP85 scenario is given in figure 4.17 on page 50. The result shows the upper Awash will experience extreme drought, eight times in the future period (2041-2070) where there was only once in the past out of thirty years drought assessment. Severe droughts are also observed higher in the future than in the past. It has raised by 25% compared to the past. Droughts with category of moderate and above have raised by 12% compared to the past refer table 4.3 on page 52. Severe drought is revealed once in every two to three years. A trend of drought happening in every five years with severe to extreme magnitude is found. Other drought episodes are also observed in a much higher occurrence than before. Much higher severe droughts than extreme droughts are seen in the past and future. The two climate models are giving almost similar out puts of the future climate change impact on the drought episodes of the Upper Awash refer figure 4.17 on page 50.

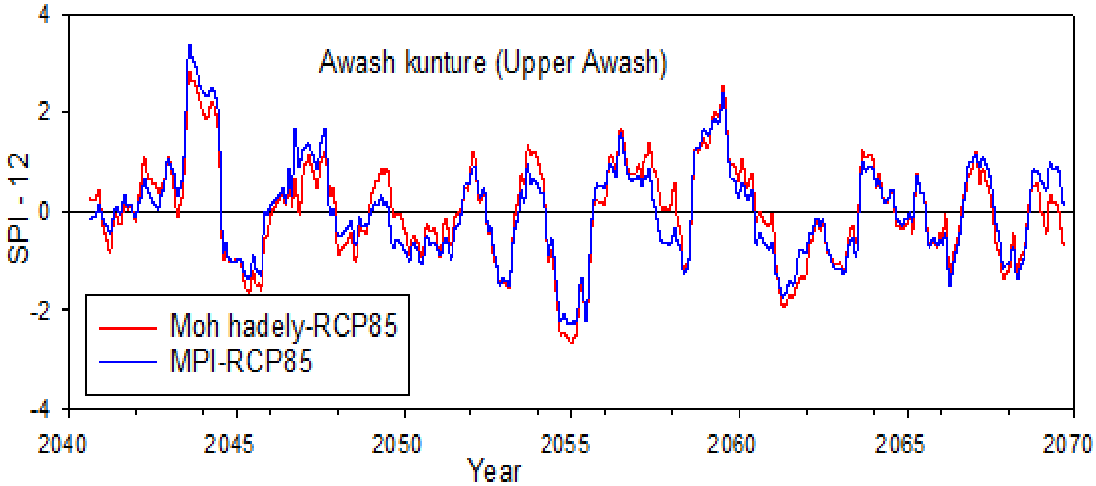

Figure 4.17.: Annual SPI time series of Awash kunture (Upper Awash) in the future period (2041-2070)

In the middle awash a similar analysis is performed and extreme drought is seen thirteen times in the future thirty years (out of 360 months) of drought analysis refer figure 4.18 on page 51. Extreme drought occurrence in the near future (2041-2070) is increased by 8.3% from the past while severe drought occurrence is reduced by 37.5%. Drought occurrences with magnitude of moderate and above are increased by 5.13% from the past. Occurrence of extreme drought is much higher than the occurrence of severe droughts refer table 4.3 on page 52. Five severe and thirteen extreme droughts are observed out of future thirty years. A much higher drought episodes are revealed compared to the occurrence of wetness or non drought condition. More than 50% of the time is experiencing drought. The duration of drought episodes are longer than wetness episodes. Longer duration is also observed in extreme drought categories compared to severe, near normal and moderate drought occurrences. This shows how the risk of drought is increasing due to change in climate.

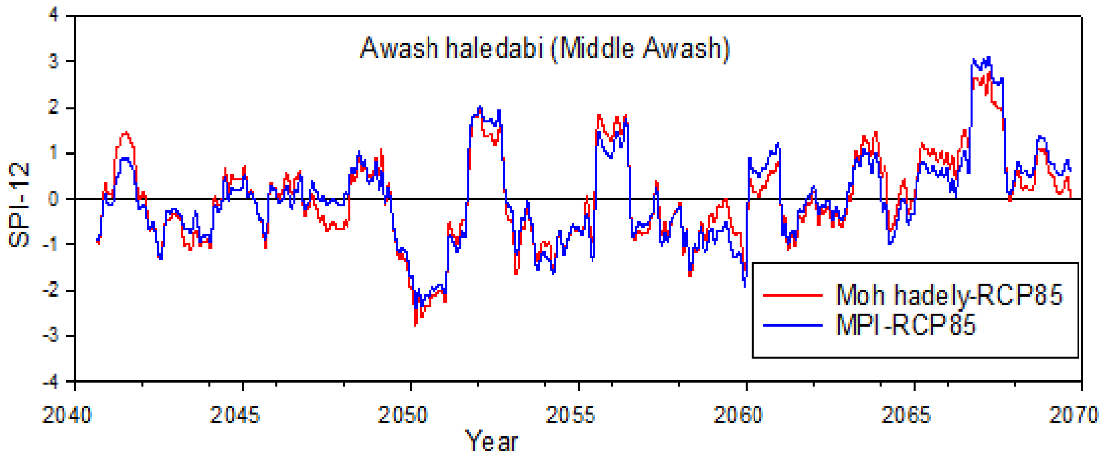

Figure 4.18.: Annual SPI time series of Awash haledabi (Middle Awash) in the future period (2041-2070)

In the same manner as the upper and middle part assessment of future climate change impact on drought is analysed for the lower part of the basin. The time series of the future drought is given in figure 4.19 on page 52. Less severe drought is observed in the future analysis than the past analysis but it is still a considerable drought occurrence. Almost same number of extreme drought occurrence is observed in the past and future with slightly higher in the past. In general, moderate and above droughts are reduced by 21% compared to the past. The expectation in the lower Awash was to see a higher drought occurrences in the future than in the past. But the actual analysis result gives the reverse. This may be due to the poor correlation of downscaled climate data with observed data at the lower awash. Despite the weak correlation of the data, drought analysis in the future scenario is still giving a considerable result. Higher severe droughts than extreme droughts are observed in the future period (2041-2070) as in the upper Awash refer table 4.3 on page 52. Eleven severe and nine extreme droughts are observed. Magnitude of some peak wet episodes are smaller compared to the magnitudes in the middle and upper part as expected.

In general the risk of drought is increasing in the near future (2041-2070) in both the upper and middle Awash where almost same type of drought risk is found in the lower part. Summary of the drought conditions and their respective number of occurrences in the past and future is given in table 4.3 on page 52. Both climate models are giving almost same results hence either of them can be used to estimate the impact of climate change in the future.

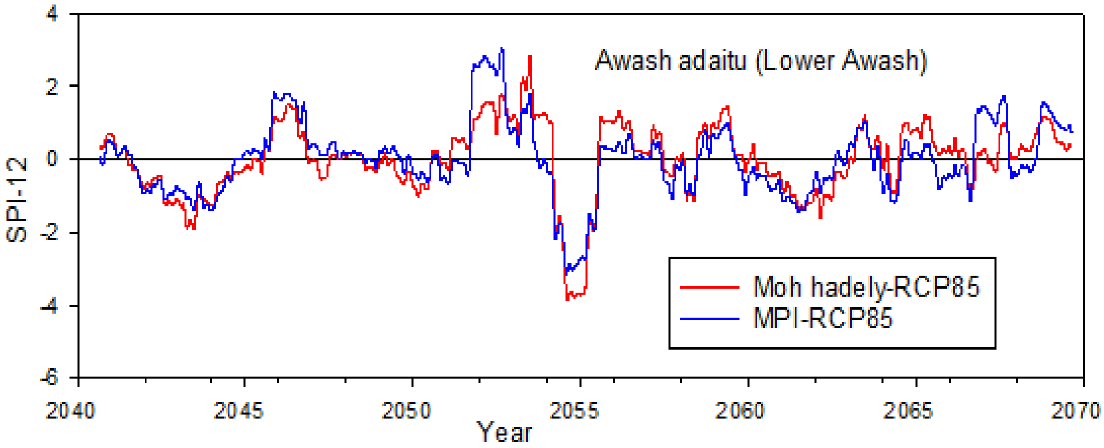

Figure 4.19.: Annual SPI time series of Awash adaitu (Lower Awash) in the future period (2041-2070)

Drought	Past(1971-2000)			Future(2041-2070)			Future(2071-2100)		
	Upper	Middle	Lower	Upper	Middle	Lower	Upper	Middle	Lower
Extreme	1	12	11	8	13	9	8	4	12
Severe	12	8	19	15	5	11	18	13	7
$\geq$ Moderate	49	39	62	55	41	49	52	52	41

Table 4.3.: Summary of changes in drought occurrences using Moh hadely climate model for RCP85

In the future period (2071-2100) similar analysis is performed in the upper, middle and lower part. Time series of future droughts of the second phase (2071-2100) is given in figure 4.20 on page 53. From the time series graph it can be seen that future drought pattern in the middle and lower part are behaving almost similar trend on most of the years while the drought in the upper part is trending in different way in most of the time. This is due to the reason that the climate data pattern in the upper part is different compared to the middle and lower part.

Significant changes in drought occurrences are observed in the upper Awash refer table 4.3 on page 52. A much higher extreme drought condition is revealed compared to the historical drought and exactly same number compared to the period 2041-2070. Severe drought occurrence is increased by 50% compared to the past and by 20% compared to the first phase (2041-2070). Moderate droughts and above are increased by 6.1% compared to the past (1971-2000) and reduced by 5.5% compared to the first phase (2041-2070).

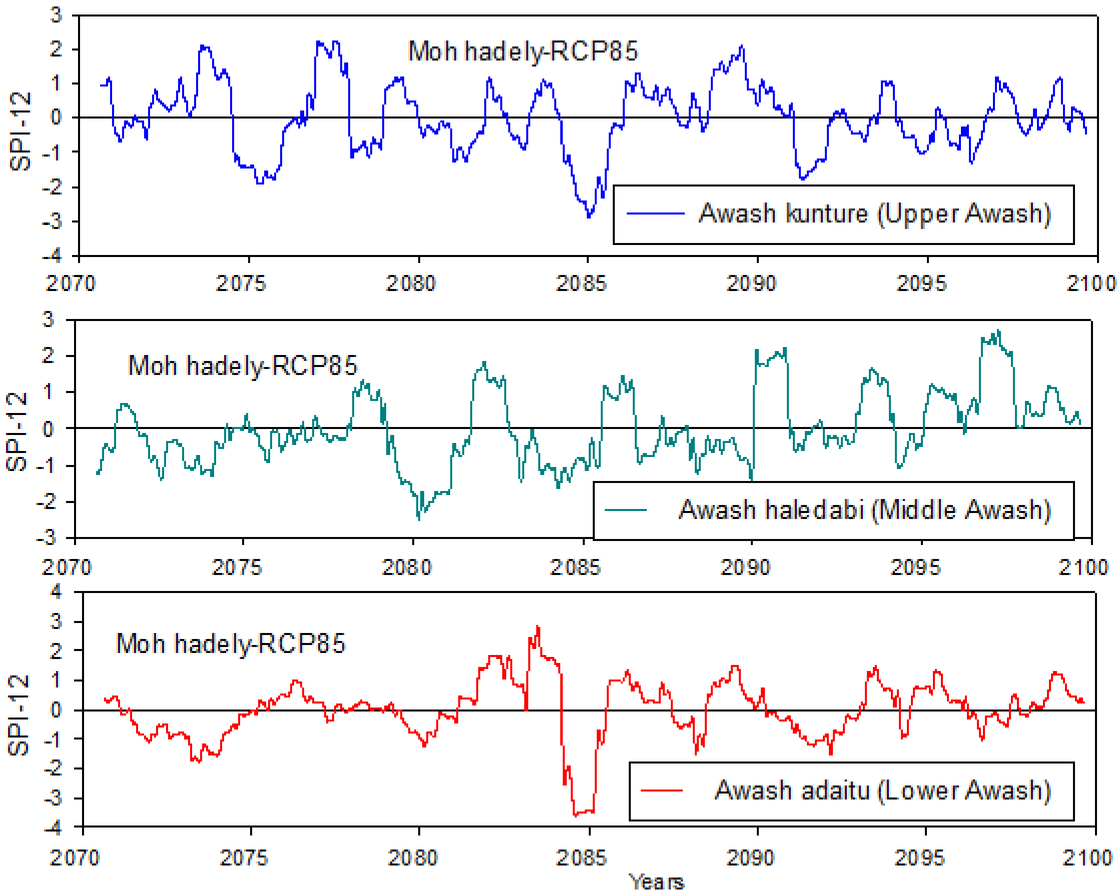

Figure 4.20.: Time series of future droughts (2071-2100) of representative sub basins based on Moh hadely model

In the middle Awash occurrence of extreme droughts are reduced by 66% compared to the past and reduced by 69.2% compared to the first phase (2041-2070) while on the other hand the occurrence of severe drought is increased by 62.5% compared to the past and increased by approximately two and half times compared to the first phase. Droughts with magnitude of moderate and above are raised by 33.3% compared to the past and by 26.8% compared to the first phase.

In the lower part occurrence of extreme droughts are increased by 9% compared to the past and increased by 33.3% compared to the first phase (2041-2070), while occurrence of severe drought is reduced by more than two times compared to the past and reduced by 36% compared to the first phase of future drought analysis. A reduction by 33.8% and 16.3% from the past and the first phase respectively is found for moderate and above drought occurrence.

Analysis of drought in the future period 2071-2100 using the MPI climate model gives almost similar result as the moh hadely model. The only visible difference is that the pick drought episodes are reduced in magnitude in the MPI compared to the episodes in Moh hadely model. But this doesn't change the drought category, That is extreme drought observed in Moh hadely is still extreme in MPI with lesser magnitude.

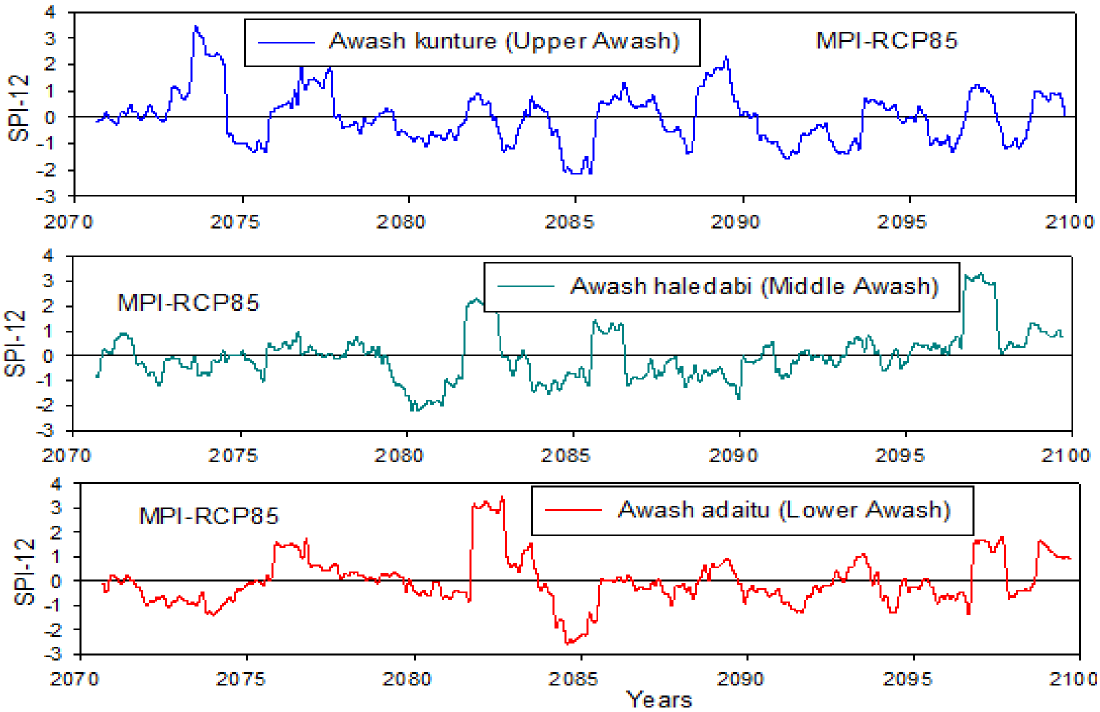

Figure 4.21.: Time series of future droughts (2071-2100) of representative sub basins based on MPI model

5. Water Resource Management During Drought

High population growth, climate change and increased water demand for different purposes are among the factors that are creating water shortage problems. The effect is high in water stressed areas. In water stressed areas demand increases through time while water resources are becoming scarce either due to natural hazards such as drought, precipitation variability or man made activities and policy failures. The challenge of water scarcity, drought and climate change is becoming an international issue. It is getting more attention by researchers and policy makers. The reason is that they are happening frequently in most of the world right now. The Awash valley is amongst the water stressed and drought prone basins in Ethiopia. It has experienced water scarcity of variable magnitude. The effect ranges from low water availability to famine. It also affects energy production, economic growth and social stability. Hence integrated water resource management is an important aspect in the Awash valley. Drought should be integrated with water resource management plans and policies. The spatial scale to develop drought management plans can be a river basin or a sub basin. The drought management plans can be considered as supplementary to river basin management plans that can be developed and implemented by the responsible authorities Berland et al. (2012). The current practice in managing water resources during drought is based on immediate reaction to a current risk that is waiting till it happens then crisis management. This has to be changed by proper contingency plans along with integrated resource and demand management. Hence, Drought mitigation and prevention should be planned in advance to reduce the impact on people, livestock, agriculture, ecosystem and the environment as a whole.

At this stage of the study an already calibrated Water Evaluation and Planning (WEAP) model of the basin developed by FAO is used to asses the supply and demand management options on a sub basin level during drought periods. WEAP model is developed by the Stockholm Environment Institute, Boston to enable evaluation, planning and management of water resources development. It is a comprehensive, straight forward and easy to use, and attempts to assist rather than substitute for skilled planner. As a data base it provides a system for maintaining water demand and supply information in which the current study data input is mainly taken from. As a policy analysis tool, WEAP evaluates a full range of water development and management options. Operating on the basic principle of water balance accounting, WEAP is applicable to municipal and agricultural systems, single subbasins or complex river systems. Moreover, WEAP can address a wide range of issues, e.g., sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and streamflow simulations, reservoir operations, hydropower generation and energy demands, pollution tracking, ecosystem requirements, and project cost analysis Sieber and Purkey (2007).

With the help of WEAP model systematic ways of managing water resource can be invented during and after drought. The management could be from demand side or supply side. This management option could be tested as what if scenario in WEAP model. WEAP can answer plenty of questions that can happen with in water resources planning and management in the future so that water professionals and policy makers can have a common ground for decision making.

5.1. Model Evaluation

A quick evaluation of the model set up and its input data is done to assure quality. In most of the cases it was found that the model set up is good enough for the current study. The model calibration results are found to be acceptable. Some changes are adopted regarding the building up of a current and reference scenario to create what if scenario based on selected options regarding water resource management and planning during drought. During the model development there was on going dam construction in the basin namely Kesem and Tendaho which were planned to be completed in 2008 exactly at the time of the model development. But, in the model it was assumed as they are already operating in the current account which is not acceptable according to WEAP user manual. Current accounts provide a snap shot of actual water demand, pollution loads, resources and supplies for the system Sieber and Purkey (2007). Hence, these two projects should have been considered as a what if scenario of the future instead. But now they are already operational and can be active in the current account. So they are basically used as a snap shot of an existing storage facilities. All future scenarios will be based on these full development.

5.2. Model Scheme

The model schematic view contains the demand sites, supply and existing hydraulic infrastructures of each sub basins in their respective spatial boundaries. The demand sites could be agricultural, domestic, livestock and industrial sites which are shown by red circle in the view of the model refer figure 5.1 on page 57.

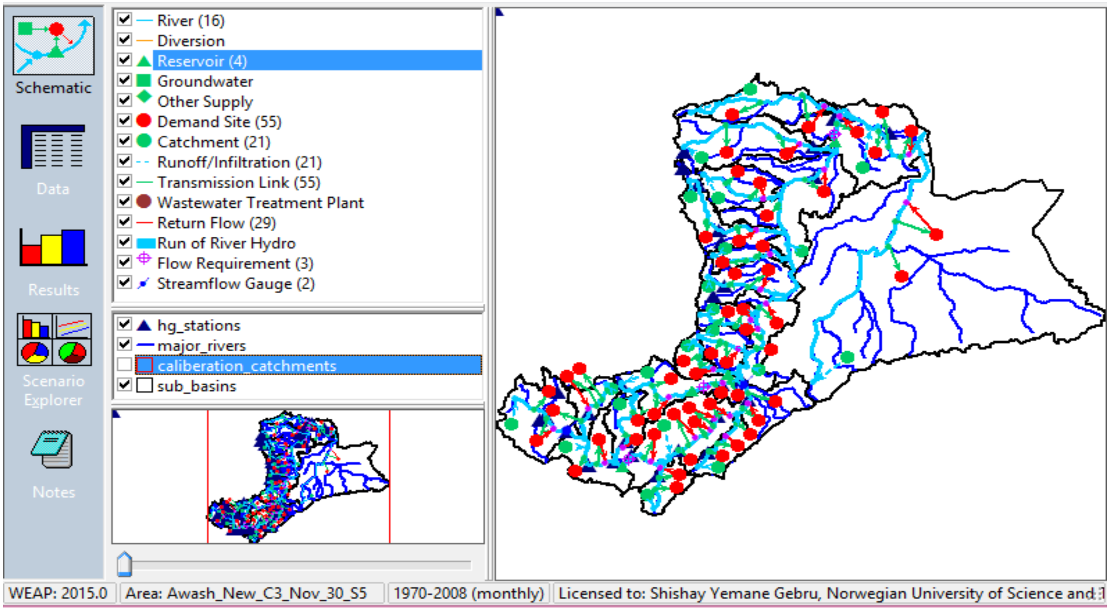

Figure 5.1.: Awash basin WEAP model schematic view

Main rivers and reservoirs (storage fscilities) are also shown on the schematic view for each sub basin. In general each sub basin have three nodes, one representing the supply side where as the other two represents demand side. Demand Nodes are connected with supply sites (Rivers) by man made water conduits such as canals, pipe lines and channels. These are represented as transmission links and return flow in WEAP. Environmental flow requirement is also represented as flow requirement down stream of storage facility.

5.3. Catchment Simulation Method

WEAP model has a room to use either of the following methods to perform the hydrological simulation such as evapotranspiration, runoff, infiltration and irrigation demand down a catchment; 1) Rainfall Runoff, 2) Irrigation Demand-FAO Crop Requirement Approach, 3) Soil Moisture Method, 4) MABIA Method and 5) The Plant Growth Model Sieber and Purkey (2007). The selection depends on the level of complexity desired to represent the catchment processes and data availability.

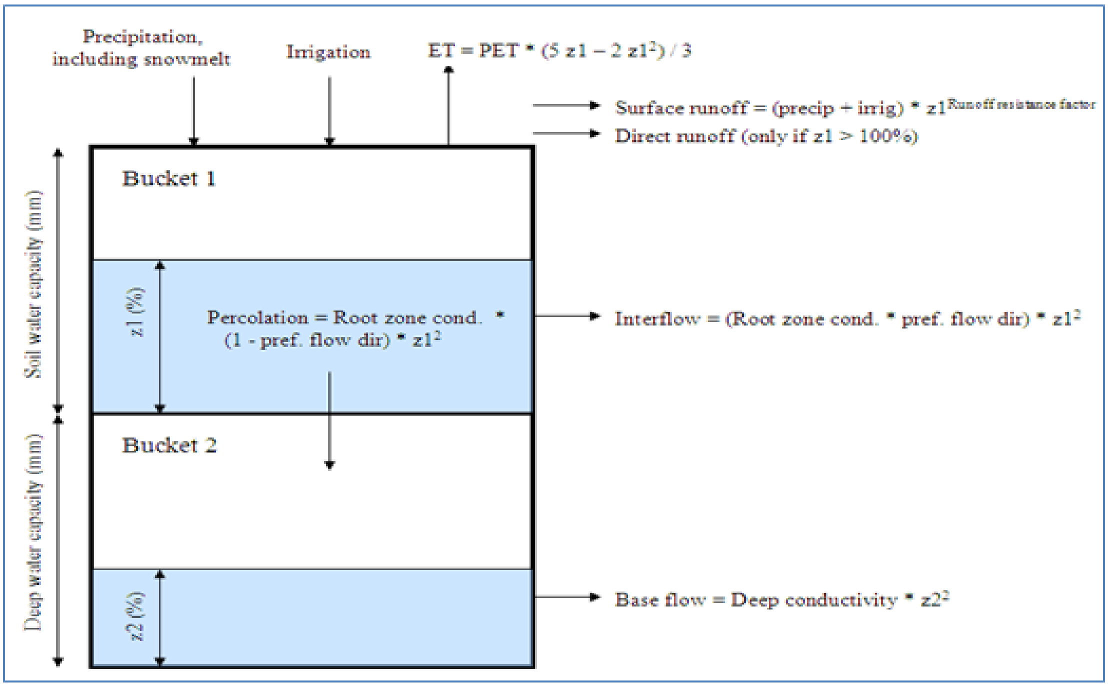

Figure 5.2.: Conceptual diagram and parameters involved in the soil moisture method

The Soil Moisture Method was used during the development of the Awash model. It is more complex method which represents a catchment with two soil layers (two compartments) as well as a potential for snow accumulation not a case in Awash valley though refer figure 5.2 on page 58. In the upper soil layer it simulates evapotranspiration considering rainfall and irrigation on agriculture and non-agricultural lands, runoff and shallow interflow. It allows characterization of the land use type to these processes. Base flow routing to the river and sol moisture changes are simulated in the lower compartment.

5.4. Modelling Reservoir Operation

In WEAP Reservoir storage is divided into four zones; flood control zone, conservation zone, buffer zone and inactive zone from top to bottom respectively refer figure 59 on page 59. The conservation and buffer zone accounts for the reservoir's active storage. The zone below the out let is a dead pool or inactive zone where water is not utilized for down stream purpose. WEAP will ensure the reservoir capacity not to exceed top of the conservation pool. WEAP allows the reservoir to freely release water from the conservation zone to fully meet down stream water requirements. Once the storage level drops into the buffer zone, the release will be restricted according to the buffer coefficient Sieber and Purkey (2007).

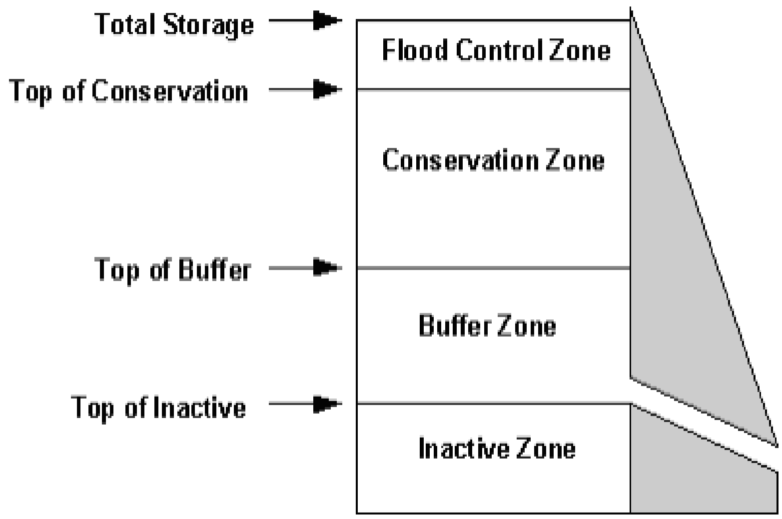

Figure 5.3.: Reservoir storage zones used to describe operating rules

The amount of water available to be released from the reservoir is the full amount in the conservation and flood control zones plus a fraction of the amount available in the buffer zone.

$$S_r = S_c + S_f + (b_c * S_b) \tag{5.1}$$

Where S_r is amount available to be released, S_c is water available in conservation zone, S_f is amount in flood zone, S_b is water in buffer zone and b_c is a buffer coefficient of value 0 to 1. WEAP uses the buffer coefficient to slow release when the storage level falls into the buffer zone. The buffer coefficient is fraction of the water in the buffer zone available each month for down stream release. Hence the buffer coefficient can be used as a means of limiting the water to be released during drought months. Simulation tests by varying operating rules of a reservoir is presented in future scenario sub topic below.

5.5. Scenario Development

In this study scenarios are built to test if there are sound management options to mitigate drought so that impacts on people and economic development can be minimized. Different trials have been simulated in WEAP model in an effort to increase the water availability or reduce unmet water demands for different purposes. Previous studies in the Awash basin shows that as there are plenty of options to minimize water scarcity. Belete Berhanu (2013b) tested a couple of simulation using WEAP model mainly based on irrigation water management. It was found that by improving the existing irrigation efficiency and cropping system which is 43.3% to 50% and 55% can save 12.33% and 19.57% of water respectively. Similar options can be tested on domestic demand management by suggesting efficient use of water. Hence, by doing so a good deal of managing water can be achieved.

5.5.1. Current Account and Reference Scenario

Current account is is a base year to build future scenarios based on actual or existing water demand, supply and hydrology of given basin or sub basin with a specified spatial boundary. Future scenarios are built based on a set of assumptions and policies. Finally, they are evaluated based on water sufficiency, costs and benefits, compatibility with environmental targets. But for now due to time and other constraints, scenarios are evaluated only based on water sufficiency targeting on drought mitigation and impact minimizing.

After the current account of the basin is established, a reference scenario is created based on hydrological, economic, demographic and technological trends. Then from this reference scenario a number of scenarios can be developed based on future policies or assumptions. A reference scenario of 38 years (1970-2008) is built in this study. After this plenty of questions can be addressed by WEAP. For Example; what if population growth and economic development pattern change? what if reservoir operation rules are altered? what if groundwater is more fully exploited? what if water conservation is tightened? what if new source of water pollution are added? what if a more efficient irrigation technique is implemented? what if the mix of agricultural crops changes? what if climate change alters the hydrology? Sieber and Purkey (2007). By addressing some of these questions, ideas and methods can be suggested to minimize drought impact. Two future scenarios from supply side management and one from demand side management are developed in the current study. Climate change impact on water deficiency is also analysed based on existing assumption on the model set up. Detail assumptions and results are discussed in the coming topics.

5.5.2. Future Scenarios

Future scenarios of the Awash basin are built in an effort to reduce the unmet demand and water demand. A domestic management option is proposed using the demand management option in WEAP model. A monthly percentage of domestic demand management during drought period compared to the existing is proposed which is given in table 5.1 on page 61. This can be achieved through different ways of water conservation systems such as water pricing, regular water meter auditing and validation, leakage management in distribution network and introducing storm water harvesting technology. During the rainy season there is no unmet demand due to the fact that water requirement is higher in dry periods than wet periods.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
%age Savings	15	15	15	20	20	15	10	10	10	15	15	20

Table 5.1.: Assumed monthly percentage of demand side management savings

The result of the simulation shows that the total domestic unmet demand will be reduced by 13.02% compared to the reference scenario unmet domestic demand if the management option given in table 5.1 on page 61 is implemented. The monthly unmet demand for the reference and demand management scenario can be referred in table 5.2 on page 62. It can be seen that from July to October there is no unmet domestic demand in both scenarios.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	sum
Reference million.m^3	0.37	0.36	0.43	0.60	1.02	0.69	0.00	0.00	0.00	0.00	0.04	0.04	3.55
DSM million.m^3	0.36	0.33	0.39	0.49	0.84	0.59	0.00	0.00	0.00	0.00	0.04	0.04	3.09
Change million.m^3	0.01	0.03	0.03	0.10	0.18	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.46
%age saved	3.49	8.86	7.86	17.48	17.53	14.40	-	-	-	-	0.00	0.00	13.02

Table 5.2.: Simulation results of unmet demand for reference and DSM (Demand Side Management) scenarios

A future scenario by changing operational rules of Koka reservoir is tested. The aim is to investigate the effect of changing water withdrawal from the reservoir to downstream demand sectors. These is very important when there is water scarcity. During these periods it will be wise to operate the reservoir by considering the inflow. Four parameters namely top of conservation zone, top of the buffer zone, top of inactive zone all entered as a volume and buffer coefficient entered as a fraction ranging 0 to 1, are used to simulate different systems of operating rules of the reservoir in WEAP. To define a rule Values of these parameters can be entered directly in the model. Top of conservation zone is usually the reservoir storage capacity while top of inactive zone is at the mouth of out let refer figure 5.3 on page 59. WEAP uses the buffer coefficient to slow water release when the storage level drops into the buffer zone. When this happens the monthly release can not exceed the volume of water in the buffer zone multiplied by this fraction. A coefficient close to 1 will cause demands to meet fully while rapidly emptying the buffer zone, while a coefficient close to 0 will leave demands unmet while preserving the storage in the buffer zone Sieber and Purkey (2007). The top of the buffer represents volume at which releases are to cut back but the buffer coefficient determines the amount of the cut back. Simulation result of monthly average unmet demand by allowing the storage of the buffer zone to be released with out any delay that is with a buffer coefficient 1 shows high unmet demand from January to June. But when the inflow hydrology changes due to drought the release from the reservoir shall be restricted so that the buffer storage do not become empty rapidly. To achieve this another simulation based on 0 buffer coefficient is tested and almost similar trend of unmet demand is observed except that the unmet demand has raised from February to June compared to the simulation with buffer coefficient 1 refer figure 5.4 on page 63. It can be seen that the unmet demand of the other months are not affected due to the change in reservoir operation hence slow withdrawal of water can be applied in those months to mitigate drought impact. Hence a monthly varying buffer coefficient can be used to limit water release without affecting the downstream water demand.

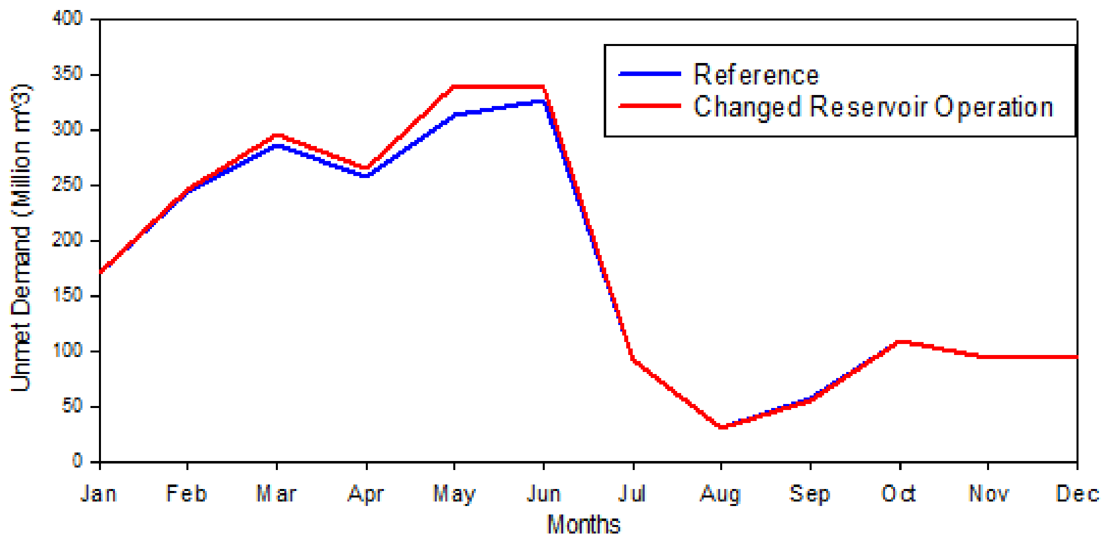

Figure 5.4.: Monthly average unmet demand of reference and future scenario with changed reservoir operation

A monthly varying buffer coefficient as given in figure 5.5 on page 64 is proposed to see how the average monthly unmet demand will be affected. The simulation result given in figure 5.6 on page 64 shows changing reservoir operation from full utilization of water in the buffer zone in all months to partial utilization will not affect the unmet demand significantly.

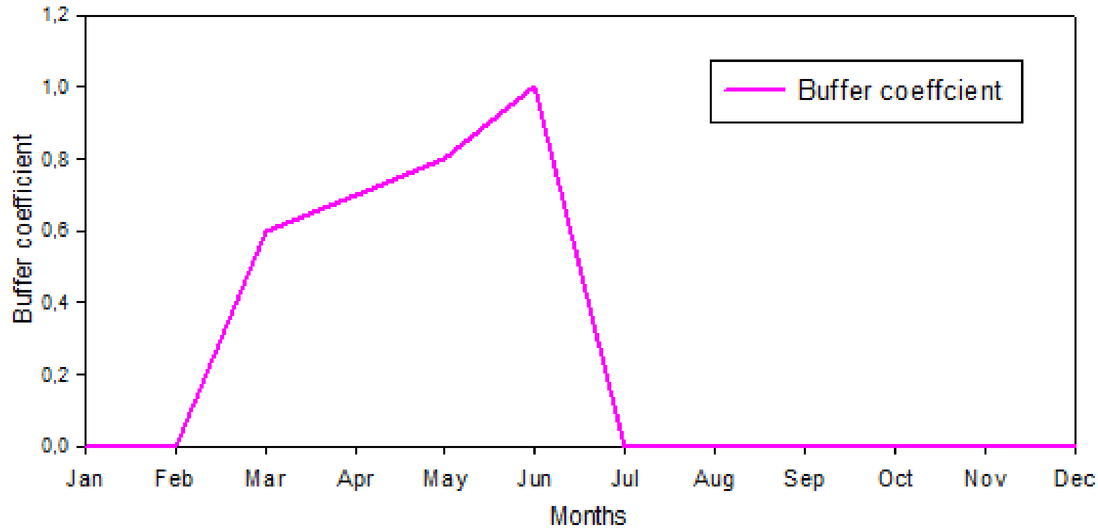

Figure 5.5.: Proposed buffer coefficient of Koka reservoir

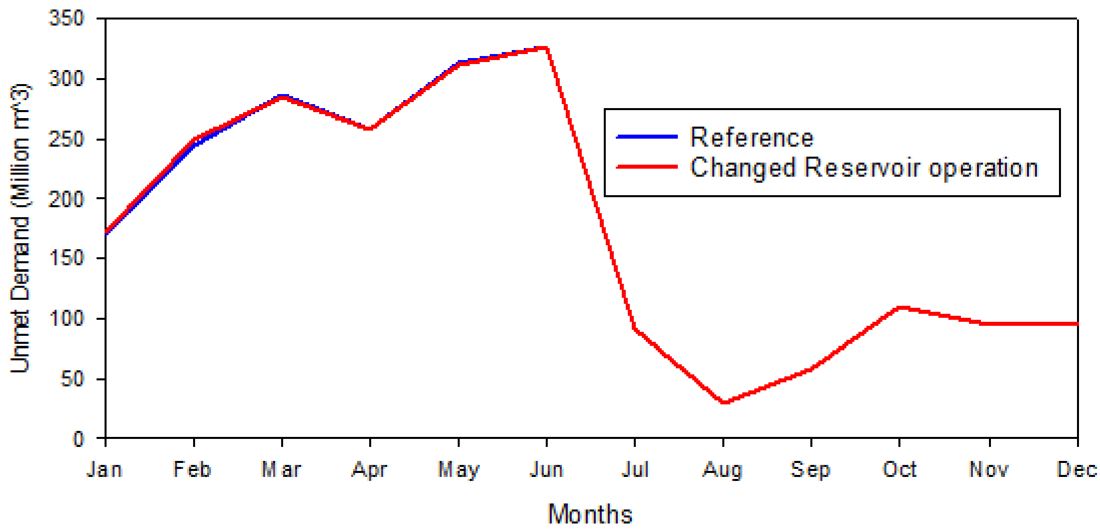

Figure 5.6.: Unmet demand of reference scenario with constant buffer coefficient (b_c=1) and future scenario with varying buffer coefficient

During low water demand water in the buffer zone can be fully conserved, i.e; buffer coefficient of zero. However, this doesn't restrict WEAP from releasing water that flows water into the reservoir during that period. It only conserves the buffer storage. Even if the the buffer coefficient is zero, the model still withdraws water flowing into the reservoir if needed for downstream demand. This is why the unmet demand during most of the months is not affected significantly even if the buffer coefficient is zero.

A third future scenario is tested by adding storage reservoir at Kebena river which is actually a future plan to be developed in the basin. The proposed reservoir at Kebena is tested with different capacity and as the size increases the unmet demand reduces. A sample of simulation test is given in figure 5.7 on page 65. The reason why the future scenario's effect is beginning later is that, the new reservoir is planned to be implemented five years later from the current account. Even though, it is not a significant reduction in unmet demand but it shows still more reservoirs need to be developed in the basin to met the demands and to minimize water scarcity. A very recent study in Awash basin water availability by Adeba et al. (2015) also suggested that more storage reservoirs still need to be developed to satisfy the demand.

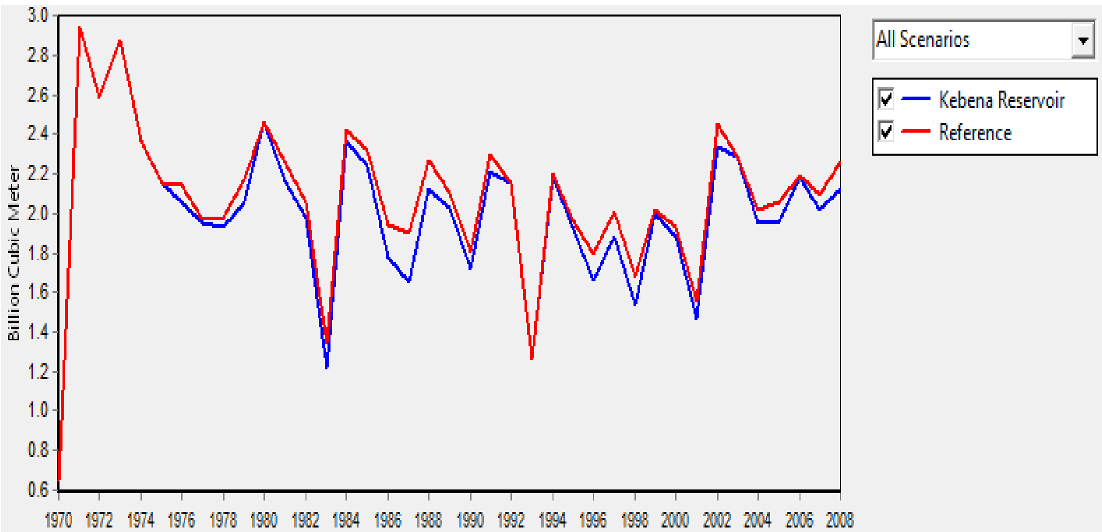

Figure 5.7.: Annual total unmet demand of reference and future scenario (Kebena reservoir)

Another scenario based on impact of climate change is also tested. The assumptions are taken from National Adaptation Programme of Action (NAPA) of Ethiopia (2007). The percentage change of precipitation and temperature for 2030 and 2050 climate change is given in table 5.3 on page 66. The simulation result shows that water deficiency of the basin increases due to climate change in the future refer figure 5.8 on page 66. Higher deficiency is observed in both years of climate change compared to the reference scenario. The effect in 2030 is higher than in 2050. The climate change impact is lower August and September compared to other months.

In general from the scenario analysis it can be concluded that water scarcity in the future time is increasing due to climate change. In times of drought the situation will be difficult to handle unless efficient water management option and sufficient storage facilities are implemented.

Climate change	2030	2050
Precipitation (%)	+3.4	+6.4
Temperature (°C)	+1.0	+1.8

Table 5.3.: Change in precipitation and temperature due to climate change (source; Belete Berhanu (2013b))

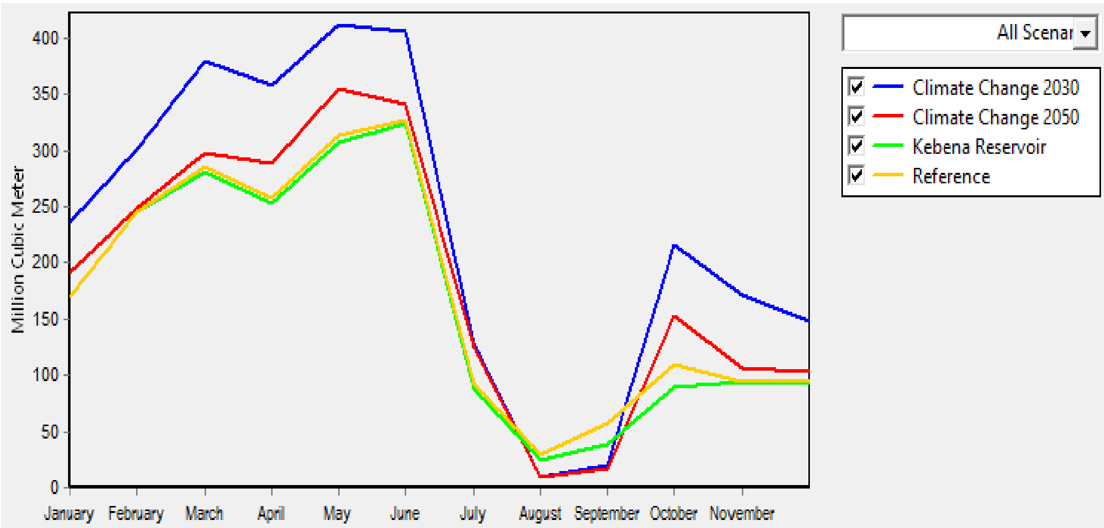

Figure 5.8.: Scenario comparison of reference (existing) with new reservoir and climate change

5.6. Interbasin Transfer System

Even though developing additional storage facility is an important structural measure to mitigate water scarcity, its location with respect to the affected area has a significant impact on the water allocation and distribution process. Water has to be delivered to demand sites when it is needed. Diversion of water for irrigation purpose is a common practice in the basin. But most of the diversion infrastructures are for commercial agriculture. Hence, transfer systems has a key role in mitigating the impact of extreme and severe droughts. Through those facilities water can be allocated to the most affected areas. Apart from their main purpose, these water transfer systems plays a big role in minimizing potential conflict of ethnic groups during extreme or sever droughts due to resource competition.

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6. Conclusion and Recommendation

6.1. Conclusion

In this thesis work drought characteristics of Awash river basin is studied on a sub basin level. After drought is analysed for each sub basin impact of climate change is studied on three representative sub basins. These three sub basins are assumed to represent the upper, Middle and Lower parts of the basin. To analyse the impact of climate change historical and future precipitation of 54 index points is downscaled with in the catchment. Then drought mitigation options are also analysed using a WEAP model. The main findings are listed below.

- The Awash basin is found to be a drought prone basin as majority of its area is located in the North East of the country where the climate is dry and warmer/semi arid zone.
- Most of the droughts happened in the basin are due to failure of precipitation
- Standardized precipitation index is found to be able to reflect the actual drought events happened so far in the basin.
- More drought events are found using short time scale but have shorter duration, vice versa, Less drought events are found using longer time scale such as annual time scale but have longer duration.
- Extreme and severe drought events are mostly happening in the middle and Lower part of the basin.
- Drought durations are longer in the middle and lower Awash compared to the upper Awash.
- Drought events with one year duration is a common phenomenon in all sub basins.
- A good correlation between meteorological and hydrological droughts duration is found based on shorter time scale of drought indices calculation.
- A good correlation between observed and downscaled precipitation of monthly data of 30 years is found in the upper and lower part of the basin in both considered climate models (Moh hadely and MPI) while poor correlation is

found in the lower part.

- Higher percentage of precipitation changes in RCP85 is observed in most of the months in both climate models while In few occasions RCP26 is found to give higher percentage changes.
- Future estimated precipitation values are found to follow the trend of precipitation changes.
- For most of the months in the future precipitation is raising in the lower part while reducing in the upper and middle part.
- Drought risk in the future is increasing in the upper and middle part while almost similar type of drought event or less risk is found in the lower part due to climate change. Even though less risk of drought in the future is detected compared to the base line in the lower part it is uncertain as the correlation of observed and downscaled precipitation is very weak in this part.
- Both climate models (Moh hadely and MPI) are found to give almost similar results of assessment of the impact of climate change on drought risk.
- By changing reservoir operation rules it is found that the downstream demand sectors will not be affected rather water will be saved for emergency.
- Demand side management technique is found to mitigate water scarcity as the water demand is high in the basin.
- The existing reservoirs in the basin are found not to satisfy the demand and mitigate drought risk. Hence More reservoirs need to be developed with water transfer facilities.
- Water transfer facilities are found to be important hydraulic infrastructures for drought mitigation as the people of the Awash basin are located far.
- Water deficiency is increasing due to climate change in the near future.
- Water Evaluation and Planning tool is found to be a helpful tool in analysing scenarios of different water management options not only that but it is also a unique model to use it as a data base.

6.2. Recommendation

Summary of suggested proposals to mitigate and reduce impact of drought on peoples, livestock and economic development of the Awash basin are listed below. The proposals contain both risk and crisis management strategies.

- Developing more storage reservoirs with water transfer system.
- Implementing efficient water management practices and creating awareness.
- Improvement of existing weather forecasting and early warning system.
- Well documentation of ongoing droughts and creating data base of historical drought impacts.
- Developing regional drought forecasting model.
- Carrying out virtual drought exercises to train experts, reflect new events and test management plans.
- Developing a compendium of statistical information that can be used by water managers to answer questions related to the frequency, duration and magnitude of droughts.
- Implementation of soil and water conservation practice in each sub basins.
- Construction of check dams in the tributaries and small streams.

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References

Abramowitz, M. and Stegun, I. A. (1964). Handbook of mathematical functions, 1965.

Adeba, D., Kansal, M., and Sen, S. (2015). Assessment of water scarcity and its impacts on sustainable development in awash basin, ethiopia. *Sustainable Water Resources Management*, 1(1):71–87.

Awulachew, S. B., Yilma, A. D., Loulseged, M., Loiskandl, W., Ayana, M., and Alamirew, T. (2007). *Water resources and irrigation development in Ethiopia*, volume 123. Iwmi.

Belete Berhanu, S. (2013a). Hydro-meteorological trend analysis. *Unpublished report. Food and Agriculture Organization of the United Nations (FAO), Ethiopia.*

Belete Berhanu, SemuAyalew, Y. I. Y. (2013b). Developing a water audit for awash river basin. *Unpublished report. Food and Agriculture Organization of the United Nations (FAO), Ethiopia.*

Berland, Saeed, V. I. W. M. G. C. A. et al. (2012). Extended guidance document after conference on drought management and policy options. `http://www.feem-project.net/xerochore/files/D5.2.pdf/`. [Online; accessed 23-May-2016].

Bondestam, L. (1974). People and capitalism in the north-eastern lowlands of ethiopia. *The Journal of Modern African Studies*, 12(03):423–439.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., and Tavoni, M. (2009). International climate policy architectures: Overview of the emf 22 international scenarios. *Energy Economics*, 31:S64–S81.

Degefu, W. (1987). *Some aspects of meteorological drought in Ethiopia*. Cambridge University Press.

Dracup, J. A., Lee, K. S., and Paulson, E. G. (1980). On the definition of droughts. *Water resources research*, 16(2):297–302.

Edossa, D. C., Babel, M. S., and Gupta, A. D. (2010). Drought analysis in the awash river basin, ethiopia. *Water Resources Management*, 24(7):1441–1460.

Edwards, C., McKee, T., Doesken, N., and Kleist, J. (1997). Historical analysis of drought in the united states. In *7th conference on climate variations, 77th AMS annual meeting*, volume 27.

Flintan, F. and Tamrat, I. (2002). Spilling blood over water? the case of ethiopia. *Scarcity and Surfeit: The Ecology of Africa's Conflicts. ISS, Pretoria, South Africa. p*, pages 243–319.

Halcrow, W. (1989). Master plan for the development of surface water resources in the awash basin. *Final Unpublished Report. Ethiopian Valleys Development Studies Authority*, 4.

Harbeson, J. and Beshah, T.-W. (1974). Ethiopian nomads in transition: Political and economic development in the awash valley. *Unpublished IDR Document, Addis Ababa*.

Langbein, W. and Iseri, K. T. (1960). Manual of hydrology: Part 1. general surface-water techniques. *Geological Survey Water-Supply Paper A*, 1541.

Mishra, A. K. and Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, 391(1):202–216.

Nalbantis, I. (2008). Evaluation of a hydrological drought index. *European Water*, 23(24):67–77.

Nalbantis, I. and Tsakiris, G. (2009). Assessment of hydrological drought revisited. *Water Resources Management*, 23(5):881–897.

Riahi, K., Grübler, A., and Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change*, 74(7):887–935.

Said, A. (1994). Resource-use conflict between pastoralism and irrigation developments in the middle awash valley of ethiopia. *Eastern Africa Social Science Research Review*, 10(2):21.

Sieber, J. and Purkey, D. (2007). Water evaluation and planning system user guide for weap21. *Stockholm Environment Institute, US Center.*

Thom, H. C. (1958). A note on the gamma distribution. *Monthly Weather Review*, 86(4):117–122.

Tigkas, D., Vangelis, H., and Tsakiris, G. (2015). Drinc: a software for drought analysis based on drought indices. *Earth Science Informatics*, 8(3):697–709.

Toulmin, C. (1985). Livestock losses and post-drought rehabilitation in sub-saharan africa.

Tsakiris, G., Pangalou, D., and Vangelis, H. (2007). Regional drought assessment based on the reconnaissance drought index (rdi). *Water resources management*, 21(5):821–833.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., et al. (2011). The representative concentration pathways: an overview. *Climatic change*, 109:5–31.

Vrochidou, A.-E., Tsanis, I., Grillakis, M., and Koutroulis, A. (2013). The impact of climate change on hydrometeorological droughts at a basin scale. *Journal of Hydrology*, 476:290–301.

Wilhite, D. A. (1997). State actions to mitigate drought lessons learned1.

Wilhite, D. A. (2000). Drought as a natural hazard: concepts and definitions.

Wilhite, D. A. and Glantz, M. H. (1985). Understanding: the drought phenomenon: the role of definitions. *Water international*, 10(3):111–120.

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Appendices

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A. Meteorological and Hydrological Drought Relationships

Meteorological Drought					Hydrological Drought					
start	end	Duration(Days)	Magnitude	Magnitude(mm)	start	end	Duration(days)	Magnitude	Magnitude(m3/s)	Lag(days)
Apr-70	Jun-70	61	2.26	316.34	May-70	Jun-70	31	2.05	124.10	30
Feb-71	Apr-71	59	1.65	257.75	Feb-71	Apr-71	59	1.33	90.55	0
Mar-73	Apr-73	31	1.27	220.84	May-73	Jul-73	61	4.94	260.01	61
Jan-74	Feb-74	31	1.81	272.86	Apr-74	May-74	30	0.89	69.86	90
Jun-74	Aug-74	61	2.00	291.77	Jun-74	Jul-74	30	1.34	90.97	0
Dec-74	May-75	151	3.85	468.92	Dec-74	Jun-75	182	4.33	231.15	0
Oct-75	Dec-75	61	1.23	217.75	Nov-75	Feb-76	92	2.60	149.95	31
Mar-76	Apr-76	31	0.52	149.18	Mar-76	Apr-76	31	1.21	85.01	0
Sep-76	Oct-76	30	1.62	255.18	Sep-76	Oct-76	30	2.39	140.09	0
Apr-77	Jun-77	61	2.61	349.83	Apr-77	Jun-77	61	1.54	100.34	0
Dec-77	Jan-78	31	1.40	233.69	Apr-78	Jun-78	61	1.16	82.66	121
Apr-78	May-78	30	1.03	198.24	Jul-78	Sep-78	62	0.45	49.20	91
Aug-79	Sep-79	31	1.60	252.87	Aug-79	Sep-79	31	2.39	140.15	0
Jun-80	Aug-80	61	1.83	274.69	Sep-80	Nov-80	61	2.37	139.17	92
Nov-80	Feb-81	92	2.93	380.68	Dec-80	Feb-81	62	3.16	176.32	30
May-81	Jun-81	31	2.85	373.34	May-81	Jun-81	31	1.87	115.94	0
Jun-82	Jul-82	30	3.78	462.45	Jun-82	Jul-82	30	2.67	153.31	0
Jan-84	Apr-84	91	4.34	516.56	Jan-84	May-84	121	4.66	246.80	0
Jul-84	Oct-84	92	4.70	551.06	Aug-84	Dec-84	122	5.62	291.68	31
Jan-85	Mar-85	59	2.20	310.09	Jan-85	Apr-85	90	6.44	330.21	0
Nov-86	Dec-86	30	0.93	188.85	Dec-86	Jan-87	31	3.30	183.00	30
Jun-87	Sep-87	92	3.48	433.84	Jul-87	Oct-87	92	6.48	332.35	30
Mar-88	Jun-88	92	2.25	315.69	Mar-88	Jul-88	122	5.16	270.24	0
May-89	Jun-89	31	2.43	332.58	May-89	Jun-89	31	2.01	122.27	0
Apr-90	Jul-90	91	3.00	387.23	May-90	Aug-90	92	2.45	143.01	30
Sep-90	Oct-90	30	0.25	122.87	Sep-90	Oct-90	30	0.19	37.00	0
Mar-91	May-91	61	3.43	428.45	Apr-91	Jun-91	61	3.48	191.23	31

Figure A.1.: Detail calculation used to find out how meteorological and hydrological droughts are related using 1-month time scale of drought indices calculation.

Meteorological Drought					Hydrological Drought					
start	end	Duration(Days)	Magnitude	Magnitude(mm)	start	end	Duration(days)	Magnitude	Magnitude(m3/s)	Lag(days)
Mar-92	Jun-92	92	1.26	220.35	Mar-92	Jul-92	122	2.72	155.87	0
Aug-92	Sep-92	31	2.06	297.19	Oct-92	Nov-92	31	0.46	49.70	61
Oct-93	Feb-94	123	3.35	420.75	Feb-94	Jun-94	120	2.66	152.76	123
Dec-94	Mar-95	90	2.26	316.77	Dec-94	Mar-95	90	1.97	120.74	0
May-95	Jul-95	61	2.28	318.46	Jun-95	Aug-95	61	2.27	134.62	31
Sep-95	Nov-95	61	3.06	393.54	Oct-95	Dec-95	61	2.75	157.40	30
Oct-96	Dec-96	61	0.87	182.64	Oct-96	Nov-96	31	0.55	54.01	0
Feb-97	Mar-97	28	4.54	534.99	Feb-97	Mar-97	28	1.32	90.08	0
May-97	Sep-97	123	4.17	499.42	May-97	Oct-97	153	7.26	368.81	0
Nov-98	Dec-98	30	0.96	191.44	Feb-99	Mar-99	28	1.14	81.59	92
Feb-99	Mar-99	28	1.84	275.46	Apr-99	May-99	30	2.15	129.18	59
Aug-99	Sep-99	31	1.68	260.26	Aug-99	Sep-99	31	1.77	111.10	0
Dec-99	Mar-00	91	4.31	513.73	Feb-00	Jun-00	121	3.06	171.89	62
Jul-00	Aug-00	31	2.04	295.32	Jul-00	Sep-00	62	1.82	113.77	0
Jul-01	Sep-01	62	2.63	351.91	Aug-01	Oct-01	61	1.28	88.41	31
Jul-02	Nov-02	123	5.70	646.65	Jul-02	Nov-02	123	3.79	205.94	0
Aug-03	Oct-03	61	2.78	366.16	Oct-03	Nov-03	31	0.47	49.98	61
Feb-04	Mar-04	29	1.75	266.91	Feb-04	Mar-04	29	0.47	49.98	0
Mar-07	Apr-07	31	1.54	246.99	Mar-07	Apr-07	31	0.50	51.76	0

Figure A.2.: Continued from Figure A.1

Meteorological Drought					Hydrological Drought					
start	end	Duration (Days)	Magnitude	Magnitude(mm)	start	end	Duration (days)	Magnitude	Magnitude(m3/s)	Lag(days)
Apr-70	Jun-70	61	2.85	373.05	May-70	Jun-70	31	1.38	92.95	30
Feb-71	Apr-71	59	1.94	285.97	Mar-71	Apr-71	31	1.34	91.06	28
Jun-72	Jul-72	30	0.43	140.47	Aug-72	Nov-72	92	4.77	251.92	61
Mar-73	May-73	61	1.63	256.12	Mar-73	Jun-73	92	6.32	324.73	0
Jan-74	Mar-74	59	3.03	390.28	May-74	Jul-74	61	2.14	128.63	120
Jul-74	Sep-74	62	1.93	284.39	Dec-74	Feb-75	62	1.03	76.23	153
Jan-75	May-75	120	5.95	670.81	Mar-75	Jun-75	92	3.46	190.52	59
Aug-75	Sep-75	31	1.16	210.25	Dec-75	Jan-76	31	1.10	79.95	122
Nov-75	Dec-75	30	1.85	277.33	Feb-76	Mar-76	29	2.64	151.81	92
Mar-76	May-76	61	0.84	180.14	May-76	Jul-76	61	1.81	112.91	61
Aug-76	Sep-76	31	0.58	154.82	Aug-76	Sep-76	31	1.17	82.94	0
Apr-77	Jun-77	61	3.47	432.26	Apr-77	Jun-77	61	2.14	128.54	0
Jan-78	Feb-78	31	0.80	175.64	Apr-78	Jun-78	61	1.14	81.54	90
Apr-78	Jun-78	61	1.41	234.77	Jul-78	Sep-78	62	0.62	57.25	91
Jul-79	Dec-79	153	2.70	358.48	Jul-79	Dec-79	153	4.84	255.27	0
Jul-80	Oct-80	92	1.64	256.44	Sep-80	Dec-80	91	2.87	162.58	62
Jun-81	Jul-81	30	2.13	303.49	Jun-81	Aug-81	61	1.83	113.92	0
Apr-82	Oct-82	183	7.58	827.12	Apr-82	Oct-82	183	5.62	291.78	0
Jul-83	Aug-83	31	0.16	114.87	Jul-83	Aug-83	31	1.29	88.51	0
Jan-84	May-84	121	5.69	645.85	Jan-84	May-84	121	5.88	304.12	0
Aug-84	Nov-84	92	5.22	600.98	Aug-84	Dec-84	122	4.69	248.06	0
Jan-85	Apr-85	90	3.44	430.16	Jan-85	May-85	120	8.76	439.20	0
Jun-85	Jul-85	30	0.21	119.54	Jun-85	Jul-85	30	0.52	52.53	0
Nov-85	Jan-86	61	2.07	297.69	Nov-85	Feb-86	92	5.75	298.08	0
Dec-86	Jan-87	31	1.41	234.26	Dec-86	Feb-87	62	4.06	218.79	0
Jul-87	Oct-87	92	3.78	462.12	Jul-87	Nov-87	123	8.02	404.40	0
Apr-88	Jun-88	61	2.86	374.30	Apr-88	Jul-88	91	4.46	237.42	0

Figure A.3.: Detail calculation used to find out how meteorological and hydrological droughts are related using 2-month time scale of drought indices calculation.

Meteorological Drought					Hydrological Drought					
start	end	Duration (Days)	Magnitude	Magnitude(mm)	start	end	Duration (days)	Magnitude	Magnitude(m3/s)	Lag(days)
May-89	Jun-89	31	1.88	280.22	May-89	Jun-89	31	1.37	92.58	0
May-90	Aug-90	92	3.52	437.30	Jun-90	Sep-90	92	2.29	135.54	31
Oct-90	Nov-90	31	0.94	189.25	Oct-90	Nov-90	31	0.54	53.65	0
Jan-91	Feb-91	31	0.50	147.35	Jan-91	Feb-91	31	1.39	93.34	0
Apr-91	Aug-91	122	4.69	550.26	Apr-91	Aug-91	122	3.33	184.49	0
Nov-91	Jan-92	61	2.17	307.38	Nov-91	Jan-92	61	2.06	124.72	0
Apr-92	Sep-92	153	3.65	449.68	Apr-92	Sep-92	153	3.51	192.95	0
Nov-93	Feb-94	92	4.95	574.83	Feb-94	May-94	89	2.46	143.58	92
Oct-94	Dec-94	61	0.78	174.46	Oct-94	Dec-94	61	0.40	46.98	0
Feb-95	Mar-95	28	1.29	222.77	Feb-95	Mar-95	28	1.56	101.19	0
Jun-95	Sep-95	92	3.74	458.33	Jun-95	Sep-95	92	2.70	154.70	0
Oct-95	Nov-95	31	2.67	356.14	Nov-95	Dec-95	30	1.73	109.19	31
Nov-96	Dec-96	30	1.37	230.90	Feb-97	Mar-97	28	0.91	70.63	92
Mar-97	Apr-97	31	3.91	474.82	Apr-97	May-97	30	1.28	88.30	31
Jun-97	Oct-97	122	4.41	523.14	Jun-97	Nov-97	153	7.53	381.37	0
Dec-98	Mar-99	90	3.90	473.64	Feb-99	May-99	89	3.44	189.46	62
Jul-99	Oct-99	92	2.28	318.20	Aug-99	Oct-99	61	1.97	120.35	31
Dec-99	Apr-00	122	5.29	607.45	Feb-00	Jun-00	121	3.45	190.14	62
Jul-00	Oct-00	92	2.27	317.45	Jul-00	Oct-00	92	2.85	161.74	0
Aug-01	Oct-01	61	4.11	494.24	Sep-01	Nov-01	61	1.67	106.45	31
Aug-02	Nov-02	92	6.53	726.67	Aug-02	Nov-02	92	3.69	201.19	0
Jul-04	Aug-04	31	1.66	258.80	Sep-04	Oct-04	30	0.45	49.16	62
Mar-07	Apr-07	31	1.80	272.46	Mar-07	Apr-07	31	0.39	46.35	0

Figure A.4.: Continued from Figure A.3

B. Percentage Change in Precipitation for future period (2071-2100)

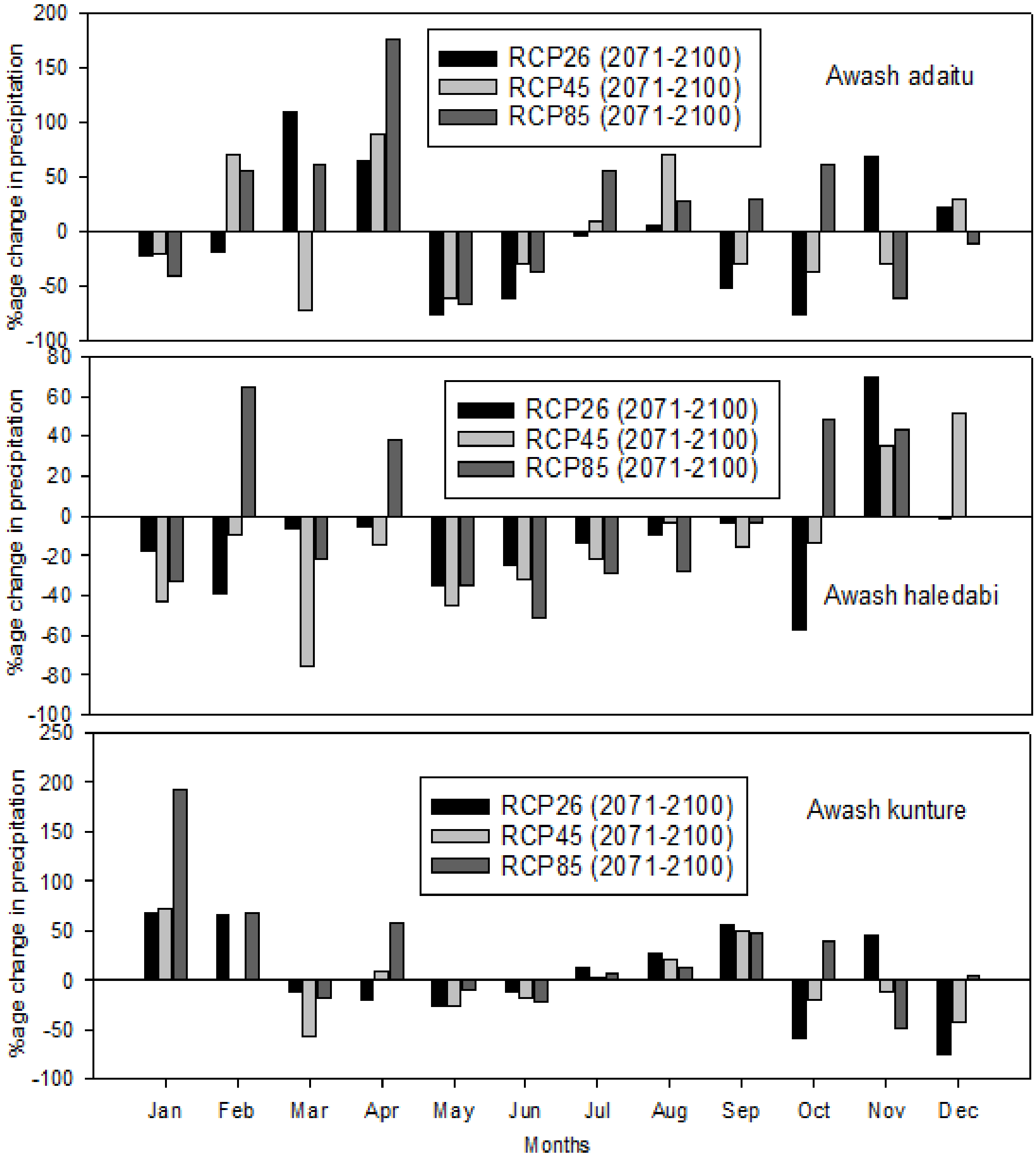

Figure B.1.: %age changes in precipitation of representative sub basins using Moh hadely model

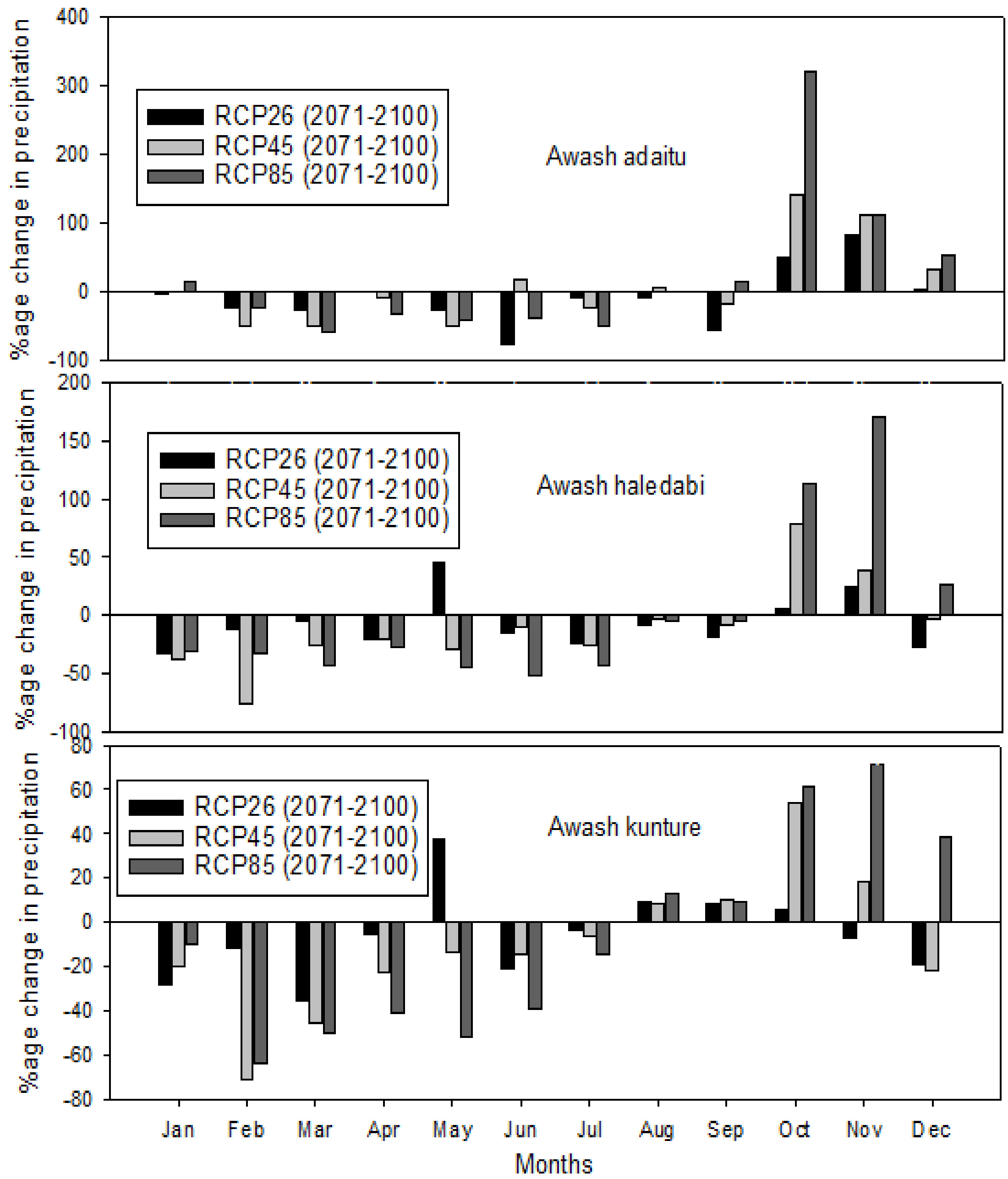

Figure B.2.: %age changes in precipitation of representative sub basins using MPI model

C. Future estimated precipitation of Awash kunture (Upper Awash) using MPI model

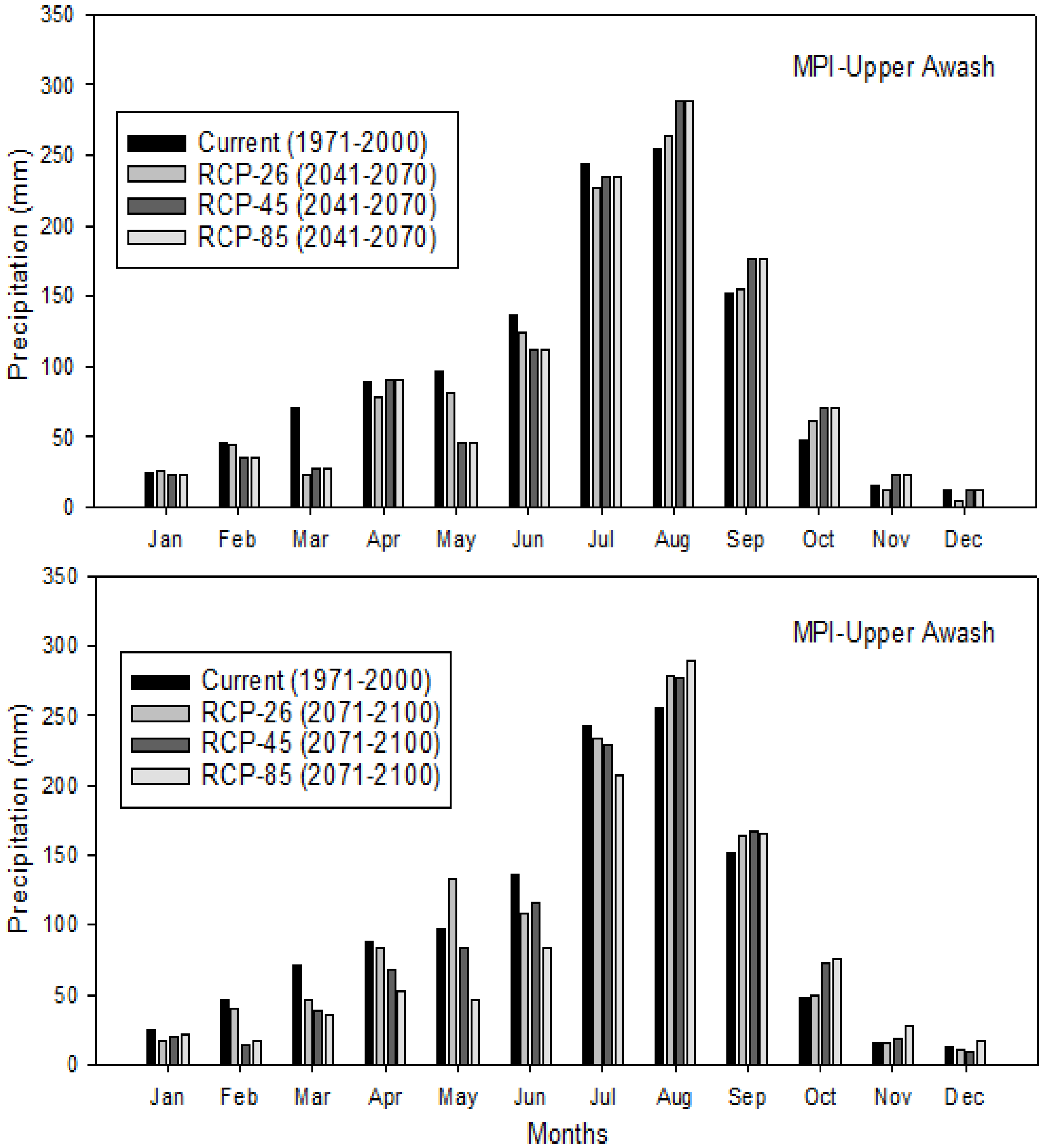

Figure C.1.: Future annual average monthly precipitation of Awash kunture (Upper Awash) using MPI climate model

D. Future estimated precipitation of Awash haledabi (Middle Awash) using MPI model

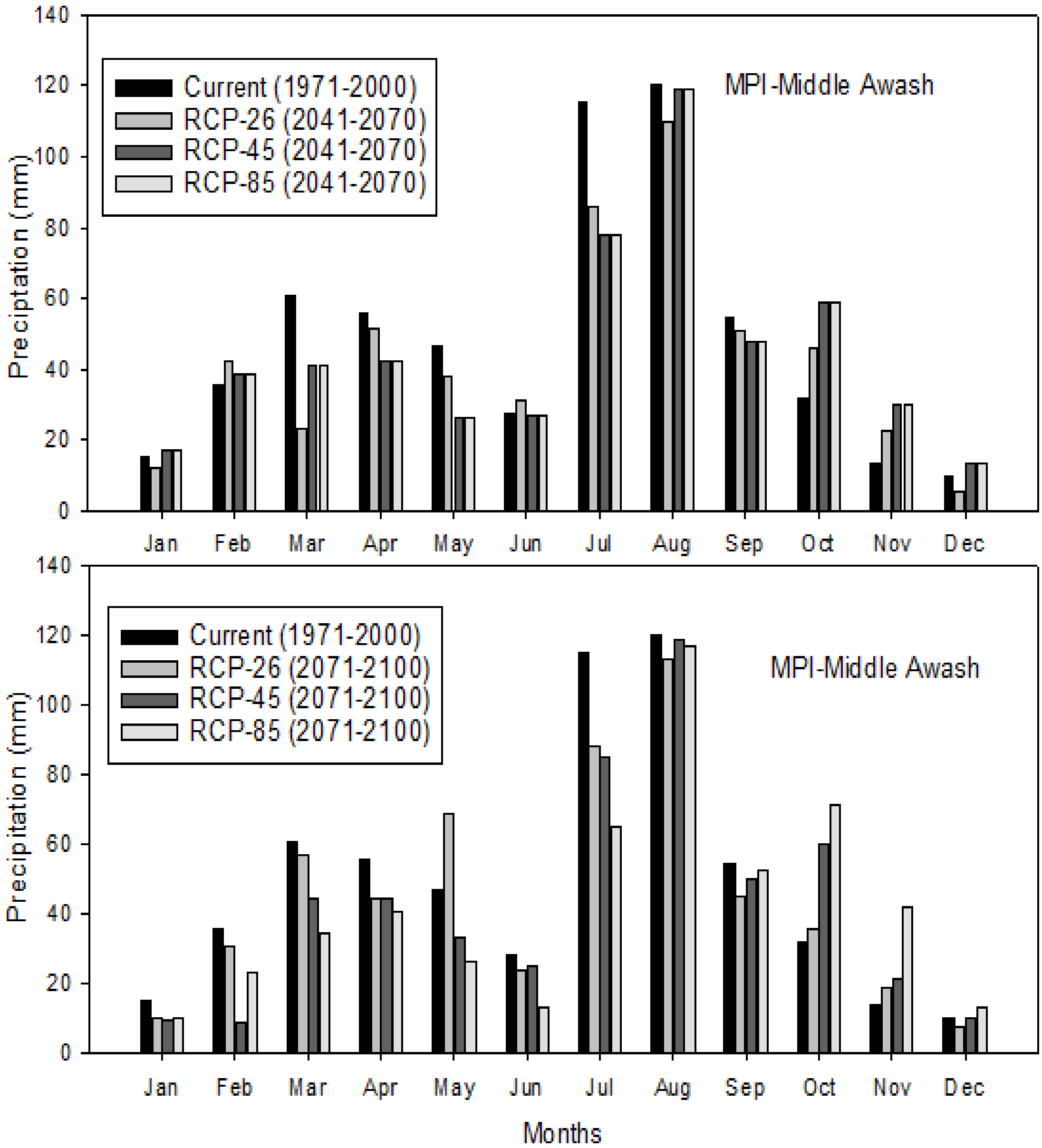

Figure D.1.: Future annual average monthly precipitation of Awash haledabi (Middle Awash) using MPI climate model

E. Future estimated precipitation of Awash adaitu (Lower Awash) using MPI model

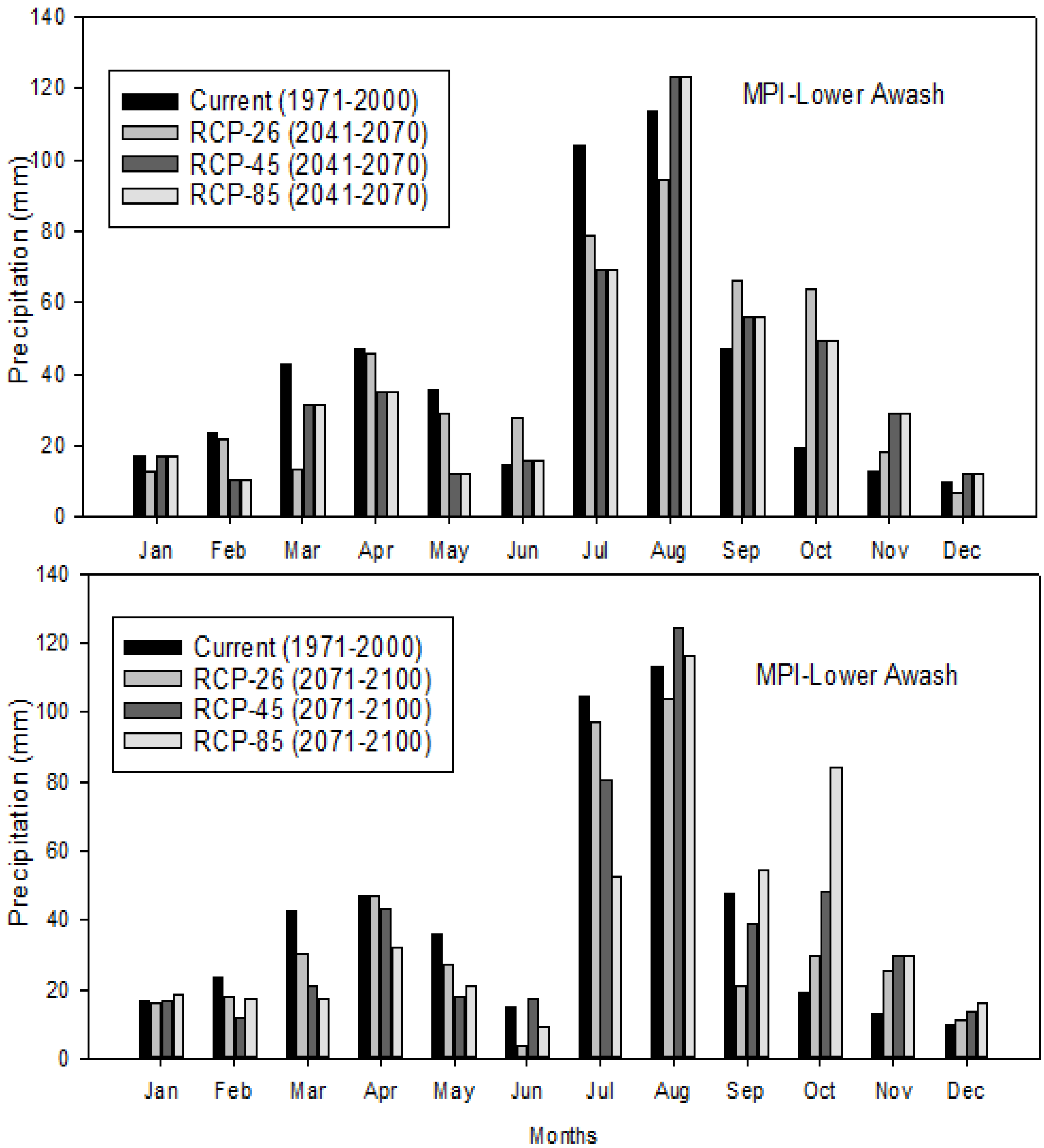

Figure E.1.: Future annual average monthly precipitation of Awash adaitu (Lower Awash) using MPI climate model