Hydrol. Earth Syst. Sci. Discuss., 7, 3733–3763, 2010
www.hydrol-earth-syst-sci-discuss.net/7/3733/2010/
doi:10.5194/hessd-7-3733-2010

Hydrology and Earth System Sciences Discussions

Climate resources analysis for use of planning in crop production and rainfall water management in the central highlands of Ethiopia, the case of Bishoftu district, Oromia region

F. Yemenu[1] **and D. Chemeda**[2]

[1]Asso Researcher, Ethiopian Institute of Agricultural Research, POB-32, Debre Zeit, Ethiopia
[2]Asso Professor,Haramaya Univesity, POB-138, Dire Dawa, Ethiopia

Received: 4 May 2010 – Accepted: 10 May 2010 – Published: 23 June 2010

Correspondence to: F. Yemenu (fitsum_yimenu@yahoo.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Agricultural practices and water resources management in the central highlands of Ethiopia is highly dependant and associated with climatic resources and their pattern and hence wise use of those resources is a priority for the region. Accordingly, a study was conducted to asses and critically quantity the climate resources of the central high lands of Ethiop, Bishoftu district. Thirty three years of weather record data has been used for the work. The onset, duration and end of the growing seasons were defined and quantified based on FAO and Reddy models while the dry and wet spell distributions and the drought events were calculated using the Markov chain models and the standardized precipitation index (SPI) respectively. The results revealed that the mean onset of the main (Kiremt) growing season was found to occur during the second meteorological decade and ended during the end of September. Similarly, though unreliable and only few occurred during the entire study period, the mean onset of the shorter (Belg) season was found to occur during the beginning of the first decade of April. The length of the growing season during the main rainy season, (Kiremt,) ranged from 112 to 144 days with a standard deviation of 9.6 days and coefficient of variation of 7.5%. However, the mean growing length during the Belg season was found to be 22.4 days with a standard deviation of 27 days and coefficient of variation of 122%. The results of analysis obtained both from the Markov Chain and Reddy models indicated higher probabilities of dry spell occurrences during the shorter season (Belg) but the occurrences of the same in the main rainy season (Kiremt) was very minimal. Like wise, the SPI model detected some drought events ranging from mild to severe classes in both seasons based on one a month time scale analysis. A considerable attention of maximizing crop harvest during the main rainy season is practically important.

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1 Introduction

Rain fed agriculture, on which the Ethiopian economy rests, has been the dominant sources of food production. Recent studies reported that this sector is still contributing more than 50% to GDP and about 60% to foreign exchange earnings and provides livelihood to more than 85% of the population (Goodswill et al., 2007). However, yields from rainfed agriculture are often very low due to repeated failure of crop yield associated with irregularity in onset, temporal and spatial distribution of rain in most parts of the region during the growing season.

Some studies conducted in sub-Saharan Africa indicated that there is a potential opportunities for increasing crop yields in the region. An assessment made by Baron (2004) showed that the cereal crop yields could reach as high as 3.5 t ha^{-1} against the existing yield 1 t ha^{-1} yield estimated by Rockstrom (2003). This wide gap suggests that there is an enormous opportunity to raise crop yield from rainfed agriculture. This is entirely linked to focusing attention on maximizing yield per unit of water.

According to Meinke (2003), climate resources assessment work determined through possible estimation of rainfall onset date, end date, duration and seasonal totals and dry spell length, which together make up the overall rain feature, can provide deep insight into the rainfall variability and into the field management options through proactive responses. The assessment and prediction of the onset and cessation dates of the rainy season is also a key issue in countries which rely on rain-fed agriculture for better explanation of the growing season of a given area (Camberlin and Diop, 2003).

In line with this, few studies have been conducted in Ethiopia mainly focusing on climate resources assessment based on the analysis of growing periods. Some researchers tried to quantify the agro-climatic resources of Ethiopia for land use planning. However, certain limitations have been observed in the model they used in that it assumes an optimal matching between the length of the climatic growing period and the crop growth cycle to the extent that they are often used interchangeably (Mersha, 2005).

In addition, the main limitations of these works are also that they used aggregated climatic data that do not enable of assessing the dry spells on crop yields and the model did not also account for the conserved soil moisture in determining the growing period (Mersha, 2000). Moreover, one month time step was used in the analysis of the growing period, which is so long for the proper characterization of the moisture status and planning of agricultural operations in the growing season. Besides, little efforts were made, if any, in characterization, quantification and assessment of climatic resources such as dry-wet spell and drought events on a district scale for decision making purposes.

With this in mind, only little efforts were made in the central highlands of Ethiopia to characterize the climate resources for use in planning of agricultural and water resources management. Most of them use to focus on long-term monthly and seasonal rainfall characterization whose results are meant to give only general information about the rainfall climatology of the area. It lacked the integration of other weather elements (Temperature, sunshine hours, wind speed...) with rainfall data for proper quantification of the resources (Sileshi and Demaree, 1995).

Therefore detailed climate resources investigations are highly important for precisely quantify the climate resources of the central high lands of Ethiopia for use in planning of agricultural water resources management. This paper has given the first very attention in such kind of work for a district in the central highlands of Ethiopia which is prominently a leading in agricultural production and also having a full and sufficient data set for the work.

For successfully carrying out climate resources assessment, several models have been proposed for determining the dates of onset and end of the rainy season and the length of growing season as a tool for rainfall water resources assessment. This ranges from traditional to semi-empirical and scientific techniques (Ati, 1995). Awadulla (1981), cited by Hulme (1987), designed a water balance model using pentad rainfall amount and potential evapotranspiration (PET) and under certain assumptions about the soil moisture capacity. However, recent studies have shown that the determination of onset of rain, length of growing season and recession period developed by FAO (1978) sounds better if appropriate unit of time for the analysis is employed (Engida, 2005).

With regard to dry and wet spell analysis, recently many more researchers are becoming interested in using the Markov Chains model (Pabitra et al., 2008). McKee et al. (1993) also developed the Standardized Precipitation Index (SPI) for the purpose of defining and monitoring drought. The nature of the SPI allows an analysis to determine the rarity of a drought or an anomalously wet event at a particular time scale for any location in the world that has a precipitation record of more than thirty years period of time.

With a view of this, an attempt was made to critically investigate the climate resources of the Bishoftu district in the central highlands of Ethiopia, with the following specific objectives:

- to determine the onset and end of growing periods in Belg (shorter) and Kiremt (main) seasons in the watershed, assess their probability of occurrences of onsets and asses the variability of growing period over years,
- to analyze the distribution of dry and wet spells during the two seasons and quantify the drought magnitude and intensity in the study district

2 Methodolgy and data annalysis

2.1 Rainfall in the central highland

The central highland of Ethiopia is predominantly tropical highland climate, with dry winter season. Mahdi and Petra (2002) reported a minimum rainfall of 335 mm and a maximum of 1594 mm were recorded in the central highlands of Ethiopia based on the analysis of one hundred years rainfall data (1898–1997). Rainfall in this region followed a clearly decreasing observed trend during the period mentioned.

2.2 The study district

The study district is located at 45 km south east of Addis Ababa, Ethiopia. The district is the most agricultural important area in the central highlands of Ethiopia. The area receives an annual mean rainfall of around 789 mm (Yemenu) with medium seasonal variability and bimodal pattern. The “Belg” or the shorter season’s rain, which is quite small to support crop production, usually occurs during the periods from the second week of March to second or third week of May. The long rainy season extends from the second week of June to the last week of September. The area is intensively cultivated for crop production. The major crop types grown in the district are wheat, chickpea and indigenous Ethiopian crop, “teff”.

2.3 Data summary

A weather record of thirty three years (1975–2007) was obtained from the Debre Zeit Agricultural Research Center’s weather archive and was organized at decadal time unit for appropriate analysis. Though it is point weather data, it is believed that the analysis would serve a wider area of the district (Mersha, 2003). The standard or meteorological decades (SMDs) are constructed in such a way that each month of a given year was divided in to three decades and subsequently the first two ten days are considered as the first and second decade for each month, respectively. The rest of days in each month again will be summed up to form the last or third decade (Messay, 2006). In other words, the whole year will have 36 decades starting from the month of January which will have the first three decades (decade number 1, 2 and 3) and it follows the same pattern where the last three decades of a given year will be for December (decade number 34, 35 and 36) respectively. Table 1 is given for better illustrations of the organizations of the meteorological or standard decades.

The reference evapotranspiration (ETo) data for each decade of a given year was obtained from the CropWat model based on the Penman-Month equation.

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2.4 Determination of beginning and end of the growing seasons and length of growing period

The beginning or the start of the rainy season both for Kiremt (the main growing season) and Belg (the shorter) was identified based on FAO (1978) simple soil water balance model which suggested that a growing period starts when a decadal (ten-days) rainfall amount is equal or greater than half of the reference evapotranspiration (ETo) during the beginning of the rainy season. Accordingly the end of the rainy seasons was set when the decadal rainfall of amount during the end of season is again less than half of the corresponding reference evapotranspiration (ETo). Finally, the length of the growing period (LGP) was defined by counting the number of days between the start and the end of the growing period plus the period required to evapotranspire the 100 mm moisture stored in the soil reserve during the rainy season (FAO, 1978; Mersha, 2005). The 100 mm of soil moisture reserve after the recession of the rainy season is accounted after an extensive work done in Eastern Africa (Mersha, 2003)

2.5 Dry-wet spell and drought analysis

2.5.1 Dry and wet spell analysis

Reddy (1990) has already stated that a 3 mm rainfall depth per day is the minimum threshold value for crops to satisfy their crop water requirement during a growing season. Accordingly, in this study, an average of 30 mm per decade of precipitation depth was taken as a threshold value for evaluating whether a decade is in a dry or wet spell. A decade with a depth of precipitation below this value was considered as dry and vice-versa for a decade with precipitation value of above the threshold level and a Markov chain model of first order as illustrated in "Eqs. 1–6" was used to explain the dry-wet spell probability of occurrences during the two rainy seasons.

$$P_D = \frac{F_D}{n} \quad (1)$$

$$P_W = \frac{F_W}{n} \quad (2)$$

$$P_{WW} = \frac{F_{WW}}{F_W} \quad (3)$$

$$P_{DD} = \frac{F_{DD}}{F_D} \quad (4)$$

$$P_{WD} = 1 - P_{DD} \quad (5)$$

$$P_{DW} = 1 - P_{WW} \quad (6)$$

Wet spell duration is defined as sequence of k wet decades preceded and followed by the dry dekades and correspondingly the dry spell duration is the sequence of dry decades followed and preceded by the wet ones. The distributions of the spells by length or duration are found to be geometric (Gabriel and Neuman, 1962; Pabitra, 2000) with the probability of wet spell of length k given by the following equations:

$$P(W = k) = (1 - P_1)P_1^k - 1 \quad (7)$$

$$P(W > k) = P_1^k \quad (8)$$

Similarly, probability of a dry spell of length m and greater than m were calculated using the following equations respectively.

$$P(D = m) = P_O(1 - P_O)^m - 1 \quad (9)$$

And

$$P(D > m) = (1 - P_O)^m \quad (10)$$

Where, P_D is the probability of a decade being dry
F_D is the number of dry decade

P_W is the probability of a decade being wet
F_W is the number of wet decades
n is the number of observations
P_{WW} is the probability of wet decade followed by another wet decade
F_{WW} is he number of wet decades followed by other wet decades
P_{DD} is the probability of a dry decade followed by another dry one
F_{DD} is the number of dry decade followed by another dry one
P_{WD} is the probability of a wet decade followed by another dry decade
P_{DW} is the probability of a dry decade followed by a wet one.
P_1 is the probability that a decade is wet give that the previous decade is wet and denoted by P(W/W)
P_0 is the probability that a decade being wet given that the previous is dry and is denoted by P(W/D)

2.5.2 Standardized precipitation index (SPI)

The same time step (decadal) can not be used to obtain SPI values in this study as there has not been any practice of similar case so far in the world. Therefore the time series of monthly rainfall data of 33 years (1978–2007) was made to fit the gamma distribution function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{b}} \quad (11)$$

Where: $\alpha > 0$, is a shape parameter; $\beta > 0$, is a scale parameter; X is the precipitation amount

$$\Gamma(\alpha) = \int_0^{\infty} y^{a-1} e^{-y} dy \quad (12)$$

Where, $\Gamma(\alpha)$ is the gamma function. The values of alpha and beta (α and β) in the function were estimated using the following equations;

$$\overset{\lambda}{\alpha} = \frac{1}{4}\mathrm{A}\left[1 + \sqrt{1 + \frac{4A}{3}}\right] \quad (13)$$

$$\beta = \frac{\bar{X}}{\overset{\lambda}{\alpha}} \quad (14)$$

$$\mathrm{A} = \ln\left(\bar{X}\right) - \frac{\sum \ln x}{n} \quad (15)$$

Where, X is the precipitation amount and, $\bar{x}$ is the mean precipitation of the series.

The resulting parameters, alpha and beta, were then entered into excel program of gamma distribution function to obtain the cumulative probabilities of each rainfall event for monthly rainfall total. Since the gamma function is not defined for zero values and the cumulative probability of each rainfall event was then estimated through the following equation:

$$\mathrm{H}_{(\mathrm{X})} = q + (1 - q)\mathrm{G}_{(\mathrm{X})} \quad (16)$$

q is the probability of zero which was estimated as the proportion of zeros in the rainfall data series.

The SPI was then computed as (Abramowitz and Stegun, 1965)

$$Z = \mathrm{SPI} = +\left[t - \frac{c_o + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \quad (17)$$

For $0 < \mathrm{H}<(\mathrm{x}) \leq 0.5$

$$Z = \mathrm{SPI} = +\left[t - \frac{c_o + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \quad (18)$$

For 0.5 < H(x) < 1 where,

$$t=\sqrt{\ln\frac{1}{(H_{(x)})^2}} for 0 < H(x) \leq 0.5 \tag{19}$$

and

$$t=\sqrt{\ln(\frac{1}{(1-H(x))^2}} 0.5 < H(x) < 1 \tag{20}$$

$C_{0=}2.515517$ $d_1 = 1.432788$ $C_1 = 0.802853$ $d_2 = 0.189269$ $C_2 = 0.010328$ $d_3 = 0.00130$

The cumulative probability was then transformed in to standard random variable, Z being described as the SPI values for each of the precipitation events of desired time scale.

The drought magnitude was also derived from SPI values already obtained through the equation:

$$\mathrm{DM} = -\left(\sum_{j-1}^{K} \mathrm{SPI}_{ij}\right)) \tag{21}$$

Where DM is the drought magnitude for the desired time scale.

This study gave a due attention to analyze the drought events and magnitude only for one month time scale analysis which is practically important for agricultural resources characterization.

3 Results and discussions

3.1 Onset, end and length of the growing period

The analysis results revealed that the main rainy season (Kiremt) starts during the second meteorological decade of June (decade 17/ second decade of June) and the

rainy season ends during the last decade of September ,decade 27 (Table 2). The mean starting decade of the main growing season, Kiremt, had low standard deviation amounting to 6 days (Table 2) and hence the onset date of the season is promisingly stable (Reddy, 1990). The lower standard deviation of the onset date of the season implies that patterns could be easily understood and consequently decisions pertaining to crop planting and related activities could be made more easily and with less risk. The general characteristics of the onset of the identified growing period for the main rainy season are presented in the Table 3.

The length of growing period (LGP) in the main rainy season in the district ranges from 112 to 144 days with a mean of 129 days and with CV and SD of 7.5% and 9.6 days, respectively (Fig. 1). The period includes the duration of the time that 100mm of soil moisture reserve has already been evapotranspired after the end of the rainy season (FAO, 1978 and Mersha, 2005). The deviation magnitude of the LGP obtained in the study could not be regarded as high because the length of growing period even with minimum length is fairly enough to support the cereal crops (Teff and Wheat) which are commonly grown in the areas of the district that require not far more than 100 days of growing period to their maturity.

Moreover, most of decades of the main growing season were observed to have a precipitation depth sufficiently higher than the threshold value of the crop water requirements (0.5*ETo) and the result pinpoints that moisture limitation is not the limiting factor for crop production in this particular season (Fig. 2).

Unlike the main rainy season, the mean onset decade of this particular season (decade no. 9) had a standard deviation of 1.5 decades i.e., 15 days on average (Table 4). The occurrence of the Belg growing season as a whole is less frequent (Table 5). Surprisingly, the same table showed that the Belg season failed to occur in 30% of the study period.

The results in the above tables imply that the onset of the growing season in the shorter rainy season is uncertain and subsequently planning of agricultural practices related to crop management is difficult for making decisions. In addition, the precipitation depth is observed to be much lower than the threshold of the crop water requirements of the study area. Hence a substantial amount of precipitation deficit is experienced during this particular season (Fig. 3). The result substantiates that rainfall water is critically a limiting factor and one can draw a conclusion that the season needs to be out of the major activities of crop production, like planting.

However, the moisture during this period could be used to facilitate land preparation activities for early planting in the main rainy season. Consequently, planting could be carried out earlier during the start of the season and the probable loss of moisture for the land preparation activity during Kiremt could be minimized.

3.2 Dry and Wet Spell analysis and drought assessment

3.2.1 Dry and wet spell analysis

The probability of a decade being wet in the Kiremt was found to be greater than 40% throughout the meteorological decades with the exception of decade number 16 and 17, which gave a corresponding probability, value of 21% each (Table 6). The probability of getting a wet decade after wet in the study watershed during the main rainy season was also found to be in the range of 14–100% with most of the meteorological decades skewed to the maximum. In general, the Kiremt season is having well above the threshold limit for most of the years during the study period. Therefore, crop harvesting during the same season is less likely affected by moisture stress.

But the probability of getting a wet decade during this season was found to be in the range of 15 to 30% (Table 7) throughout the meteorological decade. The same table also showed that high probability of occurrence of dry spells was observed in the season throughout the meteorological decades (greater than 70% in all decades), as expected. Consequently, one can infer from these figures that the particular season is getting below the threshold minimum requirement of rainfall and hence planting during Belg season is less likely.

To sum it up, the chance of having wet spell duration of at least 2 decades in a growing season is above 40% and similarly the probability of occurrences of dry decades for greater than a length three decades is very minimum, 19% (Table 8). But belg season is likely to have more than 55% dry decades of a length of three decades.

3.2.2 Standardized precipitation index analysis (SPI)

Based on a one month time scale of SPI analysis, no extreme drought events were detected in the months of the main growing season (Table 9). But two sever drought events were experienced each in June and August while one was observed in July. Overall, the district experienced more occurrences of drought events with equal magnitude in August and September (17) followed by July (13) and the least was in June, amounting 12.

Similarly, the highest drought magnitude of 3.41 was recorded in the year 1995 followed by 1996 (3.28) and 1982 (3.28) as clearly stated in Fig. 2 below.

Results of this analysis indicated that there was only one extreme drought event (in March, 1998) during the short rainy season (Belg) based on one-month time scale. Three dry events were recorded each for March and May and two were in April. Mild drought events were experienced in about 23% of all months of March and April during the 30 years of record. Maximum mild drought events of 26.7% were experienced in the month of May. In general drought events are not uncommon during the months of this particular season. Drought events ranging from mild to extreme and or severe categories (SPI<0) were experienced in about 43.3% of the months of March and April while the same category of drought events were detected in about 46.7 % of the months of May (Table 10).

Further more, the highest drought magnitude was observed in 1993 (4.23) followed by the years: 1992 (2.99) and 1996 (2.92) (Fig. 5). However, the highest intensity was recorded in the year 1985 having an amount of 1.85 while the year with highest drought magnitude had only 1.41. This difference is explicitly ascribed to the fact that the drought in year 1993 occurred on a longer period while the same appeared on a very short time span in 1985 (Fig. 3).

4 Conclusions

It can be noted from this study that planning of agricultural activities is fairly simple and involves less risks in and around the study area during the main rainy season because of the stability of the onset dates of the main rainy season and occurrences of the sufficient amount of the wet spell. However, it was found that the variability of length of growing period in Belg (the shorter rainy season) season is extremely high (CV=121%) implying difficulties associated with its prediction and frequent occurrences of dry spells and drought events. More over the shorter rainy season, Belg is liable to drought and its impacts. Hence crop production during this particular period needs a due attention and monitoring of planted crops. Therefore a considerable attention of maximizing crop harvest during the main rainy season is practically important. In general a kind of analysis work is extremely helpful for decision making in agricultural operation and related activities especially at a watershed scale. Therefore this work needs to be promoted in a similar fashion across the country.

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Table 1. Classification of SPI values and corresponding probability of occurrences.

SPI classes	Probability	Period classification
SPI< −2	0.0228	Extremely dry
−2<SPI< −1.54	0.0441	Severely dry
−1.5<SPI< −1	0.0918	Moderately dry
−1<SPI< 1	0.6827	Near normal
1<SPI<1.5	0.0918	Moderately wet

Table 2. Summary of the onset date of the main growing season.

Mean onset decade no	SD (in decade)	CV (%)	Frequency (%)	Stability of the onset
17	0.62	3.6	58.6	Very high

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Table 3. Characteristics of the Kiremt growing period in the watershed.

Characteristic	Decade no
Earliest onset	16
Mean onset	17
Delayed onset	18
Earliest recession of the rainy season	26
Mean recession of the rainy season	27
Delayed recession of the rainy season	28

Table 4. The onset characteristics of the Belg growing season.

Mean onset	SD	CV	Frequency of mean onset (%)
9	1.5	17	18.8

Table 5. The occurrence distribution of the onset of Belg season.

Dekade no	7	8	9	10	11	12	With no occurrence of Belg
Number of occurrences	5	3	6	2	2	1	10
Percentage of occurrences	15.15	9.09	18.18	6.06	6.06	3.03	30.30

Table 6. (1975–2007)

Decade No	Pw	PD	Pww	PDD	PWD	PDW
16	21	79	14	92	8	86
17	21	79	57	88	12	43
18	42	58	29	89	11	71
19	64	36	52	75	25	48
20	88	12	69	25	75	31
21	88	12	66	0	100	34
22	91	9	87	0	100	13
23	94	6	90	0	100	10
24	94	6	100	0	100	0
25	88	12	100	0	100	0
26	61	39	90	8	92	10
27	52	48	53	56	44	47

Table 7. Dry-wet spell probability distribution of Belg based on the Markov Chain model (1975–2007).

Dekade No	Pw	PD	Pww	PDD	PWD	PDW
9	30	70	30	87	13	70
10	30	70	60	78	22	40
11	30	70	50	74	26	50
12	18	82	33	67	33	67
13	18	82	17	74	26	83
14	21	79	14	81	19	86
15	15	85	20	75	25	80

Table 8. Dry-wet spell duration distribution in the two seasons.

	Probability of wet sequences at least				Probability of dry
k	2	3	5	7	spell > 3 dek
Bega	0.13	0.048	0.0062	0.00082	0.58
Kiremt	0.43	0.28	0.12	0.01524	0.19

Table 9. Frequency of occurrences of drought events during Kiremt.

	Months			
Drought Category	June	July	August	September
Extremely dry	0	0	0	0
Severely dry	2	1	2	0
Moderately dry	3	4	3	5
Mildly dry	7	8	12	12
Total	12	13	17	17

Table 10. Frequency of drought severity during the Belg growing season.

	Months		
Drought class	March	April	May
Extremely dry	1	0	0
Severely dry	3	2	3
Moderately dry	2	4	3
Mild	7	7	8
Total	13	13	14

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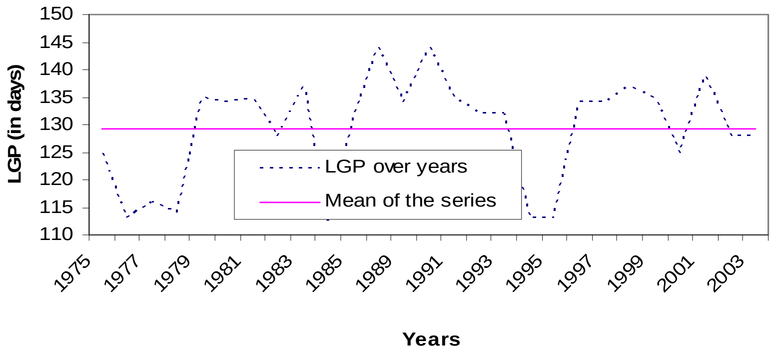

Fig. 1. Length of the growing season in the district across years (Mean 129 SD 6.2 CV 7.5%).

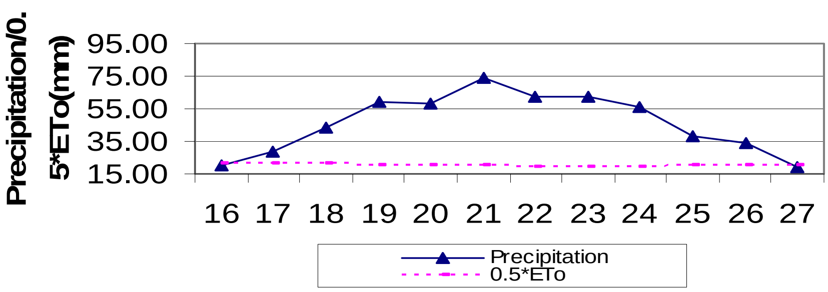

Fig. 2. Average Precipitation and the threshold crop water requirements (0.5*ETo) in Kirem.

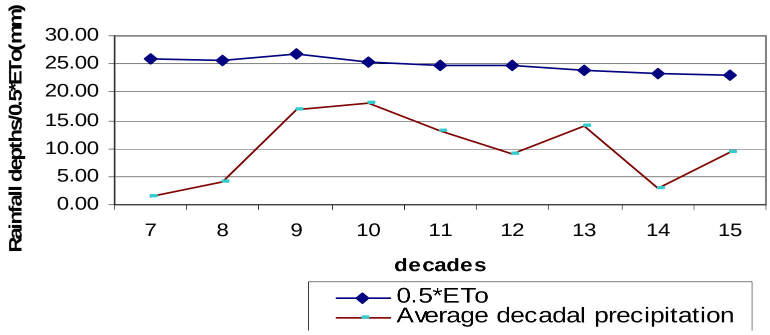

Fig. 3. Average Precipitation and the threshold crop water requirements (0.5*ETo) in Belg season.

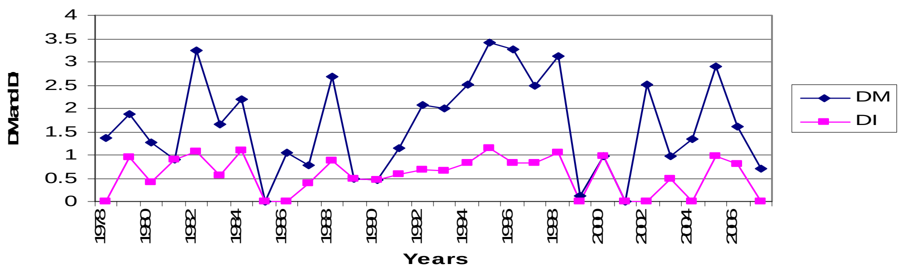

Fig. 4. Drought magnitude (DM) and intensity in the main rainy season (Kiremt).

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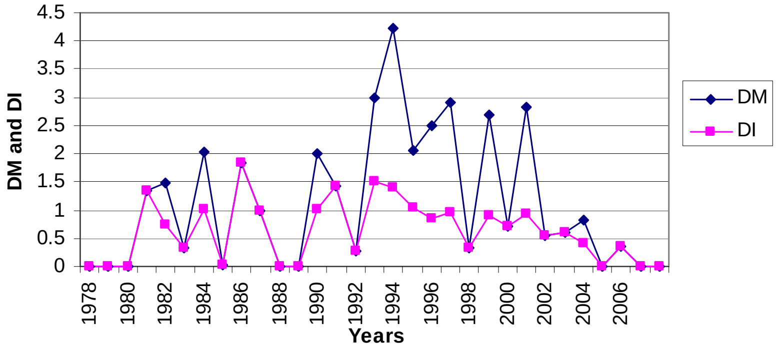

Fig. 5. Drought magnitude (DM) and intensity (DI) in the shorter rainy season.