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Paper:

Bayissa, Y., Moges, S., Xuan, Y., Van Andel, S., Maskey, S., Solomatine, D., Griensven, A. & Tadesse, T. (2015). Spatio-temporal assessment of meteorological drought under the influence of varying record length: the case of Upper Blue Nile Basin, Ethiopia. *Hydrological Sciences Journal*, 1-16.

http://dx.doi.org/10.1080/02626667.2015.1032291

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Spatio-temporal assessment of meteorological drought under the influence of varying record length: the case of Upper Blue Nile Basin, Ethiopia

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Abstract This study investigates the spatial and temporal variation of meteorological droughts in the Upper Blue Nile (UBN) basin in Ethiopia using longer historical records (1953 to 2009) of 14 meteorological stations, and 23 other stations with relatively shorter records (1975 to 2009). The influence of using varying record length on drought category was studied by comparing the Standard Precipitation Index (SPI) results from the 14 stations with long record length, by taking out incrementally one year record from 1953 to 1975.These analyses show that the record length from 1953 to 1975 has limited effect on changing the drought category and hence the record length from 1975 to 2009 could be used for drought analysis in the UBN basin. The spatio-temporal analyses of the SPI values show that throughout the UBN basin seasonal or annual meteorological drought episodes occurred in the years 1978/79, 1984/85, 1994/95 and 2003/04. Persistency from seasonal to annual drought, and from one year to the next, has been found. The drought-years identified by this SPI analysis for the UBN basin, are known for their devastating impact in other parts of Ethiopia.

Keywords: SPI; UBN; meteorological drought; Influence of data length

INTRODUCTION

Drought is a natural hazard characterized by a significant decrease of water availability during a prolonged period of time over a large area. It occurs in different parts of the world and may cause substantial impact on economic activities, human lives, and various elements of the environment (Dracup *et al*. 1980, Bryant *et al*. 1992, Keyantash and Dracup 2002, Barua and Perera 2011). In Ethiopia, drought is a frequently recurring phenomenon often accompanied by very serious and diversified impacts on human lives and environment (Tagel *et al*. 2011). The historic drought events show frequent occurrences of severe drought and famine in Ethiopia (Tagel *et al*. 2011). In the past few centuries, more than 30 major drought episodes have occurred, of which 13 were severe and covered the entire country and affected several nations (Tagel *et al*. 2011). Some studies show that the frequency of drought occurrence in Ethiopia has been increasing over the last decade (Edossa *et al*. 2009, Tagel *et al*. 2011). Since 1970, severe drought has hit Ethiopia every ten years on average with an increasing frequency in recent years. For instance, Margaret (2003) found that drought in Ethiopia now occurs every two to three years.

Drought in the year 1984/85 caused a million people to lose their life, destroyed crops and livestock, and forced millions of people into displacement and destitution (Tagel *et al*. 2011). More specific figures from recent drought episodes in Ethiopia illustrate the magnitude of drought associated impacts. For example, the drought of 2003 led to the worst famine since mid-1980s which affected 13.5 million people (Wagaw *et al*. 2005) and caused large devastation interms of life and economical losses. Thus, drought management has become an important issue in the drought prone parts of Ethiopia in order to reduce the adverse effects of drought hazards and potential disasters through drought prevention and mitigation measures as well as preparedness. Thus far, few drought studies have been conducted on the drought management using the historic time series of hydro-meteorological variables at a local level (e.g., zones or basins) in Ethiopia (Ramakrishna and Assefa 2002, Edossa *et al*. 2009, Araya *et al*. 2010, Tagel *et al*. 2011). More specific studies need to be conducted to better describe and characterize drought and to associate its characteristics with temporal and spatial variability of rainfall at a local level (e.g. at sub-basin level).

The Upper Blue Nile (UBN) contributes one of the largest of runoff portions (48.5 billion m^3 per year) to the Nile flow (Conway 2000). The UBN basin considered less prone to drought because of the large amount of rainfall it receives annually and its location on the highlands of Ethiopia where evaporation losses are minimal. Although not documented, north-eastern and some pocket areas towards the central part of the basin are historically associated with drought

(Conway 2000). This study assesses the spatial and temporal characteristics of meteorological drought in the Upper Blue Nile Basin. The study first investigates whether climate records with shorter-length affect the assessment of drought events interms of drought categories (e.g. moderate, severe, extreme drought), before making use of all available observations to assess the spatial and temporal distributions of drought over the UBN basin. Long-term monthly rainfall data has been a prerequisite for carrying out drought analysis and modelling for many studies. While the presumption is widely followed, there has been a lack of studies on the effect of data length, which in fact hampers researchers from using records with shorter length.

The standard precipitation index (SPI) was used to study the effect of the length of records and to characterize drought in the UBN basin. The SPI is a probability index that uses monthly rainfall data as input. It has been demonstrated to perform better in comparing drought across different regions (Guttman 1998). The SPI also gives better spatial standardization than other drought indices such as Palmer Drought Severity index (PDSI) on analyzing extreme drought event (Sönmez *et al*. 2005). The SPI has been widely applied and tested in many watersheds. However, very few studies have been conducted in different parts of Ethiopia to analyze drought using SPI. Edossa *et al*. (2009) reported the temporal and spatial analysis of meteorological and hydrological droughts for the Awash basin of Ethiopia applying SPI for the assessment of meteorological drought using monthly rainfall data from 1963 to 2003. The study showed the potential benefits of SPI for drought assessment and examined the lag time between the hydrological and meteorological droughts. Tagel *et al*. (2011) evaluated the spatial and temporal variability of drought using SPI and vegetation condition index (VCI) for the Tigray Zone located in the high lands of Ethiopia. The Tigray Zone is proximal to the UBN basin and located in the Northern part of Ethiopia. The study demonstrated that the large part of the study area is prone to drought. Further, the results showed a time lag between the period of the peak of vegetation condition index (VCI) and precipitation values (Tagel *et al*. 2011). Cancelliere *et al*. (2007) used stochastic techniques for seasonal forecasting of SPI and showed the importance of SPI for drought assessment and forecasting. Bonaccorso *et al*. (2003) analyzed drought for Sicily Island using SPI and showed that the entire Island is characterized by drought variability with a multi-year fluctuation and a tendency towards drier periods from the 70s onward. Generally, many studies have been conducted using SPI in different part of the world for drought assessment and forecasting (Guttman 1998, Yamoah *et al*. 2000, Cancelliere *et al*. 2007, Livada and Assimakopoulos 2007, Patel *et al*. 2007, Wu *et al*. 2007, Khan *et al*. 2008, Li *et al*. 2008). However, testing the effect of data length and incorporating the findings on the spatio-temporal assessment of drought using SPI in Ethiopia has not yet been considered. The overall objective of this study is to analyse and assess the spatio-temporal variation of drought in the UBN basin, Ethiopia, using the SPI. Moreover, this study analyses the effect of the length of rainfall time series data used on drought assessment with the aim to validate the use of large number of stations with relatively shorter data record to investigate drought characteristics of the UBN basin.

STUDY AREA

The Ethiopian part of Blue Nile also known as the Abbay Basin in Ethiopia is located in the north-western region of the country between 7^{o} 40’ N and 12^{o} 51’ N latitudes, and 34^{o} 25’ E and 39^{o} 49’ E longitudes (Fig. 1). The Upper Blue Nile basin ranks as the largest river basin of the country by its volume of discharge and the second by its area (Yilma and Awulachew 2009). It is also the largest tributary of the Nile River (60% of the Nile total flow) and covering a total drainage area of 176,000 km^2 (Conway 2000). The basin is the most important water resource for

Ethiopia, Sudan and Egypt. The topography of the UBN basin signifies two distinct features: the highlands with rugged mountainous areas in the central and eastern part of the basin, and the lowlands in the western part of the basin. The altitude in the basin ranges from 490m in the lowlands up to 4261m in the highlands. Whilst the highlands are the main source of water, the lowlands have expanses of flat lands through which the accumulated flow travel from the highlands to the lower riparian countries. The annual rainfall ranges from 787 mm to 2200 mm with the highlands having the highest rainfall ranging from 1500 to 2200 mm and the lowlands receiving less than 1500 mm (Conway 1997, Kebede *et al*. 2006, Yilma and Awulachew 2009).

Data

The monthly rainfall recorded by local meteorological stations was the basis upon which the SPI and drought categories were calculated. The rainfall records of 45 stations were collected on monthly time step from the national meteorological service agency of Ethiopia. Most of these stations are located inside and nearby the UBN basin. However, few of the other stations used in this study are located in different watersheds that have distinct agro-climatic zones. These supplementary stations were used to study the effect of data length on the drought category. The years covered by the records of each station range from 1953 to 2009. While some stations cover the whole period, others start from the 1970s. Regardless of the data length, the quality of the rainfall record needs to be assured prior to applying the data in any drought study. The double mass curve technique was applied to check the consistency and homogeneity of each station. The annual rainfall data for each of the 45 stations was first cumulated in chronological order. The pattern of the mean of the cumulative rainfall is then used to test individual station records. The cumulative rainfall of each station was plotted against the mean of the cumulative rainfall. A break in the slope of the plot indicates a change in the precipitation regime. This criterion was used in this study to select the meteorological stations considered for the spatio-temporal assessments of drought. The double mass curve produced for Debremarkos station (Fig 3) demonstrates the consistency of the rainfall record. The plot shows the consistent record of rainfall data in this station and a break in slope was not observed throughout the record length. Similar procedure was applied for the other stations and similar results were obtained. The results from the data quality assessment led to the choice of 37 rainfall stations data for further use. There were a maximum of four years of missing data in some of the selected stations. No techniques were applied to fill the gaps. Instead the missing data was omitted during the SPI calculation.

In this study, two distinctive groups of meteorological stations supplied the monthly rainfall data. The first group includes 14 meteorological stations with relatively long records (i.e., over 50 years), located in different parts of the country and different rainfall regions. This group of stations were used to test the effect of data length on drought category. The second group comprises a total of 29 stations located inside and in a close proximity to the UBN basin. Out of the 29 stations, six stations had longer data length and also were used in the first group. The other 23 stations had a shorter data record (i.e., 35 years, from 1975 to 2009). The second group of the stations was used to study the spatial and temporal assessment of drought in the UBN basin.

In the first group, most of the meteorological stations have monthly rainfall data and the data recording began in the early 1950's, with two exceptions (Mekelle and Debreziet) where recording started in1960. Debremarkos and Gondar stations are located inside the basin whereas the rest of the other stations are located outside the UBN basin boundary (Fig. 2).

The analysis of the spatial and temporal assessment of droughts was made with the second group of 29 stations with monthly rainfall data from 1975 to 2009. As shown in (Fig. 2) most of these stations are located within the UBN basin, except five stations that are located just outside of the basin. Although there are many meteorological data recording stations in the basin, getting long term data records was one of the main challenges that prompted for the necessity of this study.

STANDARD PRECIPITATION INDEX (SPI)

The effect of the record length on the drought category and the spatial and temporal assessment of droughts were performed using SPI. This index utilizes the current and historic rainfall data to compute its value which is proportional to the deviation from the long term average rainfall. The computation employs fitting the probability density function to the frequency distribution of precipitation summed over the period of interest in this case from 1970 to 2009 (Khan *et al*. 2008, Moreira *et al*. 2008, Tagel *et al*. 2011). This was performed separately for each month and for each location. Each probability density function was then transformed into the standardized normal distribution. Thus, the SPI is said to be normalized in location and time. The conversion of cumulative probability to the standard normal random variable employs fitting the curves for all stations at all time scales and for each year. This process can be cumbersome and the SPI value is more easily computed using an approximation method suggested by Abramowitz and Stegun (1965) as shown in equation 7 and 8. Once standardized, the values of the anomaly of the SPI are categorized based on McKee *et al.* (1993) classification as shown in Table1.

The SPI calculation involves the selection of a probability distribution function (PDF) that fits best with the Belg, Kiremt and Annual rainfall of each meteorological station. The commonly used statistical probability distributions such as Normal, Gamma, Log-Pearson and

Weibull were tested for each station in the study area. We presented the detail calculation procedure of Gamma distribution below and the detail of the other models can be referred on the following literatures (Abtew *et al.* 2009; Hanson and Vogel 2008; Sharma and Singh 2010). Each model was then fitted to the Belg, Kiremt and Annual rainfall and the goodness of fit of each model was evaluated using Kolmolgorov-Smirnov test, Anderson Darling test and Chi-squared test (χ2) (Sharma and Singh 2010). We used the EasyFit software to fit the probability distribution functions to the rainfall data for each of the stations. Overall, the gamma distribution fitted the rainfall record well in the majority of the stations and hence the gamma distribution has been selected in this study to assess the drought.

The gamma distribution is defined by its frequency or probability density function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{\frac{-x}{\beta}} \qquad 1$$

Where $\alpha > 0$ is the shape parameter, $\beta > 0$ is a scale parameter and $x > 0$ is the amount of precipitation. $\Gamma(\alpha)$ defines the gamma functions.

Fitting the distribution to the data requires $\alpha \, and \, \beta$ to be estimated using the approximation of Thom for maximum likelihood as stated in Edwards and McKee, (1997) as follows

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \qquad 2$$

Where, for n observations

$$A = \ell n\left(\bar{x}\right) - \frac{\sum \ln(x)}{n} \qquad 3$$

$$\hat{B} = \frac{\bar{x}}{\hat{\alpha}} \qquad 4$$

G(x) = Cumulative probability excluding probability of zero precipitation

$$G(x) = \int_{o}^{x} g(x)dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\,\Gamma(\alpha)} \int_{0}^{x} x^{\alpha} e^{\frac{-x}{\beta^\wedge}} dx \qquad 5$$

H(x) = Cumulative Probability including probability of zero precipitation

$$= q + (1-q)\,G(x) \qquad 6$$

q= is the probability of zero precipitation where gamma distribution becomes undefined

For X=0 and q = p (x=0) (probability of zero precipitation is simply the number of observations of zero precipitation divided by the total number of observations).

To convert cumulative probability to the standard normal random variable Z:

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \qquad for\; 0 < H(x) \le 0.5 \qquad 7$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \qquad for\; 0.5 < H(x) \le 1 \qquad 8$$

where: $$t = \sqrt{\ln\left(\frac{1}{(H(X))^2}\right)} \qquad for\; 0 < H(x) \le 0.5 \qquad 9$$

$$t = \sqrt{\ln\left(\frac{1}{(1 - H(X))^2}\right)} \qquad for\; 0.5 < H(x) \le 1 \qquad 10$$

$c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$

EXPERIMENTS

The SPI values were computed for two time-scales i.e. three month (SPI-3) and 12 months or annual (SPI-12). The SPI-3 was used to assess drought during Belg (February - April) and Kiremt (June - August) seasons, which represent the two rainy seasons in Ethiopia and SPI-12 was used to assess the annual drought. In assessing the effect of data length on drought category, two data withholding procedures were applied. The procedure followed in the first data withholding experiment was that one additional year of data was taken out starting from 1953 and then SPI values were calculated accordingly. The data withdrawing started from 1953 and was repeated up to the year 1975 where most of the other stations started recording. Then, the SPI values for a particular drought year between 1975 and 2009 were checked whether or not the values indicate the same drought category. As cross-validation of the results of the first experiment, in the second procedure the one year of data was withdrawn one by one starting from the middle of the data record (from 1970 to 1988).

Since drought is a regional phenomenon, the point-based SPI time series values of each meteorological station have been interpolated using the inverse distance weighted (IDW) method to assess the spatial extent of drought in the basin. The inverse distance weighted method gives better representation for interpolation of rainfall distribution over heterogeneous topographic terrain (Tagel *et al*. 2011). In order to identify the area most frequently struck by drought, the frequency of occurrences of drought was computed by taking the ratio of the number of drought years to the total number of years used in the analysis. The frequency of occurrence of drought was also spatially interpolated using inverse distance weighting.

RESULTS AND DISCUSSIONS

Effect of record length on drought analysis

Overall, all stations showed that the SPI values are within the same drought categories irrespective of the length of records (Figs. 4 to 7). The results of Debremarkos (Fig. 4b), Hossana (Fig. 5h) and Welaita Sodo (Fig. 7n) give consistent SPI values (no clear trends or abrupt changes). The SPI drought categories computed from data records starting from 1953 and data records starting from 1975, therefore, remained the same. The results for Addis Ababa (Fig. 4a), Gondar (Fig. 4c), and Jimma (Fig. 4d) demonstrate that most of the data series (SPI values) remained in the same drought category. Three exceptional SPI values were found falling out of the range of severe drought category at Gondar (Fig. 4c) and Jimma (Fig. 4d) for data length of 45 and 46 years. Compared with the total number of drought events considered, the impacts of these exceptions are thought to be negligible. An increasing trend within the drought category was observed at Gore (Fig 5g) for the first data withdrawing procedure (discussed in the method section), but not to the extent that the drought category changed.

In the cross-validation procedure, the second data withdrawing experiment discussed in the method section, for meteorological stations located in the UBN basin as well as in other parts of Ethiopia, results also did not show any sensitivity of the SPI index to the data length. Only in Kebridhar station (Fig 6j), increasing trends of SPI values were observed, however all the values observed fall in the same drought category.

These analyses show that the record length from 1953 to 1975 has limited effect on changing the drought category and hence the record length from 1975 to 2009 can be used for drought analysis in UBN.

Temporal assessment of drought

Based upon the findings from the first analysis on the influence of data length, the use of more stations with shorter data records in the study area was justified. Thus, the second group that includes all the 29 meteorological stations was used to study drought characteristics using the SPI.

Figure 8 illustrates the time series values of SPI for two selected stations (Gondar and Debremarkos). Both stations are located inside the UBN basin (Fig. 2).

Belg season

As shown from the time series of the SPI for the Belg season (short rainy season from February to April) in Debremarkos (Fig. 8a) and Gondar (Fig. 8b) stations, moderate drought episodes were indicated for the years 1965, 1978 and 1985 in Debremarkos station; 1977 and 1998 in Gondar station. Severe drought occurred in the years 1954, 1971 and 1999 in Debremarkos station; 1970, 1974, 1984 and 1994 in Gondar station. Extreme drought episodes were also indicated in the years 1984 and 1998 in Debremarkos station; 1968 and 1983 in Gondar station. The drought episodes in the Belg season show multi-year persistency at most stations, although severity often changed from year to year. The moderate, severe and extreme droughts were followed or preceded by mild drought episodes. Although the mild drought episodes represented below the long term mean, its impact is much less and closer to the normal condition. For this reason the mild drought episodes were not presented in the temporal assessment of drought in the UBN basin.

The occurrences of moderate, severe, or extreme drought episodes in the Belg season, in some year manifested at the annual time scale as well. However, the impact of the Belg droughts on the annual droughts were not one to one, which means that severe drought in the Belg season might be mild on the annual time scale and vice versa. Moderate drought was the dominant drought category in most of the meteorological stations for the Belg season. Severe drought was the next predominant drought category in most of the stations and it appeared even more frequent than moderate drought during the Belg season for some stations.

Kiremt season

Referring to figures 8a and 8b, moderate drought episodes in Kiremt season (main rain season from July to September) were observed in the years 1963, 1977, 1978, 1984 and 1986 at

Debremarkos station; 1966, 1971, 1983 and 1987 at Gondar station. Severe drought occurred in the year 1954 and 1992 at Debremarkos station and 1981, 1982 and 1997 at Gondar station. Extreme drought occurred in the year 1987 and 2005 in Debremarkos station; 2009 in Gondar station. The minimum SPI value was detected on the year 2009 (-2.59) at Gondar station. Similar to the Belg season, the Kiremt season droughts also appeared to be persistent with varying severity at most stations. For instance, five years persistent droughts have been occurred at Gondar station during Kiremt season from the year 1981 to 1985, with the severity decreasing from -1.58 to -0.32. The occurrence of Kiremt drought is found to be a precursor of the drought occurring at the annual time scale in the majority of the stations. However, the severity varies, which means moderate or severe or extreme droughts in Kiremt season might be in most cases mild drought at the annual time scale and vice versa. Moderate droughts are the most dominant category in Kiremt season.

The analysis of the two rainy seasons, Belg and Kiremt, shows that droughts can occur in both seasons.

Annual droughts

The drought years in the annual time scale have been identified in figures 8a and 8b. Moderate annual droughts have been observed in 1973, 1982, 1987 and 1995 at Debremarkos station; 1968, 1983, 1990 and 1992 at Gondar station. Severe drought was observed in 1965, 1978, 1986 and 2005 at Debremarkos station; 1970 at Gondar station. Extreme drought occurred in 1991 at Debremarkos station; 1982 and 1991 at Gondar station. Moderate droughts are the most dominant drought category at the annual time-scale.

Overall the temporal SPI analysis shows that most of the 29 stations measured severe, moderate and mild drought episodes in the years 1978/79, 1984/85, 1994/95 and 2003/04. Indeed these years were among the worst drought years in the history of Ethiopia (Edossa *et al*. 2009, Tagel *et al*. 2011). Several studies confirm that severe droughts have occurred in these years and caused substantial damage in terms of life and economical losses and covered the entire country (Wagaw *et al*. 2005, Tagel *et al*. 2011).

Trend analysis of drought occurrence

A statistical test was conducted to check whether a trend exists or not in the SPI time series of the stations using the Mann-Kendall (Yue *et al*. 2002, Hamed 2008) method. The result shows that a negative slope (trend) was observed in both stations for the three SPI time-scales, however, the trend was statistically insignificant at 95% confidence level. This shows that there is no statistical evidence of any positive or negative trend of meteorological drought severity and frequency for the study area. Although the trends at all time-scales were statistically insignificant, a relatively strong trend of increasing frequency was observed during Kiremt season with the average value of regression coefficient (R) greater than 23%. It is, therefore, recommended to regularly re-check if this increasing trend becomes significant in a later stage. It is important to note that Kiremt is the main rainy season in Ethiopia from which agricultural production is highly dependent.

Areal extent of drought

The spatial coverage of drought over the UBN basin was obtained using the Thiessen Polygon method. The resulting areal extent was expressed as the percentage of the basin in drought conditions. The drought area percentages were calculated for all SPI time-scales, however, only the result for Kiremt and annual time-scales are presented in figures 9a and 9b for further discussion.

The areal extent of annual droughts (Fig. 9a) shows that more than 40% of the area was struck or impacted by mild droughts in 1982, 1987, 1997, 2002, and 2003. The years of 1982 and 2003 could be marked as critical as 63% and 56% of the entire study area was struck by mild drought. In 1984, 1985, 1986 and 1995, the 12-month SPI values indicated 15% of the total area under moderate or more severe droughts. The year 1995 was considered as a critical year as the areas of moderate and severe drought reached up to 26% and 28% respectively. This analysis of spatial extent of droughts in the UBN basin shows, with over 25% of the area having been hit by moderate, severe, or extreme droughts, that substantial parts of the basin are drought-prone.

Spatio-temporal analysis to assess the spatial variability of drought frequency

Drought frequency in the UBN basin of Ethiopia was investigated using SPI for Kiremt, Belg, and annual time-scales for each meteorological station. Frequency of occurrence of each drought category was computed for each station at each time-scale by taking the ratio of the number of occurrence of particular drought of a particular category and time-scale to the total number of data years (Edossa *et al*. 2009). The main objective of this analysis was to identify the areas that are most frequently struck by drought. Figure 10a shows that the relative frequency of mild drought in Kiremt time-scale was high in the south-west, central and the north to north-east of the UBN basin. The annual frequency of mild drought also shows most frequent mild droughts occurred over the south-western part of the UBN basin. Relatively large prevalence of moderate drought occurred in central towards south and northeast part of the study area for Kiremt and Annual time-scales (Fig. 10b). The map with frequency of occurrence of the severe droughts at annual time-scale shows that a large part of the study area was free from severe droughts. The North and North-west parts, however, do show severe droughts during Kiremt time-scale (Fig. 10c). The frequency of occurrence of extreme droughts (Fig. 10d) further shows that the central and the northern parts of the study area are struck more frequently by extreme droughts for Kiremt and annual time-scales.

From the analysis above it is clear that the maps of drought frequency show differences for the time-scales and severity considered. A conclusion on which sub-areas of the basin are more prone to droughts is difficult to make. Therefore, the drought frequency was also calculated for the mild, moderate, severe, and extreme drought categories together. The resulting drought frequency maps for annual and Kiremt time-scales are shown in Fig. 11. For the Kiremt time-scale (Fig. 11a) the only clear pattern is that in the eastern parts of the basin drought-frequencies are lower. For the annual time-scale (Fig. 11b) high drought frequencies (50%) were observed in the south, central and west. It can be concluded that in the UBN basin the central, south, and western parts are the most drought-prone, while the North and East are less drought-prone. The conclusion needs, however, to be taken with care, because patterns are not very distinct and may be influenced by the limited coverage of rainfall stations in the north-west and north-east parts.

CONCLUSION

The spatial extent and distribution of drought frequency in the UBN basin was analysed by interpolating the station SPI values across the study area. For assessing the impact, the spatial analysis of drought severity and frequency of the SPI needs to be coupled with information that assimilates evaporation and/or soil moisture and land use to characterize hydrological and agricultural drought. This needs further research that is beyond the scope of this study.

The methodology employed to test the influence of record length on SPI index proved successful in validating the use of a large number of additional stations with shorter data record for the UBN basin. The findings of this study may help other researchers and practitioners who have faced similar challenges of insufficient data length by checking the effect of data length for their drought study using SPI.

The trend analysis of the SPI index from 1953 to 2009 showed no conclusive evidence that meteorological drought in the Upper Blue Nile is increasing or declining. SPI droughts occurred throughout the basin. Persistency from seasonal to annual drought, and from one year to the next, has been found. The temporal analysis showed that the historical drought years in the area (1978/79, 1984/85, 1994/95 and 2003/04) were successfully captured using SPI index. Therefore, the SPI index can be used as an important index to identify the historical drought patterns in the UBN basin, which could help in predicting drought. Further, a study needs to be conducted to test the procedure employed in this research for other basins and/or the entire country of Ethiopia, emphasizing areas most frequently hit by severe droughts.

Acknowledgements

This research constitutes part of the doctoral study of the first author and was partly funded by Nuffic, the Netherlands. The authors are indebted to the National Meteorological Agency (NMA) of Ethiopia for providing historical monthly rainfall data.

References

Abramowitz, M., and Stegun, I.A., 1965. Handbook of mathematical functions. *Dover New York*.

Abtew, W., Melesse, A.M., and Dessalegne, T., 2009. Spatial, inter and intra-annual variability of the Upper Blue Nile Basin rainfall. *Hydrological processes*, v. 23, p. 3075-3082.

Araya, A., Habtu, S., Haile, M., Sisay, F., and Dejenie, T., 2010. Determination of Local Barley (Hordeum Vulgare) Crop Coefficient and Comparative Assessment of Water Productivity for Crops Grown Under the Present Pond Water in Tigray, Northern Ethiopia.

Barua, S., Ng, A., and Perera, B., 2011. Comparative Evaluation of Drought Indexes: Case Study on the Yarra River Catchment in Australia. *Journal of Water Resources Planning and Management*, v. 137, p. 215-226.

Bonaccorso, B., Bordi, I., Cancelliere, A., Rossi, G., and Sutera, A., 2003. Spatial variability of drought: an analysis of the SPI in Sicily. *Water resources management*, v. 17, p. 273-296.

Bryant, S., Arnell, N., and Law, F., 1992. The long-term context for the current hydrological drought.

Cancelliere, A., Mauro, G.D., Bonaccorso, B., and Rossi, G., 2007. Drought forecasting using the standardized precipitation index. *Water resources management*, v. 21, p. 801-819.

Conway, D., 1997. A water balance model of the Upper Blue Nile in Ethiopia. *Hydrological sciences journal*, v. 42, p. 265-286.

—, 2000. The climate and hydrology of the Upper Blue Nile River. *Geographical Journal*, v. 166, p. 49-62.

Dracup, J.A., Lee, K.S., and Paulson Jr, E.G., 1980. On the definition of droughts. *Water Resources Research*, v. 16, p. 297-302.

Edossa, D.C., Babel, M.S., and Gupta, A.D., 2009. Drought analysis in the Awash River Basin, Ethiopia. *Water resour manage*, v. 24, p. 1441-1460.

Edwards, D., and McKee, T., 1997. Characteristics of 20th century drought in the United States at multiple scale. *Atmospheric Science Paper* No, 634, v. May 1-30.

Guttman, N.B., 1998. Comparing the Palmer drought index and the standardized precipitation index. INDEX1. *JAWRA Journal of the American Water Resources Association*, v. 34, p. 113-121.

Hamed, K.H., 2008. Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis. *Journal of Hydrology*, v. 349, p. 350-363.

Hanson, L.S., and Vogel, R., 2008. The probability distribution of daily rainfall in the United States. *Conference proceeding paper*, World Environmental and Water Resources Congress.

Kebede, S., Travi, Y., Alemayehu, T., and Marc, V., 2006. Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. *Journal of Hydrology*, v. 316, p. 233-247.

Keyantash, J., and Dracup, J.A., 2002. The quantification of drought: An evaluation of drought indices. *Bulletin of the American Meteorological Society*, v. 83, p. 1167-1180.

Khan, S., Gabriel, H., and Rana, T., 2008. Standard precipitation index to track drought and assess impact of rainfall on watertables in irrigation areas. *Irrigation and Drainage Systems*, v. 22, p. 159-177.

Li, W., Fu, R., Juárez, R.I.N., and Fernandes, K., 2008. Observed change of the standardized precipitation index, its potential cause and implications to future climate change in the Amazon region. *Philosophical Transactions of the Royal Society B: Biological Sciences*, v. 363, p. 1767.

Livada, I., and Assimakopoulos, V., 2007. Spatial and temporal analysis of drought in Greece using the Standardized Precipitation Index (SPI). *Theoretical and applied climatology*, v. 89, p. 143-153.

Margaret, K.E., 2003. Planning for the Next Drought: Ethiopia Case Study. USAID, Washington.

McKee, T.B., Doesken, N.J., and Kleist, J., 1993. The relationship of drought frequency and duration to time scales. *In Proceedings of the 8th Conference of Applied Climatology*, 17-22 January, Anaheim, CA. American Meterological Society, Boston, MA. 179-184.

—, 1995. Drought monitoring with multiple time scales, In Proceedings of the 9th Conference of Applied Climatology, 15-20 January, Dallas TX. *American Meteorological Society*, Boston, MA. p. 233–236.

Moreira, E.E., Coelho, C.A., Paulo, A.A., Pereira, L.S., and Mexia, J.T., 2008. SPI-based drought category prediction using loglinear models. *Journal of Hydrology*, v. 354, p. 116-130.

Patel, N., Chopra, P., and Dadhwal, V., 2007. Analyzing spatial patterns of meteorological drought using standardized precipitation index. *Meteorological Applications*, v. 14, p. 329-336.

Ramakrishna, G., and Assefa, D., 2002. An emperical analysis of food insecurity in ethiopia, the case of North Wello. Afr. Dev, 27, 127-143.

Sharma, M.A., and Singh, J.B., 2010. Use of probability distribution in rainfall analysis. *New York Science Journal*, v. 3, p. 40-49.

Sönmez, F.K., Koemuescue, A.U., Erkan, A., and Turgu, E., 2005. An analysis of spatial and temporal dimension of drought vulnerability in Turkey using the standardized precipitation index. *Natural Hazards*, v. 35, p. 243-264.

Tagel, G., van der Veen, A., and Maathuis, B., 2011. Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. *International Journal of Applied Earth Observation and Geoinformation*, v. 13, p. 309-321.

Wagaw, M., Coleman, T.L., Tsegaye, T.D., and Tadesse, W., 2005. GIS implementation to support poverty reduction policy and drought management in Ethiopia. *In Proceeding of the United Nations Economic Commission for Africa Committee for Development Information (UNECCODI) IV.* April 22-30. Addis Ababa, Ethiopia.

Wu, H., Svoboda, M.D., Hayes, M.J., Wilhite, D.A., and Wen, F., 2007. Appropriate application of the standardized precipitation index in arid locations and dry seasons. *International Journal of Climatology*, v. 27, p. 65-79.

Yamoah, C., Walters, D., Shapiro, C., Francis, C., and Hayes, M., 2000. Standardized precipitation index and nitrogen rate effects on crop yields and risk distribution in maize. *Agriculture, ecosystems & environment*, v. 80, p. 113-120.

Yilma, A.D., and Awulachew, S.B., 2009. Characterization and Atlas of the Blue Nile Basins and its sub-basins.

Yue, S., Pilon, P., and Cavadias, G., 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology*, v. 259, p. 254-271.

LIST OF TABLES

Table 1. SPI values that shows the different categories of drought severity.

SPI Values	Drought category
−2.00 and less	Extreme drought
−1.50 to -1.99	Severe drought
−1.00 to -1.49	Moderate drought
0 to -0.99	Near normal or mild drought
Above 0	No drought

LIST OF FIGURES

Figure 1. Location map of the Upper Blue Nile Basin.

Figure 2. The double mass curve produced for Debremarkos station and used to demonstrate the consistency of the rainfall record.

Figure 3. The location map of the rainfall stations. Note: the stations represented by triangular shape and labelled their name were used to study the effect of the data length. Stations represented by rectangular shape were used to study the spatial variability of droughts.

Figure 4. Moderate (SPI: -1 to -1.5), severe (SPI: -1.5 to -2) and extreme (SPI: > -2) drought in Addis Ababa, Debremarks, Gondar and Jimma stations. Note: the number in the parenthesis in the legend section indicates the drought year. The roman number I and II in the parenthesis next to the name of each rainfall stations indicate the graphs obtained for data withdrawing from the beginning and from the middle respectively.

Figure 5. Moderate (SPI: -1 to -1.5), severe (SPI: -1.5 to -2) and extreme (SPI: > -2) drought in Debrezeit, Diredawa, Gore and Hossana stations. Note: the number in the parenthesis in the legend section indicates the drought year. The roman numbers I and II in the parenthesis next to the name of each rainfall stations indicate the graphs obtained from the data withdrawing from the beginning and from the middle respectively.

Figure 6. Moderate (SPI: -1 to -1.5), severe (SPI: -1.5 to -2) and extreme (SPI: > -2) drought in Kombolcha, Kebridhar, Mekelle and Nazaret stations. Note: the number in the parenthesis in the legend section indicates the drought year. The roman numbers I and II in the parenthesis next to the name of each rainfall stations indicate the graphs obtained from the data withdrawing from the beginning and from the middle respectively.

Figure 7. Moderate (SPI: -1 to -1.5), severe (SPI: -1.5 to -2) and extreme (SPI: > -2) drought in Negele and Welaita Sodo stations. Note: the number in the parenthesis in the legend section indicates the drought year. The roman numbers I and II in the parenthesis next to the name of each rainfall stations indicate the graphs obtained from the data withdrawing from the beginning and from the middle respectively.

Figure 8a. Standard precipitation index time series values of Debremarkos station.

Figure 8b. Standard precipitation index time series values of Gondar station.

Figure 9a. Areal extents of drought severity graph based upon 12 month SPI for September.

Figure 9b. Areal extents of drought severity graph based upon 3 month SPI for September.

Figure 10a. Frequency of occurrence of mild drought.

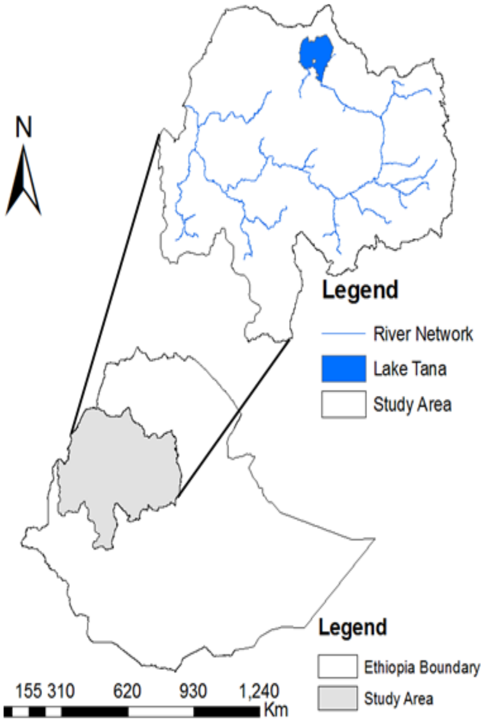
Figure 10b. Frequency of occurrence of moderate drought.

Figure 10c. Frequency of occurrence of severe drought.

Figure 10d. Frequency of occurrence of extreme drought.

Figure 11a. Frequency of occurrence of moderate, severe and extreme droughts in Kiremt time scale.

Figure 11b. Frequency of occurrence of moderate, severe and extreme droughts in annual time.



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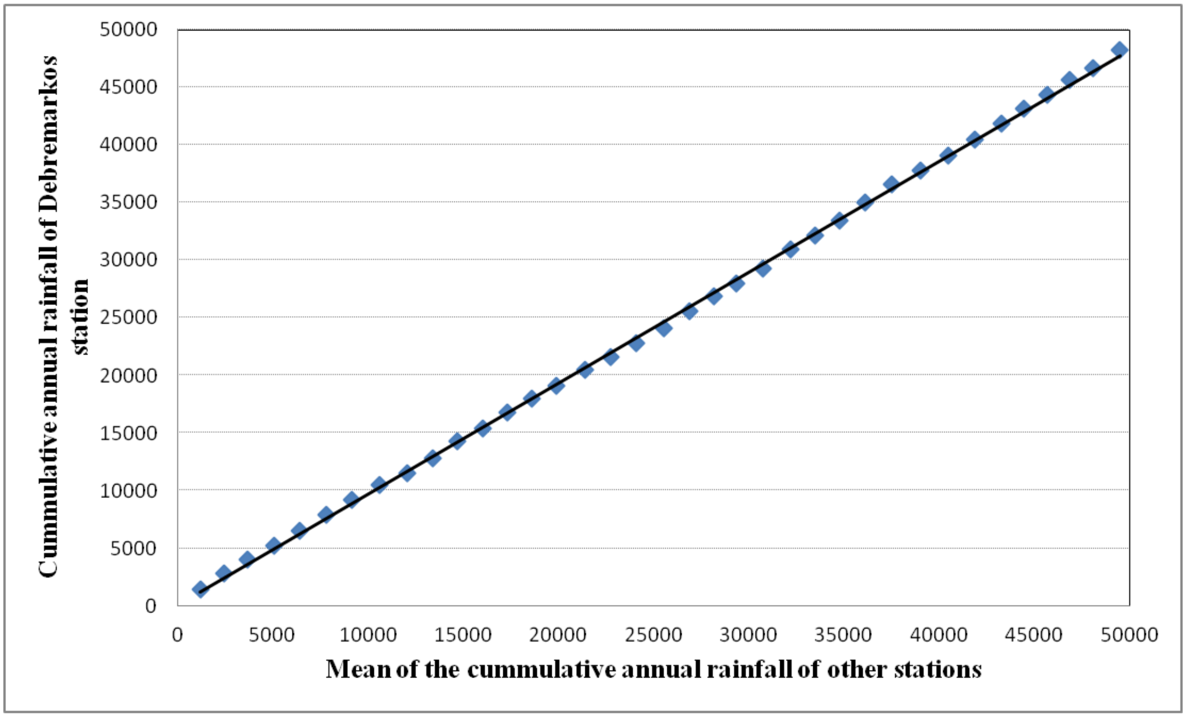

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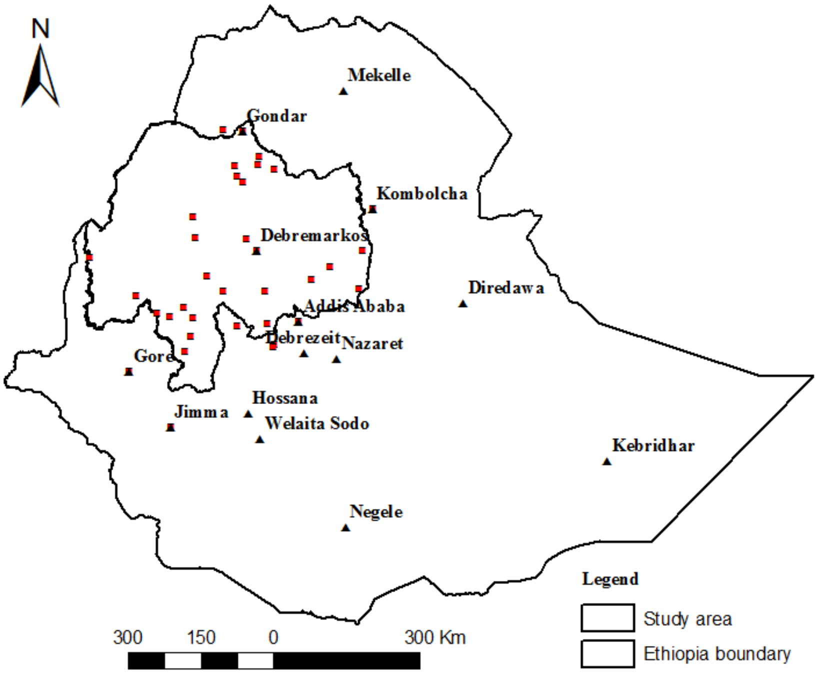

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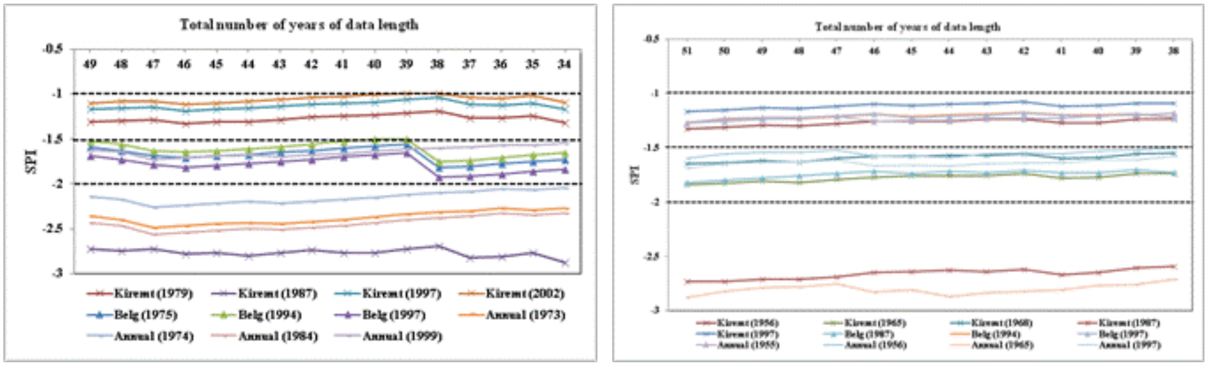
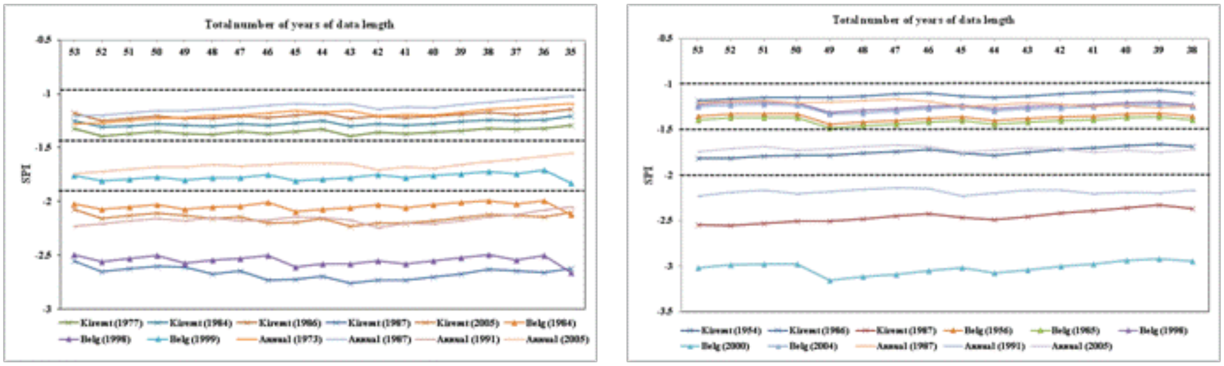


a. Addis Ababa (I)

a. Addis Ababa (II)



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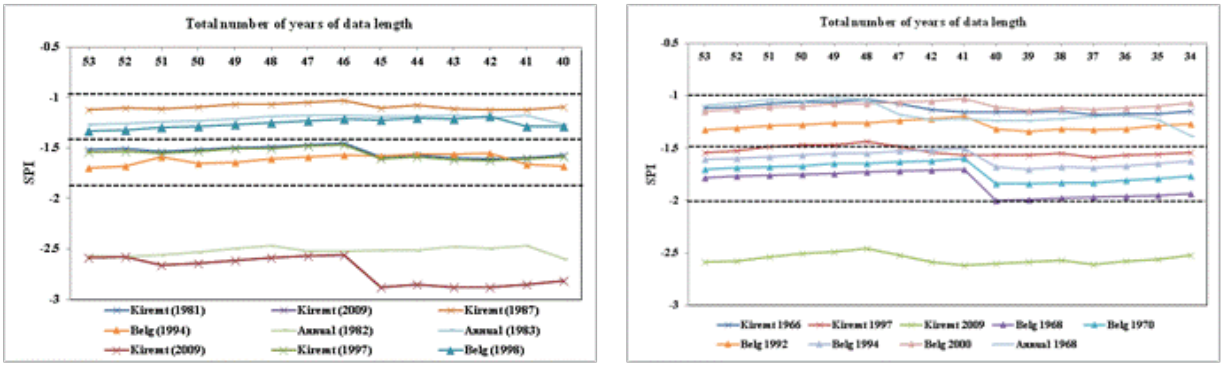
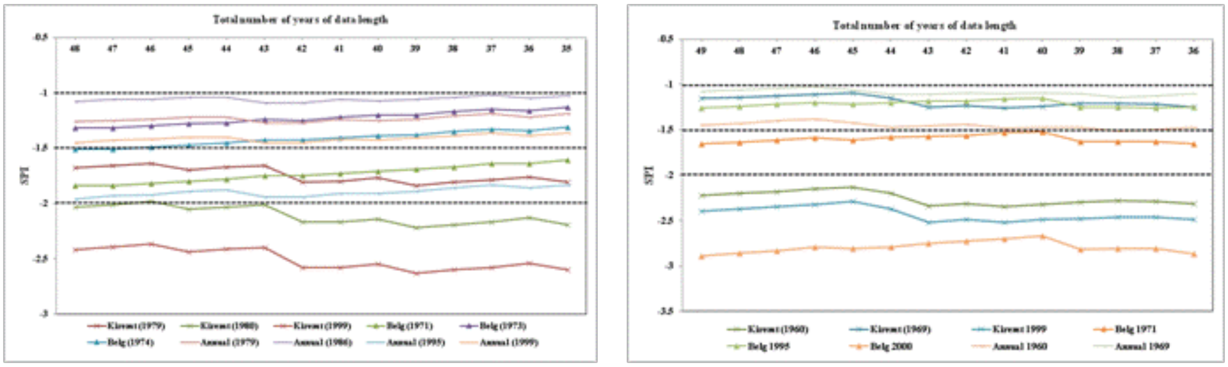
b. Debremarkos (II)



c. Gonder (I)

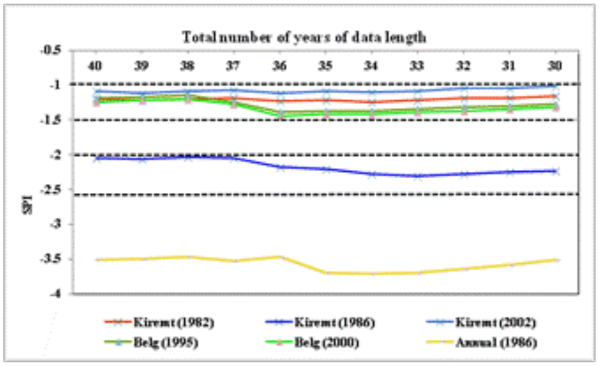
c. Gondar (II)



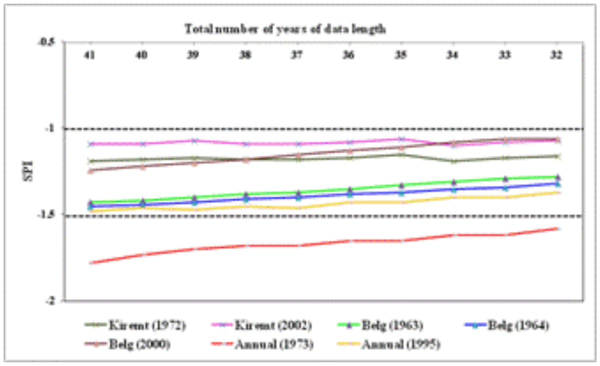
d. Jimma (I)

d. Jimma (II)

Figure 4. Moderate (SPI: -1 to -1.5), severe (SPI: -1.5 to -2) and extreme (SPI: > -2) drought in Addis Ababa, Debremarkos, Gondar and Jimma stations. Note: the number in the parenthesis in the legend section indicates the drought year. The roman number I and II in the parenthesis next to the name of each rainfall stations indicate the graphs obtained for data withdrawing from the beginning and from the middle respectively.



e. Debrezeit (I)



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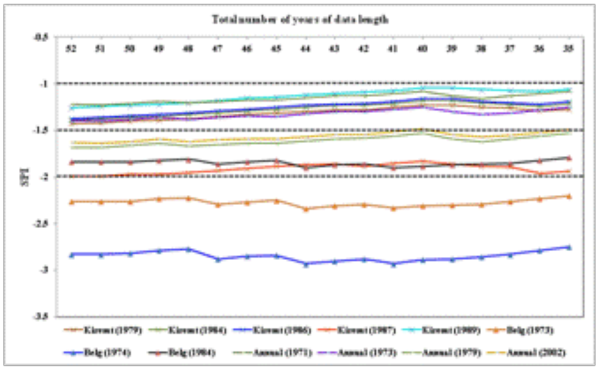

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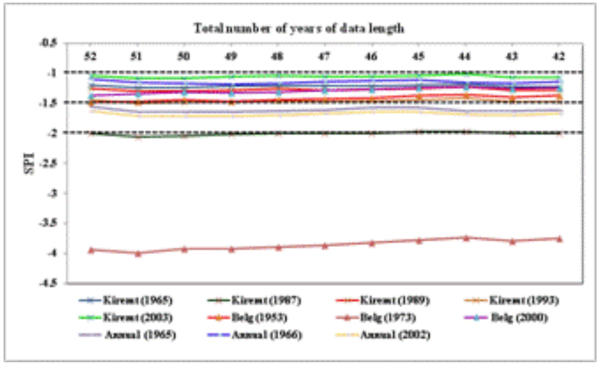
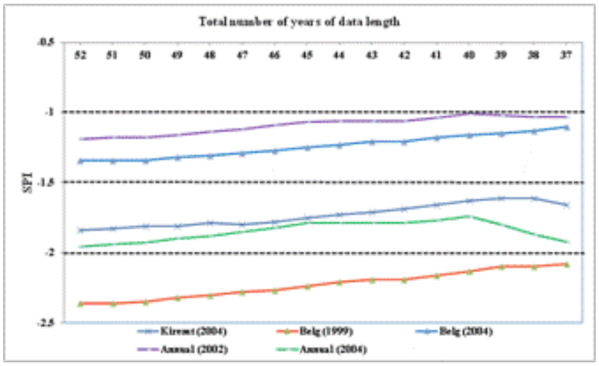


f. Diredawa (II)



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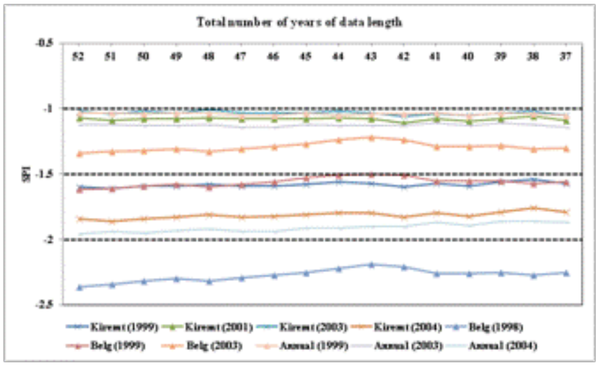

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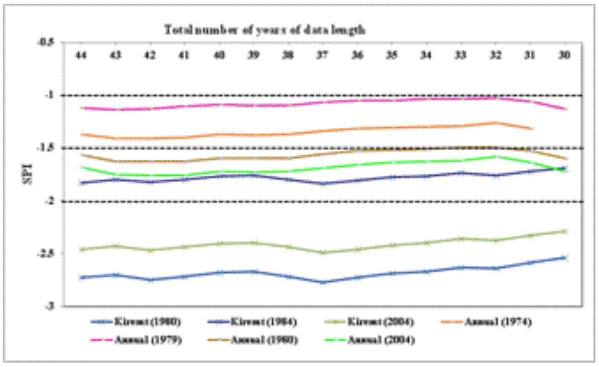
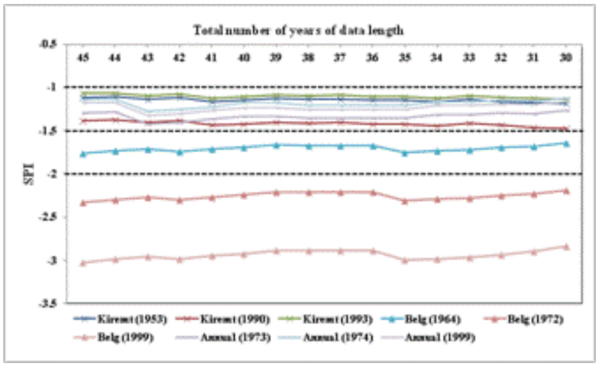
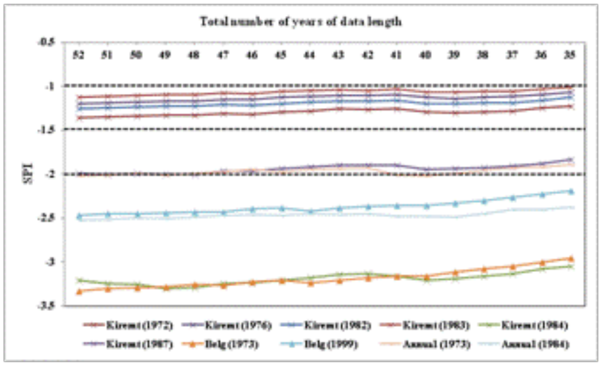


h. Hossana (I)

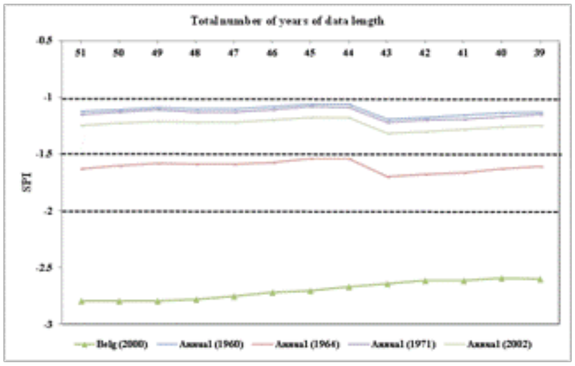


h. Hossana (II)

Figure 5. Moderate (SPI: -1 to -1.5), severe (SPI: -1.5 to -2) and extreme (SPI: > -2) drought in Debrezeit, Diredawa, Gore and Hossana stations. Note: the number in the parenthesis in the legend section indicates the drought year. The roman numbers I and II in the parenthesis next to the name of each rainfall stations indicate the graphs obtained from the data withdrawing from the beginning and from the middle respectively.



i. Kombolcha (I)



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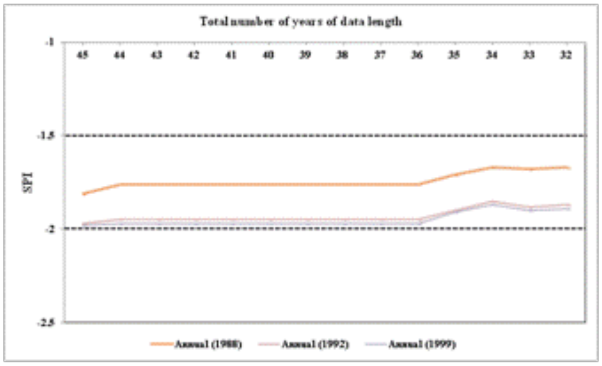
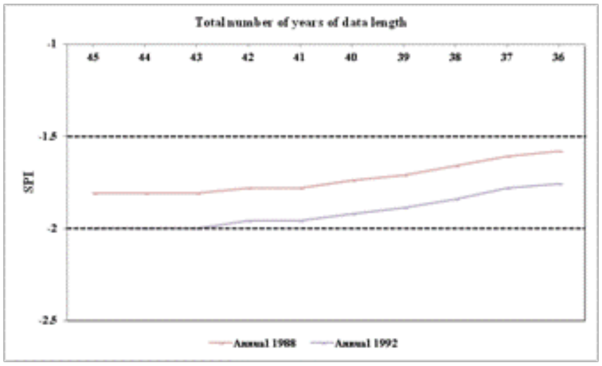
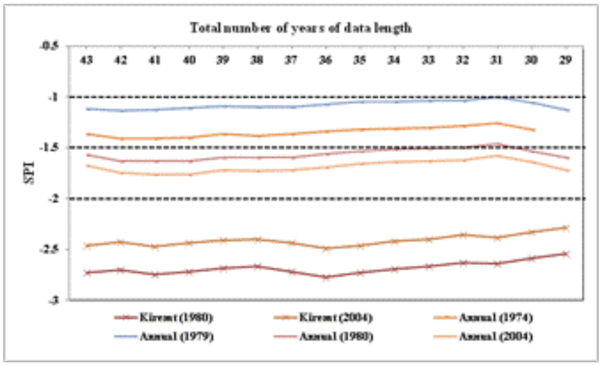


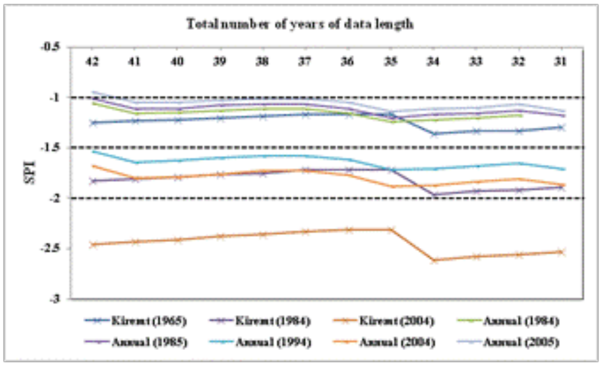
j. Kebridhar (I)



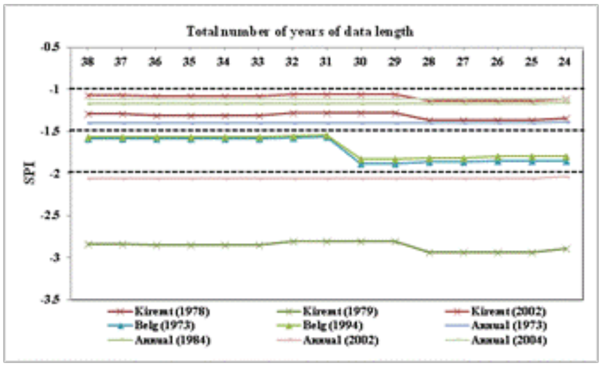
j. Kebridhar (II)



k. Mekelle (I)



k. Mekelle (II)



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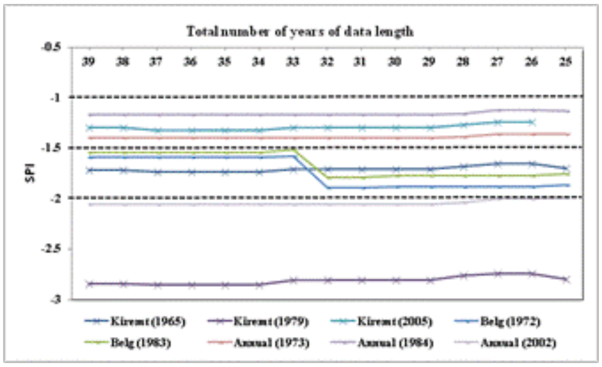

l. Nazaret (II)

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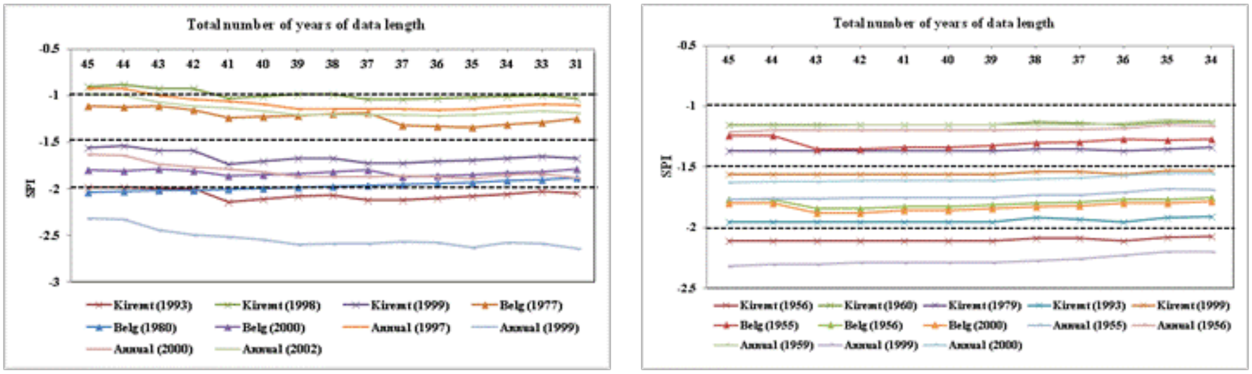
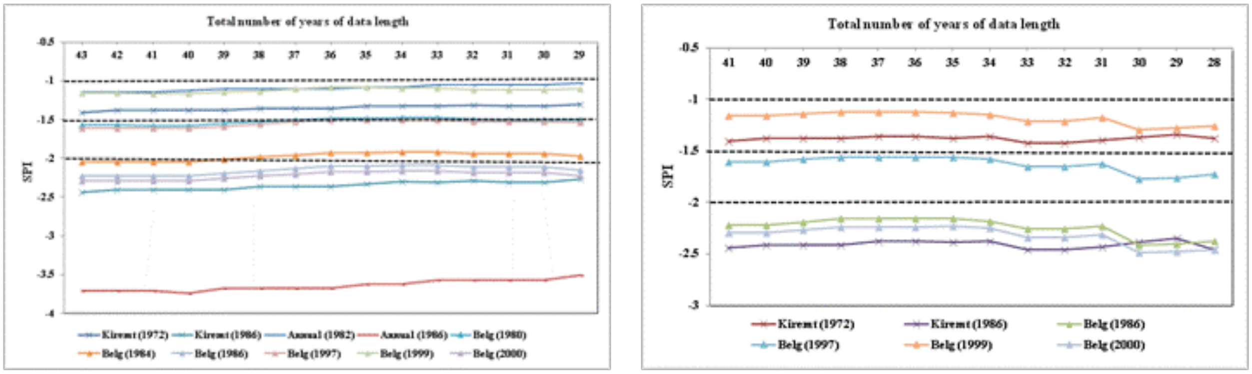


m. Negele (I)

m. Negele (II)



n. Welaita Sodo (I)

n. Welaita Sodo (II)

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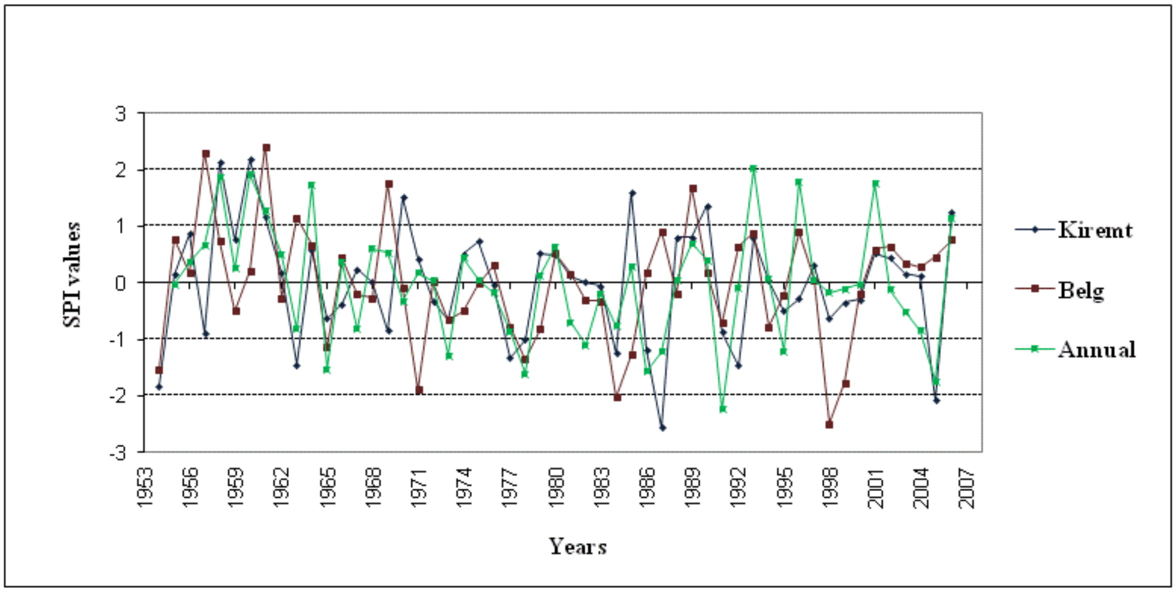

Figure 8a. Standard precipitation index time series values of Debremarkos station.

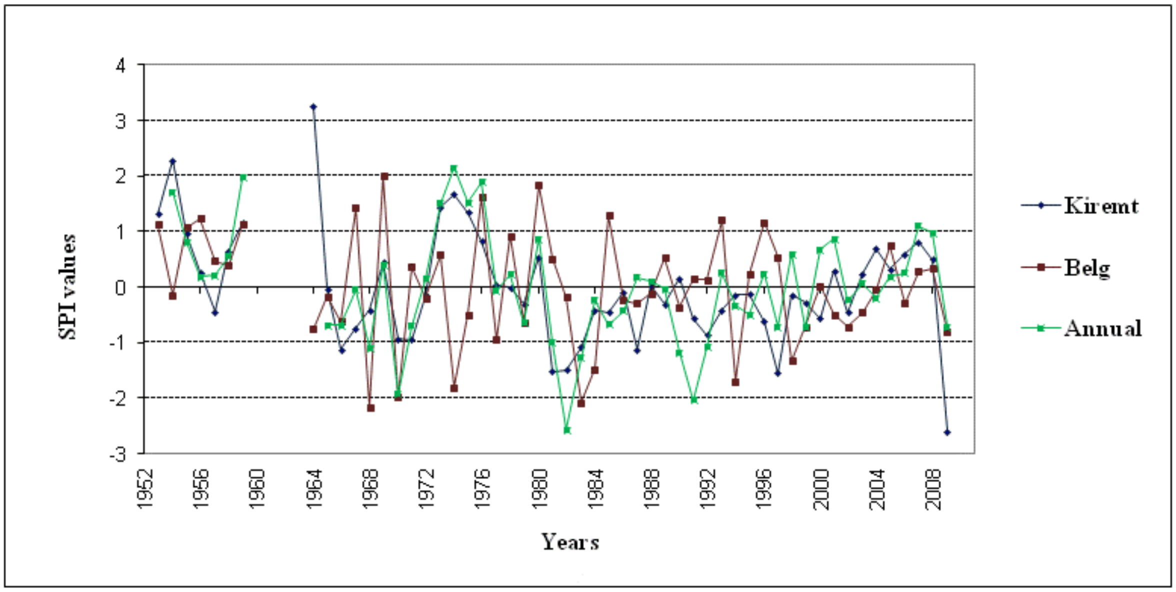

Figure 8b. Standard precipitation index time series values of Gondar station.

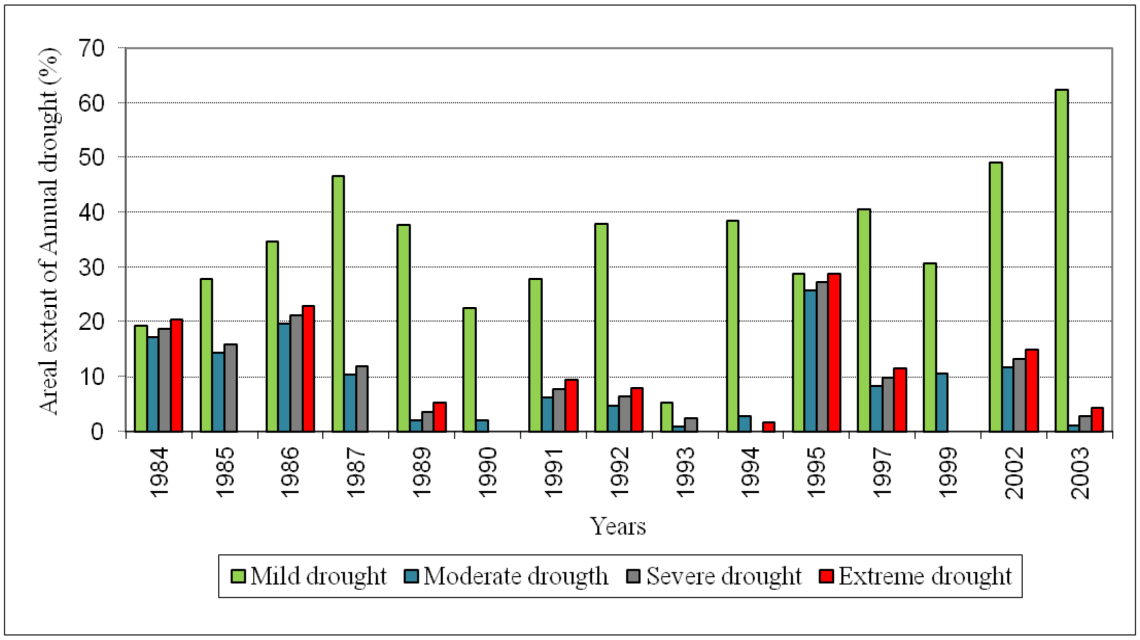

Figure 9a. Areal extents of annual drought severity graph based upon 12 month SPI for September.

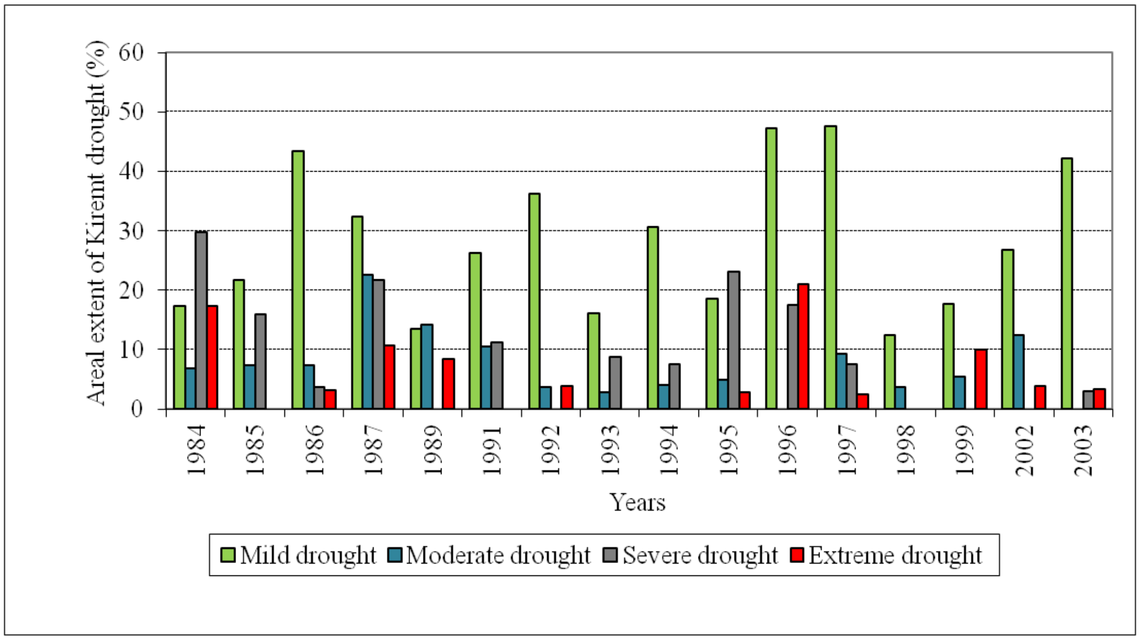

Figure 9b. Areal extents of Kiremt drought severity graph based upon 3 month SPI for September.

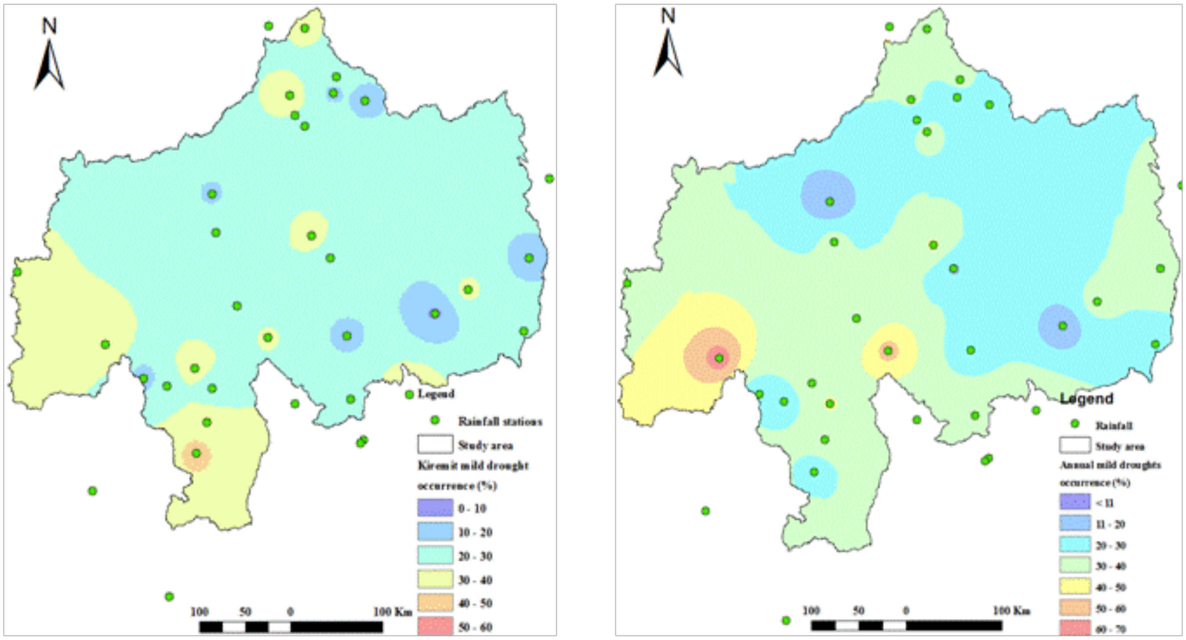

Figure 10a. Frequency of occurrence of mild drought.

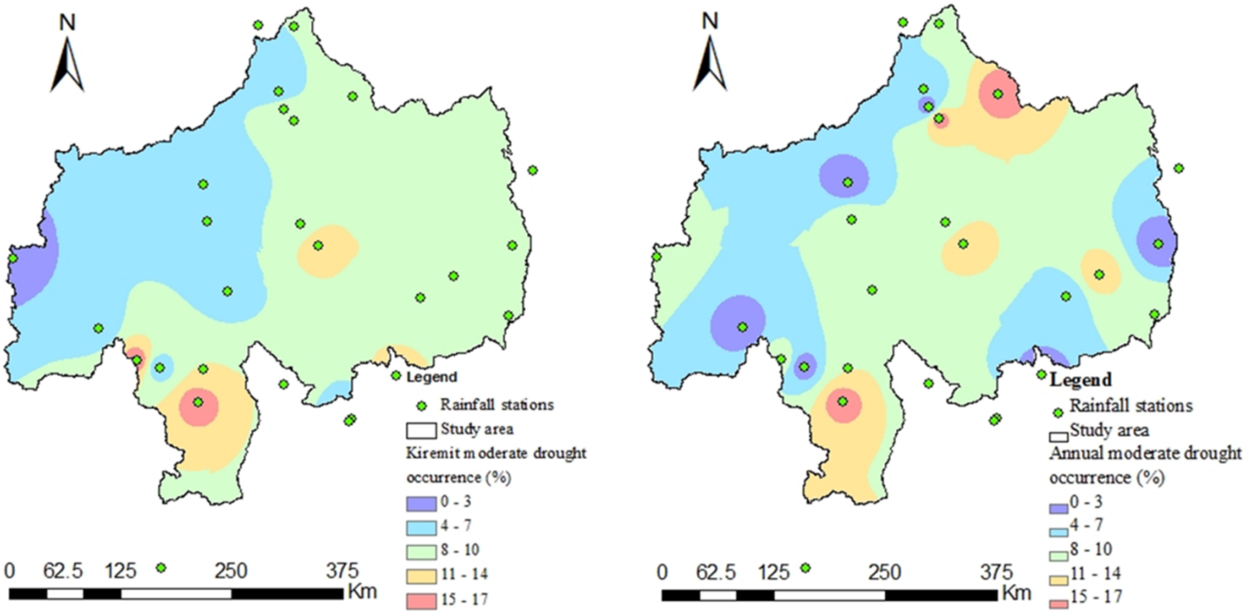

Figure 10b. Frequency of occurrence of moderate drought.

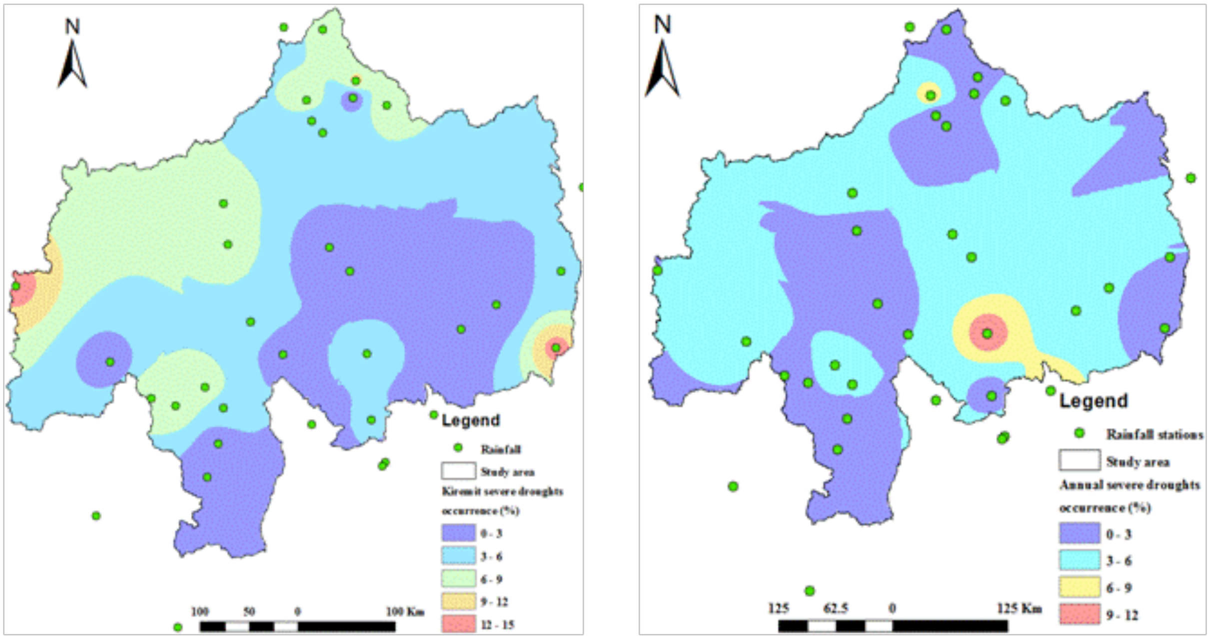

Figure 10c. Frequency of occurrence of severe drought.

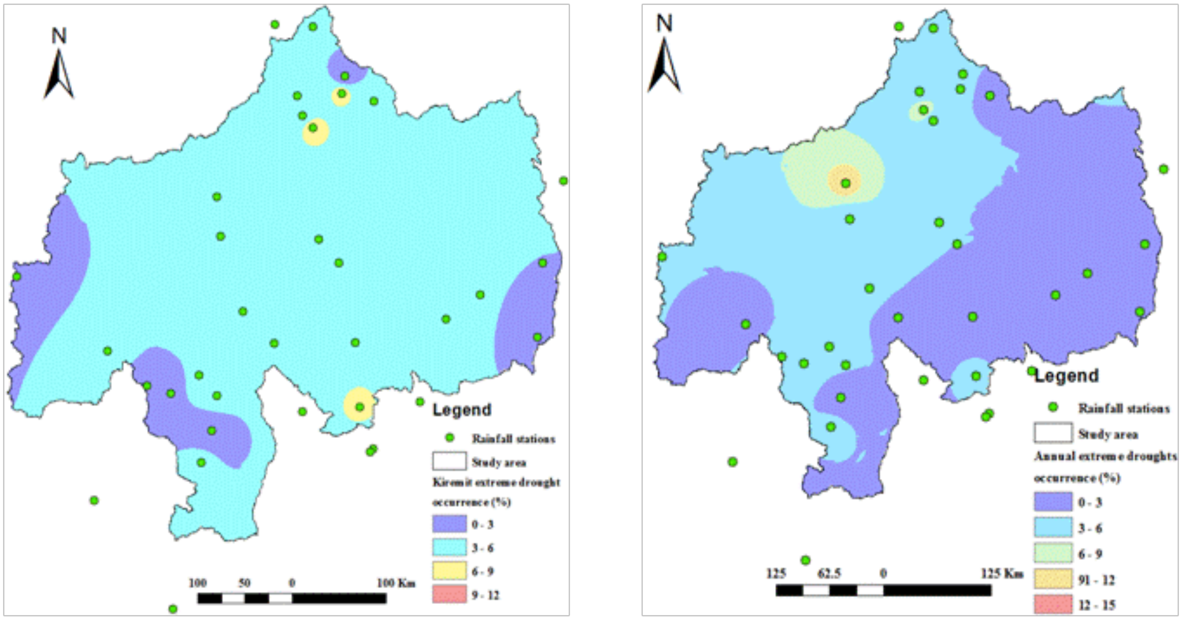

Figure 10d. Frequency of occurrence of extreme drought.

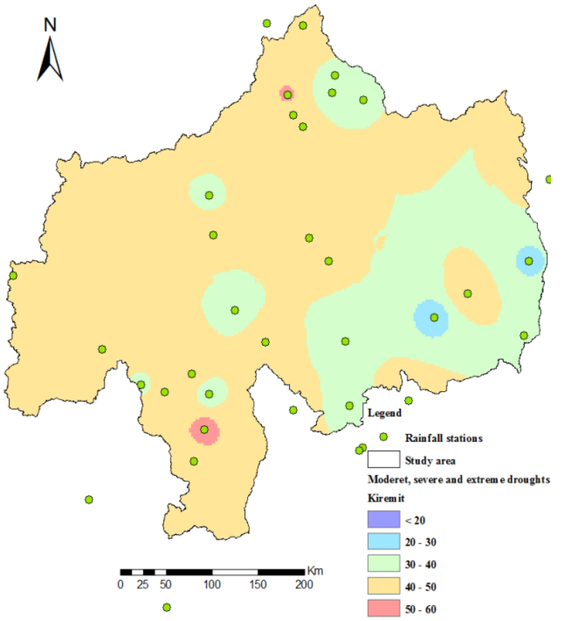

Figure 11a. Frequency of occurrence of mild,

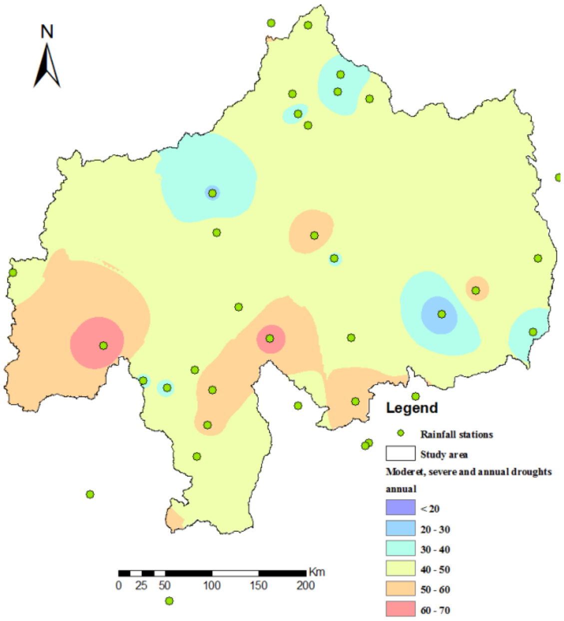

Figure 11b. Frequency of occurrence of mild,

moderate, severe and extreme droughts in Kiremt time scale.

moderate, severe and extreme droughts in annual time.