Sustainability in Environment
ISSN 2470-637X (Print) ISSN 2470-6388 (Online)
Vol. 7, No. 2, 2022
www.scholink.org/ojs/index.php/se

Original Paper

Hydrological Extremes and Their Association with ENSO Phases in Ethiopia

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Received: May 3, 2022 Accepted: May 27 2022 Online Published: June 1, 2022

doi:10.22158/se.v7n2p50 URL: http://dx.doi.org/10.22158/se.v7n2p50

Abstract

In this study, an attempt has been made to determine the occurrence of droughts and floods on monthly basis, by calculating the monthly Standardized Precipitation Index using the available rainfall data during (1975-2005) in Ethiopia.

Based on the monthly SPI values computed, the droughts and floods of different intensities; extreme, severe and dry have been determined for all stations. The frequencies of the droughts and floods during the two rainy seasons, Belg (Feb-May) and Kiremt (Jun-Sep) seasons have been determined. For instance, during Belg season, there were 11 extreme (SPI < -2.0) at Nazreth, 10 severe (SPI between -1.99 and -1.50) at Diredawa and 14 moderate (SPI between -1.49 and -1.00) droughts at Kulumsa. The total number of droughts of all intensities over the study period is also highest (22) at Kulumsa and lowest (8) at Mekelle. Moreover, at Kulumsa the numbers of droughts and floods during Belg are more, which shows that the rainfall variability is highest at this station.

The association of the hydrological extremes during the two rainy seasons, belg and kiremt with the ENSO phases has also been examined, which forms a basis for the prediction of the occurrence of droughts and floods at individual station using ENSO phases.

Keywords

drought, ENSO phase, flood, standard precipitation index

1. Introduction

Extreme rainfall events, floods, and droughts are hydrological extremes that occur virtually in all climatic regions; they are normal and recurring features of climate (Wilhite, 1993). They occur in both high and low rainfall areas. Drought is a temporary deviation, which is a permanent feature of the climate in contrast to aridity and is restricted to low rainfall areas while the flood is a permanent feature of the climate and restricted to high rainfall areas. A natural reduction in the amount of precipitation received over an extended period, usually, a season or more in length leads to drought. Drought is also related to the effectiveness of the rains (i.e., rainfall intensity, number of rainfall events) and timing (i.e., the principal season of occurrence, delays in the start of the rainy season, occurrence of rains with principal crop growth stages). Drought differs from other natural hazards in numerous ways. First, the onset and end of the drought are difficult to determine because the effects of drought often accumulate slowly over a considerable period and may linger for years after the event terminated. Because of this, drought is often referred to as a creeping phenomenon (Tannehill, 1947). Second, there is confusion about whether or not a drought exists and, if it does, its degree of severity due to the absence of a precise and universally accepted definition of drought.

Similarly, a flood is another natural hazard that causes human suffering, inconvenience and extensive damage to different assets such as crops, buildings, structures, and infrastructures. Floods have been observed to set back a nation's security & development by destroying roads, buildings, and other assets and disturb personal, economic & social activities. The recent major recorded flood disaster that still lingers in our mind is the (2006) flood in Ethiopia. During the 2006 flood in Ethiopia, the flooding occurred in almost all parts of the country. In the North, localities in Tigray and the northeast, Amhara region have been affected by emerging floods. In the south and east, the major flood damage was registered with the loss of a huge number of human and animal lives and loss of property. In the South, the Baro River was swelling to create a flood situation (Semu, 2007).

Droughts and floods may adversely affect the social, economic, cultural, political and other functions of a region. Predictions of drought and flood may prevent these adverse consequences to a significant extent. It is essential to develop a method of prediction based on the available past experiences as well as on environmental conditions to reach such a target.

Frequent and severe droughts are common in the Horn of Africa. A severe drought may be expected once every couple of years on average in this region. Although it is difficult to quantify, the impact of hydrological extremes like drought and flood on society and agriculture is a real issue. Reliable indices that can detect the spatial and temporal dimensions of hydrological extreme occurrences and their intensity are essential to assess the impact and also for decision-making and crop research priorities for mitigation (Seiler et al., 1998).

ElNino-Southern Oscillation (ENSO) was found to be one of the main factors that cause climate variability in Ethiopia (Bekele, 1997; Wolde-georgis et al., 2000). Now it is believed by many researchers that the physical processes related to the occurrence of ENSO events thousands of miles away lead to various droughts in Africa, especially in Southern Africa and the Horn. The availability of valid and reliable information about the linkages between these occurrences could help to forecast Sub-Saharan African droughts (Woldegiorgis et al., 2000). Empirical data show an association between droughts and ENSO events in Ethiopia. Therefore, if used effectively by policymakers, an ENSO-based early warning system could help to reduce the societal impacts of droughts and floods in Ethiopia

(Woldegiorgis et al., 2000).

It has been suggested that monitoring the Southern Oscillation Index (SOI), which is the atmospheric component of the ENSO phenomenon, could predict the hydrological extremes with a longer lead time. It has been observed that the SOI phase as determined by the change in average monthly SOI over the two previous months can give future seasonal rainfall probabilities more accurately than using SOI averages (Stone et al, 1996). Therefore, this study aims at determining the frequencies of droughts and floods at various rainfall stations in Ethiopia using the Standardized Precipitation Index (SPI) and examining their association with SOI phases within the historical record of rainfall data.

2. Materials and Methods

2.1 Data Used in the Study

Monthly rainfall datasets have been acquired from the National Meteorological Agency (NMA) for 31 years from1975-2005 for 26 stations spread across the country (Figure 1). Monthly rainfall for all these rain stations has been used to derive the Standardized Precipitation Index (SPI). For the other 5 stations, as the data is missed continuously for 3 or more years, they have been omitted in the study.

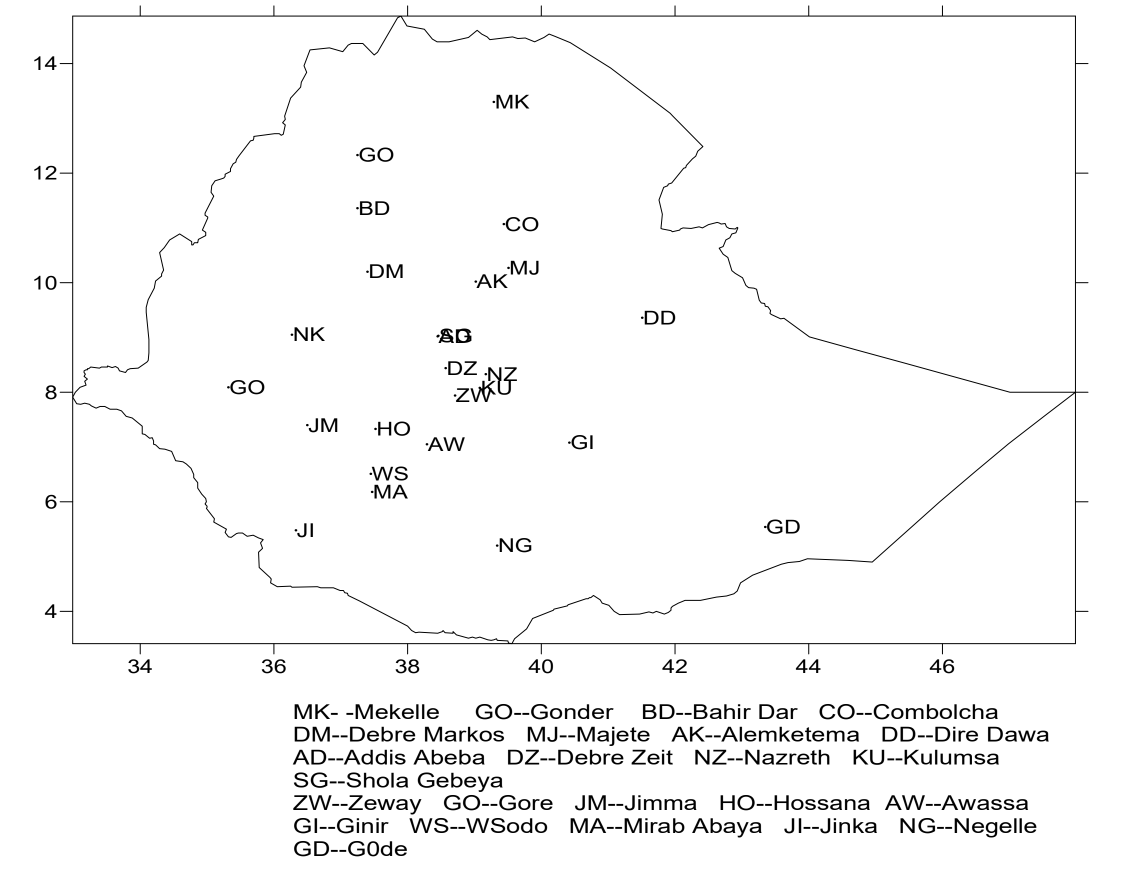


Fig: Station Distribution

Figure 1. Distribution of Rainfall Stations

For a few of the selected 26 stations, the missing monthly rainfall data (which is around 2%) has been supplemented with the corresponding mean monthly rainfall of that station. Similarly, the monthly SOI phases during the period 1975-2005 have been collected from the Long Paddock web page (http://www.longpaddock.qld.gov.au/Help/SOIPhases/index.html).

2.2 Methods

Standard Precipitation Index: The SPI was chosen for this study because of its simplicity and is based solely on the available precipitation data. The SPI method was first developed by Mckee et al. (1993) to transform the precipitation parameter to a single numerical value for defining the drought and flood conditions of areas with different climates. It is possible to determine the duration, magnitude, and intensity of droughts and floods using SPI (Hayes et al., 1999). The main advantage of SPI is that it can be calculated for several time scales (McKee et al., 1995) and identifies various drought types: hydrological, agricultural or environmental. This index enjoys several advantages over the others. Its nature allows an analyst to determine the rarity of drought or an anomalously wet event at a particular time scale for any location in the world that has a precipitation record.

Therefore, SPI is calculated from monthly precipitation record by first fitting the gamma probability distribution function and then transforming into a normal distribution so that the mean SPI is set to zero (McKee et al., 1993; Edwards & McKee, 1997). Positive and negative SPI values indicate wet and dry conditions, respectively. The alpha and beta parameters of the gamma probability density function are estimated for each station, for each time scale of interest (1, 3, 6, 9, 12 months, etc.), and each month of the year. The gamma distribution is defined by its frequency or probability density function:

$$\mathbf{g(x)} = \frac{\mathbf{1}}{\boldsymbol{\beta}^{\boldsymbol{\alpha}}\boldsymbol{\gamma}(\boldsymbol{\alpha})}\mathbf{x}^{\boldsymbol{\alpha}-\mathbf{1}}\mathbf{e}^{\frac{-\mathbf{x}}{\boldsymbol{\beta}}} \quad 2.1$$

Where α and β are the shape and scale parameters respectively, x is the precipitation amount and $\boldsymbol{\gamma}(\alpha)$ is the gamma function. Maximum likelihood solutions are used to optimally estimate α and β:

$$\hat{\boldsymbol{\alpha}} = \frac{\mathbf{1}}{\mathbf{4A}}\left[\mathbf{1} + \sqrt{\mathbf{1} + \frac{\mathbf{4A}}{\mathbf{3}}}\right] \quad 2.2$$

Where:

$$\hat{\beta} = \frac{\overline{x}}{\hat{\alpha}}$$

$$\mathrm{A} = \ln(\bar{\mathrm{x}}) - \frac{\sum \ln(\mathrm{x})}{\mathrm{n}} \quad 2.3$$

Where n = number of precipitation 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 station in question. The cumulative probability is given by:

$$\mathbf{g(x)} = \int_0^x \mathbf{g(x)\,dx} = \frac{1}{\beta^{\hat{\alpha}}\gamma(\hat{\alpha})}\int_0^x \mathbf{x}^{\hat{\alpha}-1}\,\mathbf{e}^{\frac{-x}{\hat{\beta}}}\,\mathbf{dx} \quad 2.4$$

Letting $t = \frac{x}{\hat{\beta}}$, this equation becomes the incomplete gamma function:

$$g(x) = \frac{1}{\gamma(\hat{\alpha})}\int_0^x t^{\hat{\alpha}-1}\,e^{-t}dt \quad 2.5$$

Since g(x) is undefined for x=0 and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$h(x) = q + (1-q)\,g(x) \quad 2.6$$

Where q is the probability of zero and g(x) is the cumulative probability of the incomplete gamma function. If m is the number of zeros in a precipitation time series, then q can be estimated by m/n. By applying Eq. (2.6), errors are eventually introduced to parameters α and β of the gamma distribution. These errors depend on the number of months with null precipitation (x=0) and they are evident only for the 1-month precipitation. For larger time scales (e.g. 3-month, 6-month, etc.) the probability of null precipitation was zero.

The cumulative probability, h(x), after its computation is transformed to the standard normal random variable z with mean equal to zero and variance of one, which is the value of the SPI. Once standardized the strength of the anomaly is classified as set out in Table 1. This table also contains the corresponding probabilities of occurrence of each severity arising naturally from the normal probability density function. Thus, at a given location for an individual month, moderate dry periods (SPI <=-1) have an occurrence probability of 9.2%, whereas extreme dry periods (SPI<=-2) have an event probability of 2.3%. Extreme values in the SPI will, by definition, occur with the same frequency at all locations.

An analyst with a time series of monthly precipitation data for a location can calculate the SPI for any month in the record for the previous I months where i=1, 2, 3, 12, 24, 48, depending upon the time scale of interest. Hence, the SPI can be computed for an observation of a 3-month total of precipitation as well as a 48 month total of precipitation. For this study, a 3-month and 6-month SPI is used for a short-term or seasonal drought index, a 12-month SPI is used for an intermediate-term drought index. Therefore, the SPI for a month/year in the period of record is dependent upon the time scale.

Table 1. Classification by SPI Values and Corresponding Event Probabilities (%)

SPI value	Category	Probability (%)
2.00 or more	Extremely wet	2.3
1.5 to 1.99	Severely wet	4.4
1.00 to 1.49	Moderately wet	9.2
-0.99 to 0.99	Near normal	68.2
-1.49 to -1.00	Moderately dry	9.2
-1.99 to -1.50	Severely dry	4.4
-2 or less	Extremely dry	2.3

3. Results

Based on the monthly SPI values computed over the period 1975-2005, the droughts (dry conditions) and floods (wet conditions) of different intensities; extreme, severe and moderately dry (Table 1) were determined for the 26 stations considered in the study. It could be clearly observed from the graphs that droughts and floods were frequently occurred across these stations which indicated the climate variability in the study area during the study period was very high.

3.1 Droughts

The drought frequencies during Belg, Kiremt, and Bega over the study period have been presented in graphs (Figure 2). Figure 2 shows that, droughts of different severity have been occurred frequently during the three seasons (Belg, Kiremt, & Baga) in most of the weather stations considered in this study. The highest frequency of moderate drought have been experienced in almost all stations among these drought severity level.

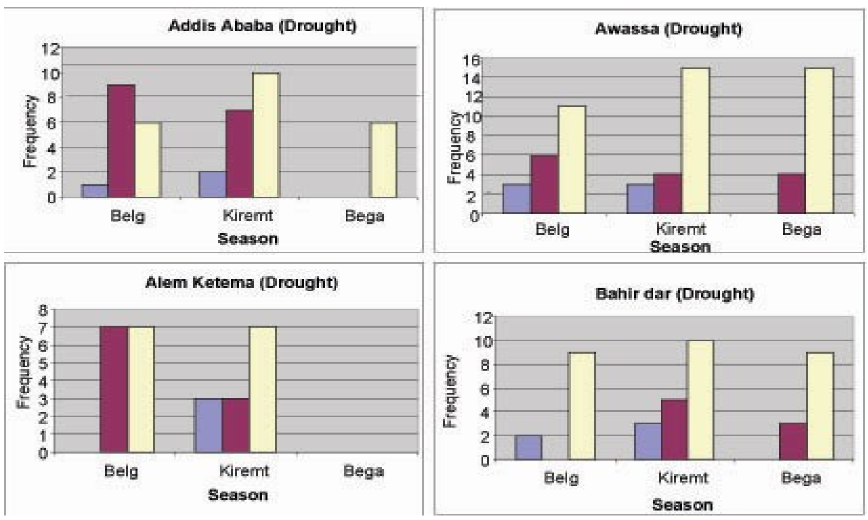
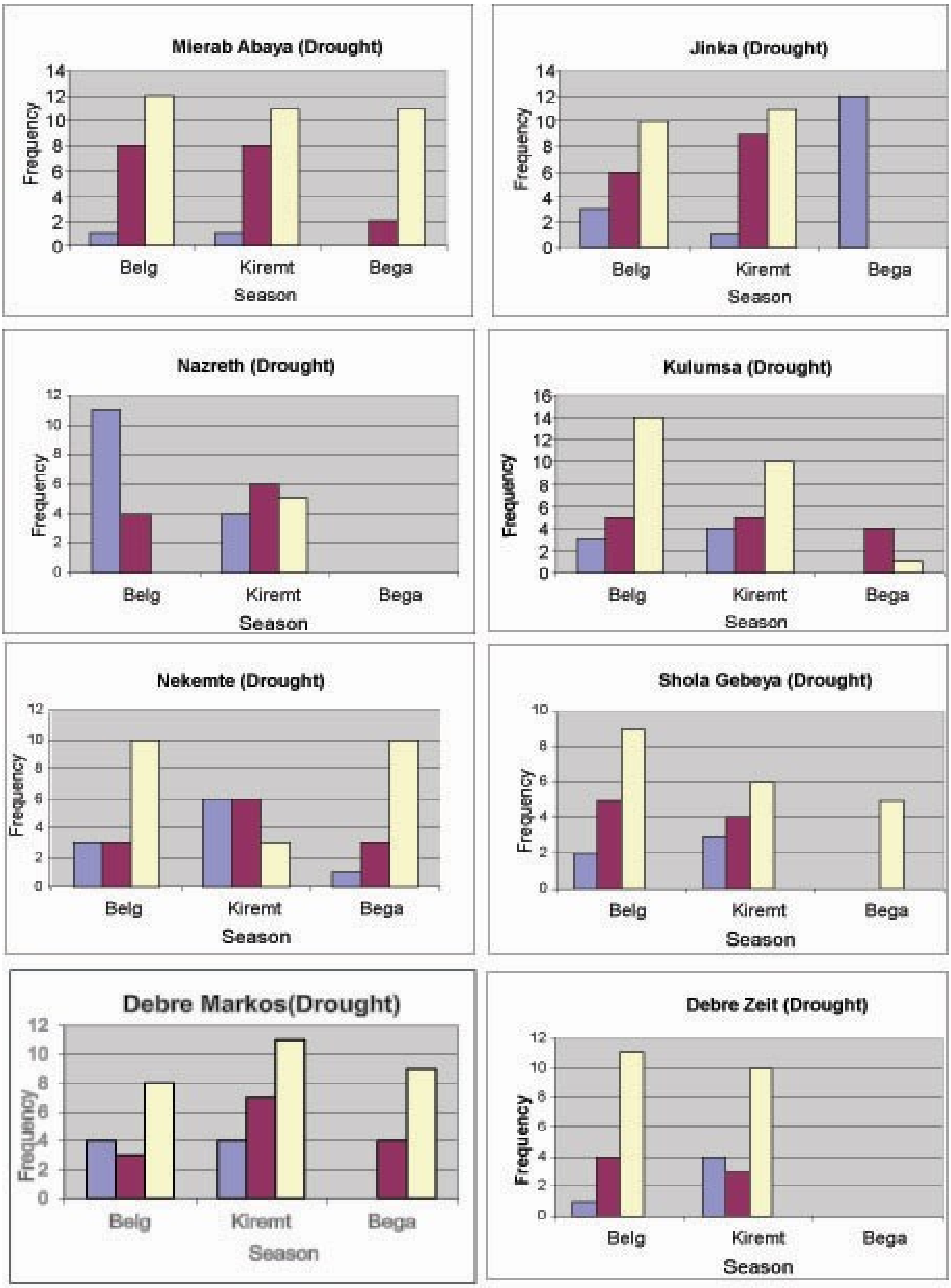


Figure 2. Frequencies of Droughts of Different Intensities (Extreme – Blue; Severe – Brown and Moderate – Yellow) over the Period 1975-2005



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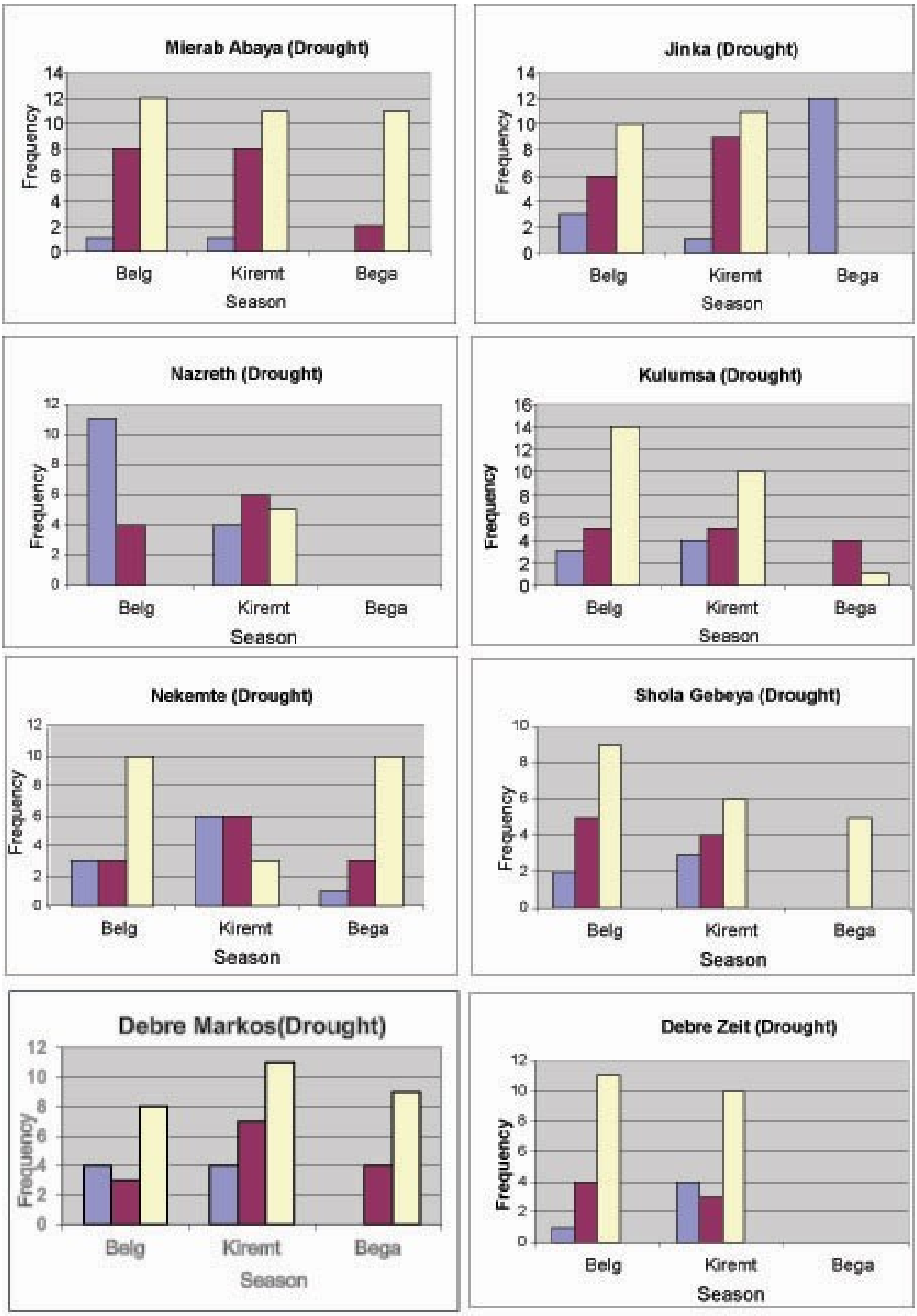

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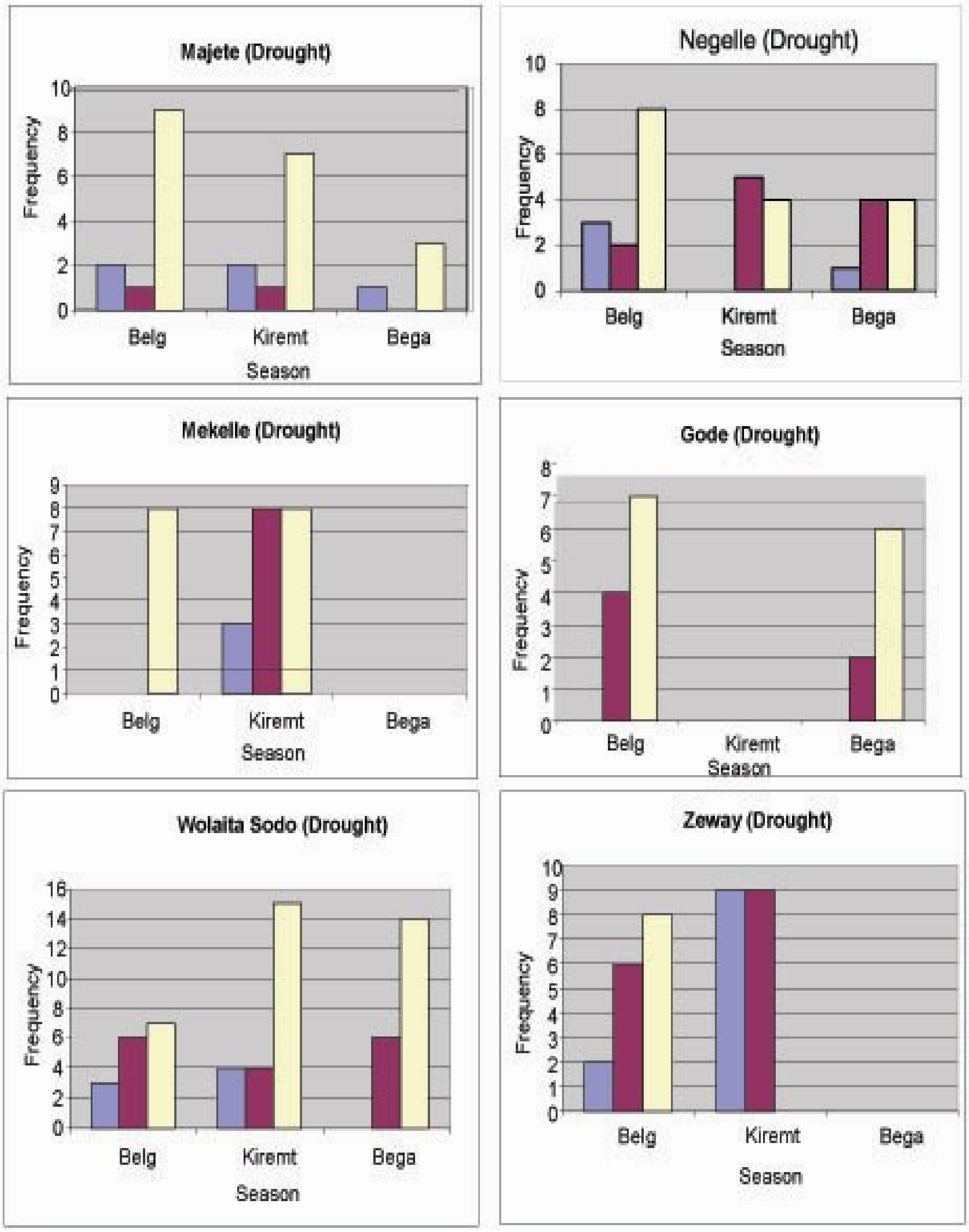


Figure 2. (Continued)

3.2 Floods

The flood frequencies (of different intensities) during belg, kiremt and bega over the study period have been presented in graphs (Figure 3). As shown in Figure 3, the number of moderate flood was very high in almost all weather stations during all seasons. Moreover, high frequency of severe drought have been experienced at some station during the study period.

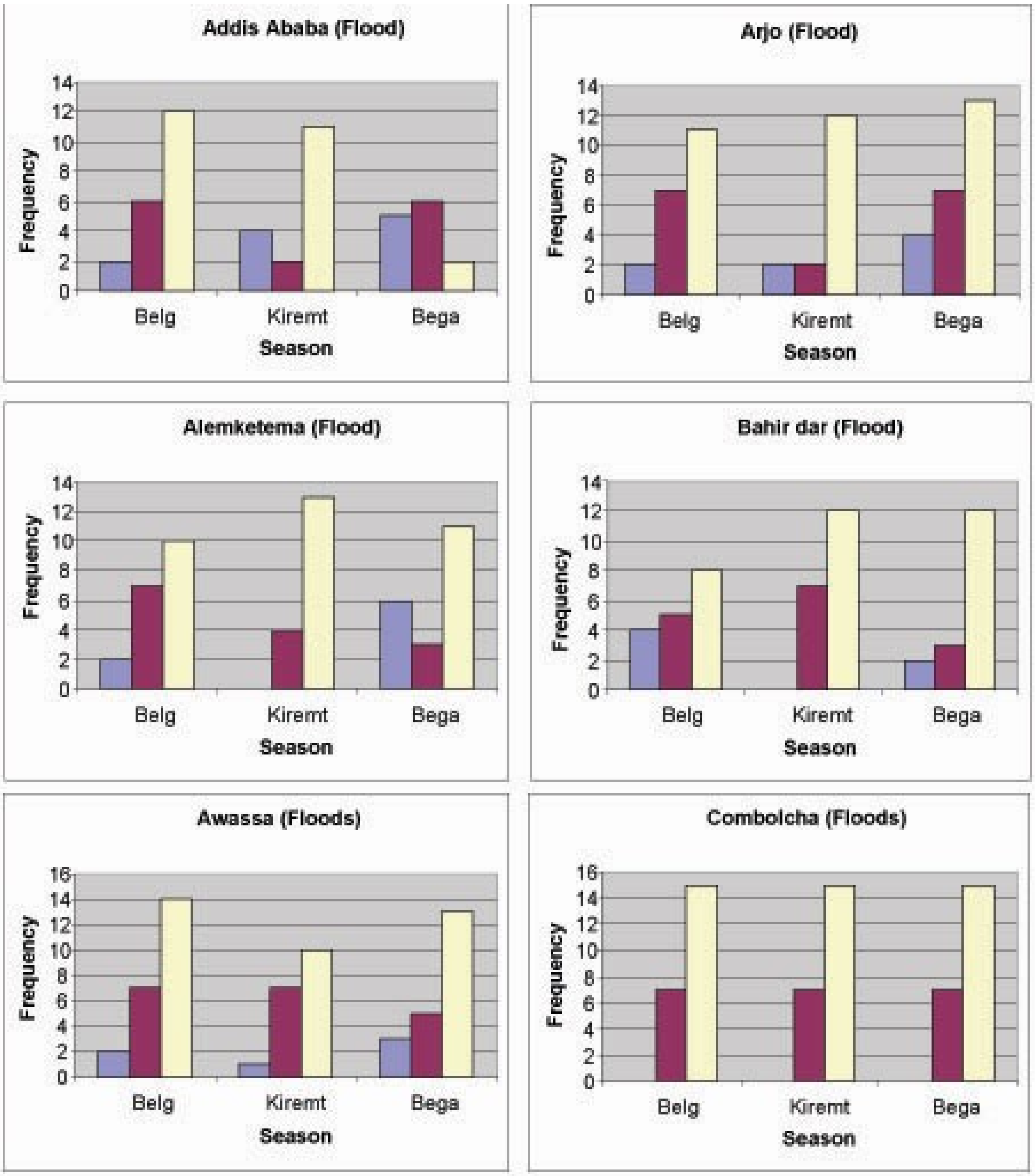
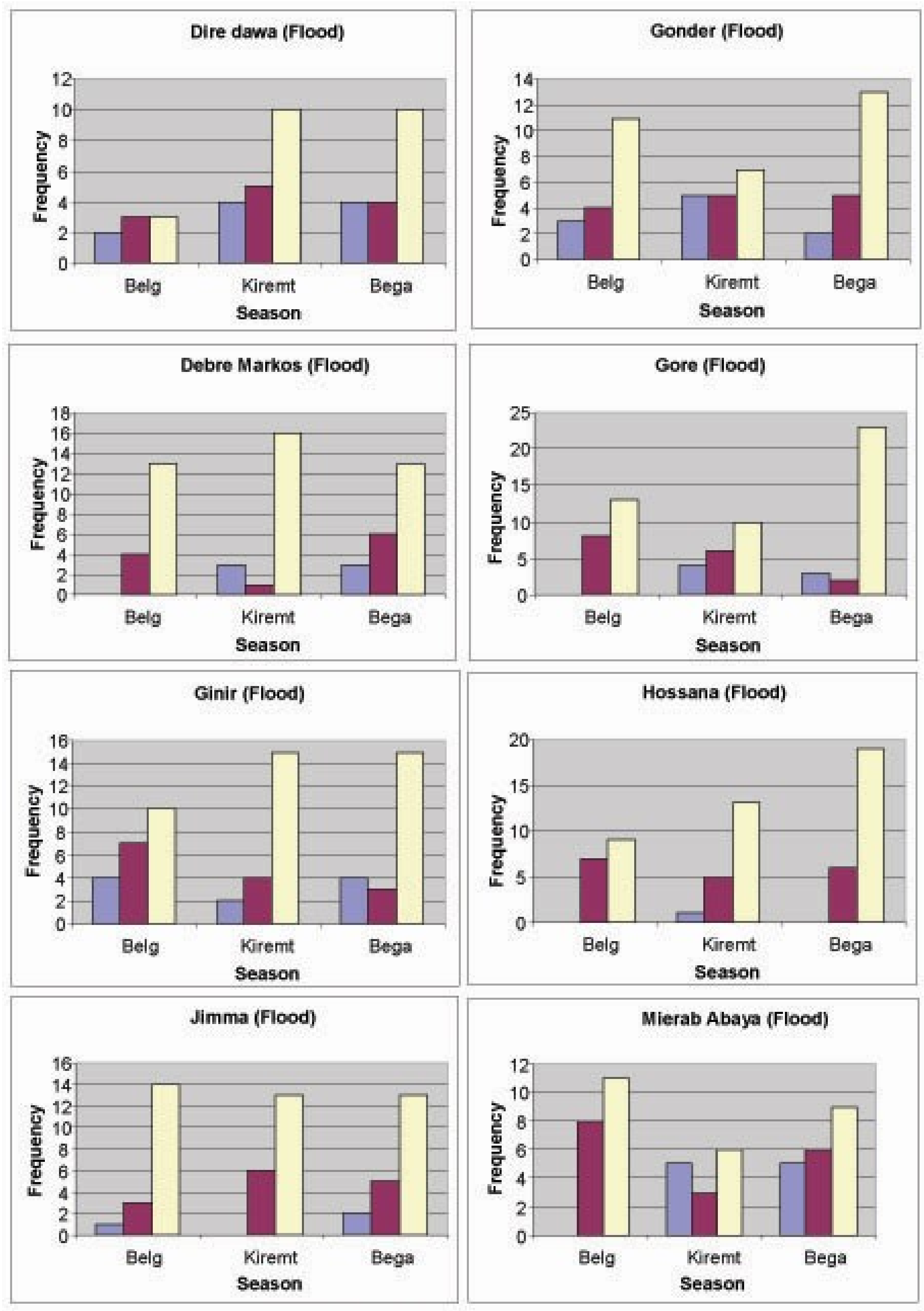


Figure 3. Frequencies of Floods of different Intensities (Extreme – Blue; Severe – Brown and Moderate – Yellow) over the Period 1975-2005



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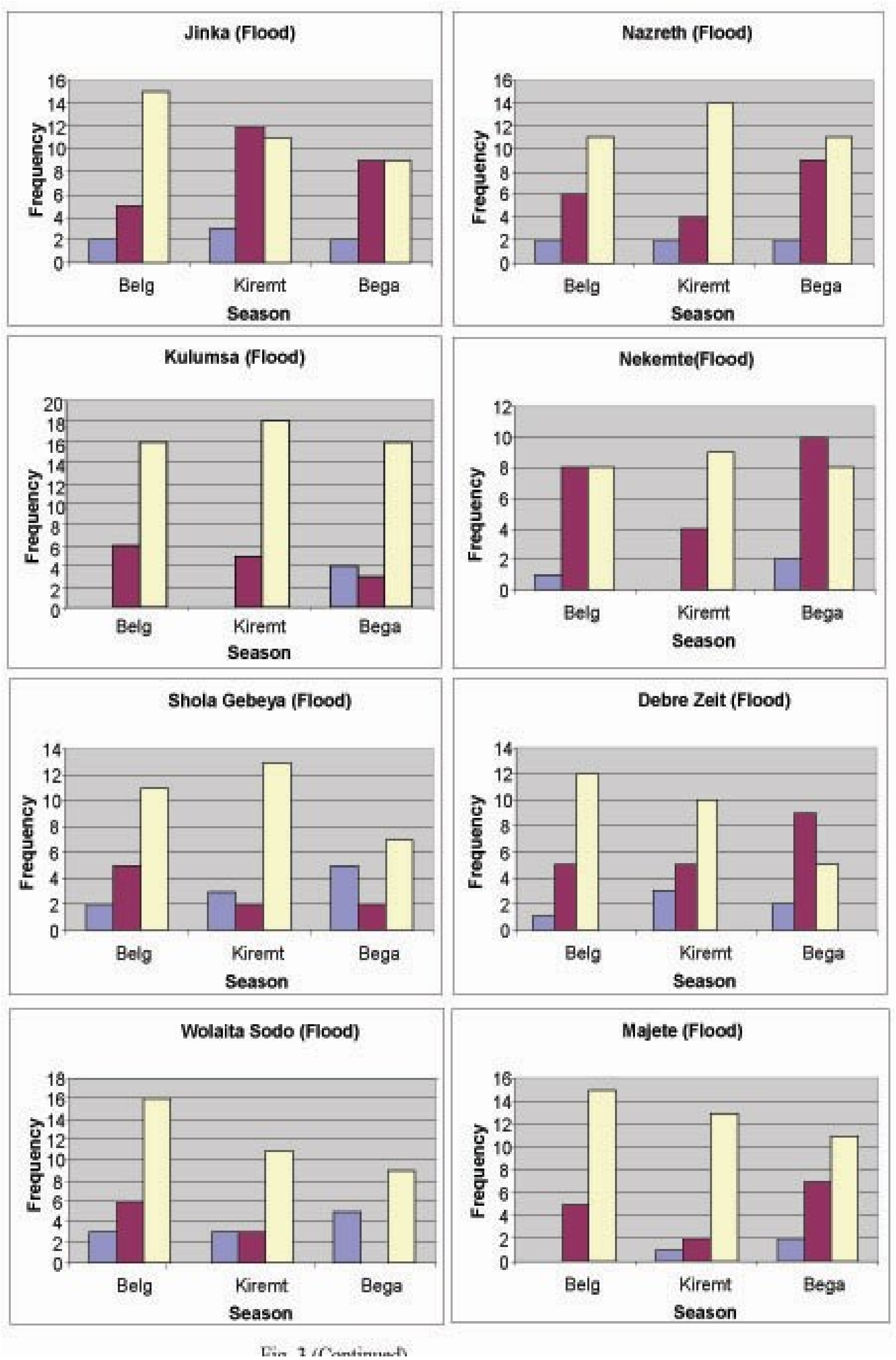

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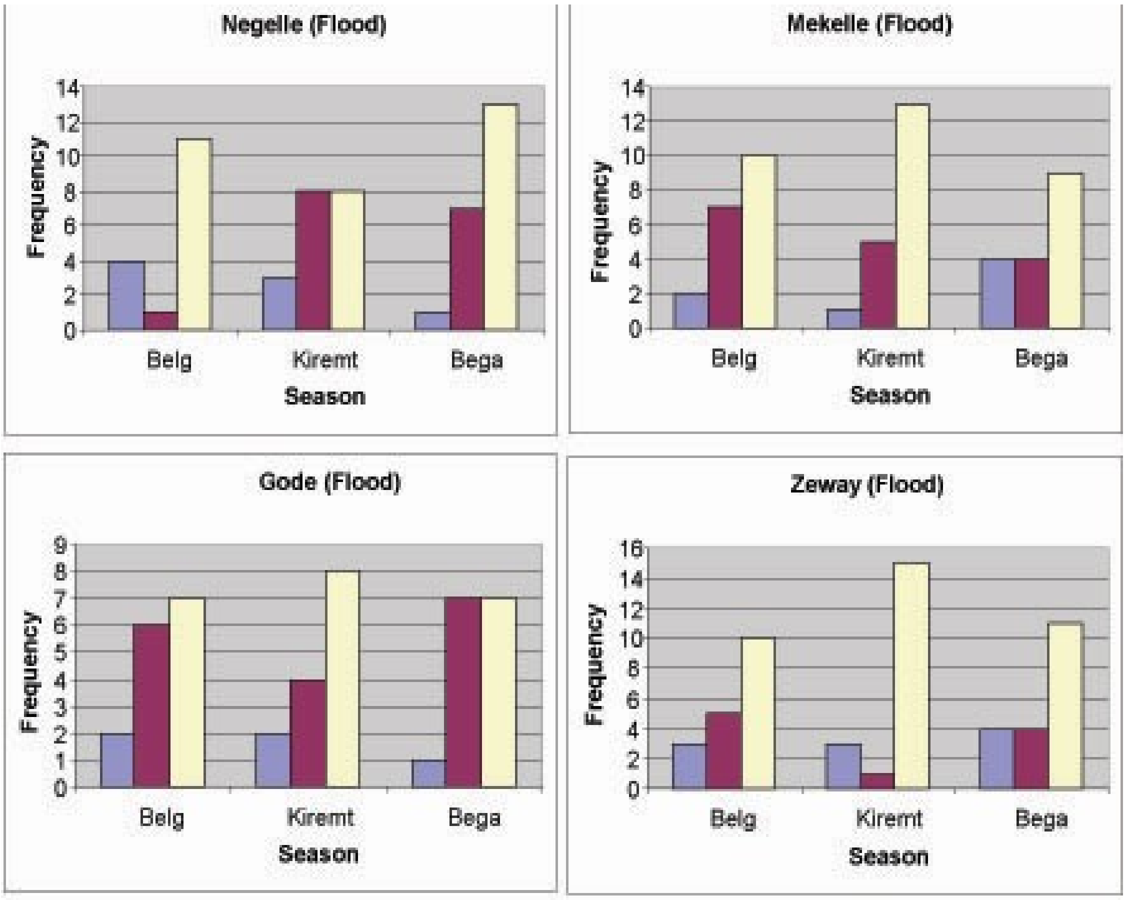

3.3 Hydrological Extremes and Their Association with ENSO

In this section, at each of the 26 stations considered in the study, the association of the hydrological extremes, namely the droughts and floods with ENSO phases has been examined every month. For this, the monthly occurrences of the hydrological extremes during the two rainy seasons, belg (Feb-May) and kiremt (Jun-Sep) associated with each of the five SOI phases (namely 1, 2, 3, 4 and 5) for all the months (starting from January) preceding and up to the last month have been evaluated over the period 1975-2005. As an example, these frequencies for Addis Ababa have been presented in Table-2 while placed in Appendix-I for the remaining stations.

Table 1. Drought and Flood Frequencies Associated with SOI Phases during Belg and Kiremt for Addis Ababa

Belg (Feb-May)

SOIP Month	Phase	Drought Frequency Feb	Mar	Apr	May	Total
Jan	5	0	2	3	3	8

SOIP Month	Phase	Flood Frequency Feb	Mar	Apr	May	Total
Jan	5	1	2	2	2	7

Feb	4	0	2	3	2	7		Feb	3	3	1	2	2	8
Mar	3	_	1	4	2	7		Mar	1	_	1	1	3	5
Apr	4	_	_	2	3	5		Apr	1	_	_	0	3	3
May	4	_	_	_	2	2		May	4	_	_	_	3	3

Kiremt (Jun-Sep)

SOIP Month	**Phase**	**Drought Frequency Jun**	**Jul**	**Aug**	**Sep**	**Total**		**SOIP Month**	**Phase**	**Flood Frequency Jun**	**Jul**	**Aug**	**Sep**	**Total**
Jan	1	1	3	1	1	6		Jan	4	2	1	2	1	6
Feb	3	2	4	1	2	9		Feb	5	1	1	1	2	5
Mar	4	1	3	0	1	5		Mar	2	0	3	1	0	4
Apr	1	3	2	2	2	9		Apr	5	2	2	1	3	8
May	4	3	2	1	1	7		May	5	3	2	1	1	7
Jun	1	0	1	2	2	5		Jun	4	2	2	1	1	6
July	4	_	2	1	2	5		July	2	_	2	2	1	5
Aug	3	_	_	2	3	5		Aug	2	_	_	1	2	3
Sep	4	_	_	_	2	2		Sep	2	_	_	_	2	2

As shown in the Table, when the SOI is consistently near zero (phase-5) in January there were eight drought cases (of all intensities) during Belg season at Addis Ababa, over the study period. Similarly, when the SOI is falling (phase-3) in February, there were eight flood cases during Belg and nine drought cases during Kiremt. This reverse variation of ENSO with Ethiopian rainfall between belg and kiremt has been observed by several other researchers also. The table also shows that when the SOI is in phase-5 in April, there were eight flood cases during kiremt.

Similar, analysis has been carried out for the remaining 25 stations and the SOI phases associated with the highest frequency of droughts and floods at all the 26 stations considered in the study, have been summarizedand presented in Appendix-I for belg and kiremt seasons.

3.1.1 ENSO and Hydrological Extremes during Belg

The monthly occurrences of the hydrological extremes during belg (Feb-May) associated with each of the five SOI phases (namely 1, 2, 3, 4 and 5) for all the months (starting from January) have been evaluated over the period 1975-2005 for the stations considered in the study. The SOI phases associated with the highest frequency of Droughts and Floods during this season are summarized in Table 3.

As shown in the table, during belg more stations experienced the higher drought frequencies when the SOI is in phase-5 (nine stations) in January and also when the SOI is in phase-4 (eight stations) in February. Similarly, when the SOI is in phase-1 (six stations) and phase-5 (five stations) in January and phase-3 (six stations) in February, more stations experienced higher flood frequencies. It can be observed that when the SOI is in phase-5 in January, while nine stations experienced higher drought frequencies, six other stations have experienced higher flood frequencies. Similarly, when the SOI is in phase-5, both the drought and flood frequencies are higher at Nazreth.

Table 2. SOI Phases Associated with the Highest Frequency of Droughts and Floods at 26 Stations Considered in the Study during Belg (Feb-May) Season

	Droughts			Floods			
Station	SOIP Month	SOI Phase	Frequency	Station	SOIP Month	SOI Phase	Frequency
Combolcha	Jan	2	9	Alemketema	Jan	1	9
Ginir	Jan	2	4	Combolcha	Jan	1	8
Shola Gebeya	Jan	2	5	Diredawa	Jan	1	8
Addis Ababa	Jan	5	8	Hossana	Jan	1	6
Alemketema	Jan	5	6	Jimma	Jan	1	5
DebreZeit	Jan	5	10	Kulumsa	Jan	1	8
Gode	Jan	5	14	Arjo	Jan	2	7
Gore	Jan	5	8	Gore	Jan	2	8
Hosana	Jan	5	9	Nekemte	Jan	2	7
MirabAbaya	Jan	5	11	DebreMarkos	Jan	4	6
Nazreth	Jan	5	7	Gonder	Jan	4	8
Nekemte	Jan	5	7	Bahirdar	Jan	5	8
Gonder	Feb	3	4	Jinka	Jan	5	9
Mekelle	Feb	3	10	Majete	Jan	5	8
WolaitaSodo	Feb	3	6	Nazreth	Jan	5	8
Awassa	Feb	4	8	Zeway	Jan	5	6
Bahirdar	Feb	4	6	Addis Ababa	Feb	3	8
DebreMarkos	Feb	4	7	Awassa	Feb	3	7
Jimma	Feb	4	7	DebreZeit	Feb	3	7
Jinka	Feb	4	10	Negelle	Feb	3	9
Kulumsa	Feb	4	9	Shola Gebeya	Feb	3	8
Majete	Feb	4	8	WolaitaSodo	Feb	3	7
Zeway	Feb	4	6	Gode	Feb	4	5
Negelle	Feb	5	7	MirabAbaya	Feb	4	9
Diredawa	Mar	2	7	Mekelle	Feb	5	9
Arjo	Mar	3	5	Ginir	Mar	3	8

3.1.2 ENSO and Hydrological Extremes during Kiremt

Similarly, the frequencies of both hydrological extremes (drought and flood) during kiremt (Jun-Sep) associated with each of the five SOI phases (namely 1, 2, 3, 4 and 5) for all the months (starting from January) preceding and up to the current month have been evaluated for all stations considered in the study over the study period have been presented in Appendix-I. The SOI phases associated with the highest frequency of droughts and floods during this season summarized in Table 4.

When the SOI is in phase-3 in March (Table 4) during kiremt season, five stations experienced the higher drought frequencies, while six stations have experienced the higher flood frequencies when the SOI is in phase-5 in January. Thus, when the SOI is in phase-5 in January, nine stations (Addis Ababa, Alemketema, Debrizeit, Gode, Gore, Hosana, MirabAbaya, Nazreth, and Nekemte) have experienced droughts during Belg (Table-3), six stations (Combolcha, DebreMarkos, Mekelle, Nazreth, Shola Gebeya, and WolaitaSodo) experienced floods during Kiremt (Table 4). This shows that SOI phase-5 is associated with droughts during Belg and floods during Kiremt at majority of the stations in Ethiopia. This preliminary analysis forms a basis for the prediction of hydrological extremes in Ethiopia based on the SOI phases.

Table 3. SOI Phases Associated with the Highest Frequency of Droughts and Floods at 26 Stations Considered in the Study during Kiremt (Jun-Sep) Season

Droughts				Floods			
Station Name	SOIP Month	SOI Phase	Frequency	Station Name	SOIP Month	SOI Phase	Frequency
Jimma	Jan	4	7	Gonder	Jan	2	10
WolaitaSodo	Jan	4	8	Diredawa	Jan	4	8
Gonder	Jan	5	9	Combolcha	Jan	5	9
Shola Gebeya	Jan	5	7	DebreMarkos	Jan	5	11
Bahirdar	Feb	2	9	Mekelle	Jan	5	10
Addis Ababa	Feb	3	9	Nazreth	Jan	5	12
Combolcha	Feb	3	8	Shola Gebeya	Jan	5	7
Diredawa	Feb	3	8	WolaitaSodo	Jan	5	10
Awassa	Mar	1	10	Bahirdar	Feb	3	7
Ginir	Mar	3	8	Gode	Feb	4	8
Hosana	Mar	3	9	DebreZeit	Mar	2	7
Jinka	Mar	3	13	Kulumsa	Mar	2	10
Kulumsa	Mar	3	9	MirabAbaya	Mar	2	8
Nekemte	Mar	3	8	Addis Ababa	Apr	5	8
Alemketema	Apr	1	9	Awassa	Apr	2	8

DebreMarkos	Apr	1	12	Ginir	Apr	3	8
DebreZeit	Apr	1	14	Gore	Apr	5	9
Arjo	May	1	13	Hossana	Apr	1	9
Negelle	May	1	7	Jinka	Apr	5	9
Zeway	May	1	9	Majete	Apr	5	5
Gode	May	4	16	Nekemte	Apr	3	5
Mekelle	May	4	15	Alemketema	May	5	6
MirabAbaya	May	4	11	Negele	May	4	11
Nazreth	May	4	9	Arjo	Jun	3	10
Gore	Jun	3	7	Jimma	Jun	3	13
Majete	Jun	3	12	Zeway	Jun	2	8

4. Discussion

In this study, the frequencies of droughts and floods at 26 rainfall stations spread across Ethiopia have been determined using the Standardized Precipitation Index (SPI), which is simple, and is based solely on the accessible precipitation data. Further, the association of the droughts and floods with SOI phases has been examined within the historical record of rainfall data.

Based on the monthly Standardized Precipitation Index (SPI) values computed over the period 1975-2005, the droughts (dry conditions) and floods (wet conditions) of different intensities; extreme, severe and dry have been determined on monthly basis for 26 stations, spread across the country. There were 11 extreme droughts (SPI < -2.0) at Nazreth, 10 severe droughts (SPI between -1.99 and -1.50) at Diredawa and 14 moderate droughts (SPI between -1.49 and -1.00) at Kulumsa during Belg season. The total number of droughts of all intensities over the period 1975-2005 is also highest (22) at Kulumsa and lowest (8) at Mekelle. It can also be observed from the figure that, during belg, extreme drought was absent at 5 stations, severe drought was absent at 2 stations and moderate drought was absent at Mekelle (Figure 2).

Similarly, during kiremt season, Zeway experienced 9 extreme droughts, while Hosana experienced 16 severe and Combolcha experienced 16 moderate droughts over the period 1975-2005. The total number of droughts during Kiremt is highest (31) at Hosana. During this season, extreme droughts were absent at 4 stations, severe droughts were absent at Gode and moderate droughts were absent at Gode and Zeway. Surprisingly, there were no droughts at all at Gode during kiremt over the period of study.

Three weather stations, Bahirdar, Ginir and Negelle have experienced the highest number (4) of extreme (SPI > 2.0) floods, while Gore, Mirab Abaya and Nekemte have experienced 8 severe (SPI between 1.50 and 1.99) floods each, and Kulumsa and WolaitaSodo have experienced 16 moderate (SPI between 1.00 and 1.49) floods. The figure also shows the total number of floods of all intensities during belg over the study period is the highest (25) at WolaitaSodo and lowest (8) at Diredawa. Thus, at Kulumsa, both the numbers of droughts (22) and floods (22) during belg are high, which shows that the rainfall variability is the highest at this station.

Similarly, during kiremt, Gonder and Mirab Abaya experienced the highest number (5) of extreme floods, while Jinka experienced 12 severe floods and Kulumsa experienced 18 moderate floods over the period (Fig.-3). The total number of floods of all intensities is highest (26) at Jinka and lowest (8) at Gode. Thus, at Gode, both the numbers of droughts (0) and floods (8) are the lowest, during kiremt, which shows that the rainfall variability is the lowest at this station. Only extreme floods were absent at 6 stations, while all the stations have experienced severe and moderate floods during this season (Fig.-3).

This seasonal and spatial (at various stations) analysis of meteorological droughts and floods, provide a framework for sustainable drought monitoring and management in Ethiopia.

The association of the monthly occurrences of the hydrological extremes during the two rainy seasons, belg (Feb-May) and kiremt (Jun-Sep) with each of the five SOI phases (namely 1, 2, 3, 4 and 5) for all the months (starting from January) preceding and up to the current month have been evaluated over the period 1975-2005. Analysis of the SOI phases associated with the highest frequency of droughts and floods at all the 26 stations considered in the study, has shown that during belg more stations experienced the higher drought frequencies when the SOI is in phase-5 (9 stations) in January and also when the SOI is in phase-4 (8 stations) in February. Similarly, when the SOI is in phase-1 (6 stations) and 5 (5 stations) in January and in phase-3 (6 stations) in February, more stations experienced the higher flood frequencies. During kiremt, when the SOI is in phase-3 in February (Table 4), 5 stations experienced the higher drought frequencies, while 6 stations have experienced the higher flood frequencies when the SOI is in phase-5 in January. The above analysis clearly shows that SOI phase-5 is associated with droughts during Belg and floods during Kiremt at majority of the stations in Ethiopia. However, no spatial coherence (zone-wise) in either the frequency of the hydrological extremes or their association with the ENSO phases has been observed with this limited number of weather stations.

This preliminary analysis forms a basis for the prediction of hydrological extremes in Ethiopia based on the SOI phases. However, by using still larger databases, better relationships of SOI phases with the hydrological extremes can be arrived. The spatial variation and coherence of the hydrological extremes and their association with the SOI phases are also to be examined using larger databases for better prediction.

To compensate the scarcity and un-availability of long term rainfall data, remote sensing data obtained from satellites such as NDVI, can be used to compute indices based on such data like Standard Vegetation Index (SVI) or Vegetation Condition Index (VCI), as remote sensing data have better spatial and temporal coverage compared to ground data.

The outcome of this study provides for concerned bodies the meaningful and understandable information about the frequencies of hydrological extremes at various stations in Ethiopia and their association with SOI phases which forms a basis for the prediction of these hydrological extremes based on SOI phases. This kind of information is essential for a broad group of users who are interested in monitoring, mitigation and management of droughts and floods in the country.

Acknowledgments

I am grateful for the data I received from the National Meteorology Agency (NMA) of Ethiopia. I would like to express my heartfelt thanks to all Meteorology and Hydrology department staff members of Arba Minch University who have been contributing a lot to the success of this work.

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