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Assessing drought risk and irrigation need in northern Ethiopia

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ABSTRACT

Long-term climate data of four stations in the northern Ethiopia were analyzed in combination with information from local farmers and documented materials. From this analysis, a suitable drought-assessing technique was developed and site-specific needs for supplementary irrigation were explored. Results showed that our technique for assessing drought and crop failure corresponded well with farmer observations. The three major causes of crop failure (dry spells, short growing period and "total lack of rain") which were explicitly listed and ranked by the local farmers were found to match the analyzed data well. The agro-meteorological variables with the most severe consequences were "short growing period" and "total lack of rain". To prolong the growing period, supplementary irrigation is recommended in the month of September for three of the stations (Maychew, Mekelle and Adigudom) because: (1) rain frequently stops in early September or late August and crops have no other source of water for the rest of the growing period; (2) sufficient surface runoff can be harvested in July and August to be stored in farm ponds and used in September; (3) more cultivable land can be irrigated if supplementary irrigation is scheduled only for the month of September; and (4) giving supplementary irrigation in September can cut yield reduction by over 80% and crop failure by over 50%, except at Alamata. At Alamata, supplementary irrigation must be scheduled for July. The conditions experienced during the famine years of the early 1980s were primarily caused by the continued total rain failure over multiple years. Giving supplementary irrigation in July or September would probably not have mitigated the effects of these droughts, especially at Alamata and Maychew stations.

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1. Introduction

The Ethiopian economy is based on agriculture. It is also the source of income for about 80% of the labor force in Ethiopia (Bewket and Conway, 2007). Natural rainfall is the major source of water for agriculture. Assessing seasonal or dekadal[1] rainfall characteristics based on past records is essential to evaluate drought risk and to contribute to development of drought mitigation strategies such as supplementary irrigation.

Rainfall variability has been reported to have significant effect on the country's economy and food production for the last three decades. There have been reports of rainfall variability and drought-associated food shortages (Tilahun, 1999; Bewket and Conway, 2007). In most cases, what determines crop production in semi-arid areas of Africa is the distribution rather than the total amount of rainfall, because dry spells strongly depress the yield (Barron et al., 2003; Segele and Lamb, 2005; Meze-Hausken, 2004).

Early onset of the rainy season leads to crop germination, since most farmers sow in dry soil. If a long dry spell follows, the seedlings die – a "false start" (Ati et al., 2002; Raes et al., 2004; Kipkorir et al., 2007) – and often the crop must be resown. The major causes of crop failure in northeastern Ethiopia are frequent dry spells of about 10 days length, as well as a shorter growing period due to replanting or late onset and/or early cessation of rain (Segele and Lamb, 2005; Araya et al., 2010b). Reliable estimation of onset and cessation of rain could help optimize rainwater use in semi-arid areas (Sivakumar, 1992; Ati et al., 2002; Raes et al., 2004; Kipkorir et al., 2007; Mugalavai et al., 2008).

Dry-spell analysis has been carried out in various parts of Africa. Many authors define a dry spell as *n* consecutive days without appreciable rainfall (Stern, 1980; Sivakumar, 1992; Sharma, 1996; Ceballos et al., 2004; Gong et al., 2005). In many studies, days with rainfall less than 0.1 mm per day are considered a dry spell. The severity of dry spells depends on their frequency and duration and on the crop stage during which they occur. However, sometimes such analysis may not be useful for assessing whether the crop water demand will be met, for three reasons: (i) it does not consider the evaporative demand of the atmosphere; (ii) a day of rainfall with little agronomic effect may be counted as a wet day and (iii) effective rainfall is not considered.

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[1] We use the term dekad for a period of 10 days.

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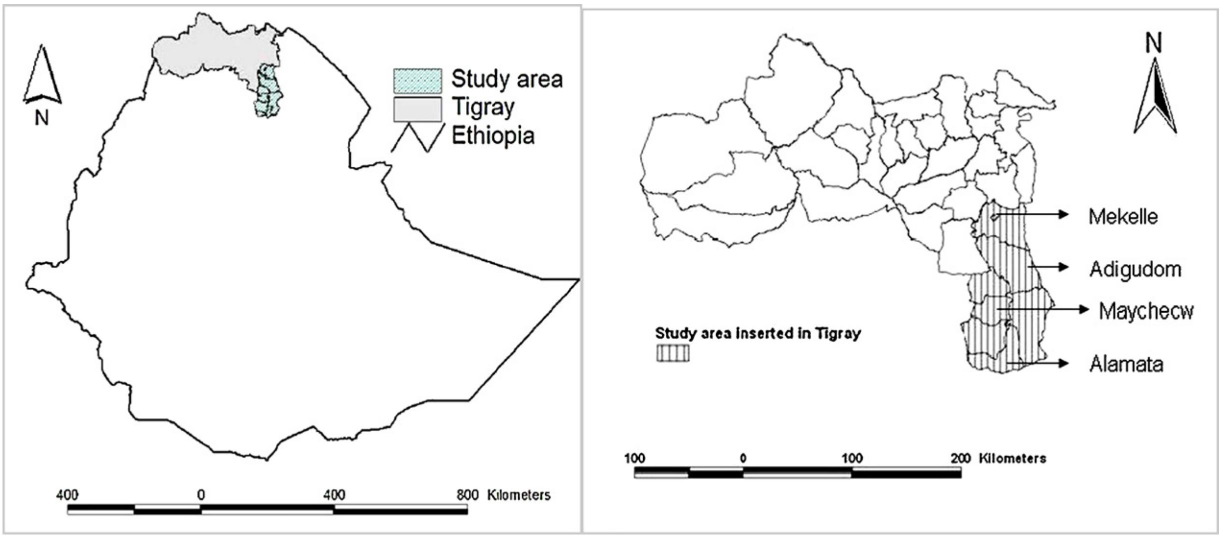

Fig. 1. Map of the study area in Tigray region in north Ethiopia.

Given that agriculturists are mainly concerned with actual crop water stress, the analysis would be more meaningful if it considered dry spells in relation to meeting crop water demand (Barron et al., 2003). Moisture deficit and the crop-growing risks and suitability of rain-fed agriculture can be evaluated on the basis of relationships between rainfall and reference evapotranspiration (Tilahun, 2006; Araya et al., 2010b). However, effective rainfall, not total rainfall has to be considered, because in semi-arid northern Ethiopia a substantial amount of the rainfall is lost as runoff (Araya and Stroosnijder, 2010). Crop water stress becomes severe when the available water meets less than half the crop water demand (Doorenbos and Kassam, 1979). Thus, one way of analyzing dry spells is to describe the dekadal effective rainfall in relation to the dekadal reference evapotranspiration. A dry spell in our case is thus any dekad in which effective rainfall is less than 50% of the dekadal reference evapotranspiration, whereas a wet spell is any dekad in which effective rainfall exceeds 50% of the dekadal reference evapotranspiration.

There are many definitions of drought, but from the viewpoint of local people, drought is any season with low rainfall in relation to crop water demand that results in poor crop harvest or total crop failure and/or livestock suffering or dying from because of feed shortages as a consequence of poor rainfall distribution/amount. Dry spells affect a crop when only a small amount of soil water is available to the crop due to reduced soil water holding capacity.

A dry spell can occur at the start, mid, or late season of the crop. When dry spells occur at the late season stage of the crop, the growing season is shortened. Late season drought has been reported to reduce yields significantly at Mekelle in northern Ethiopia (Araya et al., 2010b). Despite the risk of drought and the vulnerability of the people to the recurrent drought, little has been done to develop techniques for assessing drought risk and to determine how and which variables are related to crop failure circumstances in the northern Ethiopia.

There are various techniques for assessing and predicting drought. Each has merits and limitations (Alley, 1984; Guttman, 1991; Heddinghaus and Sabol, 1991; Guttman, 1998). In this study we set out to develop a simpler technique that can be used to assess the occurrence of past drought (crop failure) years easily and adequately for northern Ethiopia.

Drought can be mitigated by various agronomic and water conservation methods and with supplementary irrigation. The objectives of this paper are: (1) to analyze critically the quality of past growing seasons in northern Ethiopia in order to elucidate the main causes of crop failures; (2) to develop a simple suitable drought assessment technique and (3) to study the probability of occurrence of drought and indicate site-specific time and quantity recommendations for supplementary irrigation as a drought-coping strategy. Data from four rainfall stations in northern Ethiopia, each with 30–46 years of observation, and on two major crops: barley (*Hordium vulgare*) and teff (*Eragrostis tef*) were studied.

2. Materials and methods

2.1. Site and data description

The study site is located in northern Ethiopia (longitude 39°5′–39°8′ and latitude 12°3′–13°7′) and has four climate stations (Fig. 1). The climate is characterized by bimodal rainfall. About 70–80% of the rain falls in the *Kiremt* season (June–September) (Araya et al., 2010b). There is great inter-annual spatial and temporal rainfall variation. The mean minimum and maximum temperature range is from 8 °C to 30 °C, with small annual variations. In all months except the month of August, the dekadal reference evapotranspiration exceeds the mean dekadal rainfall.

In this area, the agriculture is mixed crop and livestock farming. Land degradation and deforestation are among the major problems caused by human factors in the area (Hurni, 1990; Nyssen et al., 2000; Meze-Hausken, 2004). The fertility of the agricultural lands is deteriorating. In this area of Ethiopia the soils are shallow (<0.5 m) and have poor water-holding capacity.

The major crops in the study area are barley, teff, sorghum, chick pea and wheat. Early-maturing and drought-resistant crop cultivars are widely grown (Meze-Hausken, 2004). The growing period starts in early July and ends in early to late September, with a rainy period of a maximum of 80 days (Araya et al., 2010b). More than 95% of the arable land is cultivated with out irrigation.

The site was chosen not only due to availability of relatively long series of meteorological data but also because recurrent drought is common in this part of the country. As the farmers in this area have frequently experienced drought, their perceptions of drought and crop failure are valuable to consider when analyzing climatic data.

Daily weather data such as rainfall, sunshine, temperature, humidity and wind were obtained from the Ethiopian

Table 1
Details of the four rainfall stations in north Ethiopia used in this study.

Station	Altitude (m)	Years of observation	Number of years with no data
Alamata	1700	1975–2008	2
Maychew	2800	1953–2008	11
Mekelle	2112	1960–2008	2
Adigudom	2050	1978–2008	1

Meteorological Services Agency. Seasons with missing daily values were excluded from the analysis. The homogeneity of all dekadal, monthly, seasonal and annual rainfall records were proved based on Buishand (1982).

Two stations had shorter periods (30 years) of observation than the other two (44 and 46 years) (Table 1). There have been reports of climatic variability over the region (Tilahun, 2006; Araya et al., 2010b). Therefore the comparisons of stations for different kinds of analysis were done using only the years common to all stations (1978–2008). However, full data sets from each station were also used to describe the situation, especially when evaluating the drought assessment technique.

2.2. Farmers' information

About 500 farmers in the study area, in teams or as individuals, were invited to characterize and classify past growing periods. They were able to list most of the years with abundant rainfall and many of the drought years, including the infamous 1984/85 drought. In addition, data was gathered from the Ministry of Agriculture and the statistical authority offices. We compared our analyzed information with that from the farmers. We designated farmers' data "observed" data and compared it with the analyzed data ("calculated") from the four climatic stations.

Farmers and extension workers were asked to list and then rank the cause of crop failure in the study area. Our ranking of the analyzed data was then compared with the farmers' rankings.

2.3. Analysis of onset, cessation and length of growing period (LGP)

The onset and cessation of the rainy period were determined from the rainfall–reference evapotranspiration relationship. This approach was presented in Ati et al. (2002) and was validated with slight modification for this region by Araya et al. (2010b). Accordingly, onset was assumed to occur; (1) after 15 June when long-term cumulative 5-day rainfall is greater than or equal to the cumulative half of the 5-day reference evapotranspiration and (2) a greater ratio of rainfall to reference evapotranspiration for at least two consecutive pentads during which period the rainfall sum exceeds 25 mm and within 30 days there is no dry spell of more than seven consecutive days.

Similarly the growing period was assumed to cease after 20 August (1) a week after half of the 5-day cumulative rainfall is less than the 5-day cumulative reference evapotranspiration and (2) this must be followed by a dry period of more than 10 days. The length of the growing period (LGP) was considered as the period from the onset to the cessation of rain. Frequency analyses were performed for both onset and cessation of the rainy period and were grouped as early, normal and late over the observation period for each of the stations. A frequency analysis was also performed for LGP.

2.4. Analysis of reference evapotranspiration, dry and wet spell data analysis

Dekadal reference evapotranspiration (D_{ETo}) was computed using the Hargreave's equation for all stations in the study area. In addition, for those stations with full data sets, the D_{ETo} was computed using the FAO-Penman–Monteith method. The estimates of Hargreaves's equation were compared with the estimates of FAO-Penman–Monteith at one of the stations (Mekelle) where wind speed, humidity, temperature and sunshine hours are measured. Since the estimates with the limited data sets are less accurate (they differed slightly from the estimates calculated from the full data set), the ratio method was then used to calibrate the estimates of the Hargreaves equation for all stations in the study area. Validation revealed that ET_o values estimated with FAO Penman–Monteith at another station (Maychew) in the study area where wind speed, humidity, temperature and sunshine hours are measured agreed well with the corresponding calibrated estimates of the Hargreaves's equation for the same station. FAO Penman–Monteith analysis was carried out using ET_o software (FAO, 2009).

Dekadal rainfall and reference evapotranspiration during the growing period from the 1 July to 30 September were computed. Effective rainfall per dekad (Barron et al., 2003) was also calculated (Eq. (1)) based on the following relationship:

$$D_{Eff} = D_{Rain} \times (1 - 0.25) \quad (1)$$

where D_{Eff} is the dekadal effective rainfall (mm). Effective rainfall in this case is the amount of rainfall infiltrated into the soil; D_{Rain} is dekadal rainfall; the factor 0.25 accounts for the estimated average runoff of 25% (Araya and Stroosnijder, 2010). Dry spell occurrence in a dekad was analyzed and presented in two ways:

(i) When the ratio of dekadal effective rainfall to the dekadal reference evapotranspiration was <0.5 in any one of the dekads between onset and cessation of rain.
(ii) The percentage frequency of dry dekad was computed and evaluated for given sets of effective rainfall thresholds (10, 20, 30, 40 and 50 mm). Such analysis reveals how dry or wet the dekad was in relation to those five amounts of effective rainfall (Sivakumar, 1992). The probability of a dry dekad (Eq. (2)) in relation to a set amount of effective rainfall was calculated as:

$$P_d = \left[\frac{n}{N}\right] \times 100 \quad (2)$$

where P_d, is probability of a dry dekad receiving less than a given threshold of effective rainfall; n is the number of seasons with a dry dekad, based on the given threshold limit, and N is the total number of seasons.

Similarly, wet spells described in dekads were analyzed and presented in two ways:

(i) a wet dekad was deemed to occur when the ratio of $D_{Eff}/D_{ETo} > 0.5$,
(ii) the probabilities of wet dekads (Eq. (3)) were also calculated as:

$$P_w = \left[\frac{n}{N}\right] \times 100 \quad (3)$$

where P_w is the probability of a wet dekad receiving effective rainfall above a given threshold; n is the number of seasons with a wet dekad and N is the total number of seasons. The frequency of wet dekads was computed and evaluated for thresholds above a given amount of effective rainfall (10, 20, 30, 40 and 50 mm).

A false start was defined as occurring when the ratio of dekadal effective rainfall to the dekadal reference evapotranspiration is >0.5 in the onset dekad followed by a dekad/s < 0.5 in the dekad/s following the onset dekad. This condition was evaluated for up to 30 days following sowing. The occurrence of a false start can also be evaluated by considering the relative transpiration or evapotranspiration rate over the 30-day period following sowing (Raes et al., 2004; Kipkorir et al., 2007). As most farmers in northern Ethiopia sow their seeds in dry soil, the seed will germinate only when the rainfall wets the top 0.1–0.2 m of the soil (Araya, 2005). According to local farmers, a false start (locally called '*Afakus*' or '*Aramst*') occurs when a dry period longer than a dekad occurs after germination. Thus we assumed failure or false start when a D_{Eff} did not meet at least half of the D_{ETo} over the 10-day period following sowing. But if onset of rain was late, we considered the 1st rain after sowing as onset, as long as the seed had not been in the soil for over 10 days (seeds may also fail to germinate if they stay too long in the soil).

The inter-annual dekadal rainfall variability is shown by the coefficient of variation (Eq. (4)):

$$CV = \left[\frac{S}{X}\right] \times 100 \tag{4}$$

where CV is the coefficient of variation; X is the average long-term rainfall over the given dekad and S is the standard deviation of the dekadal rainfall.

Since rainfall in semi-arid environments is erratically distributed and unreliable, analyzing dependable rainfall is vital (Tesfay and Walker, 2004). This helps to understand to what extent the rainfall meets the evaporative demand of the atmosphere in 1, 2, or 3 years out of a total of 4 years. Thus, for each station the 25%, 50%, and 75% dekadal dependable rainfall was compared with the dekadal mean reference evapotranspiration. The dependable precipitation was determined using the Weibul's method and was best-fitted using the normal distribution with r^2 of greater than 0.85. The analysis was done using the RAINBOW program (Raes et al., 1996).

2.5. Seasonal drought and trend

Seasonal drought indices were calculated based on the following equation:

$$DI = \left[\frac{M - Z}{S}\right] \tag{5}$$

where DI is dekadal average drought index for the season; M is the average of the ratio of dekadal effective rainfall to dekadal reference evapotranspiration for each season; Z is the long-term average ratio of dekadal effective rainfall to dekadal reference evapotranspiration and S is standard deviation from the average ratio of the long-term dekadal effective rainfall to dekadal reference evapotranspiration.

A drought index above 1 was set at 1 because excess water was considered as loss. This assumption is particularly valid in shallow soils with low water-holding capacity as is the case in northern Ethiopia. The season was deemed to be dry when DI was <−0.5 and/or when the number of wet dekads was less than 6 for Maychew, Mekelle and Adigudom and less than 5 for Alamata (due to the effect of high temperature on shortening of the growing period); it was deemed to be a normal season when DI was >−0.5 and when the number of wet dekads was ≥5; and wet when DI was >0.5 and when the number of wet dekads was >7.

The following conditions were also considered: seasons shorter than 6 wet dekads in Maychew, Mekelle and Adigudom were considered to be crop failure seasons. In the Alamata area, the crops mature earlier due to the high temperature, so here seasons shorter than 5 wet dekads were considered to be failures. We designated seasons with <6/5 and >5/4 wet dekads as 1st class short growing seasons (1st CSGS). They have a small number of growing days that can lead to yield reduction or yield loss but do enable the farmers to obtain some biomass yield for their livestock. By contrast, season's ≤5/4 wet dekads were deemed to be total failures ("total rain failure") and grouped in this study as 2nd class short growing season (2nd CSGS).

A time series (1978–2008) trend analysis was carried out on the basis of the calculated drought indices.

2.6. Irrigation need

Before estimating irrigation water requirement of teff and barley, we analyzed the length of growing period (LGP) for teff and barley at the stations in the study area, because knowledge of the LGP would help calculate the crop water requirement for the period during which the crop is in the field. The LGP of the crops was estimated from their degree days and interviews with farmers. Teff and barley require about 85–90 days (920–1105 degree days) to mature (Araya et al., 2010a,b,c). Degree days (Eq. (6)) were calculated as presented in McMaster and Wilhelm (1997):

$$DD = \sum_{i}^{n} \left[\frac{T_{\max} + T_{\min}}{2} - T_b\right] \tag{6}$$

where DD is the accumulated degree day (°C day); $\sum_{i...n}$, is accumulation from day of planting to maturity; $T_{\min}$ is the mean minimum daily air temperature (°C); $T_{\max}$ is the mean maximum daily air temperature and T_b is the base temperature below which crop development does not progress (°C). T_b was assumed to be 7 °C (unpublished).

Dekadal crop water requirement for teff and barley from planting to maturity was then calculated as:

$$ET_c = k_c \times ET_o \tag{7}$$

where ET_c is dekadal crop water requirement (mm); k_c is crop coefficient and ET_o is dekadal reference evapotranspiration (mm). Irrigation water requirement was computed as:

$$In = ET_c - DR_{75\%} \tag{8}$$

where In is irrigation water requirement (mm); $DR_{75\%}$ is the 75% dependable rainfall for the dekad (Garcia et al., 2003).

3. Results

3.1. Dry spells and rainfall variability

Table 2 shows the long-term mean dekadal effective rainfall and coefficient of variation for the stations in the study area. A CV > 30% is an indicator of large rainfall variability. The decadal rainfall variability in the study area was high.

Probabilities of receiving a minimum of 10, 20, 30, 40, and 50 mm of effective rainfall per dekad are presented in Fig. 2a–d. The mean seasonal dekadal reference evapotranspiration was 52 mm for Alamata, 41 mm for Maychew, 38 mm for Mekelle and 38 mm for Adigudom. The probability of receiving more than 40 mm effective rainfall per dekad at most of the stations ranged from 20 to 50% for dekads in July, 40–70% for dekads in August, and 0–30% for dekads in September. At Mekelle station the probability of receiving more than 40 mm effective rainfall in the dekads in August was higher than in the other three stations. At all stations the probability of receiving 40 mm effective rainfall in the dekads in September was lower.

Table 3 shows probability of occurrence of a dry dekad below the threshold limits of 10, 20, 30, 40 and 50 mm effective rainfall for the four stations. For most of the stations in the study area, at least 20 mm of effective rainfall in a dekad was considered to be the threshold for meeting the 50% dekadal evapotranspiration. Any reduction or increment beyond this threshold level demonstrated

Table 2
Long-term (1978–2008) mean dekadal effective rainfall and coefficient of variation for four rainfall stations in north Ethiopia.

Month	Dekad	Alamata			Maychew			Mekelle			Adigudom		
		Effective rainfall (mm)	SD (mm)	CV (%)	Effective rainfall (mm)	SD (mm)	CV (%)	Effective rainfall (mm)	SD (mm)	CV (%)	Effective rainfall (mm)	SD (mm)	CV (%)
	J1	20	22	110	25	21	87	41	28	70	27	21	77
July	J2	26	21	82	38	30	78	42	21	49	42	29	69
	J3	41	38	94	50	35	70	65	38	59	55	38	69
	A1	51	31	61	55	26	48	60	30	50	56	43	77
August	A2	52	35	68	56	35	62	57	33	57	58	47	81
	A3	43	30	69	43	28	64	51	33	64	49	40	81
	S1	20	16	79	24	17	70	22	27	121	27	29	107
September	S2	8	7	95	14	13	92	4	8	171	3	7	261
	S3	12	11	89	12	17	135	1	1	142	1	2	327
Summer seasonal mean		29.8	23.8	84.8	34.9	25.9	82.8	37.9	22.1	80.6	34.1	27.9	139.2

how the frequency of a dry or a wet dekad changes with the amount of effective rainfall. Assuming 20 mm as threshold limit, the probability of a dry dekad occurring at the stations in July and August varied from 20 to 64% in Alamata; from 15 to 43% in Maychew; from 0 to 27% in Mekelle; and from 17 to 48% in Adigudom, whereas the probability of occurrence of a dry dekad for the dekads in September over the corresponding stations were 64–100% in Alamata; 48–82% in Maychew; 59–100% in Mekelle and 47–100% in Adigudom. At all stations the probabilities of occurrence of dry dekad increased sharply after the 2nd dekad of September and was higher at Mekelle and Adigudom (83–100%) than at Alamata and Maychew (55–76%).

Fig. 3 shows three levels of dependable rainfall for all the stations: 25% (the rainfall equaled or exceeded in 1 out of a total of 4 years), 50% (the rainfall equaled or exceeded in 2 out of a total of 4 years) and 75% (the rainfall equaled or exceeded in 3 out of a total of 4 years). Although 9 dekads were analyzed, the numbers of wet dekads in the study area were <8. The rainfall received in three out of 4 years (75% dependable) was lower than the mean reference evapotranspiration for the respective dekad in at least 7 of the 9 growing dekads, except for the Mekelle station which met this condition for only 4 dekads. The number of dekads during which the 50% dependable rainfall exceeded reference evapotranspiration was 3 for Alamata, 4 for Maychew, 6 for Mekelle and 5 for Adigudom. This implies that the rainfall received per dekad has been unreliable and too low to meet the water requirement of most cereals. Mekelle station meets the condition in 6 dekads out of the 9 growing dekads and received more rainfall than the other stations, whereas at Alamata the condition was met in only 3 of the 9 growing-season dekads.

Fig. 4 shows time series of mean annual drought indices. The early 1980s were drought years (indices −0.6 to −1.5) while the 1990s and later were normal. In most years after 1990, the pattern and trend of the drought indices were similar for all stations, but before 1990 there were different patterns for the different stations.

3.2. Onset, cessation, length of growing period and crop failure

Probabilities for onset, cessation and length of growing period, calculated for the period 1978–2008, are presented in Table 4. The farmers' sowing practices were compared with the analyzed onset and it was found that the analyzed onset agreed well with the farmers' sowing practice. The onset at Mekelle was less variable than that at the other stations; the onset at Alamata was the most variable. According to the survey, the farmers' sowing practices can be grouped into three: July 1–10 (early); July 11–20 (normal) and July 21–30 (late). In contrast to the Alamata and Maychew areas, in the Mekelle area farmers do not deliberately sow late: they sow late only if they do not have enough labor or oxen to sow on time.

The most frequent cessation of growing period was September 1–10. The cessation of growing period over the study area was more variable than the onset of the growing period. Contrary to the findings for the onset of growing period, at Alamata the cessation of growing period was less variable than at the other stations. Early cessations were more frequent at Mekelle than at the other stations.

The LGP of the major crops (teff and barley) was calculated to be 60 days at Alamata, 87 days at Maychew, and 85 days each at Mekelle and Adigudom. The LGP calculated from the degree days agreed well with the actual duration of crop-growing period in the study area. However, the length of growing period (LGP) for the major crops grown in the study area was too long to match the long-term season LGP analyzed on the basis of the difference between onset and cessation. For example, teff and barley require more than 80 days (from sowing to maturity) but most of the analysis of length from onset to cessation falls below 70 days.

Table 5 shows percentages of occurrence of drought, normal and wet seasons over the past years as determined with the technique described in Section 2.5. The estimated crop failure due to drought was 50% at Alamata, 48% at Maychew, 36% at Mekelle and 59% at Adigudom (Table 5). Dry spells can occur at any time between sowing and maturity. Long and frequent dry spells at sowing and/or during flowering time may drastically reduce the crop yield. The contribution of dry spell to crop failure was 8% at Alamata, 23% at Maychew, 40% at Mekelle and 8% at Adigudom stations (Table 6). Obviously, false starts resulting from early season dry spells also contributed to the total crop failure: in the study area the contribution was up to 20%.

The contribution of the 1st class shortening of growing period to crop failure was about 31% at Alamata, 46% at Maychew, 50% at Mekelle and 23% at Adigudom. The early cessation of growing period contributed to 1st class shortening of growing period about 33% at Alamata, 17% at Maychew, 67% at Mekelle and 63% at Adigudom whereas the late start of rain contributed to 1st class shortening of growing period about 58% at Alamata, 63% at Maychew, 25% at Mekelle and 38% at Adigudom.

The contribution of the 2nd class shortening of growing period to crop failure was 61% at Alamata, 31% at Maychew, 10% at Mekelle, and 69% at Adigudom. At Mekelle there was more 1st class shortening of growing period and less 2nd class shortening of growing period than at the other stations in the study area.

The three variables for crop failure, "short growing period", "dry spell" and "total failure of rain" that were mentioned by the farmers were ranked differently across the stations (Table 7). We compared our data with the farmers' ranking and found strong agreement (the ranking of all classes agreed for all stations). There was also excellent correspondence between the long-term observed and calculated drought assessment results (Table 8). The analysis showed that the droughts over the early 1980s in the study area were continuous. Hence, the primary cause of the famine of the 1984/85 was cumulative effect of drought during the previous years and the

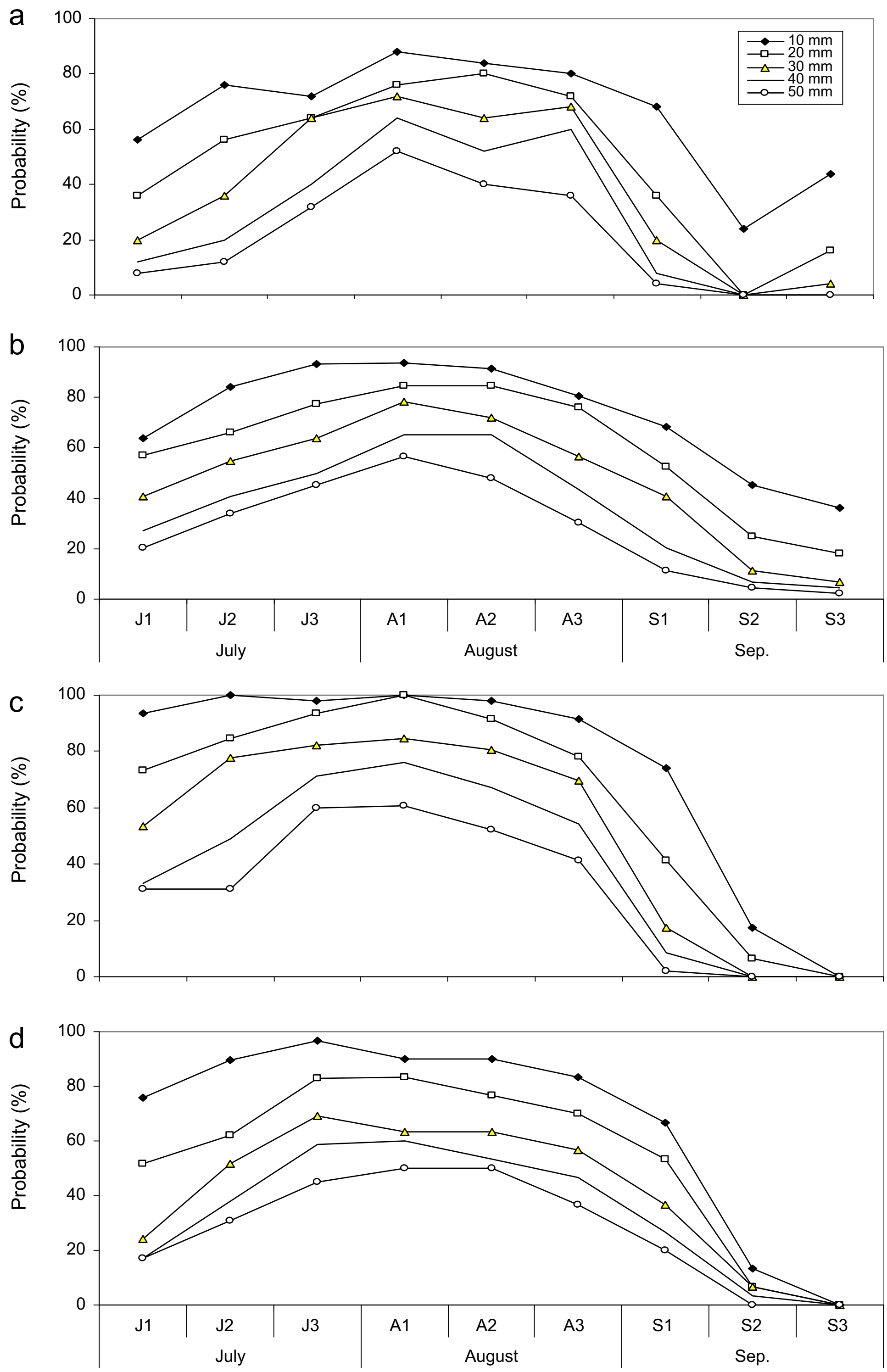

Fig. 2. Probabilities (%) of receiving a minimum of 10, 20, 30, 40, and 50 mm rainfall in a dekad during the growing season (July–September) for four stations in north Ethiopia: (a) Alamata, (b) Maychew, (c) Mekelle and (d) Adigudom.

year under consideration. The Mekelle area was less affected by such drought (Table 8) than the other three stations.

3.3. Irrigation need

The dekadal irrigation water requirement of teff and barley is presented in Fig. 5a and b and Table 9. Teff and barley need more irrigation water in the dekads in September than in the other months for all stations except Alamata. For example, the irrigation water requirement for the dekads in September for barley and teff ranged between 10 and 30 mm, while the irrigation water requirement for the dekads in August was estimated to be less than 10 mm and for the dekads in July ranged between 0 and 20 mm, except at Alamata.

Of the total irrigation water requirement in the growing period, the proportion required by teff in September was 0% at Alamata,

Table 3
Probabilities (%) of occurrence of a dry spell in a dekad below a threshold limits of 10, 20, 30, 40 and 50 mm effective rainfall for four stations in north Ethiopia.

Month	Dekad	Alamata					Maychew				
		10 mm	20 mm	30 mm	40 mm	50 mm	10 mm	20 mm	30 mm	40 mm	50 mm
July	J1	44	64	80	88	92	36	43	59	73	80
	J2	24	44	64	80	88	16	34	45	59	66
	J3	28	36	36	60	68	7	23	36	50	55
August	A1	12	24	28	36	48	7	15	22	35	43
	A2	16	20	36	48	60	9	15	28	35	52
	A3	20	28	32	40	64	20	24	43	57	70
September	S1	32	64	80	92	96	32	48	59	80	89
	S2	76	100	100	100	100	55	75	89	93	95
	S3	56	84	96	100	100	64	82	93	95	98
Month	Dekad	Mekelle					Adigudom				
		10 mm	20 mm	30 mm	40 mm	50 mm	10 mm	20 mm	30 mm	40 mm	50 mm
July	J1	7	27	47	67	69	24	48	76	83	83
	J2	0	16	22	51	69	10	38	48	62	69
	J3	0	7	18	29	40	3	17	31	41	55
August	A1	0	0	15	24	39	10	17	37	40	50
	A2	2	9	20	33	48	10	23	37	47	50
	A3	9	22	30	46	59	17	30	43	53	63
September	S1	26	59	83	91	98	33	47	63	73	80
	S2	83	93	100	100	100	87	93	93	97	100
	S3	100	100	100	100	100	100	100	100	100	100

51% at Maychew, 98% at Mekelle and 67% at Adigudom. Each of the three dekads in September constituted about 10–41% of the teff total irrigation water need in the season. Compared with the other stations, the Alamata area required a larger proportion of the total water requirement in the growing period in July. At Alamata, the irrigation water requirement in September was zero (Table 9) because the crop had already matured in early September due to the fast development enhanced by high temperatures.

For barley, out of the total seasonal irrigation needs, the proportion of irrigation water requirement in September was 0% at Alamata, 60% at Maychew, 92% at Mekelle and 72% at Adigudom. The dekadal irrigation water requirement for barley over the growing period for the study area is presented in Fig. 5b. Generally, the total irrigation water need of teff and barley was substantially lower at Mekelle than the other stations.

4. Discussion

4.1. Drought and rainfall characteristics

Rainfall over northern Ethiopia has been known to be variable (Meze-Hausken, 2004; Segele and Lamb, 2005) and not enough to meet the crop water demand (Araya et al., 2010b). This study also found great rainfall variability (CV more than 30%) and in most of the cases, the dekadal 75% dependable rainfall during the crop growing period was lower than the dekadal ET_o which means that to secure their harvests, farmers need to explore the options for supplementary irrigation.

Some previous rainfall trend reports have indicated a declining trend of *Kiremt* rains (June–September) in north central and central Ethiopia (Seleshi and Dameree, 1995; Osman and Sauerborn, 2002). However, Conway (2000), Seleshi and Zanke (2004), Meze-Hausken (2004) and Seleshi and Camberlin (2006) reported an absence of a declining trend in northeastern, northwestern and central parts of the country. Bewket and Conway (2007) did not find a consistent trend in daily rainfall characteristics over the Amhara region of northern Ethiopia either. However, the results of these studies were affected by the number of years and the type of years chosen for the analysis (Bewket and Conway, 2007). The indices we calculated with the drought assessment technique described in this paper showed a decreasing trend in the 1970s and 1980s and a normal to slightly above average trend in the years after 1990 (Fig. 4). In addition, data for the 1960s at one of the stations (Mekelle) indicated that the trend in that decade was very different from the trend in the 1970s and 1980s (data not shown).

Most of the major meteorological factors that contribute to rainfall variability over Ethiopia are not well known. Recently some studies have been carried out to elucidate the large-scale factors influencing Ethiopian rainfall (Bewket and Conway, 2007). For example, some studies showed an association between the El Nino-Southern Oscillation (ENSO) and sea surface temperatures (SST) and *Kiremt* rainfall (Gissila et al., 2004; Segele and Lamb, 2005; Korecha and Barnston, 2007; Diro et al., 2010). Segele and Lamb (2005) verified that normal *kiremt* onset and variable cessation in the northeastern Ethiopia were associated with neutral ENSO years whereas warm ENSO events were correlated with late onset of *kiremt* and a short growing period. They also found that *kiremt* cessation anomalies were associated with SST in the nearby western Indian Ocean and Arabian Sea, such that late *kiremt* cessation of rain correlates more strongly with warm SST in the western Indian Ocean and Arabian Sea than with the SST of the Atlantic Ocean.

4.2. Effect of length of growing period

One of the essential features of the Ethiopian *Kiremt* season is the northward movement of the inter-tropical convergence zone (ITCZ) (Segele and Lamb, 2005; Korecha and Barnston, 2007). The southeasterly trade winds blowing across the equator in the eastern Atlantic Ocean and western Indian Ocean arrive in Ethiopia as southwest monsoons (Shanko and Camberlin, 1998). In early September, the weather system is characterized by weakening of the eastern Atlantic and western Indian Ocean monsoon system and the cessation of rains due to the southward retreat of the moist and unstable air mass, ITCZ. The dominance of the dry northeasterly winds towards northern Ethiopia increases after early September. Segele and Lamb (2005) have stated that most of the dry spells in northeastern Ethiopia occur towards the end of the growing period, particularly in September. A shorter growing period exposes the critical flowering and yield formation stage of crops to long dry spells (Araya et al., 2010b), resulting in substantial yield losses.

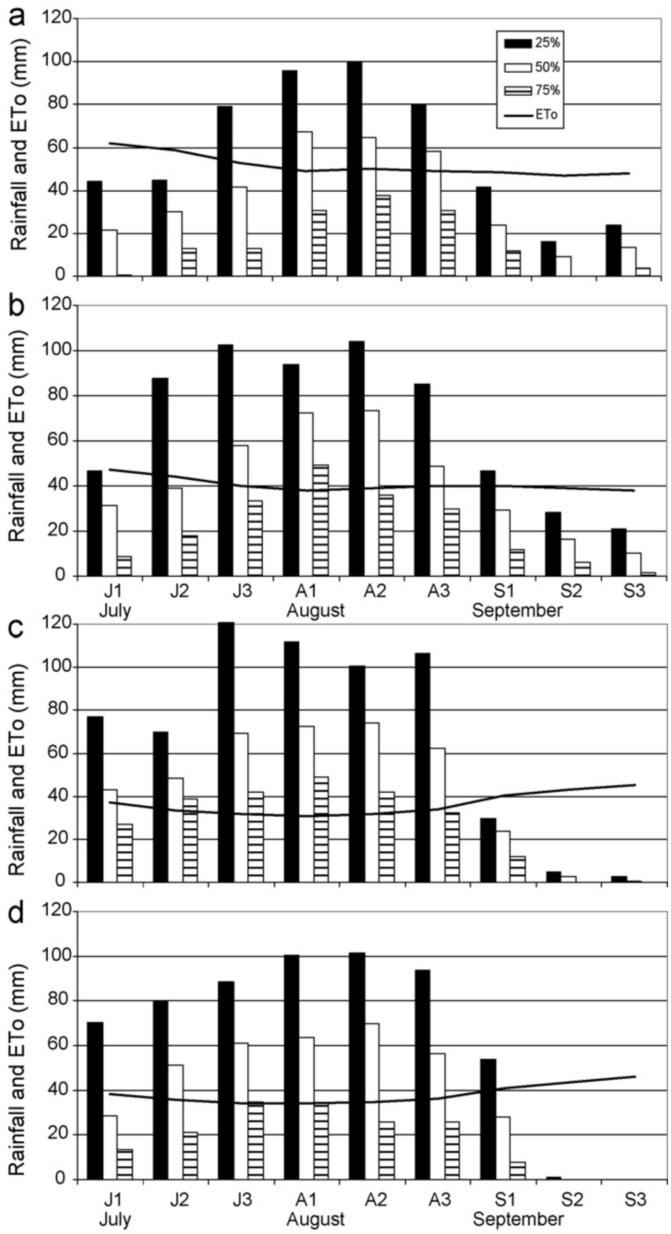

Fig. 3. Long-term (1978–2008) 25%, 50% and 75% dependable rainfall versus mean dekadal reference evapotranspiration for (a) Alamata, (b) Maychew, (c) Mekelle and (d) Adigudom in north Ethiopia.

To fully characterize and understand the climate, especially the nature and occurrence of drought over northern Ethiopia, the characteristics of the seasons in terms of the onset and cessation of rains, the length of growing period and the occurrence of dry spells were assessed. Onset of rain over the study area was less variable than the cessation. Segele and Lamb (2005) also described the *Kiremt* onset in northeastern Ethiopia, which includes the study area, as the latest and least variable in the country. The most frequent onset over the study area is from July 1 to 10. In contrast with the onset of the growing season, its cessation is more variable over the study area. This agrees with the finding by Tessema and Lamb (2003) that from1965 to 1999 the timing of the cessation of rain varied in the northeast part of the country that includes the study area. We found higher probabilities of early cessations over the study area in general. The impact of this was more pronounced at Mekelle and Adigudom than at the other two stations. It seems that the shortening of the growing period as a result of early cessation is a major cause of yield reduction and crop failure in the study area. This conclusion is backed up by the farmers ranking the shortening of the growing period as the main factor limiting crop production.

Table 4
Probabilities (%) of the long-term (1978–2008) onset and cessation of rainy period.

Growing season	Dekad	Alamata	Maychew	Mekelle	Adigudom
Onset	July1–10	24	41	89	50
	July 11–20	28	22	11	18
	July 21–30	20	11	0	11
	Failure	24	26	0	21
Cessation	August 21–30	25	18	41	25
	September 1–10	46	43	44	46
	September 11–20	4	7	4	4
	September 21–30	0	4	11	4
	Failure	25	28	0	21

Failure: Is a season with very poor rainfall distribution (no onset and cessation).

In Section 2.5 the short growing periods were subdivided into 1st and 2nd class short growing periods. The 1st class short growing season is rain failure that can lead to reduction or loss of yield but allows farmers to obtain some crop biomass for their livestock. A 2nd class short growing seasons is one with total rain failure that results in total crop failure; these are less frequent than the 1st class ones. If consecutive 2nd class short growing seasons occur, the result may be famine, as happened in 1984/85. The 2nd class short growing seasons are probably the result of larger scale or global climate influence, whereas the 1st class short growing seasons are frequent and are less intense and can be mitigated more easily. First class short growing seasons were more frequent at Mekelle, whereas the 2nd class short growing season was more pronounced at Alamata and Adigudom stations.

Most of the devastating north Ethiopian drought years that occurred during 1979–1987 were caused by the 2nd class short growing seasons ("total rain failure"). The contribution of 2nd class short growing seasons to crop failure during the long-term observations in the study area ranged between 10% and 69% and was least for Mekelle and most for Adigudom (Table 6). In Alamata and Adigudom, the prime cause of crop failure was "total rain failure" (2nd class short growing season). The total rain failure might have resulted from a shift in seasonal rainfall due to large-scale climate influence, but the fact that the stations were not uniformly affected at the same scale suggests that small-scale climate influences could also be important. The total rain failure (2nd class growing season) in the early 1980s was very severe and the population was very vulnerable due to the cumulative effect of consecutive rain failure. Millions of Ethiopians were affected and nearly a million people died of famine in 1984/85. Over half of the victims of this drought were from the study area (unpublished data). Almost all the farmers in the study area, particularly in Alamata and Maychew areas, reported that the effects of the famine were exacerbated by other factors. Governance was poor: there was poor preparedness for disaster – even foods pledged from donors were suspended; the movement of relief workers was restricted; and most people were discriminated against and neglected (associated as supporters of the opposition group). The low economic status of the rural population increased their vulnerability to the risk. The lack of knowledge about how to avoid risk was also a factor.

4.3. Dry spell and false start

In previous studies, a dry spell has had various definitions in terms of the time of occurrence and effect, depending on the purpose of the study. We studied dry spells in dekads because of the importance of these 10-day periods in crop production. A dry spell of 10 days in the study area causes great stress to crops because

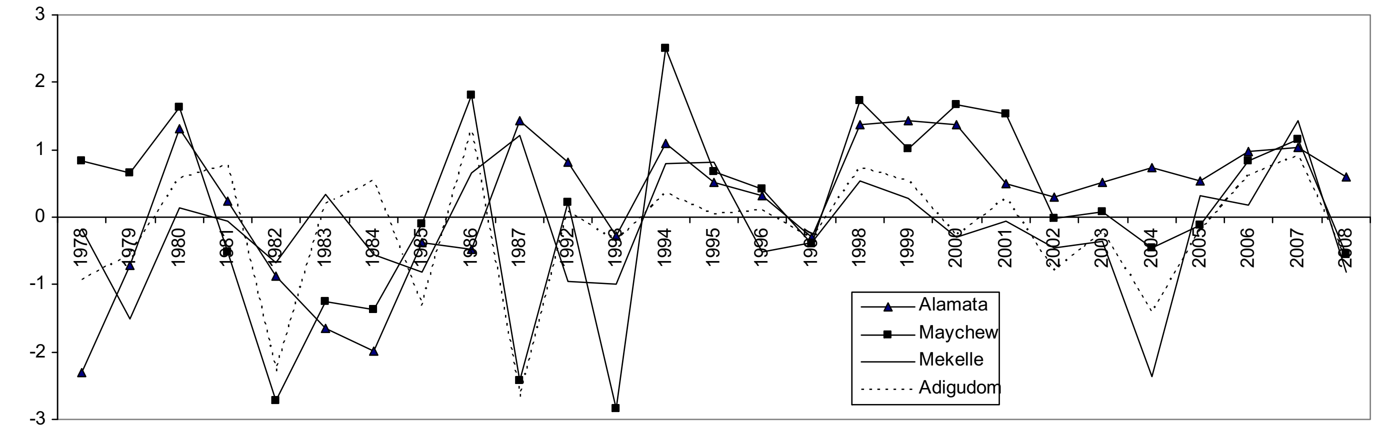

Fig. 4. Time series mean (1978–2008) dekadal drought indices for four rainfall stations in northern Ethiopia: (filled triangle, Alamata; filled box, Maychew; straight line, Mekelle; doted line, Adigudom).

Table 5
Percentage of occurrence of drought, normal and wet years determined using the technique described in the text (Section 2.5).

Stations	Drought	Normal	Wet	Years
Alamata	50	43	7	1978–2008
Maychew	48	41	10	1978–2008
Mekelle	36	61	4	1978–2008
Adigudom	59	36	5	1978–2008

the water-holding capacity of the soils has been reduced by severe land degradation (Hurni, 1990; Nyssen et al., 2000). A dry dekad may occur any time between the onset and the cessation of the rainy season. It can be expressed in terms of percent frequency of dry dekad below a given threshold amount of effective rainfall received (mm). Table 3 shows the probabilities of occurrence of a dry dekad under threshold rainfall limits of 10, 20, 30, 40, and 50 mm rainfall. Regardless which threshold limit is chosen, the results showed that a dry dekad is less likely to occur in August than in July and September. Despite the extremely low probability that dry spells would occur at Mekelle (Table 3), dry spells were the 2nd most important agro-meteorological variable causing crop failure, ranked only after 1st class short growing season. This study showed that about 36% of the long-term seasons in the Mekelle area were in drought years (Table 5). In these drought years, dry spells contributed to about 40% of the crop failure that occurred at the station (Table 6). Longer dry spells may be related to large-scale or small-scale weather systems. Segele and Lamb (2005) verified that long and consecutive dry spells were strongly related to major downturn in dew point, abnormally high temperatures, and easterly winds throughout the troposphere beneath a weak tropical easterly jet. The increased probability of dry dekads at all the stations in late August and thereafter might be related to southward shift of the inter-tropical convergence zone (ITCZ).

In Zimbabwe and Kenya, crop failure due to false start has been evaluated with a relative transpiration and evapotranspiration rate over a 30-day period following sowing (Raes et al., 2004; Kipkorir et al., 2007; Mugalavai et al., 2008). We evaluated the risk of a false start in a given season by determining the $D_{\mathrm{Eff}}/D_{\mathrm{ETo}}$ in the onset dekad and in the dekads following the onset. An onset dekad with indices >0.5 followed by dekad/s with indices <0.5 was assumed to result in false start. Since farmers in the study area sow their crops in dry soil, the result indicated higher probability of false starts. The risk of a false start was reported to be about 9.9% in Kenya (Kipkorir et al., 2007) but as much as 20% at one of our stations (Maychew), the lowest being 8% for the Alamata and Adigudom stations. Though resowing is an option, the growing period will be shorter. Our study confirms earlier findings of high frequencies of false starts in north eastern Ethiopia (Araya, 2005).

4.4. The new drought assessment technique

The established relationship of effective rainfall and reference evapotranspiration together with the number of wet dekads in a given season seems to be a suitable and a reliable indicator of crop failure over the years. There was an excellent relationship between the observed indices (information obtained from farmers and documents) and the calculated indices (see Table 8, Maychew and Mekelle). The technique uses easily accessible information such as rainfall, average runoff, evaporating power of the atmosphere and the number of wet dekads in a particular season. To produce reliable results, the numbers of wet dekads over that season must be related to the length of growing period for the commonest crops. The technique is more suitable where soil water-holding capacity has been reduced due to land degradation, as is the case in our study area.

4.5. Supplementary irrigation needs

Crops suffer from various lengths of dry spells because (1) the rainwater is not available due to low soil water-holding capacity as a consequence of land degradation (Stroosnijder, 2009); (2) the rainy season is too short when compared to the length of crop grow-

Table 6
Percentage of contribution to total crop failure of the three variables, “short growing period”, “dry spell” and “total failure of rain” determined using the technique described in the text (Section 2.5).

Stations	Short growing season (1st CSGS)	Dry spell	Total failure of rain (2nd CSGS)
Alamata	31	8	61
Maychew	46	23	31
Mekelle	50	40	10
Adigudom	23	8	69

Table 7
Farmers’ rankings of the three variables “short growing period”, “dry spell” and “total failure of rain” causing crop failure in north Ethiopia.

Causes of crop failure	Alamata	Maychew	Mekelle	Adigudom
Short growing period (1st CSGS)	2	1	1	2
Dry spell	3	3	2	3
Absence of rain (2nd CSGS)	1	2	3	1

1 = very severe; 2 = moderately severe; 3 = slightly severe.

Table 8
Calculated and observed seasonal anomalies in relation to crop performance at two stations in north Ethiopia. The calculated results are based on the drought indices and NWD values whereas the observed results are based on information from farmers and other documents. Note that 1984 at Mychew is the 4th consecutive dry year with crop failure.

Year	Maychew				Year	Mekelle			
	Indices	NWD	Calculated	Observed		Indices	NWD	Calculated	Observed
1953	0.9	7	N	S	1960	1.0	8	W	S
1954	1.6	8	W	S	1961	0.8	7	N	S
1955	−1.8	2	D	F	1962	0.6	7	N	S
1956	1.1	9	W	S	1969	0.7	7	N	S
1957	−0.3	5	D	F	1970	0.2	6	N	S
1958	0.1	6	N	S	1971	−0.6	6	D	F
1959	1.2	9	W	S	1972	0.2	7	N	S
1961	0.6	7	N	S	1973	0.1	6	N	S
1964	1.0	7	N	S	1974	−1.1	5	D	F
1965	0.2	5	D	F	1975	0.9	8	W	S
1971	−1.7	2	D	F	1976	0.8	8	W	S
1972	−1.0	2	D	F	1977	1.1	8	W	S
1973	0.3	6	N	S	1978	−0.2	6	N	S
1974	0.0	6	N	S	1979	−1.5	6	D	F
1975	−3.0	0	D	F	1980	0.1	6	N	S
1976	0.5	6	N	S	1981	−0.1	6	N	S
1977	0.7	7	N	S	1982	−0.7	6	D	F
1978	0.4	7	N	S	1983	0.3	7	N	S
1979	0.3	5	D	F	1984	−0.6	6	D	F
1980	0.8	6	N	S	1985	−0.8	5	D	F
1981	−0.3	4	D	F	1986	0.5	6	N	S
1982	−1.4	1	D	F	1987	0.7	7	N	S
1983	−0.6	5	D	F	1988	1.2	7	N	S
1984	−0.7	3	D	F	1992	−1.0	5	D	F
1985	0.0	5	D	F	1993	−1.0	5	D	F
1986	0.9	9	W	S	1994	0.8	7	N	S
1987	−1.2	2	D	F	1995	0.8	7	N	S
1991	0.1	5	D	F	1996	−0.6	6	D	F
1992	0.1	6	N	S	1997	−0.4	6	N	S
1993	−1.4	1	D	F	1998	0.5	7	N	S
1994	1.3	7	N	S	1999	0.3	7	N	S
1995	0.3	6	N	S	2000	−0.3	6	N	S
1996	0.2	6	D	S	2001	−0.1	6	N	S
1997	−0.2	4	D	F	2002	−0.4	7	N	S
1999	0.5	7	N	S	2003	−0.3	5	D	F
2000	0.8	7	N	S	2004	−2.4	4	D	F
2001	0.8	8	W	S	2005	0.3	7	N	S
2002	0.0	5	D	F	2006	0.2	7	N	S
2003	0.0	6	N	S	2007	1.4	8	W	S
2004	−0.2	5	D	F	2008	−0.8	6	D	F
2005	−0.1	4	D	F					
2006	0.4	5	D	F					
2007	0.6	7	N	S					
2008	−0.3	3	D	F					

NWD = number of wet dekads, D = dry season, N = normal season, W = wet season, S = success crop, F = failure crop.

ing period; (3) the rainfall is far below normal or is totally absent (total rain failure).

To mitigate the effect of dry spells, to avoid a false start and to prolong the growing period, supplementary irrigation can be used. The irrigation water need should be calculated taking account of rainfall, reference evapotranspiration, crop development and soil type (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979). Accordingly, we tried to assess the irrigation requirement of the two major crops in the study area.

The main reasons that the total irrigation water requirement of teff and barley in July was higher at Alamata than at the other stations (Table 9) were: (1) the relatively low amount and erratic nature of rainfall and (2) the high daily temperature and, hence, the high evaporative demand in Alamata compared to that at the stations with lower temperatures.

Although the percent of irrigation water requirement at Mekelle for the month of September was higher than for the other stations, the amount of irrigation water needed in Mekelle was nearly half of what was needed in Maychew and Adigudom because at Mekelle the rainfall in July and August is higher and better distributed than at the other stations. Supplementary irrigation is advised for the three stations (Maychew, Mekelle and Adigudom) during the month of September because: (1) most frequently rain ceases in early September or in late August (that is during flowering and yield formation which is the most sensitive period of the crop to water stress) and crops have no other source of water for the remaining part of growing period; (2) sufficient runoff can be harvested in July and August to be stored in ponds for irrigation during the month of September (Araya et al., 2006); (3) larger areas of cultivable land can be irrigated if the supplementary irrigation is scheduled only for September and (4) with the exception of Alamata, more than 80% of the yield reduction and more than 50% of the crop failure can be avoided when the rainwater in the season is integrated with the provision of supplementary irrigation in September (flowering and yield formation period). Over 50% of the drought years (in the three stations) were resulted from water stress that occurred at the critical period of the crop (in September). In the case of Alamata, supplementary irrigation must be scheduled in the month of July.

In every season, surface runoff can be collected using household ponds for supplementary irrigation. The average gross capacity of

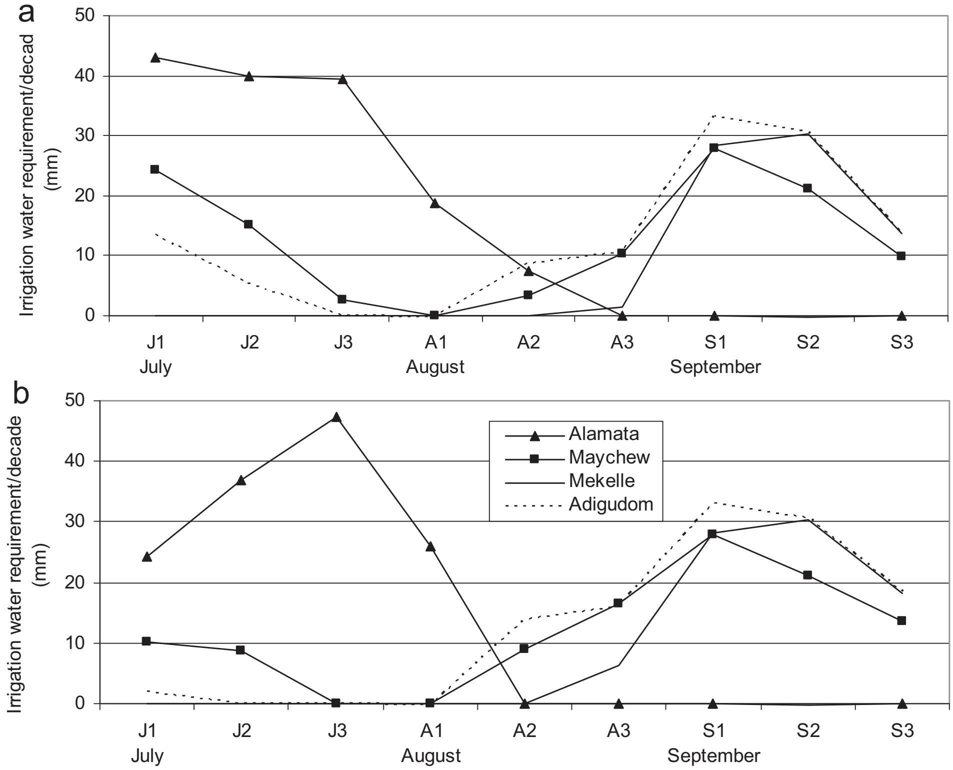

Fig. 5. Dekadal irrigation water requirement for 4 stations in north Ethiopia, (a) for tef and (b) for barley.

a household pond constructed in the study area is about 180 m^3 (Araya et al., 2006). Given the conventional systems used, this amount could be enough for an area of 0.08–0.1 ha if the supplementary irrigation is planned to be applied for the month of September only. Under present conditions, irrigation in Ethiopia is limited to some vegetable and fruit crops because the water use efficiency of the main cereal crops is less than that of vegetables (Araya et al., 2006). But crop production needs to be intensified by introducing modern water supply and application systems to cereals as well.

False starts could be avoided by irrigating crops during their establishment. However, if farmers have limited access to water for irrigation at the beginning of the rains, they should delay sowing until rainfall meets more than half of the evaporative demand of the atmosphere (at least the top 10–20 cm should be moist) or they should irrigate.

Growing quickly maturing cash crops such as chickpea may also help to avoid complete failure because they normally grow at the end of growing period, utilizing unused soil water reserves. Such crops are recommended when the seasonal rain starts too late and when there is little possibility for irrigating the crops.

Table 9
Seasonal irrigation requirements (mm) and the percent of water requirement in July, August and September for teff and barley in north Ethiopia.

Crop	Units	Alamata	Maychew	Mekelle	Adigudom
Tef	Total seasonal irr. water req. (mm)	148	115	74	115
	July (%)	83	37	0	16
	August (%)	18	12	2	17
	September (%)	0	51	98	67
Barley	Total seasonal irr. water req. (mm)	135	107	83	114
	July (%)	81	18	0	2
	August (%)	19	24	8	26
	September (%)	0	60	92	72

5. Conclusions

Our method to assess drought risk proved to be a suitable and reliable indicator of crop failure, especially for areas where the soil's water-holding capacity has been reduced by land degradation, as is the case in north Ethiopia. There was a good correlation between the observed information (obtained from farmers and documents) and the data we analyzed.

In the period 1978–2008, about 36–59% of the seasons in the study area were drought seasons (crop failure). This was attributed to three major agro-meteorological factors: (1) intra-seasonal dry spells, (2) 1st class short growing season and (3) 2nd class short growing season or total failure of rains mainly caused by shifts in large- and small-scale weather systems. Dry spells were common during the rainy season. In addition, crop failure as a result of false starts was also common. In general, the probability of dry spells causing crop failure was not as great as the risk of a too short growing period.

The most promising way to minimize drought resulting from 1st class short growing seasons and dry spells is to give supplementary irrigation in the dekads in September. More than 80% of yield reductions attributable to water stress and more than 50% of the crop failures attributable to this stress could have been avoided by irrigating adequately during the dekads in September – except in Alamata, where irrigation should have been in July. It may prove difficult for the farmers in Alamata to meet the high requirements for supplementary irrigation in July, as water resources in the area are limited, especially, if the months before July are dry. Therefore, alternative options such as groundwater need to be explored in order to meet the crop water demand in July.

Failure of rain associated with large-scale climate distortion resulted in devastating droughts in the study area in the 1980s. The 1984/85 famine was principally the effect of the year-to-year cumulative occurrence of 2nd class short growing seasons. It is unlikely that the droughts during the early 1980s at the Alamata and Maychew stations could have been mitigated by supplementary irrigation in only the month of July or September.

For optimal use of rainwater, we recommend that farmers sow their crops after the soil has received enough moisture and that in the Maychew, Mekelle and Adigudom areas they give their crops supplementary irrigation in September. Growing quickly maturing crops will enable the farmers to better utilize the rains in the growing period. We strongly advise extension workers and other responsible government bodies to follow these recommendations.

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