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Assessment of measured and estimated meteorological data in terms of sorghum production on the example of Hamelmalo, Eritrea

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Abstract: Eritrea is exposed to climate variability and extreme events like drought and precipitation variability. Hamelmalo, a sub region in Eritrea, suffers from all the problems brought by climate change, especially because local people mainly depend on rainfed agriculture. I it is difficult to conduct climate related research activities for the region due to the shortage of meteorological data. However, in 2015, a new, complete meteorological station was established providing the chance of the first observations for practical and scientific purposes. The main objective of this study was to evaluate some climatic parameters from crop productional point of view by comparing the observed values with ones calculated by the Local Climate Estimator (LCE) model. Chi-square test was used to statistically analyse the differences. Based on the results, all the studied climatic parameters, except for precipitation, were almost on a par, which means there were no statistically significant differences between the observed and the estimated values. It can be concluded that the most variable climatic parameter in Hamelmalo is precipitation and this also affects the climatic water balance hence the need for irrigation if higher yields are wanted to be achieved. Sufficient water is vital in the mid-season and the late developmental stage of sorghum. Therefore, sowing time is advised to be adjusted to early July to ensure the maximum vegetative growth and seed setting period to be reached at the end of August in order to take the advantage of the positive climatic water balance of these two months.

Keywords: climate change, meteorological data, sorghum production, Eritrea

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Introduction

Since its existence, the Earth's climate has been changing. This change is sometimes faster, sometimes slower. Nowadays human activities influence not only the micro- and macroclimate, but the global climate as well (Harnos, 2003). If we want to understand the climatic status of a region, precise observations and measurements in sufficient spatial and temporal resolution are crucial (WMO, 2010). The determination of the tendencies of the changes is of great importance besides the characterization of the climatic status of a region. Sufficiently long data series as the bases of the assessments are necessary to monitor the changes and determine their tendencies (Konkolyné Bihari et al., 2008).

Humans cannot feel climate change tendencies directly as they are relatively slow. Nevertheless, the increasing frequency of the extreme meteorological events have direct and indirect impacts on society and agriculture. Not only the frequency and intensity of weather extremes are increasing, their spatial and temporal occurrence is getting more and more variable, one of the biggest challenges of our society is to accommodate to them (Zsembeli, Kovács, et al., 2019).

Just like many African countries, Eritrea is highly vulnerable to climate change (UNFCCC, 2001), especially water is the most limiting factor for crop growth in the sub-Saharan Africa (Lal, 1991). Agriculture is the top priority for economic development in the whole country as 80% of the population depend on agricultural farming and livestock (IPCC, 2007). Agriculture is the sector highly influenced by climate variability with important involvements for agricultural efficiency and food security, mainly in the developing countries like Eritrea (FAO, 2017).

As reported by Niang et al. (2014), the countries of East Africa, including Eritrea, are especially exposed to the climate variability and extreme events like drought and precipitation variability, and specifically there is a rise in minimum and maximum temperature trends with extremes and high variation in precipitation both daily and seasonally (Cattani et al., 2018). The high variation in precipitation in East Africa is due to the complicated relations of forced and free atmospheric variations (Mutai & Ward, 2000) and this is common in both Eritrea and Ethiopia, which makes the people waiting humanitarian and other organizations assistance (Sidahmed, 2017). Besides the large unevenness in precipitation, the lack of improved technologies, poor management ability, and low agricultural efficiency are characteristic in Sub-Saharan Africa (Calzadilla et al., 2009).

Hamelmalo, a sub region in Eritrea, also suffers from all the problems mentioned above where people mainly depend on rainfed agriculture for their living. In Hamelmalo, just like all over the country, sorghum is the top crop followed by pearl millet (UNFCCC, 2001). Yields are very low, for instance, the average yield of sorghum in Hamelmalo in a period with good rainfall is 0.2-0.6 t ha^{-1} (MoA, 2005). This may be due to several factors, but one of them is climate variability that can cause variation in precipitation and evapotranspiration, hence the climatic water balance. The impacts of climate change are clearly visible on the environment manifested in land degradation, desertification, worsening food security, loss of biodiversity and elongated drought, all are common in the country. The elongated droughts have a great impact on water resources, especially on drinking water, and this leads to water scarcity in the country (Eritrea, 2004).

In Eritrea, precipitation is the most variable climatic parameter with erratic, torrential, short duration, high intensity features from year to year. Two rainy seasons are characteristic in the whole country: June-September (extends from highlands to western region of the country) and October-March (covers eastern escarpments) and also there are short precipitations in April and May along with the highest precipitation records in July and August (FAO, 1994). The mean annual rainfall ranges from less than 200 mm (in the semi-desert) to 1,100 mm (in the sub-humid zone) (UNFCCC, 2001), and in the most part of Eritrea, south-western monsoon winds are the main source of precipitation during the summer and spring seasons (FAO, 1994). Mean annual temperature varies from 18 °C in the moist and arid highlands to 35 °C in the semi-desert (FAO, 2005a).

In conjunction with the shortage of precipitation, it is already proven that supplying additional irrigation water increases the yields in Hamelmalo. As reported by Tripathi et al. (2015), sorghum yield lifted to over 3.9 t ha^{-1} by applying 70 mm irrigation for 21 days after the cut-off of precipitation in September, which is much above the usual without irrigation. This observation is an accurate estimation of water and the appropriate date to save water during irrigation as an important factor for the increase of the production.

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The forecast or measurements of meteorological data used to estimate crop evapotranspiration can also provide important information for having better irrigation scheduling and controlling extreme conditions. Irrigation scheduling uses meteorological data in addition to soil and crop data for determining evapotranspiration of a crop and water balance of the soil (Todorovic, 2006). The Penman Monteith equation method also uses meteorological data from meteorological stations to calculate reference evapotranspiration (Allen et al., 1998).

In the study area of Hamelmalo, there is agricultural college with ongoing research activities concerning climate and agriculture. Nevertheless, there is a shortage of meteorological data due to the lack of meteorological stations, therefore it is difficult to conduct climate related research activities. In general, long-term climate related studies were not common in Eritrea. However, our recent study can help the researchers to have general understanding about the climate and the weather of the region as a basic reference not only for local level, but due to the similarities (Camberlin & Philippon, 2002), for the countries of the Horn of Africa.

The general aim of this study was to assess meteorological parameters if there are significant differences between the data recorded at the meteorological station of Hamelmalo and the relevant ones estimated by means of climate estimating models. As the preconception (hypothesis) of our research work, we assumed that climate is a really complex issue and cannot be definitely quantified locally only on the base of estimated meteorological data. The meteorological data were assessed from the point of view of sorghum production. Cereal crops, inclusive of sorghum, are the most influential crops for food security in the world as a whole and in particular in Eritrea, which is a food insecure country. In Eritrea, the increase of the efficiency of sorghum production will help to reduce food insecurity and improve quality of life, because sorghum accounts 50% of the total cereal production (MoA, 2010).

Materials and Methods

The study site

The study is relevant to Hamelmalo Agricultural College located at 15°52′16″ N latitude and 38°27′44″ E longitude, and at 1,278 m elevation with semi-arid climate. In Hamelmalo, 80% of its population depends on agricultural farming and livestock, which are highly sensitive to the disturbances in the climate system (IPCC, 2007). The most common crops grown in Hamelmalo, in the order of their importance, are sorghum, pearl millet, barley, maize, ground nut, wheat, and finger millet.

Terrestrial, short-duration rainfalls are characteristic that vary from year to year. So far, there was no data about the average precipitation and mean temperature for Hamelmalo. Although precipitation seems to be sufficient for resistant crops, especially for sorghum, but the yields are low owing to the serious shortage of water during the flowering or seeding period (September-October), when additional irrigation is highly needed to increase yield (Tripathi & Ogbazghi, 2010). Agriculture is mainly rainfed and exposed to climatic variability and low agricultural productivity and land degradation have become the major features of this sub-region.

Remarkable degradation including serious soil erosion, poor rain water storage, inadequate vegetation, compaction and structural degradation in over 90% of the agricultural land are characteristic to the area. Most part of the land in this region is not cultivated owing to steep slopes. The soils of Hamelmalo are loamy sand and sandy soils with dominant sand and some percentage of silt, clay, cobbles and boulders forming a porous bed, some organic matter and average bulk density of soil surface ranged from 1.54 Mg m^{-3} to 1.69 Mg m^{-3} (Tripathi et al., 2015). In general, the soils in Hamelmalo have dominantly light and medium texture.

The meteorological station of Hamelmalo has been working since 2009, but first it was only measuring the amount of rainfall, hence they were not sufficient for extended meteorological analyses. However, in 2015, a new, complete meteorological station was established according to the standards providing the chance of the first observations for scientific purposes as well as practical ones.

Acquisition of meteorological data

The data collected from the weather station of Hamelmalo cover five years of the 2015-2019 period for all the computations in this study. The data were recorded hourly except for a few months. The observed meteorological data include precipitation, temperature (mean, maximum, minimum), relative humidity, wind speed, and sunshine hours. The evaluation of the available data includes all data that are equally related to the estimated ones. The observed values of all the recorded meteorological parameters are the averages of five years measured during the investigated period of 2015-2019.

The possibility of utilizing the meteorological data recorded in Hamelmalo for any research activities, planning and designing projects is limited as short period records may not be fully representative of the prevailing climate. With the absence of long period records, Local Climate Estimator (LCE) model by FAO was used to crosscheck the observed values with the expected ones. LCE is a free online tool that can be used to estimate local climatic data for any location in the world. Climate data recorded nearly 30,000 stations worldwide are available for the estimations (Grieser et al., 2006). The expected values were obtained from the LCE after feeding the data of Hamelmalo location (latitude, longitude and altitude) into the software, which automatically calculates the estimated values of weather variables such as the ones assessed in this study: air temperature (mean, maximum, minimum), amount of precipitation, relative humidity, number of sunshine hours, and potential evapotranspiration (PET).

The model delivers three alternative values of the estimation (the best, the minimum and the highest) of the given observatory station based on the records of at least ten neighbouring observatory stations that are maximum 1,000 km away. In the case of Hamelmalo, they are Keren, Gheleb, Nakfa, Barentu, Massawa, Asmera, Adikeyih, Agordet, Faghena, Filfil, Fishey Merara, Adinfas, Mendefera in Eritrea, and Adwa and Sheraro in Ethiopia.

Calculation of potential evapotranspiration

Generally, PET can be computed by different methods. By means of precision weighing lysimeters actual evapotranspiration (ETact) can be calculated quite accurately (Zsembeli, Czellér, et al., 2019). However, these devices are not available in most of the developing countries owing to their high price and lack of expertise. In this study, observed PET values were estimated from pan evaporation because that is the instrument installed and operated in the meteorological station of Hamelmalo and there was no gap in the measurements during the investigation period (2015-2019). Pan reading can be used to calculate PET using the pan coefficient according to Equation 1.

$$PET = K_p \times E_p$$

where K_p = pan coefficient (mm day^{-1}) determined according to Doorenbos (1976); E_p = pan evaporation (mm day^{-1}).

Calculation of climatic water balance

Climatic water balance is the difference of precipitation and potential evapotranspiration determined for a defined period of time and can be calculated according to Equation 2 (Gebreyesus et al., 2021).

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$$CWB = P - PET$$

where: CWB = climatic water balance (mm); P = precipitation (mm); PET = potential evapotranspiration (mm).

Statistical analysis

Chi-square test was used to see if there is statistical similarity between the meteorological data observed in Hamelmalo and the estimated values by the LCE model. The advantages of this method are its robustness with respect to data distribution, simple calculation, data handling flexibility from two groups and complete information obtained from the test. In this study the degree of freedom was 11 (11df), which is based on the Row-1 and Column-1 system. P-value approach was compared with α. According to the rule for p-value approach, the hypothesis (H) was rejected if H value was less or equal to α and was not rejected if it was greater than α (0.05). Alternatively, it could also be compared with the critical value: if the result was above the critical value, H could be rejected, while accepted if it was less than the critical value. The analyses were performed in Microsoft Excel software by comparing the values to accept or reject H.

Results

Air temperature

Temperature is one of the most important factors determining the success of crop production, especially in terms of the frequency and duration of extremes. In Table 1, the observed and the estimated air temperature values determined for Hamelmalo are listed.

For the mean monthly maximum temperature values, based on the test, the probability level was 0.992, which means no convincing statistically proven difference among the observed and estimated values. Nevertheless, all the monthly values were overestimated by the LCE model resulting in an average mean of 36 °C contrary to the observed 34 °C.

The probability level for the mean monthly temperatures was 1, which means that statistically there were no remarkable differences between the observed and expected values (Table 1). The LCE model slightly overestimated the monthly values for January, April, May, June, August, October, November, and December, while underestimation was found for February, March, July, and September resulting in only a little difference between the observed and the estimated average means (0.2 °C).

Probability level of 0.93 was found when the mean monthly minimum temperatures were tested, which also indicates no considerable statistically proven difference between the observed and estimated values (Table 1). All the monthly values were underestimated by the LCE model resulting in an average mean of 9.9 °C contrary to the observed 11.6 °C.

Precipitation

Natural precipitation is the only water input for sorghum if it is grown under rainfed conditions. Therefore, the amount and temporal distribution of precipitation basically determines the yields of sorghum. Furthermore, the time and amount of irrigation can be planned easier if the probability of rainfall can be estimated in advance. The observed and the estimated monthly amounts of rainfall determined for Hamelmalo are compared in Table 2.

The probability level for the mean monthly amounts of precipitation was under 0.05, which means a high variation among the observed and expected values, even the average values were very similar (Table 3). The LCE model overestimated the monthly amount of precipitation for April, June, August, and October, while underestimated for March, July, September, and November. Similar values were found for May, January, February, and December, in the latter three months actually no precipitation can be expected.

Table 1: Observed monthly air temperature values in Hamelmalo, Eritrea compared to the ones estimated by the Local Climate Estimator (LCE) model developed by FAO.

Month	Mean monthly maximum temperature		Mean monthly temperature		Mean monthly minimum temperature	
	observed	estimated	observed	estimated	observed	estimated
January	32.0	35.1	20.2	20.5	8.5	7.5
February	34.6	36.1	22.0	21.3	9.3	8.1
March	36.2	38.2	23.6	23.5	11.0	10.9
April	37.0	40.0	25.0	25.3	13.0	12.0
May	37.0	40.3	25.4	26.2	14.0	12.4
June	35.5	38.7	24.8	25.2	14.0	10.4
July	34.0	34.4	24.3	22.7	14.6	11.0
August	31.2	32.6	21.4	21.7	11.6	10.6
September	34.2	35.6	22.8	22.7	11.3	8.9
October	34.0	37.7	22.6	23.6	11.2	9.7
November	32.5	36.2	21.9	22.2	11.3	9.6
December	30.2	35.6	19.9	21.1	9.7	8.4
Average	*34*	*36.7*	*22.8*	*23.0*	*11.6*	*9.9*
	Probability level (p) = 0.992		Probability level (p) = 1.00		Probability level (p) = 0.953	

Underestimated values are underlined

Table 2: Observed monthly precipitation values in Hamelmalo, Eritrea compared to the ones estimated by the Local Climate Estimator (LCE) model developed by FAO.

Month	Mean monthly precipitation	
	observed	estimated
January	0.0	0
February	0.0	0
March	8.9	4
April	4.2	16
May	29.5	30
June	57.7	62
July	135.3	124
August	156.8	178
September	68.6	40
October	8.8	14
November	2.9	2
December	0.2	0
Average	*39.4*	*39*
Annual	472.9	470
	Probability level (p) < 0.05	

Underestimated values are highlighted with underlining

Number of sunshine hours

Sorghum is a short-day plant, the optimum photoperiod of sorghum production is 10-11 hours. Photoperiods longer than 12 hours stimulate only vegetative growth. In terms of day length, flower initiation is the most crit-

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Table 3: Observed daily number of sunshine hours in Hamelmalo, Eritrea compared to the ones estimated by the Local Climate Estimator (LCE) model developed by FAO.

Month	Mean daily sunshine hours (h)	
	observed	estimated
January	9.4	11.0
February	9.2	10.6
March	9.1	10.9
April	8.7	10.2
May	7.7	9.6
June	7.0	9.0
July	7.5	<u>6.7</u>
August	5.3	5.8
September	7.3	7.9
October	8.8	9.9
November	9.3	9.9
December	9.5	10.7
Average	8.2	9.4
	Probability level (p) = 0.996	

Underestimated values are highlighted with underlining

ical period. In Table 3, the observed and the estimated sunshine hours per day determined for Hamelmalo are compared.

The probability level for the mean monthly sunshine hours was 0.996, which means that statistically there were no considerable differences between the observed and expected values (Table 3). Nevertheless, the LCE model overestimated the monthly number of sunshine hours for all the months, except for July, resulting in a 1.2 h day^{-1} average mean difference.

Relative humidity

If relative humidity of the air surrounding the crops is high, the transpiration rate falls as it is inversely proportional to humidity. Therefore, having data about the temporal dynamics of relative humidity provides information on ETact and indirectly on crop water demand. The observed and the estimated monthly relative humidity values determined for Hamelmalo are compared in Table 4.

The probability level for the mean monthly relative humidity of the air was 0.999, which means that statistically there were no differences between the observed and expected values (Table 4). Nevertheless, the LCE model overestimated the monthly number of sunshine hours for all the months, except for June, July, and September resulting in a 2.4% average mean difference.

Potential evapotranspiration

As its definition says, PET determines the sum of water that could be evaporated from the soil surface and transpirated by the crops if water is not a limiting factor. It provides information on the theoretical water demand of crops. On the base of PET, the gap between water demand and water supply can be calculated. This gap is an important issue and generally increases under climate change (Whetton & Chiew, 2021). In Table 5, the monthly PET values calculated from the observed pan evaporation data and by means of the LCE model are compared.

For the mean monthly PET values, based on the test, the probability level was 0.96,

Table 4: Observed monthly relative humidity values in Hamelmalo, Eritrea compared to the ones estimated by the Local Climate Estimator (LCE) model developed by FAO.

Month	Mean monthly relative humidity (%) observed	estimated
January	78.2	81.0
February	74.0	81.0
March	71.5	76.0
April	70.3	75.0
May	67.3	70.0
June	66.7	<u>65.0</u>
July	78.0	<u>77</u>
August	83.1	84
September	75.4	<u>74</u>
October	70.8	73
November	75.0	76
December	76.4	84
Average	73.9	76.3
	Probability level (p) = 0.999	

Underestimated values are highlighted with underlining

Table 5: Monthly potential evapotranspiration (PET) values calculated from pan evaporation in Hamelmalo, Eritrea compared to the ones estimated by the Local Climate Estimator (LCE) model developed by FAO.

Month	Mean monthly PET (mm) observed	LCE
January	114.7	122.2
February	121.9	129.2
March	163.5	<u>162.2</u>
April	171.4	172.1
May	178.0	<u>173.4</u>
June	159.6	163.0
July	121.5	130.9
August	91.8	100.1
September	114.0	121.4
October	138.3	149.5
November	127.4	128.0
December	118.8	<u>117.4</u>
Average	135.0	139.1
Annual	1620.9	1669.4
	Probability level (p) = 0.96	

Underestimated values are highlighted with underlining

which indicates no statistically proven difference among the observed and estimated values. Nevertheless, we detected overestimated values for 9 month, only slight underestima-

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tion was found for March, May, and December resulting in 48.5 mm annual difference, which cannot be considered too big.

Monthly climatic water balance

Negative CWB is characteristic to a region when PET is lower than the amount of precipitation (Gebreyesus et al. 2021). Under the conditions of Hamelmalo, crops definitely suffer from the shortage of water as drought events are common. The drought tolerance of sorghum is better than of most other grain crops. It is due to the fact that it has an exceptionally well developed and finely branched root system, which is very efficient in the absorption of water. Furthermore, the leaf area per plant of sorghum is small limiting transpiration very effectively. The monthly and annual CWB values calculated as the difference of PET and natural precipitation determined for Hamelmalo on the base of the five-year averages are shown in Table 6.

The annual climatic water deficit (negative CWB) was found to be huge. There are only two months (July and August), when CWB is positive. These results indicate when irrigation is necessary to ensure yield safety and also provide rough quantified estimation on the irrigation water needed. For more precise calculations, information on the relevant soil properties is essential.

Discussion

In this study, we evaluated some climatic parameters from crop productional point of view by comparing the observed values with ones calculated by the LCE model on the example of Hamelmalo, Eritrea. Our results are especially of great importance for that location as there was a lack of locally measured meteorological data until 2015, when a new, complete meteorological station was established there. On the other hand, Hamelmalo, just like many other places of the world, is highly vulnerable to climate change. The main meteorological parameters were analysed, which basically determine the success of crop production.

Comparing the observed and estimated mean, maximum, and minimum air temperature values, we found them to be quite similar but in most of the cases overestimated by the LCE model. Sorghum requires high temperatures for germination and growth. The mean monthly temperatures were in the range of 19.9–25.4 ℃, which can be considered is a bit low as for optimum growth and development of sorghum, air temperature of 27 to 30 ℃ is required, even under 21 ℃, its growth is limited. Nevertheless, the mean monthly temperature is under this threshold in Hamelmalo only in December based on the observed data. The maximum temperatures varied between 30.2 and 37 ℃ calling the attention to the fact that exceptionally high temperatures also cause yield depression. In this respect, the period between March and June can be considered risky as the mean maximum temperature is above 38 ℃. For the germination of sorghum seeds, the minimum temperature must be 7–10 ℃. The minimum temperatures observed in Hamelmalo varied between 8.5 and 14.6 ℃, which means that temperature is not likely to be a limiting factor in this respect.

Mean monthly precipitation was the only climatic parameter which showed convincing difference among the observed and estimated values. Precipitation variability is common in East Africa including Eritrea (Lim & Hendon, 2017). Precipitation data were available in Hamelmalo before 2015, so based on the data of ten years and by incorporating standard deviation, we could estimate the mean annual rainfall as 445 $\pm$ 23.9 mm. Within these ten years in Hamelmalo, the lowest precipitation was recorded in 2015 and the highest in 2019, which shows increment with some variation. According to the UNFCCC (2001) in the whole country of Eritrea there

Table 6: Climatic water balances (CWB) in Hamelmalo.

Month	PET	Precipitation	CWB
January	114.7	0.0	-114.7
February	121.9	0.0	-121.9
March	163.5	8.9	-154.6
April	171.4	4.2	-167.2
May	178.0	29.5	-148.5
June	159.6	57.7	-101.9
July	121.5	135.3	+13.8
August	91.8	156.8	+65.0
September	114.0	68.6	-45.4
October	138.3	8.8	-129.5
November	127.4	2.9	-124.5
December	118.8	0.2	-118.6
Annual	1620.9	472.9	-1148.0

is an increasing trend in terms the amount of annual precipitation.

On the base of the observed precipitation data, in the months of January and February, no rainfall can be expected in the studied region. Practically the same is valid for December and October, almost no effective rainfall is characteristic during these months. These results suggest that additional irrigation is important to acquire the daily crop water needs if any crop is supposed to be grown in these four months. Rainfed sorghum is endangered by the risks of water stress during critical growth stages and droughts. Sorghum yields of about 4 t ha^{-1} can be assured only by irrigating once in terraced plots with high amount of residual soil moisture (Tripathi & Ogbazghi, 2010; Weldeslassie et al., 2016).

In terms of sunshine hours, it can be concluded that the observed mean daily sunshine hours, with their range of 5.3–9.5 h day^{-1}, do not reach the optimal photoperiod of 10–11 hours in neither of the months. Nevertheless, this range is also under the critical value of 12 hours when only vegetative growth is stimulated.

Potential evapotranspiration in inverse conjunction with relative humidity of the air determine transpiration of crops. Annual PET rates range from 1,700–2,000 mm in the northern highland of Eritrea (FAO, 2005b) where Hamelmalo is found. On the base of the observed meteorological data, we calculated 1620.9 mm of annual PET, which is a bit less than the general trend, but close to the estimated value by LCE (1669.4 mm). Crop ETact increases with increasing air temperature and solar radiation, the two primary drivers of evapotranspiration (Irmak, 2009). The annual ETact of the sorghum was reported as 450–650 mm by Doorenbos and Kassam (1979) and 210–293 mm by Kuo et al. (2006). There was also a study about crop water requirement in Ethiopia, which is not far from Eritrea, and the result was 500.4 mm during the growing season (Shenkut et al., 2013). So, the demand for water was less in Eritrea than in Ethiopia may be due to difference in rainfall variation between the two countries. Generally, this indicates that ETact is very much dependent on the atmospheric conditions experienced at a particular location.

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The monthly climatic water balances were figured out to be strongly negative in ten months of the year, only July and August can be characterized with positive CWB. The results indicate that irrigation is critical in the mid-season stage and late developmental stage of sorghum crop. To avoid yield reductions in sorghum cultivation more water should be applied in the late developmental stage. This is probably because large quantities of water are needed for grain formation (Abou Kheira & Atta, 2009). In areas where water is a limiting factor in crop production like in Eritrea, deficit irrigation may be preferable. It is believed to be the least sensitive to water stress (Fereres & García-Vila, 2018).

For sorghum, early sowing dates start from 1st April, while late sowing dates last from mid-May till mid-June (Haile & Hofsvang, 2001). Based on our results, sowing time and early growth period can be adjusted from around 20th June up to early July to take the advantage of the positive CWB of July. The maximum vegetative growth and seed setting period should be adjusted from the first week of July up to the end of August as the latter month has the most positive CWB. The first two weeks of September is the suitable period for ripening. Otherwise, supplementary irrigation is a must, especially for sorghum as it has a short growing season of around 125 days (Smith et al., 2002). All these should be considered by the farmers to adjust the planting and harvesting time if the amount of water is limited.

As a conclusion it can be stated that sufficient water is vital in the mid-season and the late developmental stage of sorghum, more than for other developmental stages. Especially in the initial and development stages, irrigation is not definitely needed. This indicates that proper planning and timing of planting dates to coincide the late developmental stage with high rainfall months is vital in water resource management, especially under the semi-arid climate of Eritrea. Up-to-date, accommodating crop and soil water management practices need to be adopted for the production to be economically sustainable. Therefore, it is recommended to shift planting dates to coincide with the rainy season and also to allocate water according to the critical developmental stages of sorghum in order to maximize yields without adverse implications for water resources.

The evaluation of the climatic parameters shows that the LCE model we used to observe the studied variables is functional. There were no any significant differences ($p = 0.05$) between data of the observed and the estimated data except for rainfall. Naturally, our results can be extended to other locations with similar agri-ecological conditions, and the methods we used can be applied for similar studies in terms of the comparison of observed and estimated meteorological data. Therefore, we encourage researchers to carry out similar studies based on the approaches we used.

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