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The impact of rainfall variability and crop production on vertisols in the central highlands of Ethiopia

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Abstract

Background: Understanding the yearly, seasonal, monthly, and weekly rainfall variability is crucial for improved agricultural practice in Ethiopia, where agriculture depends on rainfall. In particular, knowledge of rainfall onset, withdrawal, amount, distribution, and the length of the crop growing period would protect farmers from crop damage due to climatic anomalies. This study collected and described 39 years of rainfall data using the Markov chain model. Based on the rainfall probability levels at different threshold values, the length of the dry and wet spells and the length of the growing period were determined.

Results: The study shows dependable rainfall at a 75% probability level commences in June. The chance of receiving greater than 10 mm at a 50% probability level starts in week 10 (5 March–11 March), with much discontinuity up to week 21st (21 May–27 May). The dependable weekly rainfall begins the week of 22 May (28th May–3rd June) with a probability of greater than 20 mm. The study revealed that the short rainy season rainfall (February to May) is unreliable for growing crops at Ghinchi as opposed to other highland areas of Ethiopia. The major crop growing season is therefore confined to periods of the long rainy season (weeks 22nd to 39th, or 28th May–30th September). The water balance for the study area indicates that the moisture availability index is greater than 0.5, and potential evapotranspiration is lower than precipitation during these months.

Conclusions: Climate change and rainfall variability is creating a problem with crop production constraints in the rain-fed agricultural production system in the highlands of Ethiopia. Physical properties of the soil coupled with the unfavorable soil-rainfall relationship limit increased crop production on vertisols. Improving the drainage system and capturing rainfall variability in agronomic-relevant terms is essential. Improving the physical limitations of the soil, adapting to rainfall variability, and practicing improved agronomic practices may help farmers overcome the production problem. This study provides critical information on rainfall variability concerning vertisol management and crop production. However, to overcome the problem, technological support is needed from researchers and policymakers.

Keywords: Variability, Probability, Markov chain model, Threshold, Vertisol

Introduction

Ethiopia is endowed with substantial water resources (Melesse et al. 2013). However, the agricultural sector is entirely rainfall-dependent, and smallholder farmers plow their land under climate change and rainfall variability using traditional technologies of low input and low output agricultural production practices (Baye

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2017; Menale et al. 2011Segele and Lamb 2005). Farmers' weak socioeconomic status, limited access to agricultural technologies, and limited options for diversifying crop production constrained the use of the country's water resources (Yigezu Wendimu 2021). Therefore, the traditional rain-fed agricultural production system is subsistence-oriented, and smallholder farmers suffer from food shortages due to rainfall variability and recurrent droughts (Lewis 2017; Awulachew and Ayana 2011). Land degradation, soil and water erosion, and soil fertility depletion are widespread on the vertisols of the Ethiopian highlands, causing nutrient losses and reducing soil productivity (Elias et al. 2022; Kharchenko 2011; Dubale 2001; Mamo 1988).

Ethiopian agriculture is susceptible to frequent draughts, usually related to the deficiency in total annual and seasonal rainfall amounts, affecting farmers' livelihoods (Mera 2018). Climate change, rainfall variability, and soil determine the food security situation of a given area. From the perspective of rainfall variability, agricultural crop production depends on soil moisture availability, rainfall amount, onset, cessation, and length of the growing period. Rainfall variability impacts the soil's water availability to crops, causing reduced crop production. In particular, annual and seasonal rainfall information is important to overcome the social and economic problems for farmers who entirely depend on rainfall. Farmers usually rely on prior knowledge of weather conditions when planning farm activities. However, in a changing climate, it may be difficult for them to capture the variability of rainfall and accordingly plan agricultural management practices. A research-supported study of climate change and rainfall variability may help traditional farmers plan agricultural crop management options and develop adaptation and mitigation mechanisms. The sustainability of any agricultural production system depends on prior knowledge of climate change, rainfall variability, and soil properties (Pulwarty et al. 2009). The function of soil and proper ecosystem services determine the optimal relationship between soil and water, minerals, organic matter, and organisms. Excessive precipitation increases soil moisture and thereby enhances waterlogging, surface runoff, and erosion (Tian et al. 2021; Sehler et al. 2019; Pimentel et al. 2007), while less rainfall in a dry environment leads to reduced organic matter and nutrient availability (Jeong et al. 2018; Dairaku et al. 2004). Changes in precipitation affect vegetation, which has an impact on the soil organic matter cycle and changes in soil properties (Bansal et al. 2014).

Vertisols are one of the major soil types covering a large portion of the Ethiopian highlands (Elias et al. 2022; Srivastava et al. 1989) and suffering from excess or shortage of rainfall, which makes land preparation difficult for sowing and for the implementation of agronomic practices (Manik et al. 2019; Mamo et al. 1993; Mamo 1988). These soils are moderately fertile, but rainfall variability, their physical characteristics, and unsustainable land management practices limit the ability to exploit the full potential and produce sufficient food. The dominant clay minerals exhibit distinct characteristics of swelling and shrinking properties with changes in soil moisture. During wet conditions, the soil becomes sticky and plastic, and in dry conditions, it becomes hard, and wide cracks develop down through the soil profile, restricting the use of traditional farm implements to plow and prepare the land for sowing crops. The soils have a narrow moisture range between drought stress and excess moisture (Elias 2019; Mamo et al. 1993). When rainfall is heavy, waterlogging creates unfavorable soil and water relationships, restricting the use of traditional farm implements. Vertisols are usually regarded as problematic soils that severely restrict cultivation due to climate change and soil physical characteristics that need attention for sustainable crop production (Patil et al. 2016; Erkossa et al. 2004).

Crop production on vertisols at Ghinchi is predominantly rain-fed. The major crops grown are wheat and teff, which have different responses to waterlogging conditions. Wheat is sensitive to waterlogging conditions, while teff can better tolerate waterlogging. As a result, the decision to plant either of the two crops in kiremt is based on indigenous knowledge and the farmer's previous experience with local farming practices in relation to seasonal rainfall scarcity, adequacy, or excess. The net potential effect of rainfall is always based on its patterns, which dictate surplus or deficit crop production, leading to food self-sufficiency or food insecurity, respectively. The vertisol farmers of the study area usually grow crops on residual moisture just after the withdrawal of the main rainy season in September to avoid waterlogging. This practice allows the soil to be bare without any crop cover and makes the soil vulnerable to soil and water erosion. The crops planted on residual moisture sometimes suffer from thermal drought and dry spells.

The study area's agro-climatic characteristics must be understood in order to achieve food self-sufficiency and reduce climatic risk. For rain-fed dependent agriculture like Ethiopia, knowledge of rainfall features in agronomic terms is essential. It is not always possible to determine which agricultural technologies are profitable to develop and which farming methods are sustainable in the face of climate change. In the past, research was frequently focused on finding solutions to technical issues; today, it also aims to establish research objectives and the best technologies to meet the needs of the farming community today and in the future related to climate change.

These top goals include studying the likelihood of rain, forecasting, and adapting the results to the needs of farmers. Climate variability and its interconnections have a greater and greater impact on agricultural production. Rainfall variability may affect farmers and the environment in many ways, most importantly by reducing crop production and aggravating poverty. Understanding how climate change and rainfall variability impact agricultural productivity and food security may encourage farmers to implement local adaptations and reduce their susceptibility. Given that climate change is unavoidable and intensifying, farmers need assistance from weather forecasting and prediction. Farmers that have a pressing need for food can adapt to local conditions and reduce weather anomalies. Farmers may find it easier to adjust to local conditions and cultivate acceptable crops if the interpretation and forecasting of weather aspects are strengthened in terms of their agronomic significance.

Therefore, crop production (onset, withdrawal, duration, seasonal totals, and dry and wet spells) provides a better understanding of rainfall variability (Manik et al. 2019), which is a crucial criterion for strategic agricultural development planning (Stern and Coe 2009; Virmani et al. 1982). For this purpose, the long-term rainfall data of the Ghinchi area was interpreted using the Markov chain model (Appendix 1). Therefore, the goals of this study were (i) to examine the pattern of rainfall distribution, (ii) to estimate expected rainfall amounts at various probability levels, (iii) to determine the start and end of the crop-growing period using a Markov chain model of the first order, and (iv) to interpret climatic data for agricultural planning and operations as well as the timing of cultural practices involving Ghinchi Vertisol.

Methodology

Description of the study area

Rainfall (R) data for 38 years (1982–2020) was provided by the First Class Weather Station at Ghinchi Agricultural Research Sub-Centre and the National Meteorological Agency at Addis Ababa, Ethiopia. The study area is 75 km west of Addis Ababa, in the Oromia region of Ethiopia, with geographical coordinates of 09° 0′ 03″ N, 38° 0′ 30″ E, and an elevation of 2200 m a.s.l. (Fig. 1). The study area has flat to undulating topography and is dominated by dark black, high clay soils (vertisols).

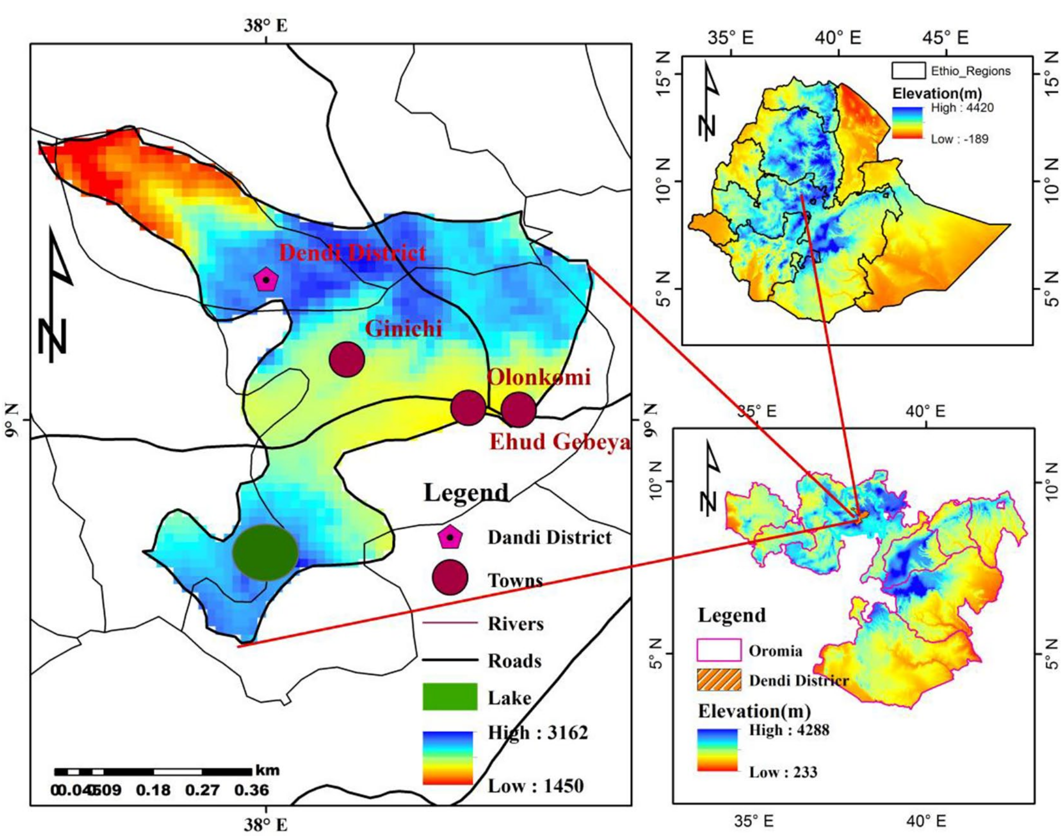

Fig. 1 Location map of the study area

In Ethiopia, according to the traditional classification, seasons are divided into three based on rainfall amount and distribution. The seasons are known locally as Kiremt, which represents the long or primary rainy season, which runs from June to September, and Belg, which represents the short or minor rainy season, which runs from February to May. October through January is the driest season and is named bega (Diro et al. 2011).

Data management and methods used

The Ghinchi agricultural research sub-center's first-class meteorological station and the Ethiopian national meteorological agency provided the daily rainfall data from 1982 to 2020. The mean, standard deviation, and coefficient of variation of annual, seasonal, monthly, and weekly rainfall were computed using the information received. A 5-year moving average analysis was used to estimate annual rainfall trends. Using historical rainfall data, the first-order Markov chain model, the initial and conditional probabilities, and the incomplete gamma model were utilized to assess the likelihood and expected amounts of rainfall (Liu et al. 2009; Mugalavai et al. 2008; Jail et al. 2005; Ochola and Kerkides 2003).

Several researchers have used the incomplete gamma distribution technique to compute the monthly rainfall amount at 10, 25, 50, 75, and 90% probability levels using long-term daily rainfall data gathered using standard meteorological weeks (SMW). The SMWs are widely used in agroclimatological studies (Sabarish et al. 2017; Goyal et al. 2015; Mandal et al. 2015; Sharma and Singh 2010). In a year, 52 weeks are assigned, and in leap years, the 52nd week will have 8 days. The Markov Chain Probability Model (Appendix 1) was used for weekly rainfall of >10, >20, >30, >40, and >50 mm based on the quantity of precipitation received each week. The model can estimate the likelihood of future rainfall probability and variability at tolerable threshold levels. The conditional probability level study focused on a rainy week after a wet week, a wet week following a dry week, and the beginning probability of rain this week being wet (Table 2; Appendix 3). A threshold level of between 10 and 20 mm of rain in a week was chosen for agricultural management activities. The anticipated rainfall amounts were calculated using incomplete gamma distributions using different probability levels (da Silva Jale et al. 2019; Virmani et al. 1982).

The monthly probabilities at 10, 25, 50, 75, and 90% confidence levels were calculated using an incomplete Gamma distribution. Reliable rainfall is defined as the quantity of precipitation received with a probability of 75% for a Gamma distribution by Hargreaves (1975). The 50% and 75% likelihood levels serve as the threshold values to indicate rainfall during the growing season. The 75% likelihood level is normally used to establish the start and end of the growing season's rainfall. PET is the loss of water by transpiring plants and evaporating water from the earth that is influenced by temperature, humidity, sunlight, and the wind.

The end of the growing season was determined by rainfall below 10 mm at a 50% probability level. A value of $R/PET > 0.75$ (R-rainfall) was also chosen because it represents an optimum range of plant growth. The start of sowing rains is considered to be the week that comes just before the start of the available effective rainy period. Generally, this is the amount of rain needed to wet the topsoil layer and allow seed germination. It is specified by $R/PET > 0.50$, in addition to a continuous humid period later. The length of the growing season was then estimated using the calculated start and end dates. The other climatic factors were omitted from the analyses because they are frequently tropical, consistent, and predictable.

As Zotarelli et al. (2014) described, Penman's model was used to estimate the weekly and monthly PET values. The ratio of assured rainfall at 50 and 75% probability levels to PET on a monthly and weekly basis is known as the moisture availability index (MAI), and an MAI of greater than 0.5 was deemed adequate for growing crops (Hargreaves 1975). Based on the determined start and withdrawal of rainfall dates, the length of the growing season was then estimated. If there is a greater than 50% chance of obtaining 20 mm of precipitation per week and the following week is rainy or wet, the growing season begins (Reddy 1983). Therefore, planting would be possible in the first week following February if there was a 50% chance of receiving at least 20 mm of rain in back-to-back days without a 10-day dry period (Stern and Coe 2009; Abeyasekera et al. 1983).

Result and discussion

Annual rainfall statistics

The recent trend in climate change and rainfall variability affects crop production in developing nations like Ethiopia, where rain-fed agriculture dominates the farming system (Alemayehu et al. 2020a, b; Dereje et al. 2012). In particular, the sub-African region is greatly affected by climate change due to various socio-economic situations and a lack of low adaptation and mitigation capacity (Kotir 2011). Ethiopia has a wide range of agroecologies, from higher (>4550 m.a.s.l.) to 125 m below sea level. Rainfall and temperature vary greatly depending on altitude and topography (Reda et al. 2015).

The annual, the long-term mean, and the 5-year moving average rainfall are shown in Fig. 2. The mean annual rainfall of Ghinchi was 1099 mm. The yearly rainfall varied from 813 mm in 2002 to 1456 mm in 1988, showing high variability between the years. The mean annual

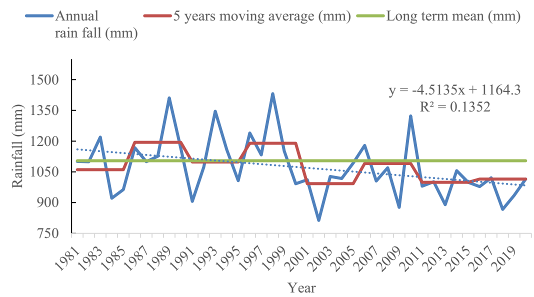

Fig. 2 Annual, long-term mean, and 5-year moving average rainfall for Ghinchi (database 1981–2020)

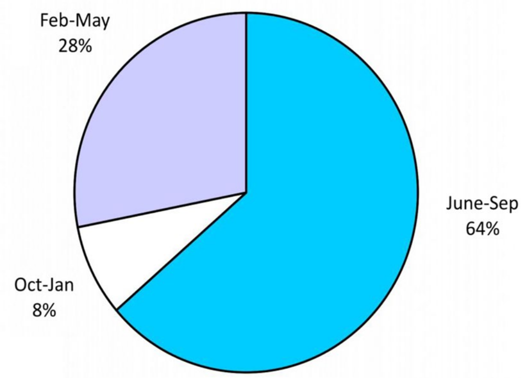

Fig. 3 Calculated long term mean seasonal rainfall for the three seasons at Ghinchi (database 1981–2020)

rainfall for the 39 years was 1099.6 mm. The total annual rainfall observed over the 39 years showed that 16 years (41.7%) has more rainfall than the long term meanwhile 23 years (58.3%) recorded more rain than the annual average. The long-term annual rainfall has decreased in amount since 2000. In effect, for the 39 years (1982–2020), the total average rainfall amount is declining yearly by an average of 351 and 267.2 for the long and short rainy seasons, respectively. The Magnitude of the rainfall in the study area decline at the rate of −4.51 mm/year. Negative anomalies were common in 2 to 3 years. Since 2000, the annual total rainfall has been far lower than the long-term mean. The rainfall in 1985 and 1986 was significantly below the long-term mean and was the drought year in Ethiopian history (Mera 2018). The coefficient of variation and annual standard deviation was 78.3 and 85.3%, respectively. The results of the coefficient of variations depicted in Table 2 show the dry and the short rainy season rainfall are more variable than the kiremt season rainfall. The study agrees with past studies conducted elsewhere in Ethiopia (Alemayehu et al. 2020b; Seleshi and Zanke 2004). Mekasha et al. (2014) also concluded that rainfall variability and inconsistency are prevalent over the Ethiopian highlands.

The 5-years moving average shows that six of the 8 years had rainfall below the long-term average (75%). Only two of the 5-years moving averages rainfall had above the long-term mean. In particular, since 2000, the continuous decline in yearly rainfall below the long-term average indicates the need to find alternative management options and farming strategies considering rainfall variability and soil conditions.

Seasonal rainfall variability

The rainfall of Ghinchi is characterized by a bio-modal rainfall pattern of two rainy seasons, namely the long and short rainy seasons, and a dry season. The long rainy season, known locally as kiremt (July to September), accounts for approximately 699.9 mm (64%) of the annual rainfall, while the short rainy season (February to May), known locally as belg, accounts for approximately 28% of the annual rainfall. The dry season, known locally as bega (October to January), provides 90.8 mm of rainfall, or 8% of the annual total (Fig. 3). The bega rainfall has no agronomic importance, as it is not adequate for crop production during this time. Except for the bega season, the long-term seasonal rainfall showed an upward tendency throughout the 39-year period. The rainfall exhibits a slightly decreasing tendency during the belg (little rainy) season and a negative trend during the bega season. The yearly rainfall pattern shows dry and wet years, altering one after the other.

The amount and distribution of seasonal rainfall are more crucial for rain-fed agriculture than the annual amount. The length of the growing season for crop production depends on the timely onset and cessation of rain in a particular area (Robinson et al. 2013). As a result, decisions regarding crop production depend on the seasonal variation in rainfall amount and distribution, which supplies the soil with the water required for plant growth. Reduced yields could result from the seasonal rain's unpredictability, start, and cessation (Torres et al. 2019). Thus, to plan and make decisions in rain-fed farming systems, it is crucial to understand the features of seasonal rainfall concerning the growing season (Guido et al. 2020).

The rainfall pattern, amount, and distribution of the rainfall greatly vary between the three seasons. Farmers in the Ghinchi area expect rainfall during the long rainy season starting in June. Sometimes, rainfall comes early or late, making traditional farming difficult (Jutzi 1988). Vertisol sowing always needs precautions. As soon as the rain starts and the soil gets friable, planting is normally done on vertisols. Once the soil is saturated, the land becomes sticky and plastic; when dry, vertisol forms hard clods, making farm operations difficult (Jutzi 1988). Sometimes, in years of above-average rainfall in the short rainy season, the long rainy season tends to be lower, and vice versa. Obtaining the optimal soil moisture range becomes difficult as the climate and rainfall variability change.

The rainfall pattern, amount, and distribution greatly vary between the three seasons. Farmers in the Ghinchi area expect rainfall during the long rainy season starting in June. Delay in onset or early withdrawal has a profound effect, making traditional farming difficult (Jutzi 1988). Vertisol farming is sensitive to excess or shortage of rainfall because, in both extremes, planting would be impossible. Once the soil is saturated, the land becomes sticky and plastic; at dry conditions, vertisol forms hard clods, making farm operations difficult (Jutzi 1988). Sometimes, in years of above-average rainfall in the short rainy season, the long rainy season tends to be lower, and vice versa. Obtaining the optimal soil moisture range becomes difficult as the climate and rainfall variability change. The area's short rainy season rainfall is variable and unreliable across years and seasons. Crop production during the short rainy season is constrained by inadequacy or a limited duration of rain. High and erratic rain during the long rainy season brings waterlogging to the farmlands. To overcome the waterlogging problem, farmers have traditional ways of draining the excess water from their farmlands. These practices include ridge and furrow, opening drainage furrows at different spacing along slopes, and sowing crops on residual moisture after the cessation of the long rainy season in September. Sowing crops on residual moisture results in crop failure due to dry spells in December or November. If the land is fallow during the long rainy season, it is exposed to erosion, causing land degradation and soil fertility depletion.

Traditional farming practices cannot fully drain the water from the farmlands. Therefore, the research has developed the broad bed and furrow maker (BBM), an implement that constructs the broad bed and furrow (BBF) capable of draining the excess water from the farmland. The BBM is a curved metal sheet attached to two unmodified traditional plows, usually oxen-drawn. Metal wings scoop the soil towards the center between the two plows (Astatke et al. 2002). The BBM builds raised beds 80 cm wide and alternates them with furrows 40 cm wide and 15 cm deep. The implement needs friable soil to make the necessary bed and drainage furrows. Crop production losses are inevitable if an intense and heavy shower comes at the onset of rain because of the soil puddles, and it becomes difficult for local oxen to pull the soil and make the bed. Continuous rainfall for a longer period prohibits the use of farm implements on vertisols. As a result, most farmers leave their farmland fallow during the rainy season and sow pulse crops on residual moisture after September.

Monthly rainfall statistics and seasonal variability

Monthly rainfall variability is very high for Shinichi. The long-term mean monthly rainfall ranged from the lowest of 9.9 mm in December to the highest of 242.1 mm in August. The long rainy season months have high amounts of rain, with the highest rainfall amounts received in July and August. The monthly rainfall's standard deviation ranged from 16.3 to 67.4, the lowest for the dry seasons. The coefficient of variation (CV) was between 21.5 and 206.7%, the highest being for the drier months. The coefficient of variation (CV) shows how the individual data points vary about the mean value. A higher CV indicates higher spatial variability, and vice versa. The long rainy season's rainfall has a lower coefficient of variance. The monthly average standard deviation and CV were 78.3 and 85.3%, respectively. The lowest standard deviation was observed for the dry season, while an almost similar standard deviation was observed for the long and short rainy seasons. The highest coefficient of variation was observed for the short rainy and dry periods, while the long rainy seasons had a lower coefficient of variation (Table 1). Statistical parameters for monthly rainfall analysis for Ghinchi (database 1981–2020). This study confirmed that the result is in agreement with the findings of previous studies conducted in the highlands of Ethiopia (Dereje et al. 2012; Asfaw et al. 2018). Variability in seasonal and interannual rainfall affects the livelihood of rainfall-dependent smallholder farmers (Adamseged et al. 2019).

Monthly rainfall and PET relationships

The study area's long-term rainfall and PET data of 2000–2020 were summed up to find the mean annual rainfall and PET, as illustrated in Fig. 4. According to the data, nearly 8 months of the year had higher PET than rainfall. These months are divided into the short rainy season and the dry season (October–May). Higher PET values create a negative water balance, resulting in soil dryness and necessitating irrigation for crop production (Cui and Zornberg 2008). During the short rainy season, in some highlands, the rainfall is inadequate to grow short- and long-duration crops. However, particularly in the Ghinchi area, rainfall in the rainy season is insufficient to plant crops. The short rainy season rain is important for farmers to prepare their land before the long rainy season rain commences.

The long rainy season (July–September) has rainfall above the PET; therefore, the water requirement of crops can be met. During this period, excess soil moisture may

Table 1 Summary of monthly rainfall statistics (data base 1981–2020)

Months	Mean rainfall (mm)	Standard deviation	CV (%)	Maximum rainfall (mm)	Minimum rainfall (mm)	Range (mm)
January	24.3	24.4	120.2	98.9	0.0	98.9
February	41.8	41.7	113.4	194.9	0.0	194.9
March	76.5	67.4	91.8	188.5	0.0	188.5
April	94.9	50.4	56.7	240.5	12.3	228.2
May	95.7	49.8	55.5	179.7	4.7	175.3
June	157.2	46.1	31.3	253.2	62.2	191.2
July	173.9	50.4	21.5	403.3	158.8	244.5
August	242.1	49.1	21.9	330.1	149.9	180.2
September	126.7	44.1	33.2	208.1	48.0	160.1
October	37.1	37.7	104.8	157.6	0.5	157.1
November	19.5	21.9	162.2	83.6	0.0	83.6
December	9.9	16.3	206.7	68.3	0.0	68.3
Annual	1099.6	78.3	85.3	2406.6	436.4	1970.2

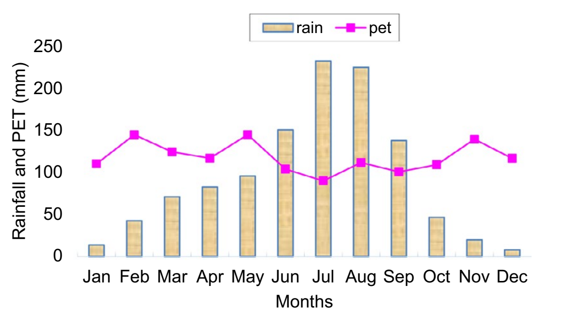

Fig. 4 Monthly rainfall and PET for Ghinchi (database 1981–2020)

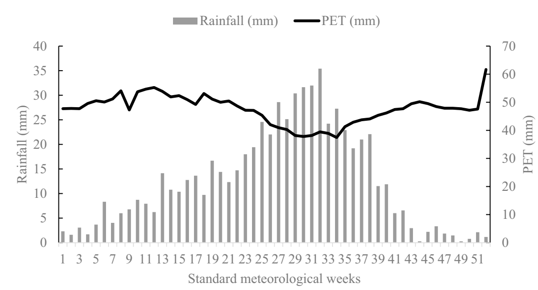

Fig. 5 Expected weekly rainfall distribution (mm) and PET for Ghinchi (database 1981–2020)

be expected, causing waterlogging, flooding, and soil and water erosion.

Weekly rainfall and PET relationships

Weekly and monthly rainfall data were used to evaluate the 39-year rainfall trend. The first standard week for this study is January 1 to January 7. Every standard week following this consists of 7 days, ending on December 30. The mean weekly rainfall for the last 39 years was 82.3 mm. Thirty-one weeks (60%) had rainfall below the weekly average of 82.3 mm, while the remaining 21 weeks (41%) had rainfall above the mean. The maximum mean weekly rainfall of less than 20 mm per week was observed for weeks 2, 3, 4, 8, and the weeks from the 43rd to the 52nd (Fig. 5). These weeks are confined to the dry seasons. The rainfall that commences during the dry season may cause problems with crops that are ready to be harvested or threshed because these activities are done during the dry season immediately after the withdrawal

Table 2 Monthly Incomplete Gamma distribution at different probability levels for Ghinchi (database 1982–2020)

Month	Precipitation (mm) for the probabilities				
	90	75	50	25	10
January	1	3	9	20	35
February	2	8	25	60	110
March	16	12	59	99	147
April	18	36	67	114	171
May	18	38	75	133	204
June	84	116	151	187	219
July	171	201	233	266	296
August	152	187	225	264	299
September	86	107	134	165	197
October	5	14	33	66	110
November	0	2	10	28	56
December	0	1	5	12	22

of the long rains. On the other hand, the October rainfall may have positive and negative effects. Crops that grow on residual moisture favor the dry season rain, while crops planted during the long rainy season are ready to be harvested or threshed and cause discomfort. This shows the complexity of the farming system on vertisols. During the long rainy season, rainfall above 100 mm is expected in a week, with the highest being 231.7 mm in August. The weekly standard deviation was 69, and the average CV of the rainy season was above 100%. A lower CV was recorded for weekly rainfall during the short rainy and dry seasons (Fig. 5). The high CV of the long rainy season is explained by the high variability of rainfall between years.

A trend in weekly rainfall distribution and PET is shown in Fig. 5. Weekly rainfall was higher than the PET during the weeks from 22nd (28 May–03 June) to 39th (24 September–30 September. The maximum weekly rainfall was recorded during the 22nd to 38th (May 28 to September 23) weeks, with an average of 163.8 mm (68%). The weeks belong to the long rainy season and crop planting period. Overall, the mean weekly rainfall for the dry period was 16.8 mm (6%), while in the short rainy season, it was 61.5 mm (24%). The mean weekly rainfall distribution during the three seasons shows that the dry and short rainy periods' rainfall was below PET, while the long rainy season had rainfall higher than PET. Four months of water surplus (June–September) and 8 months of water deficit (October–May) were identified. The management of water resources, rain-fed agriculture, food security, and the fight against poverty are all seriously threatened by the spatial and temporal variability in rainfall amount and evapotranspiration brought on by global climate change, particularly in developing nations. Among many other aspects of the water balance, evapotranspiration is taken into account when determining water surplus and deficit. These two factors are consequently necessary for crop growth. The weekly rainfall data showed that the water deficit in the study area is roughly 8 months, as indicated by the PET values being higher than the rainfall (Fig. 5). The consequence is that food security will be challenged (Ashaolu and Iroye 2018).

Monthly and weekly rainfall amounts at a given probability level

The monthly minimum rainfall quantities expected at five probability levels (10, 25, 50, 75, and 90%) are shown in Table 2. The data shows that, at a 75% probability level, rainfall of more than 20 mm during the short rains can be expected in March and extends up to May but never exceeds 38 mm. During the short rainy season, the rainfall is far from the 50% value, which explains the high variability influenced by a few high values. The short rainy season rainfall is not sufficient to grow crops but is adequate for pre-sowing land preparation and other agricultural activities before the onset of the long rainy season. In June, a sharp increase in rainfall amount is expected (116 mm), which is an increase of 88 mm more rainfall than in May (42.3%). The probability of the monthly gamma distribution at a 75% probability level ranged between 107 and 201 mm, with the highest value in July (201 mm). The mean difference and 50% values in the long rainy season are similar, and the data represents a normal distribution. The abrupt increase during this period causes waterlogging on the soil, making planting difficult. Therefore, the soil requires drainage improvement.

A comparison of the long-term mean monthly rainfall and the monthly expected rainfall amount at five probability levels shows different values (Tables 1 and 2). Rainfall with a 75% probability is more reliable (Hargreaves 1975) for agricultural crop management planning than the monthly mean rainfall amount. Dependable rainfall has lower values and is less skewed compared to the annual average.

Weekly rainfall and initial and conditional probabilities

The Markov Chain Probability Model has been extensively used in agriculture to determine dry and wet spells, the onset and cessation of rainfall events, and to develop agricultural management operations. The Markov chain model was used to compute the long-term (39) year rainfall data using the initial probability level of receiving a certain amount of rainfall during a given week, i.e., [P(W)], the conditional probability level that predicts the likelihood of rain next week if we had rain this week [P(W/W)], and the likelihood of rain next week if this week is dry [P(W/D)]. The weekly precipitation was examined for probabilities by receiving a specific amount of rainfall, such as 10, 20, 30, 40, and 50 mm. The probabilities of receiving a specific amount of precipitation in a week (Table 3) can be used as a threshold level for various crops, cultivars, or soil types with various water-holding capacities. This information helps determine what crops should be grown and what agricultural practices would be employed.

Therefore, dependable rainfall at a 75% probability level on a weekly basis is more important (Hargreaves 1975; Stern et al. 1982), and careful consideration of the target environment and crop selection should be prioritized. For most field crops, at least > 20 mm of rainfall at a 75% probability level in a week could serve as a reasonable threshold. In this study, consecutive weeks with assured rainfall exceeding 20 mm occurred between the 22nd and 38th weeks. Hence, planting crops can be done during

Table 3 Initial and conditional probability (%) rainfall at Ghinchi (database 1981–2020)

SMW	> 10 mm			> 20 mm			> 30 mm			> 40 mm			> 50 mm			Mean
	w	w/w	w/d	w	w/w	w/d	w	w/w	w/d	w	w/w	w/d	w	w/w	w/d	
22	75	73	67	55	82	56	45	56	45	20	50	25	15	67	24	26.1
23	70	100	0	70	71	67	50	70	20	30	50	21	30	50	21	29.2
24	90	100	0	70	86	100	45	67	64	30	50	43	30	33	21	36.9
25	100	100	0	90	83	100	65	85	43	45	56	45	25	40	33	39.1
26	100	100	0	85	76	100	70	79	50	50	70	60	35	71	38	41.4
27	100	100	0	80	88	75	70	71	83	65	38	71	50	30	30	53.2
28	100	100	0	85	94	100	75	93	100	50	70	90	30	67	57	43.1
29	100	100	0	95	95	100	95	95	100	80	63	100	60	50	75	54.1
30	100	100	0	95	95	100	95	89	100	70	71	50	60	58	50	58.6
31	100	100	0	95	100	100	90	94	100	65	77	57	55	82	44	53.8
32	100	95	0	100	95	0	95	79	0	70	57	33	65	46	29	62.4
33	95	100	100	95	95	100	75	73	100	50	70	60	40	63	42	46.7
34	100	100	0	95	79	0	80	63	50	65	54	43	50	50	20	49.7
35	100	95	0	75	87	80	60	42	63	50	30	20	35	0	23	40.6
36	95	89	100	85	71	67	50	60	50	25	20	40	15	0	12	34.2
37	90	89	100	70	64	67	55	45	44	35	29	31	10	50	28	33.5
38	90	61	100	65	46	43	45	33	27	30	17	7	30	0	7	36.8
39	65	62	29	45	44	27	30	33	21	10	0	22	5	0	21	20.6

this period without the risk of a moisture deficit. The optimum period for planting crops for Ghinchi is around mid- to late-June. The temperature, humidity, and rainfall for June and July are conducive to rapid growth. Nevertheless, the period covering late July through August experiences a high intensity of rainfall, more cloud cover, and more saturated soil, which aggravates the problem of waterlogging. When rainfall is in excess, improved drainage systems and water harvesting structures are recommended to supplement crops grown on residual moisture with irrigation water if a dry spell may occurs.

The W/W probability indicates continuity in rainfall and suggests those weeks are favorable for crop production. At a 50% probability level, the chances of receiving more than 10 mm in a week begin around week 10, although they are inconsistent until week 21st, while increasing the threshold limits the probabilities closer to the true value. Effective rainfall of more than 20 mm/week, at a 50% probability level, starts on the 22nd week and extends to week 38 (16–22 September). At the 50-mm/week threshold limit, they are confined to weeks 29–32 (15–21 July to 5–11 August) only, indicating that there are high chances of heavy rains and a risk of soil erosion in these weeks, as well as waterlogging. In dry periods between October and January (weeks 40–52 and 1–4), the probability of getting at least 10 mm/week decreases, and the variability is very high. Particularly, weeks 45 and 46 had some rain at the 10-mm threshold level, which may indicate the harvest and threshing of crops. Considering 20 mm or more of rain in a week without discontinuity at a 50% probability level is sufficient for tillage and planting crops (Reddy 1983; Virmani et al. 1982). The period corresponds to weeks 22nd to 37th (June to mid-September), which indicates the length of the growing period.

Dependable rainfall

Rainfall is the most important climatic component since it has a detrimental effect on crop productivity. Cropping patterns in different ecological zones vary depending on rainfall quantity, occurrence, variance, and reliability. In rainfall-dependent developing countries, climate change and variability cause crop failure and food insecurity. Therefore, a rainfall probability study for a specific location becomes essential because agricultural production is highly affected by climate change and rainfall variability (Gitz et al. 2016; Chijioke et al. 2011). Since there is some there is always some variability in space and time, it is important to have a probability estimate using various models. Crop production can be sustained only under good soil conditions and conducive climatic conditions. Proper soil management, harnessing climatic risks, and improved agricultural technologies such as crop selection and irrigation practices have become prerequisites for planning agricultural activities and increasing crop productivity. Rainfall prediction is essential to protect farmers from negative weather anomalies.

Monthly dependable rainfall and MAI

Monthly rainfall has more variability than dependable rainfall and estimates less rainfall for crops, while dependable rainfall (DP gives reasonable estimates in line with global climatic changes. Dependable rainfall with a 75–80% probability of occurrence suffices for crop production (Hargreaves 1975). Estimating dependable rainfall through long-term study and analysis of long-term climatic data helps plan the water management for a specific area and crop type. If the probability of occurrence is above or below the threshold levels, agricultural crop management decisions will be made, such as irrigation or draining the excess water. For excessive rainfall, drainage improvement can overcome the problem, while during dry periods, the water requirement of crops will never be met.

The 50 and 75% probability levels are the periods of weeks in which the chances of getting dependable rainfall of more than 20 mm/week are adequate. The months coincide with the farmer's planting date for the long rainy season. The length of the growing season depends on the onset of the rain; therefore, in this study, the length of the growing season varied between 70 and 133 days for the short and long rainy seasons, respectively. The weeks of the 25th to the 32nd had 100% guaranteed rainfall, with a high risk of erosion and waterlogging. The rainfall parameters, such as onset, withdrawal, amount, cessation of distribution, and the probability of receiving dependable rainfall in a month or week, will depend on the management options and type of crops to be planted. For the Ghinchi area, the amount and distribution of annual rainfall and the growing season's length are closely related. The dependable rainfall and PET relationship (Fig. 6) also shows that PET drops below the mean annual rainfall during the long rainy season, while vice-versa during the short and dry seasons of the year.

The 75% probability level indicates that dependable monthly rainfall begins in June, while at a 50% probability level it begins around May. The monthly PET reveals a positive water balance from June to September. Rainfall throughout the remaining months is below PET; thus, short-duration crops can probably be cultivated with the help of additional irrigation. Considering the 50% probability level, precaution should be taken that the lower the probability level, the higher the threshold values, but dependability matters. The relationship between rainfall, PET, and MAI is shown in Fig. 7. According to these data, at a 75% probability level, rainfall exceeds PET from July to September, while at a 50% probability level, it covers May and September. The weekly and monthly rainfall probability levels indicate that an MAI of more than 0.75 starts in June. Sowing of wet-season crops occurs in June, while pulse crops grow on residual soil moisture after September. The relationship between rainfall and PET shows that PET is lower than rainfall starting from week 22 to week 38. The positive water balance during this period allows long-duration crops to grow because the weekly rainfall is dependable. The MAI is at a 75% probability level, implying that more than 20 mm of rain is likely.

Weekly dependable rainfall and MAI

Understanding the relationship between rainfall and PET, as well as MAI calculated as the 75% dependable rainfall ratio to PET, is critical for agricultural planning and irrigation needs. Figure 8 illustrates the weekly average and dependable rainfall at a 75% probability level, including MAI and PE for Ghinichi. Rainfall above PET (R/PET) is expected this month. Sometimes, due to the intermittent and patchy nature of the rain, it is unpredictable to establish the exact sowing week and cessation of the rainfall. Rainfall above PET (R/PET) is the amount of rain that

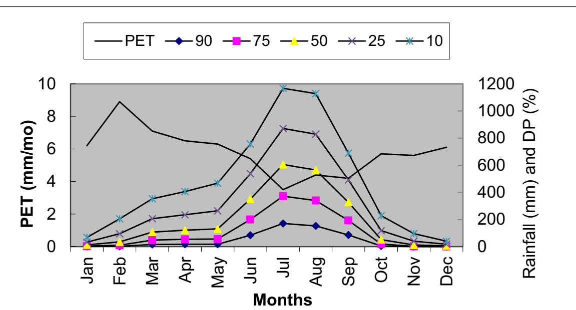

Fig. 6 Monthly expected rainfall amounts at 90, 75, 50, 25, and 10% probability levels along with normal PET for Ghnchi (database 1981–2020)

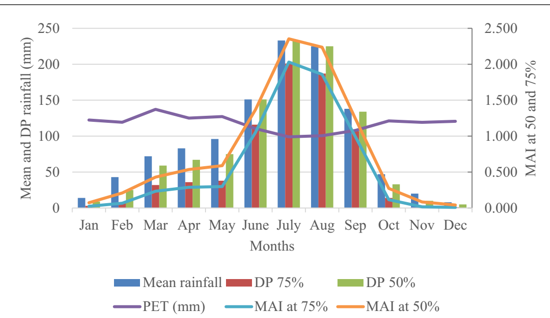

Fig. 7 Average monthly and dependable rainfall at 50 and 75% probability level, PET and MAI at 50 and 75% probability level

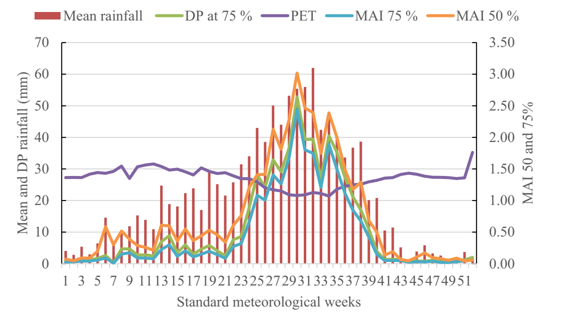

Fig. 8 Average weekly dependable rainfall at 75% probability level, PET, and MAI for Ghinchi

falls during the 4 months that are the main crop-growing periods. Sometimes, due to the intermittent and patchy nature of the rain, it is unpredictable from year to year to determine the beginning and cessation of the rain weekly. PET is lower than rainfall, and crop growth requirements can be maintained during these months. An MAI value of 0.33 is the threshold value to demarcate dry and moderately wet periods (Hargreaves et al. 1985). This value is significant at a 75% probability level and even higher at an MAI value up to the 38th week. Waterlogging and runoff occur during the rainy season when rainfall exceeds 75% of the annual average.

The MAI of Ghinchi is more than 1.33 from the 21st to the 38th week, indicating no water shortage for agricultural activities during this period. However, the rest of the months are always short of moisture.

The effective rainfall

An effective measure of the water balance is the computed ratio of 75% dependable rainfall and PET, defined as MAI. The long rainy season in Ghinchi begins in June and lasts until September. During these months, approximately 64% of the annual budget is received. A water requirement calculation at 50% probability can be used to check the ranking of the Gamma distribution (Hargreaves et al. 1985). Table 2 compares the mean (50% probability) and dependable (75% probability) assured rainfall for the long rainy season at Ghinchi. The 75% probable rainfall values are less than the mean rainfall and can be used for computations. The ratio of assured rainfall to PET, calculated weekly, gives a better understanding of water availability to plants because a month is a long period (Hargreaves 1975). Weekly rainfall at a 75% probability level and an MAI greater than 0.5 were considered optimal for plant growth in this study area. The dependable rainfall at a 50 and 75% probability level exceeds PET, starting in weeks 23 and 25 and ending in weeks 38 and 36, respectively, showing a positive water balance. The rest of the weeks had a negative water balance, meaning PET was greater than the dependable weekly rainfall. Thus, on average, for 16 weeks a year, the climatic water balance is positive, while for 35 weeks, the climatic water balance is negative. The mean annual rainfall of the study area is 1099 mm, while the mean annual PET is 1412 mm, indicating that the annual water deficit is 313 mm. According to Hargreaves (1975), the value of MA1 > 0.34 could be considered the lower value for dry land crops. The MA1 values exceed the lower threshold value of 0.34 in all the rainy months of Ghinchi, and the data for the length of the rainy seasons show that there are 133 days in Ghinchi (19th to 38th weeks), which is 280 days. During the 1st to 17th weeks and the 40th to 52nd weeks, MA1 values are below the lower threshold value. The MAI exceeds 0.5 falls from June to September (22nd–40th weeks), which indicates a crop growing period. However, MA1 during the 40th and 41st weeks was low. In some years, the October MAI falls short of the total water requirement for crops grown on residual moisture. MA1 at a 50% probability level falls between the 25th and 35th weeks, which is more than 1.00, indicates excess water, and requires an improved drainage system. The high water availability in this period would be sufficient to meet the moisture requirements of the crops in the latter part of the season. The construction of water harvesting structures that help crops grow to full maturity during dry spells is advantageous in years of unusually low precipitation.

Every month, the ratio of R/PET was below 1.00 from January to May and then dropped below the same threshold value of 1.00 from October to December. From June to September, adequate rainfall was received, whereas July and August received > 1.33 signals that the soil is saturated due to excessive rainfall, and draining the excess water from farmland is critical (FAO 2009; Hargreaves 1975).

The rainy days

Continued rainfall data is crucial to assessing the probability of dry and wet spells. It can be made possible by examining and summarizing some of the long-term climatic records of a study area. This information for calculating the probability of any specified combination of "wet" and "dry" days may be required to make long-term management decisions. The study confirmed that the amount of rain per rainy day and the number of rainy days increased from June to September and then declined. As evidenced in Table 4, the wet day count

Table 4 Statistics of mean weather elements

Variables	Units	January	February	March	April	May	June	July	August	September	October	November	December
W	Number	34	62	103	118	125	213	270	265	184	56	19	10
D	Number	276	220	207	182	185	87	40	45	116	254	281	300
W/D	Number	22	30	49	52	42	48	34	36	51	25	10	9
W/W	Number	12	32	54	66	83	165	236	229	133	31	9	1
Rainfall	Min	0.25	0.25	0.25	0.3	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Max	10.2	20.5	57.8	29.4	28.8	39.8	54.6	75.9	48.8	48.7	32.8	19.6
T_{max} (°C)	Min	18.8	18.8	21.2	15	18	18.5	16.1	17.1	18.2	18.3	19.6	21.9
	Max	29.1	32.1	32.7	34.6	30.5	31.8	25.4	25.7	25.8	26.7	27	26.9
T_{min} (°C)	Min	1.3	1.6	3.1	2.8	3.2	1.9	4.8	3.6	3.5	2.4	1.3	1.9
	Max	13.4	14.1	15.6	16.2	15.2	13.7	16.9	17.6	14.3	15.3	11.9	12.1
SR (w/m^2)	Min	23.8	23.5	17.6	2.3	15.3	10.6	1.8	6.1	16	10.2	23.3	23.6
	Max	25.4	27.2	28.3	28.3	28.1	27.4	27.2	27.9	27.9	27.4	25.7	24.3
Max. RH	Min	7.8	7.7	11.8	9.3	15.5	13.3	23.2	25.9	21.2	7.9	10.4	7.7
	Max	55.7	60	62.1	86.7	64.2	70.9	88.3	79	63.6	77.9	56.2	48.5
WS (m/s)	Min	3	3	3	3	3	3	3	3	3	3	3	3
	Max	3	3	3	3	3	3	3	3	3	3	3	3

W wet days count, *D* dry days count; *W/W* wet days count following wet days count, *W/D* wet days count following dry day count, *R* rainfall, T_{min} minimum temperature, T_{max} maximum temperature, *SR* solar radiation, *RH* relative humidity, *WS* wind speed

in July and August is more than 250 days and starts to decrease from September on. The wet day count above 100 started in March, reached 265 days, and then declined. The dry day count of more than 100 days started in September, reached 300 days in December, and then declined steadily. The lowest dry day counts below 100 days were for June, July, and August.

Dry counts were lower between February and May. The wet day count following a dry day count was higher for the short rainy season, while the values were lower for the main rainy season. The wet/wet day count was higher starting in May and extending up to September. The mean minimum rainfall amount was 0.25 mm for the dry periods. The mean maximum rainfall was 38.9 mm. The highest maximum rainfall recorded was in August, which was 74.9 mm. The other weather parameters shown in Table 4 are not clearly different between months.

Table 5 Probability (%) of receiving rainfall at different threshold levels in a week

Rainfall (mm)	Probability (50%) and above in a week			Length of the growing season	
	P(W)	P(W/W)	P(W/D)	Total no. of weeks	No. of days
> 10	13–40	21–38	21–38	27	189
> 20	22–38	20–37	22–37	17	119
> 30	25–37	21–36	26–36	15	105
> 40	26–35	22–34	26–33	12	84
> 50	29–34	28–34	28–30	7	49

[a] Length of the growing period based on > 20 mm threshold level P(W/W)

*P(W)-wet week, P(W/W)-wet week preceded by by wet week, (P(W/D)- dry week preceded by wet week.

Length of the growing period

At Ghinchi, the number of rainy days and the amount of rain per rainy day increased from June to August and then declined. June and August are the most assuredly rainy months, as is evident from the average duration between the rainy days (Table 4). The probability of receiving dependable rainfall of 20 mm is 50% in the 22nd week and extends up to the 38th week. The week coincides with the farmers' planting time during the long rainy season. For the short rainy season, the probability of receiving at least 10 mm of rainfall at a 50% probability starts around week 16, with some discontinuity in the preceding weeks. However, the chance of getting rainfall above 20 mm/week at a 50% probability for a short rainy season coincides with the long rainy season. As the length of the season mainly depends on the starting date, the effective length of the rainy season was found to vary between 120 days at a 90% probability level and 210 days at a 75% probability level (Table 5). Therefore, depending on the onset and withdrawal of rainfall, a decision will be made on the type of crop to be grown. However, dependable rainfall at a 75% probability level and a threshold level of greater than 20 mm with a conditional probability of [P(W/W)] are critical when considering the length of the growing period. In this connection, the growing season is about 17 weeks (119 days). The different threshold limits give different values for the growing season, which depend on the type of crop to be grown, the water requirement of crops, and soil suitability.

Other climatic elements

There is no major difference in weather parameters recorded for the last 10 years (Table 4). The maximum and minimum temperature ranges have relatively few variations, with a small standard deviation. The average yearly relative humidity varied between 50 and 84. Approximately 12 and 38 $MJ/m^2/day$ of solar radiation per month were measured. This study did not include weather parameters because they are consistent and predictable in all years.

Crop production on vertisols

A large variety of crops are grown in the area under various agricultural systems, allowing for much flexibility. The traditional farming practice depends on the onset of rain to grow crops. However, growing crops does not consider the water requirements, the potential yield, or the soil capability to grow crops. To assess the potential use of seasonal forecasts, the types of decisions and the factors, including the climate, that affect them need to be documented. An assessment was made to characterize some of the decisions made by farmers to improve their livelihoods. The various farming practices on vertisols specific to this area include planting long-duration crops such as maize and sorghum if the rains come during March or April (the short rainy season). The crops will grow with short and long rains. Otherwise, the land is left fallow for grazing livestock. However, the land allocation decisions for each crop depend on various factors, which vary each year, including other resources such as labor and land preparation. Most crops are planted during the long rainy season with minimal input and no irrigation facilities if weather anomalies occur. If the rain delays during the long rainy season, teff can be planted in late June.

Teff requires much labor throughout the planting, harvesting, and threshing processes. Teff also prefers waterlogged soil conditions and needs a fine seedbed preparation. The agro-climatic data analysis may indicate possible options for diversifying crops on these soils. The performance of different combinations of cropping systems under different rainfall distributions can be tested. Together with the seasonal rainfall forecasts, the probabilities can help to develop the various scenarios available to the farmers, whatever level of risk they choose. Some decisions that can be made affect land preparation, crop and variety choice, fertilizer application rate, soil and water conservation measures, and disease and pest control practices. To maximize crop production, improved management of vertisols such as double cropping, water harvesting, and improved agronomic practices are crucial.

Potential yield and crop production constraints

Vertisols are soils with high potential for crop production, but their physical characteristics limit their use and full potential. In the highlands, the major farming practice is sowing crops on residual moisture to alleviate the waterlogging problem. Using only part of the growing season may lead to low crop yields and considerable erosion hazards because fields are left without vegetative cover for much of the time. Today, most farmers use the broad bed and furrow drainage system to overcome the waterlogging problem and plant crops early in the season. However, the yield of crops grown on these soils is still much lower compared to other developing countries. To analyze the rainfall-soil-yield relationships, 20 years of rainfall and wheat yield data were taken, and regression analyses were performed (data not shown).

However, it turned out that the relationship between crop production and total annual or growing season rainfall was so weak that it could not adequately convey the effects of rainfall variability on crop productivity. Rainfall throughout the growing season, particularly rainfall in June, July, August, and September, has little link with crop productivity. The linear model approach's key flaws were that it could not distinguish between negative and positive effects while also recognizing a wider range of years with normal or around normal yield levels. However, in certain years, negative yield anomalies signified rainfall's negative impacts, just as in other years, positive anomalies signified positive impacts. On vertisols, negative impacts of the climate are more likely to result from excess rainfall and a poor drainage system during the crop-growing period. For wheat, positive climate impacts were recorded in 1993, 1995, and 1997. In the other year, crop yield anomalies did not attain the levels at which they could be considered impacts. This is not sufficient for forecasting crop yields or the impacts of climate. In the Ethiopian highlands, crop-livestock integration is very strong. Therefore, the impact severely affects the whole system.

Conclusion and recommendations

The rain-fed subsistence agriculture in the Ethiopian highlands is a victim of climate change and rainfall variability, resulting in food insecurity. Past rainfall probability studies showed that climate change is evident; the question is how to translate the results to farmers' needs so that farmers can adapt to the existing climatic conditions. Understanding rainfall variability helps farmers develop resilience and mitigation capacity. Agricultural production relies mainly on rainfall onset, cessation, intensity, amount, and distribution. As a result, it would be crucial to build development plans and programs, forecasts and early warning systems, and integrated adaptation strategies that consider local conditions. The present study tried to identify the onset, withdrawal, and length of the growing season for the Ghinchi area from the long-term rainfall data analysis. Dependable rainfall at a 75% probability level starts in June and extends until September. The planting time for main-season cropping may range from the last week of May to mid-June. The short rainy season is unreliable for planting crops due to its low amount and high variability. Double cropping can be exercised in years of optimal rain because vertisols have a naturally high waterlogging capacity. Sowing wheat in June using an improved drainage system, followed by growing pulse crops in October, as opposed to traditional practice, is advantageous. Building a water harvesting structure is another promising venture for vertisols to combat dry spells. Our findings show that the chances of receiving more than 50% of the predicted rainfall at a >20 mm (P(W/W)) threshold level begin on the 20th (14–20 May) and end on the 36th (3–9 September). Based on this calculation, the length of the growing period becomes 4 months, with 116, 201, 187, and 107 mm for June, July, August, and September, respectively. Forecasting the likely onset and cessation of precipitation on vertisols helps farmers prepare their land, plant crops, and harvest on time before the soil becomes saturated or dries out, making farm operations difficult under the traditional farming system. During years of excess rain, improving the drainage system and constructing water harvesting structures become useful so that farmers can supplement their land if an early withdrawal of rainfall occurs at any time of the year.

Limitations of the methodology and the need for future research

A lack of reliable rainfall data from nearby stations hampered comparative analysis. The untapped potential of crop production on vertisols is constrained by climate variability. Therefore, future research has to consider field-based studies on soil–water relationships, crops, and soil management for sustainable crop production. The variability of rainfall was the primary focus of this study. The rainfall-yield relationship was not conducted because this study was time bound.

Appendix 1. Probabilities of dry/wet spells based on the Markov chain model

Initial probability:	
$PD = FD/n$	(1)
$PW = FW/n$	(2)
Conditional probabilities:	
$PDD = FDD/FD$	(3)
$PWW = FWW/FW$	(4)
$PWD = 1 - PDD$	(5)
$PDW = 1 - PWW$	(6)
Consecutive dry and wet week probabilities:	
$2D = PDw1 \cdot PDDw2$	(7)
$2W = PWw1 \cdot PWWw2$	(8)
$3D = PDw1.\ PDDw2 \cdot PDDw3$	(9)
$3W = PWw1 \cdot PWWw2 \cdot PWWw3$	(10)

Where, *PD* probability of the week being dry, *FD* probability of the week being wet, *FD* number of dry weeks, *FW* number of wet weeks, *n* number of years of data, *PDD* probability (conditional) of a dry week preceded by a dry week, *PWW* probability (conditional) of a wet, *PWD* probability (conditional) of a wet week preceded by a dry week, *PDW* probability (conditional) of a dry week preceded by a wet week, *FDD* number of dry weeks preceded by another dry week, *FWW* number of wet weeks preceded by another wet week, *2D* probability of 2 consecutive dry weeks starting with the week, *2W* probability of 2 consecutive wet weeks starting with the week, *3D* probability of 3 consecutive dry weeks starting with the week, *3W* probability of 3 consecutive wet weeks starting with the week, *PDw1* probability of the week being dry (first week), *PDDw2* probability of the second week being dry, given the preceding week dry, *PDDw3* probability of the third week being dry, given the preceding week dry, *PWw1* probability of the week being wet (first week), *PWWw2* probability of the second week being wet, given the preceding week wet, *PWWw3* probability of the third week being wet, given the preceding week wet

Appendix 2. Standard meteorological weeks

SMW	Dates	SMW	Dates
1	1 January–7 January	27	2 June–8 July
2	8 January–14 January	28	9 July–15 July
3	15 January–21 January	29	16 July–22 July
4	22 January–28 January	30	23 July–29 July
5	29 January–4 February	31	30 July–5 August
6	5 February–11 February	32	6 August–12 August
7	12 February–18 February	33	13 August–19 August
8	19 February–25 February	34	20 August–26 August
9[a]	26 February–4 March	35	27 August–2 September
10	5 March–11 March	36	3 September–9 September
11	12 March–18 March	37	10 September–16 September
12	19 March–25 March	38	17 September–23 September
13	26 March–1 March	39	24 September–30 September
14	2 April–8 April	40	1 October–7 October
15	9 April–15 April	41	8 October–14 October
16	16 April–22 April	42	15 October–21 October
17	23 April–29 April	43	22 October–28 October
18	30 April–6 May	44	29 October–4 November
19	7 May–13 May	45	5 November–11 November
20	14 May–20 May	46	12 November–18 November
21	21 May–27 May	47	19 November–25 November
22	28 May–3 June	48	26 November–2 December
23	4 June–10 June	49	3 December–9 December
24	11 June–17June	50	10 December–16 December
25	18 June–24 June	51	17 December–23 December
26	25 June–1 July	52[b]	24 December–31 December

[a] Week no. 9 will have 8 days during the leap year

[b] Week no. 52 will always have 8 days

Appendix 3. Initial and conditional probabilities (%) of rainfall

Station: Ghinchi (1126.0 mm)							Database: 1981–2020									Mean
Std Week (mm)	> 10 mm			> 20 mm			> 30 mm			> 40 mm			> 50 mm			
	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	
1	10	0	11	10	0	6	5	0	0	5	0	0	0	0	0	4.0
2	10	0	11	5	0	0	0	0	0	0	0	0	0	0	0	2.8
3	10	50	6	0	0	0	0	0	0	0	0	0	0	0	0	2.5
4	10	0	22	0	0	10	0	0	10	0	0	5	0	0	0	3.0
5	20	50	25	10	50	17	10	50	17	5	100	11	0	0	15	6.4
6	30	50	14	20	25	13	20	0	6	15	0	6	15	0	0	14.6
7	25	40	33	15	33	12	5	0	16	5	0	5	0	0	5	7.1
8	35	57	31	15	67	18	15	33	6	5	0	5	5	0	5	10.5
9	40	63	50	25	40	33	10	50	6	5	100	5	5	100	5	12.9
10	55	45	33	35	29	23	10	50	17	10	50	11	10	0	6	16.6
11	40	63	33	25	60	7	20	0	6	15	0	0	5	0	0	13.7
12	45	44	64	20	50	50	5	0	32	0	0	20	0	0	20	9.9
13	55	55	67	50	40	40	30	33	21	20	0	19	20	0	19	25.3
14	60	58	0	40	50	8	25	40	20	15	0	18	15	0	12	20.7
15	35	100	54	25	100	40	25	80	33	15	33	24	10	0	11	15.2
16	70	79	33	55	36	33	45	22	27	25	20	20	10	0	6	25.3
17	65	62	29	35	71	31	25	40	27	20	50	19	5	0	16	18.0
18	50	70	60	45	56	36	30	50	29	25	40	27	15	0	24	20.8
19	65	62	14	45	22	27	35	14	23	30	17	21	20	0	25	25.0
20	45	44	36	25	60	33	20	25	19	20	25	19	20	0	13	18.4
21	40	100	58	40	75	42	20	75	38	20	25	19	10	0	17	19.0
22	75	73	60	55	82	56	45	56	45	20	50	25	15	67	24	26.1
23	70	100	67	70	71	67	50	70	20	30	50	21	30	50	21	29.2
24	90	100	100	70	86	100	45	67	64	30	50	43	30	33	21	36.9
25	100	100	0	90	83	100	65	85	43	45	56	45	25	40	33	39.1
26	100	100	0	85	76	100	70	79	50	50	70	60	35	71	38	41.4
27	100	100	0	80	88	75	70	71	83	65	38	71	50	30	30	53.2
28	100	100	0	85	94	100	75	93	100	50	70	90	30	67	57	43.1
29	100	100	0	95	95	100	95	95	100	80	63	100	60	50	75	54.1
30	100	100	0	95	95	100	95	89	100	70	71	50	60	58	50	58.6
31	100	100	0	95	100	100	90	94	100	65	77	57	55	82	44	53.8
32	100	95	0	100	95	0	95	79	0	70	57	33	65	46	29	62.4
33	95	100	100	95	95	100	75	73	100	50	70	60	40	63	42	46.7
34	100	100	0	95	79	0	80	63	50	65	54	43	50	50	20	49.7
35	100	95	0	75	87	80	60	42	63	50	30	20	35	0	23	40.6
36	95	89	100	85	71	67	50	60	50	25	20	40	15	0	12	34.2
37	90	89	100	70	64	67	55	45	44	35	29	31	10	50	28	33.5
38	90	61	100	65	46	43	45	33	27	30	17	7	30	0	7	36.8
39	65	62	29	45	44	27	30	33	21	10	0	22	5	0	21	20.6
40	50	40	0	35	43	0	25	20	0	20	25	0	20	25	0	21.9
41	20	50	44	15	33	18	5	100	16	5	0	11	5	0	0	8.0
42	45	33	9	20	25	6	20	25	0	10	0	0	0	0	0	12.1
43	20	0	0	10	0	0	5	0	0	0	0	0	0	0	0	4.5
44	0	0	20	0	0	15	0	0	5	0	0	0	0	0	0	0.3
45	20	50	6	15	33	6	5	0	11	0	0	5	0	0	5	5.3

Station: Ghinchi (1126.0 mm)							Database: 1981–2020									Mean
Std Week (mm)	> 10 mm			> 20 mm			> 30 mm			> 40 mm			> 50 mm			
	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	
46	15	0	6	10	0	6	10	0	6	5	0	5	5	0	5	9.0
47	5	0	5	5	0	5	5	0	5	5	0	5	5	0	0	3.1
48	5	0	0	5	0	0	5	0	0	5	0	0	0	0	0	2.5
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5
50	0	0	10	0	0	5	0	0	5	0	0	5	0	0	5	1.5
51	10	50	6	5	0	5	5	0	0	5	0	0	5	0	0	3.6
52	10	50	0	5	100	0	0	0	5	0	0	5	0	0	0	2.0

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Author contributions
As part of a Ph.D. study for the corresponding author, the co-authors are advisors and supervisors of this study. Therefore, their contribution to this manuscript was profound. Their contribution was higher in reviewing, editing, and interpreting results. All authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate
This manuscript is part of a Ph.D. thesis on "The Impact of Climate Change and Rainfall Variability in Relation to Drainage Improvement on Vertisols for Sustainable Crop Production in the Highlands of Ethiopia." Therefore, all authors agreed and approved of being published, and there is no ethical conflict.

Consent for publication
All authors read the manuscript and agreed to its publication.

Competing interests
The authors declare that they have no competing financial or non-financial interests directly related to the work submitted for publication.

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