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Growing Season Characteristics under Varying Rainfall Probabilities in the Blue Nile Region, Sudan

Lotfie A. Yousif[1], Shaker BabikerAhmed[2*], Hassan Elhaj Alsayim[3], Amir B. Saeed[4], Osama M. Elhassan[5], Mohamed Y. Mohamed[6]

[1]Agricultural Engineering Research Program, Agricultural Research Corporation (ARC), Wad Medani, Sudan, (E-mail:(lottfie.yousif@yahoo.com),
2Department of Agricultural Engineering, Faculty of Agriculture, Omdurman Islamic University, Omdurman, Sudan, (E-mail:(shaker33@gmail.com.com)
3Department of Agricultural Engineering, Faculty of Agriculture, Nile Valley University, Atbara, Sudan, (alsayim101@yahoo.com),
4Amir B. Saeed, Department of Agricultural Engineering, Faculty of Agriculture, University of Khartoum, Sudan (absaeed5@yahoo.com)
5Crop Production Research Program, Agricultural Research Corporation (ARC), Wad Medani, Sudan (lottfie.yousif@gmail.com)
6Oil Crops Research Center, Agricultural Research Corporation (ARC), Wad Medani, Sudan, (lottfie.yousif@gmail.com)
*** Corresponding authors:** shaker@oiu.edu.sd; shaker33@gmail.com

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ABSTRACT

Rainfed agriculture is central to food security and livelihoods in Sudan, particularly in the semi-humid zones such as the Blue Nile Region where rainfall patterns dictate crop success. This study analyzes growing season characteristics under five rainfall probability levels (20%, 40%, 50%, 60%, and 80%) using 51 years (1971–2021) of rainfall and evapotranspiration data. Monthly rainy days were categorized by intensity, and seasonal rainfall amounts were analyzed across probabilistic classifications. Results indicate that the wet season (20% probability) experiences the highest rainfall and the longest growing season (154 days), while the dry season (80%) is limited to 111 days. Rainfall distributions follow a bimodal pattern with predominance of low-intensity events and limited moderate rainfall. Pre-season and post-season rainfall have significant implications for field accessibility, crop quality, and harvest efficiency. The study highlights the need for early field preparation, improved crop varieties, and conservation agriculture practices to mitigate climate risks and optimize productivity in the face of increasing variability.

1. INTRODUCTION

The rainfed agricultural sector in Sudan plays a critical role in national food security and rural livelihoods, particularly in the cultivation of summer crops such as cotton, groundnut, sorghum, and sesame. According to [1], the rainfed sector contributes approximately 95% of the country's pearl millet, 78% of sorghum, 67% of groundnuts, and the entirety of its sesame production. Rainfall characteristics are thus central to both environmental systems and socioeconomic development in Sudan. As a dominant climatic factor, rainfall significantly shapes hydrological processes, ecosystem functions, and agricultural productivity [2]..

However, average annual rainfall has declined markedly since the early 1960s. [3-4] confirmed this decline and reported a concurrent southward shift of desert and semi-desert zones, although these trends vary across regions. Between 1921–1950 and 1956–1985, rainfall decreased by approximately 15%, the rainy season contracted by nearly three weeks, and rain zones shifted southward by 50 to 100 kilometers [5]. More recently, [6]. observed fluctuations in annual rainfall in the Blue Nile State, reflecting growing variability in seasonal patterns. In Sudan, the rainy season typically extends from June to September. [7] noted that July and August each contribute about 30% of the total summer rainfall, while June and September contribute around 20%, although these two months also exhibit higher inter-annual variability.

In recent decades, both droughts and floods have increased in frequency and intensity [8], [9] which attributed to climate variability, particularly in the Blue Nile Basin, where rising temperatures and erratic rainfall patterns have led to prolonged dry spells and extreme weather events. [2] observed that recurring droughts severely undermine agricultural production. These droughts are often linked to El Niño–Southern Oscillation (ENSO) events. While some areas of eastern Africa, including parts of the Blue Nile Region, have experienced increases in mean annual rainfall, the overall patterns remain highly variable in both time and space [10]. Nevertheless, [3] suggest that rainfall in Sudan is somewhat predictable, with the potential for improved forecasting through further research.

Quantifying rainfall characteristics is essential for understanding the water balance in agricultural systems, as it directly affects soil moisture and crop productivity. In particular, analyzing the growing season in the semi-humid zone of the Blue Nile Region is critical for effective crop planning and yield optimization. Given the spatial and temporal variability of rainfall in the region. [11], probability-based rainfall analysis can help predict seasonal totals and support adaptive management. Additionally, identifying the onset, cessation, and length of the growing season is crucial for selecting appropriate crop varieties and aligning planting and harvesting schedules. Understanding the distribution of rainfall before, during, and after the growing season helps farmers anticipate water availability and plan for risk.
Therefore, the main objective of this study is to analyze the characteristics of the growing season in the Blue Nile Region of Sudan, using 51 years of rainfall and evapotranspiration data (1971–2021).

The specific objectives are to:

1. Analyze monthly rainy days based on rainfall intensity, categorized as low (<10 mm/day), moderate (11–20 mm/day), and high (>20 mm/day).
2. Determine seasonal rainfall amounts for wet, semi-wet, normal, semi-dry, and dry years using rainfall probabilities of 20%, 40%, 50%, 60%, and 80%, respectively.
3. Identify the start, end, and duration of the growing season using monthly evapotranspiration (ETo) and rainfall data.
4. Quantify the amount of rainfall occurring before, during, and after the growing season.

2. MATERIALS AND METHODS

2.1 Study area

The Blue Nile Region lies in the southeastern part of Sudan between latitudes 9.30º and 13.34º N and longitudes 33.8º and 35.15º E, covering 45844 km^2. The region borders by Ethiopia to the east, South Sudan in the south, Sennar state in the north and White Nile State in the west.

The region lies in semi-humid zones [11]. The soil is heavy cracking clay (Vertisols), characterized by shrinking when dry and swelling when moistened. The daily mean temperature varies from 16.6°C in January to 40.7°C in April. The daily evapotranspiration ranges between 6.8 mm in April and 4.5 mm in August. Rainfall is always in the summer and most rainfall events occur within the period June to October, resulting in a single growing season. About 4.5 million feddans (one feddan = 0.42 hectare) are suitable for mechanized farming sector of which only 2.5 million feddans are under cultivation, in addition to 0.17 million feddans are under traditional farming sector. The main crops grown in the region include cotton, sorghum, and oil crops such as sunflower, sesame, and groundnut, in addition to gum Arabic.

2. 2 Data collection

To achieve the objectives of this study, daily climate data were obtained from Sudan Metrological Authority (SMA) records. The daily rainfall, maximum and minimum temperature in addition to relative humidity and sunshine duration data were obtained over a 51-year period (1971 to 2021). AquaCrop program was used to calculate evapotranspiration.

2.3 Determination of season type

The rainfall totals and their corresponding years were arranged in an excel worksheet. A computer program, developed by [12], was used to determine rainfall amount in wet, semi-wet, normal, semi-dry and dry seasons for the historical data by using rainfall probabilities of 20%, 40%, 50%, 60% and 80%, respectively. This program ranks the rainfall events in a descending order and assign each rainfall event a rank number. Then it calculates the probability of rain occurrence according to the following equation:

$$P(\%) = \frac{m - 0.375}{N + 0.25} \quad (1)$$

Where:

- P = rain probability in %
- m = the rank of the observation.
- N = total number of rainfall events.

2.4 Determination of characteristics of the growing season

Characteristics of the growing season include the start, end and length of the growing season. These characters were determined according to the method described by [11] as shown in Figure 1 by plotting the monthly rainfall data and half evapotranspiration (0.5 ET_o) in the Y axes against the months in the x axes. The intersection of the rainfall line with the 0.5 ET_o line on the left-hand side determines the point (date) at which the growing season starts whereas the intersection of the other intersection on the right-hand side determines the end of the growing season. The period between these two points describes the length of the growing season. This procedure was followed for wet (20%), semi-wet (40%), normal (50%), semi-dry (60%) and dry (80%) seasons. Moreover, rainwater occurred before, during and after the end of each season was calculated.

3. RESULTS AND DISCUSSION

3.1 Intra-seasonal distribution of rainy days and rainfall intensity

Table 1 presents the intra-seasonal distribution of rainy days from April to November, revealing distinct rainfall patterns characteristic of Sudan's climatic zone [13]. The frequency of rainy days peaked in July and August (13 days each), reflecting the core of the African monsoon season [14].

In contrast, minimal rainfall was recorded in April (1 day) and November (0 days), marking the typical start and end of the rainy season [15].

Rainy days were further classified into three intensity categories; low (<10 mm/day), moderate (11–20 mm/day), and high (>20 mm/day). The analysis showed that low-intensity rainfall events were the most frequent, with 36 days per season, peaking in July and August, followed by June and September. This dominance of low-intensity events is consistent with rainfall distribution patterns across the Sahel [16].

High-intensity events (>20 mm/day) occurred on 12 days per season, with the highest frequency also in July and August. This exceeds the regional average of 9.2 days for comparable agroecological zones [17]. In contrast, moderate-intensity rainfall (11–20 mm/day) was the least frequent, occurring on just 10 days per season. This scarcity differs from patterns observed in humid tropical regions [18].

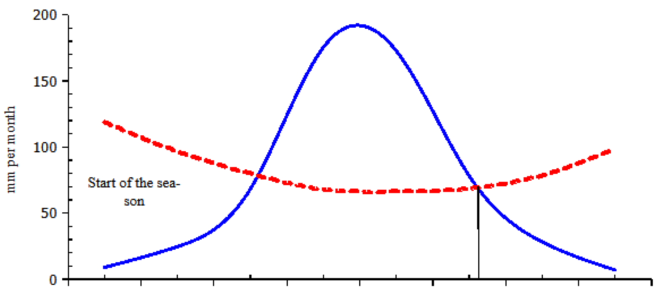


Figure 1. General Characteristics (start, end and length) of the Growing Season

The rainfall distribution follows the characteristic bimodal pattern of transitional tropical climates [19], where rainfall tends to concentrate in either low- or high-intensity events, with fewer moderate rainfall days. This imbalance has significant agronomic implications, particularly in mechanized farming systems. The high frequency of rainfall during July and August often leads to saturated soils, making it difficult to use agricultural machinery for land preparation, seeding, and weed control, especially on large-scale farms. This operational challenge partly explains the region's shift toward conservation agriculture practices. Since 2000, the Arab Authority for Agricultural Investment and Development (AAAID) has promoted zero-tillage (ZT) systems to replace traditional tillage in the Blue Nile Region, helping mitigate the limitations imposed by wet field conditions.

Table 1. Distribution of rainy days according to rain quantities in Blue Nile Region during the period from 1971 to 2021

Month	<10 mm	11 to 20 mm	> 20 mm	Total
April	1	0	0	1
May	4	1	1	6
June	7	2	2	11
July	8	2	3	13
August	8	2	3	13
September	6	2	2	10
October	2	1	1	4
November	0	0	0	0
Total	36	10	12	58

3.2 Probability analysis of annual rainfall and season types

Figure 2 presents the annual rainfall amounts for five rainfall probability levels in the Blue Nile Region from 1971 to 2021, classified according to established agro-climatic thresholds [22]. The analysis revealed that the wet season (20% probability) received an annual rainfall of 804.8 mm, a value comparable to extremely wet years documented in the Ethiopian Highlands [23], and exceeding the 750 mm threshold considered optimal for rainfed agriculture [24] (. The semi-wet season (40% probability) recorded 735.3 mm, aligning with the 700–800 mm range deemed suitable for productive sorghum cultivation [25]. For the normal season (50% probability), the annual rainfall was 700.3 mm, closely matching the long-term median of 695 mm reported in Nile Basin hydrological studies [20]. The semi-dry season (60% probability) received 664.7 mm, approaching the critical 650 mm threshold below which crops may experience water stress [17]. Finally, the dry season (80% probability) recorded 620.3 mm, corresponding to drought conditions that can result in yield reductions of 20–30% [18]. This probabilistic framework underscores the region's pronounced rainfall variability, with a coefficient of variation (CV) of 18.7%, which exceeds the Sahelian average of 15.2% [21]. The 184.5 mm difference between wet and dry season extremes highlights the significant climate risk faced by rainfed agricultural systems, consistent with observations from other transitional tropical zones [19]

3.3 Monthly rainy days under varying rainfall probabilities

Figure 3 illustrates the distribution of monthly rainy days across five-rainfall probability categories wet, semi-wet, normal, semi-dry, and dry based on data from 1971 to 2021. Rainfall events were grouped into three intensity classes: less than 10 mm, 10–20 mm, and greater than 20 mm. The highest frequency of monthly rainy days with rainfall below 10 mm (30 days) occurred in July during the wet season. This finding aligns with regional climatological patterns influenced by monsoon dynamics [26] (. Moderate-intensity events (11–20 mm) peaked at five rainy days per month, occurring in July during the semi-wet season and in August during the normal season, consistent with transitional atmospheric conditions [27]. For high-intensity rainfall (>20 mm), the maximum of five rainy days was observed in August across the wet, normal, and semi-dry seasons. This pattern likely reflects localized convective activity influenced by orographic effects [28]. These findings highlight the intra-annual variability of rainfall patterns in the region and reflect broader climatic trends documented in recent hydro-climatic studies [29].

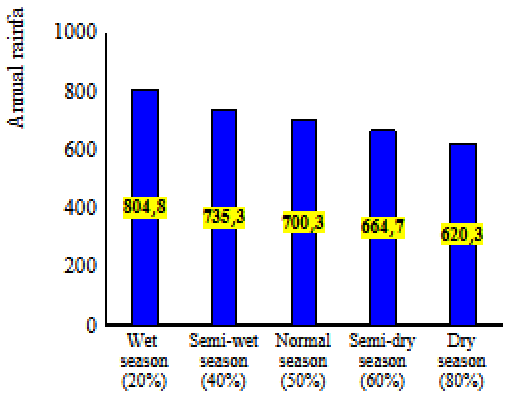
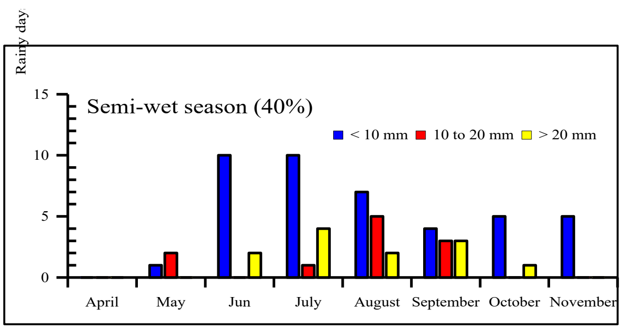


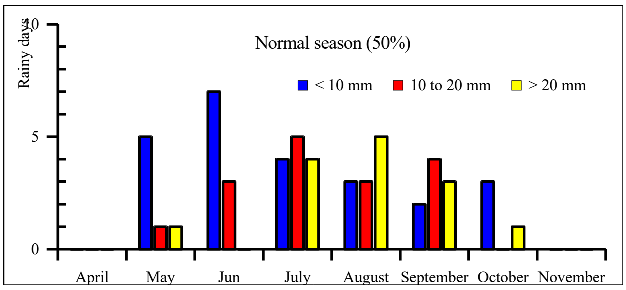
Figure 2. Annual rainfall under varying rainfall probabilities in Blue Nile Region during the years from 1971 to 2021

3.4 Characteristics of the growing season under varying rainfall probabilities

Table 2 presents the growing season parameters for different rainfall probabilities in the study area from 1971 to 2021, based on the standardized meteorological criteria developed by [22]. The results reveal variations in the onset and cessation of the growing season depending on rainfall probability. For the wet season (20% probability), the growing season typically begins in early May, aligning with early monsoon patterns in the Ethiopian Highlands [30]. In contrast, the semi-wet, normal, semi-dry, and dry seasons generally start during the first half of June, which is consistent with climatic norms across Sudan [31] (. The end of the growing season for the dry scenario (80% probability) occurs in late September, corresponding to early monsoon withdrawal observed during drought years [14]. The cessation of the growing season for the other rainfall scenarios usually takes place in the first ten days of October, reflecting typical Sahelian seasonality [33].



(a)



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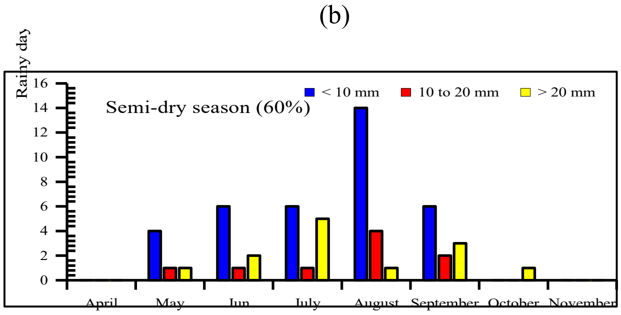

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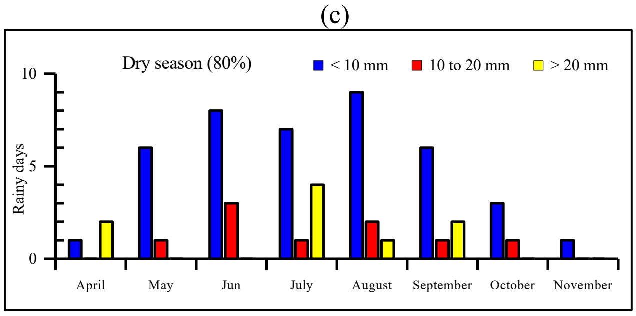

(d)

Figure 3. Distribution of monthly rainy days under varying rainfall probabilities and rain quantities in Blue Nile Region during the period from 1971 to 2021

The duration of the growing season for each rainfall category is shown in Figure 4. The wet season has the longest duration of approximately 154 days, aligning with optimal growing periods reported for western Ethiopia [33]. In contrast, the dry season lasts only 111 days, close to the critical threshold of 100 days needed for short-cycle crop cultivars [35] . The normal and dry seasons, with durations ranging from 111 to 113 days, meet the minimum growth period requirements for crops such as sorghum (90–110 days), as documented by [25], and short-duration maize varieties (100–120 days) [36].

Table 2. Season type, corresponding year start and end of the growing season in Blue Nile Region during the period from 1971 to 2021

Season type	Correspon ding year	Start	End
Wet season (20%)	2017	03-May	03-Oct
Semi-wet season (40%)	1988	12-Jun	10-Oct
Normal (50%)	2016	15-Jun	05-Oct
Semi-dry season (60%)	2012	02-Jun	02-Oct
Dry season (80%)	1979	10-Jun	28-Sep

These findings emphasize the presence of a single growing season marked by variable yet generally abundant rainfall. While the rainy season presents valuable opportunities for agricultural productivity, it also poses operational challenges that require early planning and effective resource management. To fully harness the benefits of this season, farmers are advised to prepare in advance through the use of high-capacity or additional machinery, or by streamlining field operations via multi-purpose equipment, especially in light of time limitations and wet field conditions. Moreover, adopting improved agricultural technologies is crucial. These include the use of high-yielding, drought-tolerant crop varieties, optimal sowing dates, appropriate planting densities, and the recommended application of agrochemicals. Such strategies can help ensure a productive, resilient, and sustainable agricultural season under varying climatic conditions.

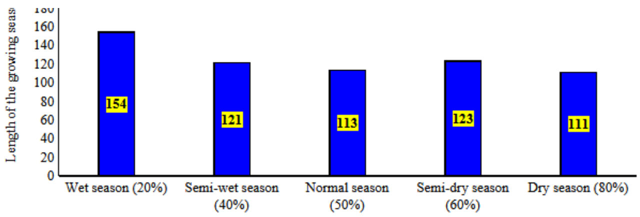

Figure 5. Length of the growing season under varying rainfall probabilities in Blue Nile Region

3.4 Distribution of rainfall relative to growing season phases

Figure 5 illustrates the distribution of seasonal rainfall across three critical agricultural phases; pre-season, in-season, and post-season, under five rainfall probability scenarios (20% to 80%) in the Blue Nile Region. Pre-season rainfall ranged from 0 to 110.7 mm, reflecting significant inter-annual variability that directly affects soil moisture and field accessibility. Notably, in the dry season scenario (80% probability), pre-season rainfall reached 110.7 mm, exceeding the 100 mm threshold required for optimal seedbed preparation [34]. These results are consistent with soil moisture patterns reported in similar climate zones [36]
The analysis further revealed that the majority of rainfall occurred during the growing season across all seasonal types (Figure 5). However, the total amount of in-season rainfall decreased with increasing rainfall probability, from wet to dry seasons, indicating an inverse relationship between rainfall probability and volume. Rainfall outside the growing season (both before the start and after the end) was generally minimal, except in a few scenarios such as the semi-wet season.

In contrast, post-season rainfall ranged from 0 mm in the wet season to 41.9 mm in the semi-wet season. Values exceeding 25 mm are known to increase the risk of harvest delays and grain spoilage by 23–30% (Elagib and Mansell, 2000). In this study, post-season rainfall of 19.1–41.9 mm was recorded across different scenarios, corresponding to an estimated 18–22% reduction in harvesting efficiency [37].

These conditions also elevate the risk of mycotoxin contamination [38] and contribute to post-harvest losses of 15–25% in traditional storage systems [39], especially for moisture-sensitive crops like sorghum [35]. These findings highlight the importance of aligning planting and harvesting schedules with rainfall distribution patterns to minimize post-harvest losses and preserve grain quality, an increasingly critical strategy in the face of climatic variability.

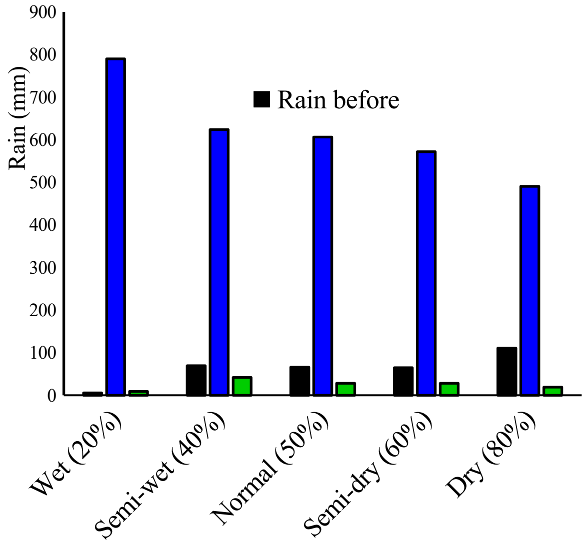

Figure 5. Rainfall before, during and after growing season under varying rainfall probabilities in Blue Nile Region

3.5 Distribution of rainy days according to growing season phases

Figure 6 presents the probabilistic distribution of rainy days across three critical agricultural phases, pre-season, in-season, and post-season, under five seasonal types. The results reveal distinct patterns in rainfall timing and frequency, with important implications for farm operations.

The analysis shows an increase in pre-season rainy days from 2 days in the wet season (20% probability) to 12 days in the dry season (80%). This inverse relationship between pre-season rainy days and total seasonal rainfall aligns with observations from the West African monsoon zone [16]. Notably, the dry season's 12 rainy days exceed the 8-day threshold required for effective soil conditioning [34], while the wet season's limited pre-season rainfall (2 days) may result in delayed planting, an issue similarly observed in comparable agroecological regions [32].

Across all season types, the majority of rainy days occurred during the growing season. However, variation in intensity was evident; the wet season recorded the highest number of in-season rainy days, while the normal and dry seasons experienced significantly fewer. This variability has direct implications for crop water availability and fieldwork scheduling.

Post-season rainfall patterns were more complex. The semi-wet season (40% probability) experienced the highest number of post-season rainy days (11), a condition associated with up to 28% harvest losses in cereal systems [25] (In contrast, the semi-dry season (60%) recorded just one post-season rainy day, creating favorable conditions for harvesting operations [35].

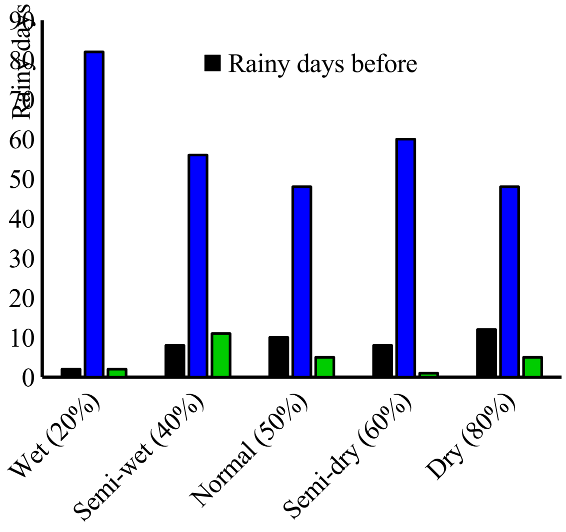

Figure 6. Rainy days before, during and after growing season under varying rainfall probabilities in Blue Nile Region

CONCLUSION

This study provides a detailed assessment of growing season in the Blue Nile Region under different rainfall probability scenarios, based on 51 years of climatic data. The findings demonstrate that rainfall is highly variable in timing, intensity, and distribution, significantly influencing growing season onset, duration, and cessation. Low and high intensity rainfall events dominate the region's rainfall profile, while moderate rainfall is relatively scarce, posing both operational and agronomic challenges. Notably, pre-season and post-season rainfall have critical effects on field preparation, harvesting, and post-harvest grain quality. The results underscore the importance of aligning crop calendars with rainfall phases to improve resilience in rainfed systems. Adaptive measures such as early land preparation, adoption of zero tillage, and the use of high-yielding, short-duration crop varieties, and investment in weather monitoring and forecasting systems are recommended. As climate variability intensifies across East Africa, such probabilistic assessments are essential tools for agricultural planning, policy development, and food security interventions in regions like the Blue Nile.

Competing Interests

Authors have declared that no competing interests exist.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript

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