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Assessing Rainwater Adequacy for Crop Cultivation under Varying Rainfall Probabilities in the Blue Nile Region, Sudan

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ABSTRACT

The amount of rainfall and the period between rainfall events play a fundamental role in watering rainfed crops, thereby improving productivity. rainfed agriculture in Blue Nile region is one of the important areas in the Sudan. This study evaluated the adequacy of seasonal rainfall compared to crop water requirements for major rainfed crops grown in the Blue Nile region under five climatic conditions: wet, semi-wet, normal, semi-dry, and dry seasons. Daily climate data were obtained from Sudan Metrological Authority (SMA) records during the period from 1971 to 2021. Start, end and length of the growing season were determined for the five season types. Rainwater before, during and after the growing season was calculated. Seven summer crops were studied, namely: sorghum, millet, sesame, sunflower, groundnuts, soya bean and cotton. Crop life cycle, length of growth stages and crop coefficients were used to calculate ETc. The results indicated that while early-season rainfall often meets crop demands, mid and late-season deficits are common, particularly in semi-dry and dry seasons. Though total rainfall was adequate, its uneven distribution underscores the necessity for using suitable crop management and soil moisture conservation practices. The study concluded that all studied crops are viable under current rainfall regimes in Blue Nile region, however, suitable crop management and soil moisture conservation practices have to be considered during mid and late season.

1. INTRODUCTION

Rainfall timing, intensity, and distribution play a critical role in determining crop yield and quality, particularly in rainfed agricultural systems. Understanding and predicting these factors prior to the onset of the rainy season is essential for selecting appropriate crops and ensuring optimal productivity. As the primary abiotic factor in rainfed farming, rainfall remains a major constraint to improved agricultural output [1]. Rainfall is the most important climatic variable, which has direct and indirect impacts on the environment and human life [2]. [3] found that the fluctuations in rainfall affect major crops, and emphasized the importance of understanding rainfall variability and its implications for agricultural practices. key characteristics influencing crop production include the onset and cessation of rains, duration and frequency of rainy and dry spells, weekly distribution, and the number of rainy days [4]. Rainfall variability also influences broader environmental and socioeconomic conditions [2], with potential impacts intensified by climate change. In the Blue Nile Basin, rainfall patterns have become increasingly erratic, contributing to both droughts and floods [5-6].

In Sudan, rainfed agriculture is practiced in the semi-dry to semi-humid agro-ecological zones within the Central Clay Plains belt. This belt extends through Kassala, Gedarif, Sennar, Blue Nile, White Nile, and South Kordofan States, covering about 12 million hectares [7]. Low yield of rainfed crops in Sudan is mainly due to rainwater mismanagement [8-9]. [10] concluded that understanding the annual variability of rainy season rainfall is a priority for agriculture decision makers. A study conducted by [11], showed some fluctuations in the amount of annual rainfall in the Blue Nile region of Sudan.

Sudan’s rainfed agricultural sector, which accounts for over 90% of the cultivated land, is primarily practiced in the central clay plains across various agro-ecological zones [12]. Major crops such as sorghum, sesame, millet, and groundnut are largely dependent on seasonal rainfall [13] (FAO, 2010). However, poor rainwater management and high spatial-temporal rainfall variability have led to low yields [8-9]. (the author mentioned poor water management many times without explaining what poor water management really means or how poor it is!)

Historical data indicate a significant decline in annual rainfall since the 1960s, along with a shortening of the rainy season and a southward shift in rain zones by 50–100 km [14]. Most rainfall in Sudan occurs from July to September, driven by the northward movement of humid air masses and their retreat [15]. However, inter-annual variability remains high, especially in the early and late phases of the rainy season [16].

Numerous studies emphasize the importance of improving rainfall forecasts and understanding its drivers [16-17]. The Blue Nile region, in particular, exhibits substantial rainfall variability, necessitating strategic agricultural planning [18]. Understanding rainfall anomalies, often linked to ENSO (The El Niño-Southern Oscillation) events, is crucial for mitigating drought impacts [2].

To address these challenges, agricultural policy must account for climate risks and provide tools to optimize water use. This includes identifying rainfall-reliable zones and calculating water requirements for various crops [19-20]. rainfed agriculture remains a cornerstone of Sudan’s economy, yet it demands urgent attention due to increasing climate variability. The objectives of this study was conducted to evaluate the adequacy of seasonal rainfall compared to crop water requirements (ETc) for major rainfed crops grown in the Blue Nile region under five climatic conditions: wet, semi-wet, normal, semi-dry, and dry seasons.

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 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 [21]. 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 ha) are suitable for mechanized farming sector of which only 2.5 million feddans is under cultivation, in addition, 0.17 million feddans are under the traditional farming sector.

2.2 Data collection

To achieve the objectives of this study, daily climate data were obtained from Sudan Meteorological 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).

2.3 Determination of crop water requirements

The crop water requirement (ET_c) was determined according to the procedures described by [22 by using evapotranspiration (ET_o) and crop factor (k_c) as follows:

$$ET_C = ET_o \times k_c \quad (1)$$

The ET_o on daily basis was estimated from the collected climate data by using AquaCrop and the k_c for each crop during their growing stages was obtained from FAO Paper 56 (Table 1). Four crop growth stages were considered in this study, initial, development, mid and late season stages (Table 2). On the other hand, rainwater was computed for each crop stage in addition to the four stages together.

Table 1. Crop factor (k_c) for the studied crops during varying growth stages

Crop	Initial	Development	Mid-season	Late season
Sorghum	0.35	0.73	1.05	0.55
Millet	0.51	0.78	0.87	0.5
Sesame	0.35	0.75	0.98	0.51
Sunflower	0.35	0.75	1.075	0.35
Groundnuts	0.45	0.75	1.15	0.6
Soya bean	0.35	0.75	1.15	0.5
Cotton	0.45	0.75	1.175	0.6

Source: FAO Paper 56

2.4 Studied crops and crop selection

Several crops were tested namely, sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), sesame (*Sesamum indicum*), sunflower (*Helianthus annuus*), groundnut (*Arachis hypogaea*), soya bean (*Glycine max*), and cotton

(*Gossypium hirsutum*). The suitability of crops to be grown in the study area was assessed based on two conditions. The first condition was: if the total rainfall during the growing period is equal to or greater than ETc for specified crop, then this crop was considered as suitable crop, otherwise not suitable. The second condition compared the length of the growing season and life cycle of each crop plus rainfall amount during the growing period which stated, if both crop life cycle and its total water requirement are equal to or less than the length of the growing season and rainfall amount during the growing period, the crop is considered as suitable, otherwise not suitable.

2.5 Growth duration of selected crops (days)

Table 2 shows the length of the growing season for the studied crops in the study area. Variations in growth stages underscore the distinct water requirements of each crop, necessitating careful consideration of agricultural practices management. [23] demonstrated that the influence of rainfall on crop production is determined not only by its cumulative seasonal quantity but also by its temporal distribution during the growing season.

Table 2. Growing period (days) for the selected crops

Crop	Initial	Develop-ment	Mid-season	Late season	Total
Sorghum	20	35	30	20	105
Millet	15	35	30	10	90
Sesame	20	25	30	25	100
Sunflower	25	35	30	20	110
Groundnuts	12	15	30	33	90
Soya bean	20	30	30	25	105
Cotton	20	40	30	20	110

Source: ARC researchers and crops specialists

3. RESULTS AND DISCUSSION

3.1 Rainfall adequacy relative to crop water requirement (ET_c) in wet conditions

Figure 1 compares between cumulative rainfall amount during the growing season and crop water requirements (ETc) for the seven major rainfed crops in the wet season. During the initial growth stage, rainfall consistently exceeded ETc for sorghum, sunflower, sesame, and soya bean, whereas rainfall and water demand remained closely aligned for pearl millet and cotton crops.

In the development stage, rainfall continued to surpass ET_c across all crops except sesame, which exhibited a crossover phenomenon. Rainfall was higher than ET_c in the first half of development stage but fell below ET_c in the latter half. At mid-season stage, every crop except pearl millet experienced a rainfall deficit relative to ETc, underscoring the risk of drought stress if unmanaged. These mid-season deficits highlight the critical need for continual crop monitoring and soil moisture management. These findings align with [24], who established a critical physiological framework linking crop water stress responses to optimized irrigation strategies. Their research demonstrated that regulated deficit irrigation, when precisely timed to crop phenological stages, can maintain yield potential while significantly improving water-use efficiency (WUE) in water-limited environments. Finally, during the late-season stage, rainfall once again exceeded ETc for all studied crops, indicating that end-of-season water requirements can generally met by rainfall under current climatic conditions. These findings highlight the need for stage-specific water management strategies, particularly, soil moisture conservation, during mid to late season stages for most crops.

3.2 Rainfall adequacy relative to crop water requirement (ET_c) in semi-wet conditions

Figure 2 presents a comparative analysis of seasonal rainfall amounts (semi-wet season) and crop water requirements (ETc) for the studied crops (pearl millet, sesame, sunflower, groundnut, soya bean, and cotton) in the Blue Nile region. The results demonstrated that rainfall during crop growth stages generally exceeded ETc for all crops, indicating adequate rainfall to meet crop water demands. However, sorghum exhibited a distinct pattern, with rainfall intersecting ETc during the mid-season stage, potentially exposing the crop to short-term water deficit that could adversely affect yield potential. The observed differential crop response underscores the necessity of tailored soil moisture conservation strategies for sorghum under rainfed agricultural conditions. These findings corroborated the conclusions of [25-26], whom demonstrated that supplemental irrigation serves as a viable adaptation strategy to enhance climate resilience in semi-humid farming systems.

3.3 Rainfall adequacy relative to crop water requirement (ET_c) in normal conditions

Figure 3 compares between rainfall amounts during a normal season and water requirements (ETc) for the studied crops. The results demonstrate that rainfall consistently exceeded crop water requirements across all growth stages, indicating favorable conditions for meeting crop water needs. This may be due to a good distribution of rainfall during the growing season. The observed water surplus presents potential hydrological risks, particularly regarding surface runoff generation in clayey soils where rainfall intensity frequently surpasses infiltration rates. This is consistent with the hydrological modeling results reported by [27], who demonstrated runoff dynamics in fine-textured soils under intensive rainfall events. Also, [28] found that water erosion widely distributed, showed an increased trend in China's drylands. These findings suggest that while water availability is adequate, soil water management strategies are crucial to mitigate runoff-related risks in clay-dominated agricultural systems.

3.4 Rainfall adequacy relative to crop water requirement (ET_c) in semi-dry conditions

The semi-dry season (Figure 4) exhibited a pattern similar to that of the normal season, though with a more pronounced divergence between the rainfall curve and crop water requirements (ETc). Notably, sorghum and cotton displayed a mid-season water deficit, where rainfall was insufficient to meet crop evapotranspiration demands.

In contrast, other crops, millet, sesame, sunflower, groundnut, and soya bean showed closer alignment between rainfall and crop water needs across different growth stages, albeit with crop-specific variations.

For millet, rainfall closely matched water requirements during the initial and developmental stages, while sesame and sunflower exhibited this alignment primarily during the developmental and mid-season stages. In the case of groundnut and soya bean, rainfall not only aligned but occasionally fully met crop water demands during the same critical growth periods.

Overall, the findings suggest that rainfall during the semi-dry season is generally adequate to meet water requirements most growth stages for the majority of crops studied, with the exception of sorghum and cotton during the mid-season period. The observed water deficit during this critical stage may lead to drought stress, potentially reducing crop productivity.

Therefore, under such conditions, implementation of supplemental irrigation is strongly recommended to mitigate yield losses and ensure optimal crop performance. This agrees with [29] who reported rainfed production systems through supplemental irrigation during short dry-spells is shown to dramatically increase water productivity.

3.5 Rainfall adequacy relative to crop water requirement (ET_c) in dry Conditions

The graphical results (Figure 5) illustrate the relationship between rainfall patterns during the dry season and the water requirements (ET_c) of the studied crops. The findings indicated that rainfall sufficiently meets crop water demands during the early growth stages (initial and developmental stages). However, deficits emerge in the mid- and late-season stages, where rainfall is markedly below crop water requirements, particularly during peak water-demand periods. Insufficient water during the critical late stages of crops growth may lead to crop failures impaling significant economic losses and financial risks which in turn jeopardizes farmer livelihoods [30]. These findings indicate that, without necessary intervention, water stress during these sensitive growth phases can lead to substantial yield reductions, as demonstrated by [31] in semi-arid agroecosystems.

3.6 Total water requirement (ET_c) under varying season type

Table 3 presents water requirements for each studied crop across different rainy season types. The analysis reveals notable variations in crop evapotranspiration (ETc) demands. Millet crop demonstrated the lowest water requirements (288.1 mm) during the semi-wet season, while exhibiting peak water demand (333.6 mm) in wet season. Cotton crop showed minimum water needs (376.5 mm) in semi-wet seasons, with maximum requirements (426.2 mm) during wet season.

Notably, the studied crops exhibited relatively consistent total seasonal water demands across normal, semi-dry, and dry conditions, suggesting similar ETc patterns under water-limited environments. This convergence in water requirements may reflect adaptive physiological responses to moisture stress, as documented in drought-prone agroecosystems [32].

Table 3. Total water requirement (ETC) for the selected crops in Blue Nile region under varying season types

Crop	Wet season	Semi wet season	Normal season	Semi dry season	Dry season
Sorghum	372.2	326.0	351.2	353.2	357.5
Millet	333.6	288.1	310.8	317.4	315.2
Sesame	341.6	293.1	318.1	319.3	320.6
Sunflower	346.0	296.9	322.7	324.3	324.6
Groundnut	366.9	298.0	329.6	341.3	337.4
Soya bean	381.3	331.2	358.3	360.1	363.0
Millet	333.6	288.1	310.8	317.4	315.2
Cotton	426.2	376.5	405.9	408.1	414.4

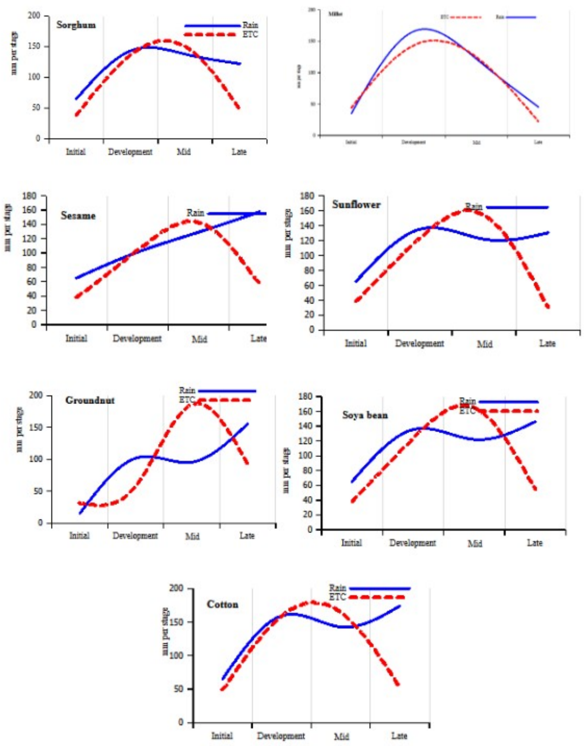

Figure 1. Rainfall versus water requirement (ETC) for seven crops at different growth stages for wet season in Blue Nile region

3.7 Rainfall distribution and growing season duration across seasonal variability

Table 4 presents the total annual rainfall at 20%, 40%, 50%, 60%, and 80% probability levels, rainfall during the growing season and length of the growing season. The results demonstrated that the wet season exhibits minimal disparity between annual (804.8 mm) and growing season rainfall (789.8 mm), with a marginal difference of 15 mm.

In contrast, dry season shows the most significant divergence (129.8 mm). Pre-growing season rainfall negatively impacts soil preparation and seed germination due to waterlogging. Other studies focused on how flooding stress affects crop production [33],[34].

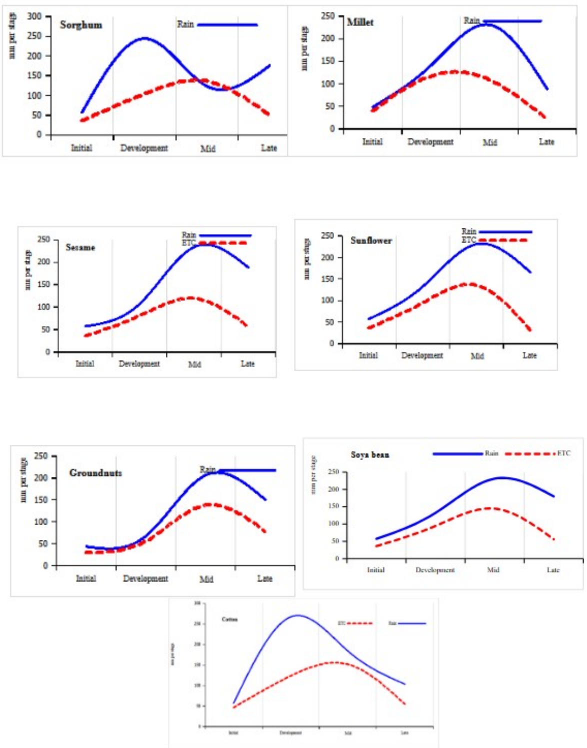

Figure 2. Rainfall versus water requirement (ETC) for seven crops at different growth stages for semi-wet season in Blue Nile region

Post-growing season rainfall disrupts harvesting and post-harvest operations, compromising yield quality. These results in the same line of the study of [35] Eshetie, (2021) who reported rainfall variability is one of the major determinant factors for variation of crop yields.

The wet season recorded the longest season duration (154 days), while dry season had the shortest (111 days) (Table 4). Crop-specific growing seasons (Table 2) ranged from 90 days (millet, groundnut) to 120 days (cotton). Cotton's extended growing season (120 days) exceeds rainfall duration in semi-wet (121 days), normal (113 days), semi-dry (123 days), and dry (111 days) seasons.

Table 4. Rainfall and length of growing season in Blue Nile region under varying season types

Probability	Season type	Total rainfall, mm	Rainfall during the growing season, mm	Length of growing season, days
20%	Wet season	804.8	789.8	154
40%	Semi-wet season	735.3	623.8	121
50%	Normal season	700.0	606.2	113
60%	Semi-dry season	664.7	571.7	123
80%	Dry season	620.3	490.5	111

3.8 Proportion of crop water requirement supplied by rainfall during the growing season

Table 5 presents proportion (%) of crop water requirements (ETc) for the studied crops across different growing seasons. All recorded values were below 100%, indicating that rainfall during the growing season across all crops and climatic conditions (wet, semi-wet, normal, semi-dry, and dry) was generally sufficient to meet crop water requirements.. The highest percentage of water requirements met by rainfall was observed for Groundnut during the wet season (99.8%), while the lowest percentage was recorded for sesame (50%) during the semi-wet season. These findings align with previous studies demonstrating that rainfall variability significantly influences crop yields and crop water use efficiency in semi-arid regions [36],[37].

Although total seasonal rainfall may be sufficient to meet crop water requirements, uneven temporal distribution often results in periods of water deficit during critical growth stages, necessitating the integration of real-time agro-meteorological data—including weather, plant physiological, and soil moisture [38]. As demonstrated in previous findings, effective water management is essential to ensure adequate moisture availability during the sensitive growth stages. Consequently, optimal rainwater harvesting techniques may be necessary to mitigate intermittent dry spells and sustain optimal crop productivity [39].

3.9 Crop cultivation potential in the Blue Nile region

Table 6 presents the potential of cultivating the studied crops in the Blue Nile region based on a single criterion; the amount of rainfall during the growing season in relation to crop water requirements under different seasonal conditions. Meanwhile, Table 7 assesses crop cultivation potential using two key parameters: rainfall during the growing season and the length of the growing season, both of which are critical in determining crop water needs. The findings indicated that rainfall during the growing season exceeds the water requirements for all studied crops. Additionally, the duration of the rainy season aligns well with the growth cycles of the crops. Similar results were obtained by Sivakumar [38] who examines how growing period length aligns with climatic water balance, supporting the concept of rainy season duration matching crop growth cycles. Consequently, all investigated crops, (sorghum, pearl millet, sesame, sunflower, groundnut, soya bean, and cotton) are deemed viable for production in the Blue Nile region under current climatic conditions.

Table 5. Percentage of water requirement from rainfall amount during growing period for the selected crops in Blue Nile region under varying season types

Crop	**wet season**	**semi-wet season**	**normal season**	**semi-dry season**	**dry season**
Sorghum	79.4	54.3	60.5	63.3	75.7
Cotton	78.7	61.5	67.7	72.7	87.0
Sesame	75.4	50.0	58.5	60.2	68.2
Sunflower	76.4	50.6	59.4	61.2	69.1
Soya bean	81.4	55.2	61.7	64.5	76.9
Groundnut	99.8	63.7	63.9	81.0	73.7
Millet	90.7	56.6	60.3	75.3	68.8

Table 6. Possibility of growing crops in Blue Nile region according to one condition under varying season types

Crop	**Wet season**	**Semi wet season**	**Normal season**	**Semi dry season**	**Dry season**
Sorghum	Possible	Possible	Possible	Possible	Possible
Millet	Possible	Possible	Possible	Possible	Possible
Sesame	Possible	Possible	Possible	Possible	Possible
Sunflower	Possible	Possible	Possible	Possible	Possible
Groundnut	Possible	Possible	Possible	Possible	Possible
Soya bean	Possible	Possible	Possible	Possible	Possible
Cotton	Possible	Possible	Possible	Possible	Possible

Table 7. Possibility of growing crops in Blue Nile region according to two conditions under varying season types

Crop	Wet season	Semi wet season	Normal season	Semi dry season	Dry season
Sorghum	Possible	Possible	Possible	Possible	Possible
Millet	Possible	Possible	Possible	Possible	Possible
Sesame	Possible	Possible	Possible	Possible	Possible
Sunflower	Possible	Possible	Possible	Possible	Possible
Groundnut	Possible	Possible	Possible	Possible	Possible
Soya bean	Possible	Possible	Possible	Possible	Possible
Cotton	Possible	Possible	Possible	Possible	Possible

CONCLUSIONS

The analysis demonstrated that rainfall during the growing season is generally sufficient to meet the crop water requirements for most rainfed crops in the Blue Nile region. However, seasonal variability mainly in mid to late season deficits, particularly under semi-dry and dry conditions, posing significant risks to crop productivity. Crops require special attention due to their sensitivity to mid-season water stress. Integration of suitable crop management practices and soil moisture conservation is essential to optimize water use efficiency and sustain yields. These findings are crucial for enhancing climate resilience in rainfed agricultural systems of semi-humid regions.

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