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OCCURRENCE OF EXTREME CLIMATE BETWEEN 2012 AND 2022 IN BADINGILO NATIONAL PARK OF SOUTH SUDAN

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ABSTRACT

The study assesses the occurrence of extreme climate from 2012 to 2022 at Badingilo National Park in South Sudan. Descriptive statistics were used to produce graphs of annual rainfall and temperature from 2012 to 2022. XLSTAT was used to run nonparametric statistics, employing Mann-Kendall and Sen's slope estimator, to establish monthly and annual trends of rainfall and temperature amounts between 2012 and 2022. Furthermore, the Rain-based Meteorological Drought Indices Tool (RDIT) software was employed to determine the occurrence and severity of droughts and floods at Badingilo National Park from 2012 to 2022. The results showed that the increase in monthly rainfall amounts was not significant ($P>0.05$) between January-March, July, and September-December from 2012 to 2022. The trend of annual rainfall amount increased, whereas monthly and annual temperature trends decreased between 2012 and 2022. Likewise, the Effective Drought Index (EDI), Standard Precipitation Index (SPI), Percent of Normal Precipitation Index (PNI), and Rainfall Anomaly Index (RAI) affirmed the occurrence of severe monthly and annual droughts between 2012 and 2019, and severe floods in 2020, with 150 percent above-normal rainfall amounts. Certainly, extreme floods require heightened awareness and early warning systems for the pastoral communities around Badingilo National Park in South Sudan.

Keywords: Extreme flooding, Monthly rainfall trends, Annual rainfall trend, Monthly temperature trend, Annual temperature trend, and Drought severity

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1.0 INTRODUCTION

South Sudan has experienced extreme temperatures, heavy rainfall, and changes in patterns of rainfall over the last 5 years, driven by increased anthropogenic activities and climate change (1). Indeed, frequent droughts were persistent in the Southern and Northeastern parts of the country (2). Drought frequencies and intensity are expected to increase from 60 percent to 100 percent by the end of the 21st century relative to the 2020s in the country. Conversely, floods have displaced 1.4 million people across 22 counties in six states between 2024 and 2025 in South Sudan (3). The floods affected the Eastern, Northern, Northwestern, and Western parts of the Country. However, extreme floods affected Jonglei and Unity States. The severity and intensity of the flood were above the historical averages, with a devastating impact on people, livestock, and wildlife. Extreme floods caused a five percent reduction in employment opportunities and access to health-care facilities, markets, educational facilities, farming activities, and grazing land across the affected states of South Sudan (4).

Consequently, droughts and floods have caused massive migration of wild animals and pastoral communities in search of water and grazing land around Badingilo National Park (1,5). The landscape of the park is characterized by marshlands, ponds, rocky hills, wooded savannah, and fertile floodplains with rich flora and fauna. These landscapes are prone to seasonal droughts and floods. Droughts emanate from significant annual warming of 0.4 °C over the last 30 years at Bandingilo National Park. Erratic and unreliable rainfall regimes are caused by climate change. This resulted in massive migration of pastoralists and wild animals from eastern savannah grassland to the floodplains of Jonglei and Eastern Equatoria States near the border of Ethiopia (6). Accordingly, flooding significantly affected over 65107ha of grazing land for domestic and wild animals in 2021 (7).

Similarly, extreme floods were observed to cause inundation of farmlands and grazing land along the riparian areas of Lake Baringo between 2012 and 2014 in Kenya (8). Accordingly, severe flooding in 2020 displaced pastoralists from the Bor region of Jonglei State to the higher grounds of Eastern and Western Equatoria State (9) because of the inundation of grazing land. Accordingly, a study in Cameroon showed a 30-40% reduction in plant species richness after flooding in mountainous and plain areas between 2003 and 2023 (10). This report is similar to the effect of severe flooding experienced in the last decade around Badingilo National Park in South Sudan. The flood led to the loss of pasture and grazing resources for livestock and wildlife around the park. However, there is insufficient information on the extent and impact of extreme droughts and floods in Badingilo National Park in the last decade. The study aims to determine the frequency of droughts and floods, and the trends of seasonal rainfall and temperature from 2012 to 2022. The study also assesses the effects of seasonal rainfall and temperature variability on grazing resources,

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biodiversity, and the livelihoods of pastoral and agropastoral communities living around Badingilo National Park in South Sudan.

2.0 DESCRIPTION OF STUDY AREA

Badingilo National Park in South Sudan covers an area of 200,000 Km^2 with the coordinates 5°25′58″N 32°16′39″E, bordered by Jonglei in the North, Boma National Park in the Northeast, the Sudd Wetland in the North, and White Nile in the West (Fig. 1). Badingilo National Park was established in 1986 principally for conserving Black Rhino and other large mammals. The park has rich biodiversity with unique physical landscapes, namely: extensive marshland and ponds, grasslands, woodlands, mountains, and hills. The Park is also part of the White Nile wetland system that supports a considerable number of people, livestock, and wild animals in South Sudan. Badingilo National Park has a tropical climate characterized by wet and dry seasons. The wet seasons range between May and October, while the dry seasons occur between November and March. The average temperature in the wet seasons ranges from 20 °C to 30 ºC whereas the dry seasons' average temperature ranges between 23 °C and 37 °C. The park harbours over 200,000 pastoralist and agro-pastoralist communities dwelling around it. Generally, most of these people dwelling around Badingilo National Park comprise different ethnicities such as the Bari, Dinka, Lokoya, Lopit, Mundari, Murle, and Pari of the Lafon County (11).

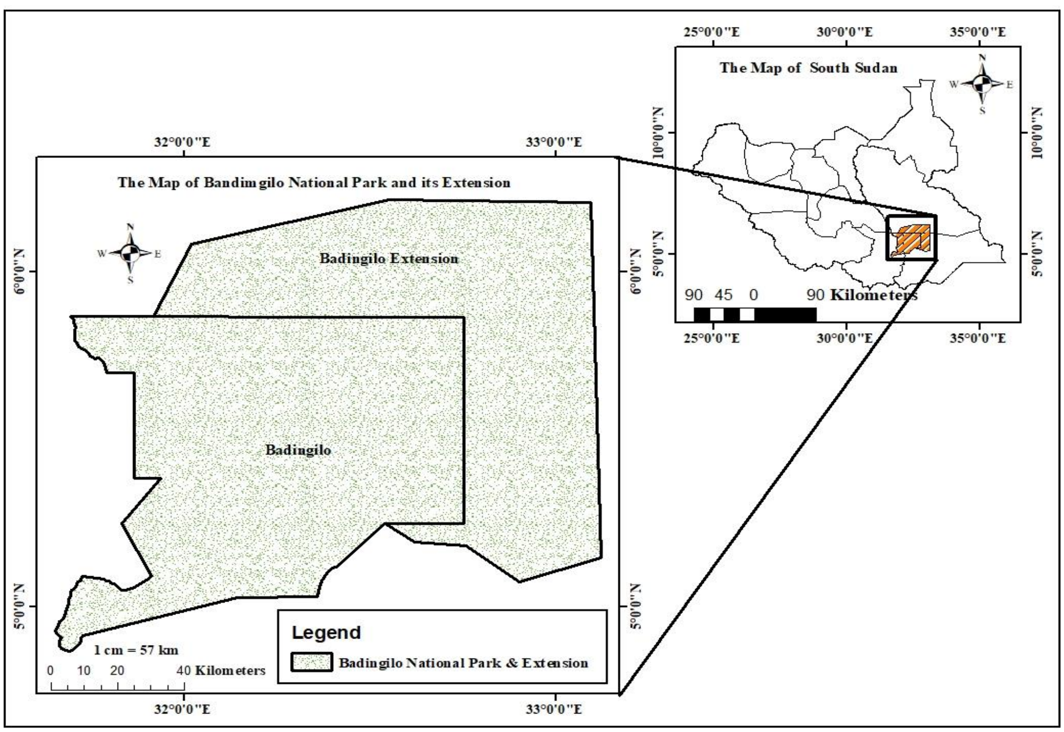

Fig. 1: The map of Badingilo National Park in South Sudan

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2.2 Climate Data

The rainfall and temperature data were downloaded from the National Aeronautic Space Administration for Prediction of World Energy Resources (NASA POWER) Climatology Resource for Agro-climatology website (https://power.larc.nasa.gov/data-access-viewer/). The meteorological climate data were sourced from Latitude 5.485 Degrees East and Longitude 32.1295 Degrees North, average resolution of 0.5x0.625 degrees, and at an elevation of 445.72 meters, between 1/1/2012 and 31/12/2022, measured at 2 meters above the land surface. Furthermore, the long-term daily rainfall dataset from 1/1/1992 to 2022 was downloaded and used to run the Rain-based Meteorological Drought Indices Tool (RDIT) software (https://rdit.soft112.com/). However, the climate data from 1/1/2012 to 31/12/2022 were used to calculate the Effective Drought Index (EDI), Standardized Precipitation Index (SPI), Percent of Normal Precipitation Index (PNI), and Rainfall Anomaly Index (RAI). Importantly, the NASA POWER dataset was selected because Badingilo National Park in South Sudan lacks weather stations. Further, the data from weather stations operating around the park, such as Bor, Juba, and Lokiliri (Nesutu) stations, are not easily accessible (https://meteosouthsudan.com.ss/our-services/climate/). Although the rainfall and temperature data for Juba Station can be accessed through the South Sudan Director of Meteorological Services, the dataset has gaps, making it difficult to use. In the same vein, NASA POWER data is a gridded dataset with coarse resolution (50 km) that may miss local microclimate details (12), particularly precipitation, due to underestimation of orographic extremes influenced by physical features such as mountains, rivers, swamps, and forests (12,13) in Badingilo National Park in South Sudan. However, studies indicate that the NASA POWER dataset has promising potential to accurately correlate with local precipitation and temperature in Spring and Autumn (12,13). Hence, the NASA POWER data can be used to assess floods and droughts at any location in the absence of weather stations (13).

2.2.1 Rainfall and Temperature Trend Analysis

Descriptive statistics were used to determine the variation in annual rainfall and temperature between 2012 and 2022 using Microsoft Excel 2019 software. XLSTAT version 2025.1.2 (https://www.xlstat.com/) was used to run nonparametric statistics to establish climate trends between 2012 and 2022 in Badingilo National Park in South Sudan. The Mann-Kendall test and Theil-Sen's slope estimator were used to establish the monthly and annual trends of rainfall and temperature, and whether the changes were significant at $P<0.05$.

Mann-Kendall Test statistic S is given by

$$S = \sum_{i=1}^{n-1} \left\{ \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \right\} \quad \ldots\ldots (1)$$

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X_i is the rank time series from i=1, 2………. n-1 and X_j=i+1, 2………. n. Each data point X_i is a reference point compared with the data point X_j, so that,

$$Sgn(x_j - x_i) = \begin{cases} +1, > (x_j - x_i) \\ 0 = (x_j - x_i) \\ -1, < (x_j - x_i) \end{cases}$$

It has been indicated that when n≥8, the statistic S is normally distributed with the mean

E(S) = 0 (14).

$$\delta = n\frac{(n-1)(2n+5)}{18} \quad \text{…………………………………………………………...….. (2)}$$

Where δ is the standard deviation, and n is the number of data points in the time series.

The Mann-Kendall statistic can also be rewritten as:

$$z = \frac{|s|}{\delta^{0.5}} \quad \text{…………………………………………………………………..……… (3)}$$

A positive value of S shows an increasing trend, while a negative value indicates a decreasing trend of rainfall and temperature from 2012 to 2022. The critical statistical test value was 1.97 at a 95 percent probability level (14,15).

Theil-Sen's estimator

The slope of n pairs of data points was estimated using Theil-Sen's estimator using the formula:

$$\beta = Median\frac{X_j - X_i}{j - i} \quad \text{………………………………………………………...…… (4)}$$

Where β is the Theil-Sen Slope and X_j and X_i are the data values at time j and i. The median of these N values of β is Sen's estimator of slope. Total and average monthly rainfall and temperature amounts were presented in graphs using Excel 2019. Further, the change in annual rainfall and temperature was obtained by multiplying annual values of Sen's Slope by the number of years between 2012 and 2022.

2.2.2 Determination of Drought Indices and Severity

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Rain-based Meteorological Drought Indices Tool (RDIT) software version 1.0 (AgriMetsoft, 2017) (https://rdit.soft112.com/) was used to determine the drought indices and severity at Badingilo National Park between 2012 and 2022.

Effective Drought Index (EDI)

The Effective Drought Index (EDI) is designed to capture daily drought severity with a range of +2.5 to -2.5. Effective Precipitation (EP) from 2012 to 2022 is obtained from the formula:

$$EP_i = \sum_{n=1}^{i} \left(\frac{(\sum_{m=}^{n} P_n)}{n} \right) \quad (5)$$

Where EP_i is the effective precipitation (mm) representing valid accumulated precipitation, P_m is the precipitation of the previous m days in millimeters (mm), whereas n is the period (day) between 2012 and 2022, i is the number of days (365) in a year. As such, EP_{365} demonstrates precipitation accumulation in a year (16).

Standardized Precipitation Index (SPI)

SPI is defined by McKee et al. (1993) as the difference between precipitation and its mean for a specified time scale, divided by the standard deviation, where the means and standard deviations are determined from previous records. However, SPI is not statistically normally distributed within 12 or fewer months, though a transformation can correct this problem. SPI can be calculated across different timescales that include: 1, 3, 6, 12, 24, and 48 months, with the magnitude of variations ranging between +2.0 and −2.0. SPI can express the two parameters as a gamma distribution computing process as follows:

$$g^x = \frac{1}{\beta^\alpha \tau(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}} \text{ for } x > 0 \quad (6)$$

Where $g(x)$ is the probability density function, α is the shape parameter $(\alpha > 0)$, β is a scale parameter $(\beta > 0)$, $(x > 0)$ and $\tau(\alpha) = \int_0^\alpha y^{\alpha-1} e^{-1} dy$ where $\tau(\alpha)$ is a gamma function.

Furthermore, the parameter α is estimated using the following formula (18,19):

$$\alpha = \frac{1}{4A}\left[1 + \sqrt{1 + \frac{4A}{3}}\right] \text{ and } \beta = \frac{x}{\alpha} \text{ where } A = \text{In}\overline{x} \text{-} \frac{\sum \text{In}\overline{x}}{n}$$ and n is the number of observed precipitations and $\overline{x}$ is the mean precipitation between 2012 and 2022 ... (7)

When the probability density function is integrated with respect to x using the estimate of α and β, a cumulative probability $G(x)$ of the observed precipitation amount in a given month between 2012 and 2022 was estimated as follows (20):

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$$G(x) = \int_0^x g(x)dx = \frac{1}{\overline{\beta}^{\overline{\alpha}}\tau(\overline{\alpha})}\int_0^x x^{\overline{\alpha}} e^{\frac{\overline{x}}{\beta}} \ldots\ldots (8)$$

Substituting t for $\frac{\overline{x}}{\beta}$ in equation (4) gives

$$G(x) = \frac{1}{\tau^{\overline{\alpha}}}\int_0^x t^{\overline{\alpha-1}} e^{-1}\ dt \ldots\ldots (9)$$

Equation (9) is the incomplete gamma function. However, the gamma is undefined for $x = 0$ and $P(x = 0) > 0$ where $P(x = 0)$ is the probability of zero precipitation. Therefore, the actual probability of non-exceedance H (x) can be calculated as follows:

$H(x) = q + (1 - q)G(x)$ where $H(x)$ is the actual probability of non-exceedance and q being the probability of $x = 0$, if m is the number of zeros in a sample size n , then q is estimated as

$$q = \frac{m}{n} \ldots\ldots (10)$$

Therefore, the cumulative probability distribution $H(x)$ is transformed into the standard normal distribution to yield SPI (19) . However, SPI was calculated using the equation:

$$SPI(x) = \frac{P(x) - \mu(x)}{\delta(x)} \ldots\ldots (11)$$

where P represents precipitation for a given month x, μ is the average precipitation, whereas δ is the standard deviation of the mean precipitation observed between 2012 and 2022 (21). Further, all SPI negative values indicate droughts, whereas positive values denote precipitation (Table 1)

Table 1: SPI Values and their Interpretation

S/No	SPI Value	Interpretation
1	≥2.0	Extremely Wet
2	1.5 to 1.99	Severely Wet
3	1.0 to 1.49	Moderately Wet
4	0.99 to -0.99	Near Normal
5	-1.0 to -1.49	Moderately Dry
6	-1.5 to -1.99	Severely Dry
7	≤ -2.0	Extremely Dry

Source: (Panigrahi & Vidyarthi, 2024)

Percent of Normal Precipitation Index (PNI)

The Percent of Normal Precipitation Index (PNI) was calculated from normal precipitation between 2012 and 2022 using the formula:

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$$PNI = \frac{P_i}{P} \times 100 \quad (12)$$

Where P_i is the incremental percent of annual precipitation i (mm), and P is the normal precipitation (mm) between 2012 and 2022 at Badingilo National Park in South Sudan (16).

RAI (Rainfall Anomaly Index)

The RAI was developed by van Rooy (1965) by arranging and ranking high precipitation and averaging as positive values, while lower values were ranked and averaged as negative anomalies, which were presented by the following equations:

$$RAI = 3 \times \left[\frac{(P-\overline{P})}{(\overline{m}-\overline{P})}\right] \quad (13)$$

$$RAI = 3 \times \left[\frac{P-\overline{P}}{\overline{\overline{m}}-\overline{P}}\right] \quad (14)$$

Where P is the actual precipitation for each month in the year in millimeters (mm), $\overline{P}$ is the long-term average precipitation (mm), and $\overline{m}$ is the mean of both the highest and lowest precipitation values of P for the positive and negative rainfall anomalies recorded between 2012 and 2022 at Badingilo National Park (16). The relationship among RAI, SPI, and EDI is summarized below (Table 2):

Table 2: Classification of Anomaly, Standardized Precipitation Index (SPI), and Effective Drought Index (EDI)

Anomaly	Range of SPI Values	Precipitation Regime	Cumulative Probability	Probability of Event (%)
	2.0 < SPI	Extremely wet	0.977 - 1.000	2.3
Positive	1.5 < SPI ≤ 2.0	Very wet	0.933 - 0.977	4.4
	1.0 < SPI ≤ 1.5	Moderately wet	0.841 - 0.933	9.2
Normal	-1.0 < SPI ≤ 1.0	Normal Precipitation	0.159 - 0.841	68.2
	-1.5 < SPI ≤ -1.0	Moderately dry	0.067 - 0.159	9.2
Negative	-2.0 < SPI ≤ -1.5	Very Dry	0.023 - 0.067	4.4
	SPI ≤ -2.0	Extremely Dry	0.000 - 0.023	2.3

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3.0 RESULTS PRESENTATION

3.1 Rainfall and Temperature Trends from 2012 to 2022 at Badingilo National Park

3.1.1 Rainfall trends

The monthly and annual rainfall amounts increased marginally (P>0.05) between 2012 and 2022 in Badingilo National Park and the surrounding areas in South Sudan. The results show an insignificant increase in minimum and total monthly rainfall amounts from January-May, July, and September-December between 2012 and 2022 (Table 3 and Table 4). The results also demonstrate that the trends of minimum and total rainfall amounts increased between 2012 and 2022 in Badingilo National Park (Fig. 2). Accordingly, the increase in average and total annual rainfall trend was insignificant (P>0.05), although the total annual rainfall amount increased by 126.02 mm from 2012-2022 in the park (Fig. 3).

Table 3: Shows Monthly Minimum Rainfall Trend between 2012 and 2022 in Badingilo National Park of South Sudan

Month	Years	Minimum (mm)	Maximum (mm)	Mean (mm)	Standard deviation	Kendall's tau	p-value	Sen's slope
Jan	11	0.000	2.360	0.271	0.697	0.283	0.269	0.009
Feb	11	0.000	0.860	0.170	0.273	0.278	0.273	0.009
Mar	11	0.030	2.320	0.764	0.784	0.220	0.390	0.070
Apr	11	0.750	5.230	2.407	1.709	0.164	0.533	0.058
May	11	2.890	8.710	5.952	1.851	0.345	0.161	0.277
Jun	11	2.360	9.700	4.812	2.147	-0.091	0.755	-0.094
Jul	11	2.290	6.510	5.225	1.135	0.200	0.436	0.085
Aug	11	1.720	6.050	4.106	1.416	-0.236	0.350	-0.114
Sep	11	2.320	7.190	5.155	1.459	0.147	0.585	0.083
Oct	11	3.040	7.160	4.611	1.221	0.018	1.000	0.017
Nov	11	0.130	4.710	1.521	1.413	0.018	1.000	0.008
Dec	11	0.010	6.610	1.316	1.846	0.200	0.436	0.059

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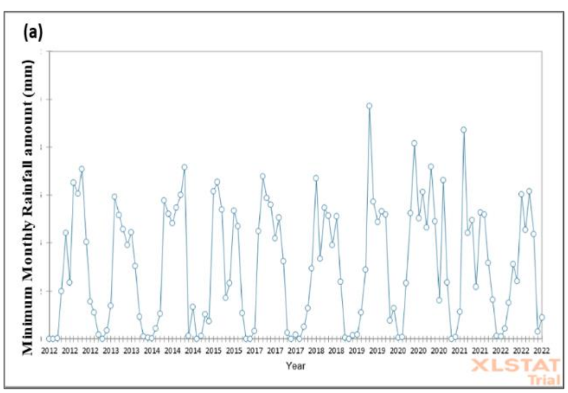
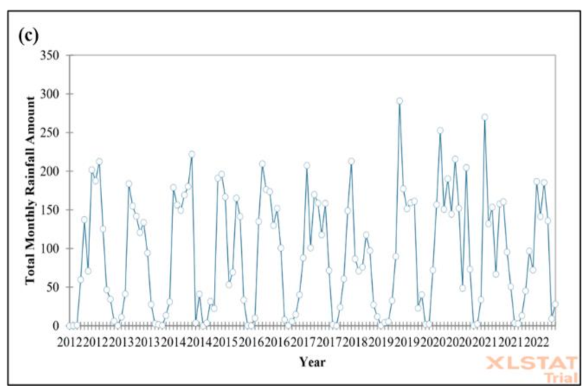
Table 4: Shows the Trend of Total Monthly Rainfall Amount Received between 2012 and 2022 in Badingilo National Park in South Sudan

Month	Years	Minimum (mm)	Maximum (mm)	Mean (mm)	Std. deviation	Kendall's tau	P-value	Sen's slope
Jan	11	0.000	73.180	8.421	21.593	0.262	0.306	0.253
Feb	11	0.010	24.110	4.769	7.657	0.294	0.241	0.263
Mar	11	0.810	71.990	23.674	24.305	0.200	0.436	2.200
Apr	11	22.410	156.790	72.215	51.251	0.164	0.533	1.756
May	11	89.740	269.940	184.564	57.376	0.345	0.161	8.610
Jun	11	70.820	291.070	144.379	64.440	-0.091	0.755	-2.846
Jul	11	71.010	201.830	161.998	35.168	0.200	0.436	2.633
Aug	11	53.180	187.660	127.280	43.957	-0.236	0.350	-3.536
Sep	11	69.520	215.790	154.639	43.778	0.127	0.640	2.480
Oct	11	94.190	222.070	142.946	37.869	0.018	1.000	0.482
Nov	11	3.750	141.370	45.620	42.419	0.018	1.000	0.213
Dec	11	0.220	204.760	40.799	57.195	0.200	0.436	1.808





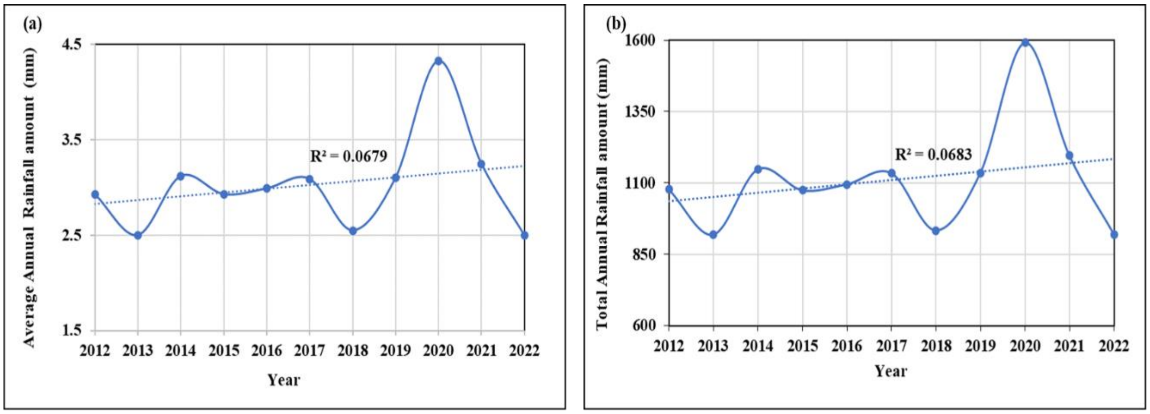
(b)

Series\Test	Period	Kendall's tau	p-value	Sen's slope
Minimum Monthly Rainfall (mm)	12	0.067	0.348	0.041

(d)

Series\Test	Period	Kendall's tau	p-value	Sen's slope
Total Monthly Rainfall (mm)	12	0.125	0.091	1.119

Fig. 2: Variations in Minimum and Total Monthly Rainfall Amount in Badingilo National Park of South Sudan: (a) Variations in Minimum Monthly Rainfall amounts; (b) The Mann-Kendall and Sen's Slope of Minimum Monthly Rainfall Trends at P<0.05; (c) Variations in Total Monthly Rainfall Amount; (d) The Mann-Kendall and Sen's Slope of Total Monthly Rainfall Trends at P<0.05



(c)

Variable	Year	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope
Total Annual Precipitation	11	918.330	1592.390	1111.305	186.911	0.236	0.350	11.456

Fig. 3: The annual rainfall trends from 2012 to 2022 at Badingilo National (N.) Park. (a) Average Annual Rainfall Trend; (b) Total annual rainfall trends; (c) Mann-Kendall and Sen's Slope rainfall trends at P<0.05

3.1.2 Temperature Trends

The results show an insignificant decrease (P>0.05) in maximum monthly temperature between 2012 and 2022 (Table 5; Fig. 4). Similarly, the trends of average and minimum temperatures decreased except from February to May, and from August to September (Table 6), whereas the trends of minimum temperature decreased between 2012 and 2022 (Fig. 4 & 5; Table 7). Overall, the trends of annual maximum, average, and minimum temperatures decreased are nonsignificant (P > 0.05) from 2012 to 2022 at Badingilo National Park (Fig. 6).

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Table 5: The trend of Maximum Monthly Temperature from 2012-2022 in Badingilo N. Park

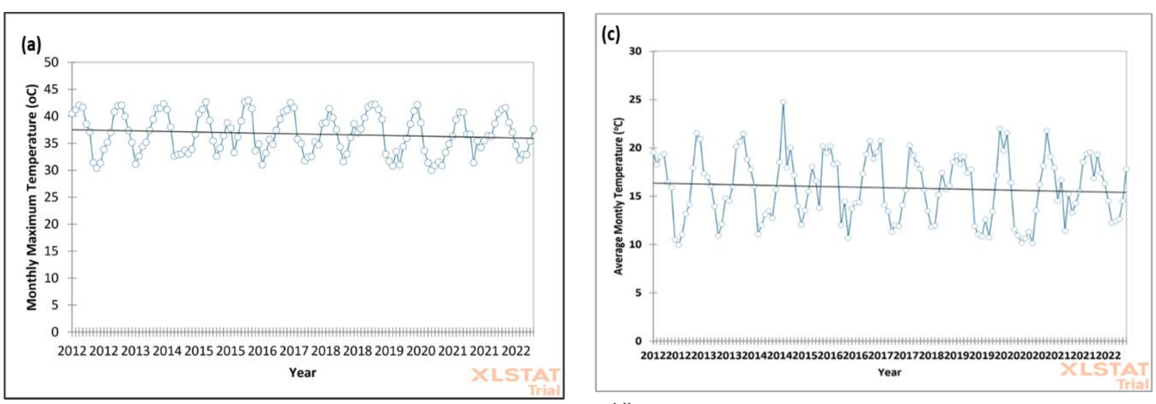
Variable	Years	Minimum (°C)	Maximum (°C)	Mean (°C)	Std. deviation	Kendall's tau	P-value	Sen's slope
Jan	11	36.340	41.680	39.746	1.597	-0.440	0.072	-0.260
Feb	11	39.370	42.660	41.295	0.869	-0.382	0.119	-0.117
Mar	11	39.730	42.940	41.869	0.938	-0.200	0.436	-0.084
Apr	11	37.530	41.670	40.457	1.395	-0.091	0.755	-0.012
May	11	33.610	39.410	36.506	2.113	-0.091	0.755	-0.180
Jun	11	31.380	37.120	34.267	2.128	-0.091	0.755	-0.053
Jul	11	30.000	34.630	32.095	1.405	0.073	0.815	0.033
Aug	11	30.400	36.400	33.009	2.112	0.018	1.000	0.054
Sep	11	31.330	38.770	34.286	2.512	-0.091	0.755	-0.057
Oct	11	30.860	37.810	34.293	2.218	-0.127	0.640	-0.123
Nov	11	33.280	37.660	35.367	1.635	0.018	1.000	0.004
Dec	11	34.860	39.750	37.433	1.652	-0.164	0.533	-0.153

Table 6: The Average Monthly Temperature Trend from 2012 to 2022 in Badingilo N. Park

Variable	Year	Minimum (°C)	Maximum (°C)	Mean (°C)	Std. deviation	Kendall's tau	p-value	Sen's slope
Jan	11	18.140	24.750	20.416	1.827	-0.330	0.184	-0.158
Feb	11	17.960	21.780	19.579	1.359	0.110	0.696	0.047
Mar	11	16.850	21.560	18.873	1.304	0.000	1.000	0.000
Apr	11	15.680	20.770	17.928	1.460	0.018	1.000	0.027
May	11	11.570	17.750	14.846	2.064	-0.127	0.640	-0.167
Jun	11	10.930	16.680	13.496	2.117	-0.018	1.000	-0.020
Jul	11	10.170	14.500	11.638	1.319	0.200	0.436	0.099
Aug	11	9.950	15.500	12.778	1.942	0.091	0.755	0.046
Sep	11	11.050	18.030	13.685	2.309	-0.164	0.533	-0.182
Oct	11	10.120	16.580	13.531	1.941	-0.273	0.276	-0.220
Nov	11	13.400	17.320	15.055	1.262	-0.200	0.436	-0.079
Dec	11	16.210	20.270	18.604	1.306	-0.309	0.213	-0.215

Table 7: The Trends of Minimum Monthly Temperature from 2012 to 2022 at Badingilo National Park in South Sudan

Month	Years	Minimum (°C)	Maximum (°C)	Mean (°C)	Std. deviation	Kendall's tau	p-value	Sen's slope
Jan	11	15.700	22.460	19.330	1.938	-0.236	0.350	-0.172
Feb	11	17.590	23.850	21.715	1.799	-0.164	0.533	-0.134
Mar	11	20.580	24.680	22.996	1.292	-0.273	0.276	-0.163
Apr	11	20.840	23.850	22.529	0.827	-0.055	0.876	-0.029
May	11	20.820	22.130	21.660	0.403	0.110	0.696	0.010
Jun	11	19.750	21.600	20.771	0.612	-0.382	0.119	-0.103
Jul	11	19.830	21.090	20.456	0.399	-0.345	0.161	-0.064
Aug	11	19.460	20.900	20.231	0.455	-0.273	0.276	-0.038
Sep	11	19.590	21.410	20.601	0.511	0.236	0.350	0.066
Oct	11	20.250	21.250	20.762	0.400	0.037	0.938	0.003
Nov	11	18.200	21.600	20.313	1.062	0.018	1.000	0.054
Dec	11	15.980	21.240	18.829	1.359	0.018	1.000	0.051



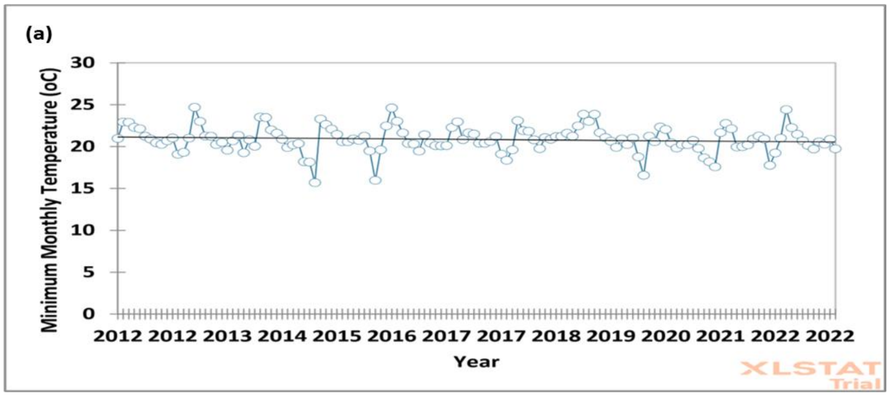
(b)

Month	No. of Months	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	P-value	Sen's slope
Monthly Maximum Temperature (°C)	132	30.000	42.940	36.719	3.673	-0.131	0.125	-0.071

(d)

Month	No. of Months	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope
Average Monthly Temperature (oC)	132	9.950	24.750	15.869	3.337	-0.084	0.303	-0.049

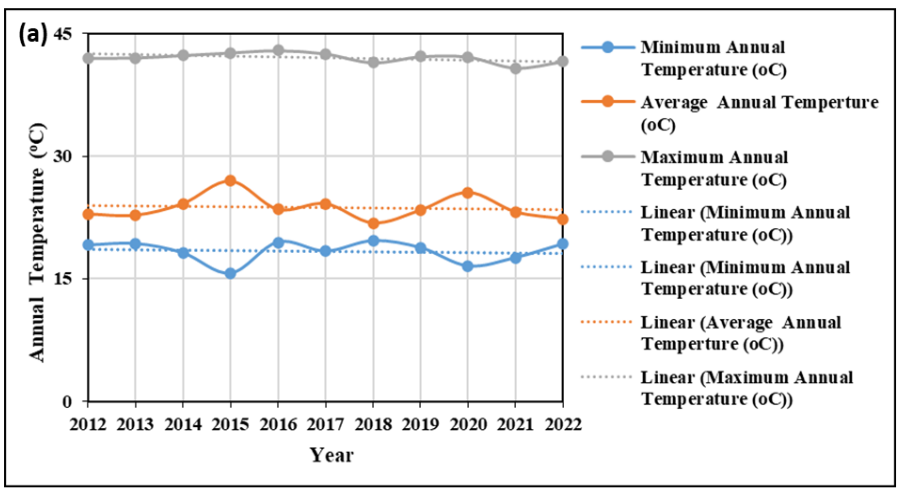
Fig. 4: Monthly Maximum and Average Temperature Trends in Badingilo National Park from 2012 to 2022. (a) Maximum temperature trends; (b) Mann-Kendall and Sen's slope maximum temperature trends at P<0.05; (c) Average monthly temperature trends; (d) Mann-Kendall and Sen's Slope trends at P<0.05



(b)

Month	Months	Minimum (°C)	Maximum (°C)	Mean (°C)	Std. deviation	Kendall's tau	p-value	Sen's slope
Minimum Monthly Temperature (°C)	132	15.700	24.680	20.849	1.548	-0.109	0.128	-0.033

Fig. 5: The minimum monthly temperature trends from 2012 to 2022 in Badingilo National Park. (a) Minimum monthly temperature trends; (b) Mann-Kendall and Sen's Slope trends at P<0.05



(b)

Period in Years	Years	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope
Maximum Annual Temperature (°C)	11	40.760	42.940	42.054	0.616	-0.236	0.350	-0.095
Average Annual Temperature (°C)	11	21.810	26.960	23.705	1.483	-0.127	0.640	-0.059
Minimum Annual Temperature (°C)	11	15.700	19.620	18.349	1.267	-0.055	0.876	-0.035

Fig. 6: Annual temperature trends between 2012 and 2022 at Badingilo National Park. (a) Annual maximum, average, and minimum temperature;(b) Mann-Kendall and Sen's slope annual temperature trends at P<0.05

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3.2 Occurrence of Meteorological Droughts and Floods between 2012 and 2022 in Badingilo National Park.

The Effective Drought Index (EDI) shows occurrence of extreme daily droughts (EDI<-2.7) in 2012, with a deficit of 340.0 mm of daily rainfall amount from January-March 2012, while extreme floods (EDI>3.0) occurred in 2020 (Fig. 7). Accordingly, the monthly SPI also indicates severe droughts (SPI<-2.0) in February 2012, with a deficit in rainfall amount of 4.7 mm (SPI<-2.7) between August and September 2015 (Fig. 8). SPI-three-month moving averages show severe droughts from January to March in 2012 (SPI<-2.0), and a deficit rainfall amount of 9.8 mm (SPI<-2.5) between July and December, 2018 (Fig 9). Further, annual SPI illustrates moderate droughts (SPI<-1.0) with a deficit in annual rainfall of 28.0 mm between 2012 and 2018.

Conversely, annual SPI demonstrated the occurrence of extreme floods (SPI>2.0) in 2019 and 2020 (Fig. 10), with the highest percentage of normal rainfall amount of 148 percent (PNI=148 percent) (Fig. 11). Further, the monthly Rainfall Anomaly Index (RAI) indicates a low precipitation amount of 99.0 mm (RAI<-48 mm) from July-September 2015, and a deficit (RAI <-45 mm) in monthly rainfall of 120.0 mm from June 2018 to January 2019 (Fig. 12). Further, the RAI indicated a surplus of 150 mm in monthly rainfall in December 2020 at Badingilo National Park. Evidently, the season between November 2012 and May 2014 had a deficit (RAI<-25 mm) rainfall amount of 75.0 mm (Fig. 13). In addition, an annual rainfall surplus of 80 mm occurred in 2020 at Badingilo National Park in South Sudan (Fig. 14).

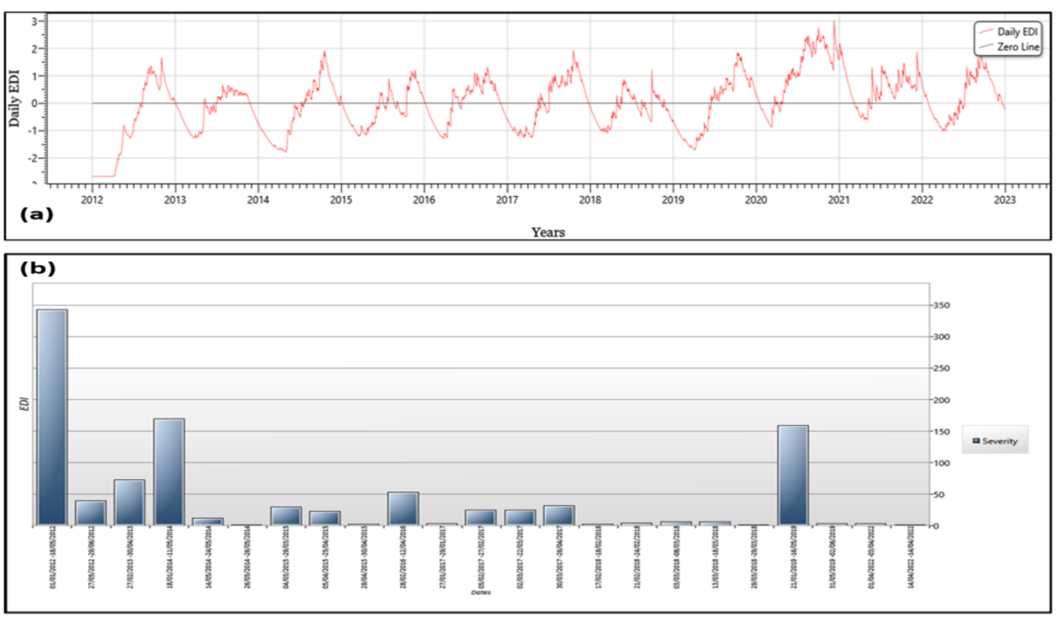

Fig. 7: Daily Effective Drought Index and Severity in Badingilo National Park from 2012 to 2022. (a) Daily Effective Drought Index; (b) Dates of Severe Drought Occurrence

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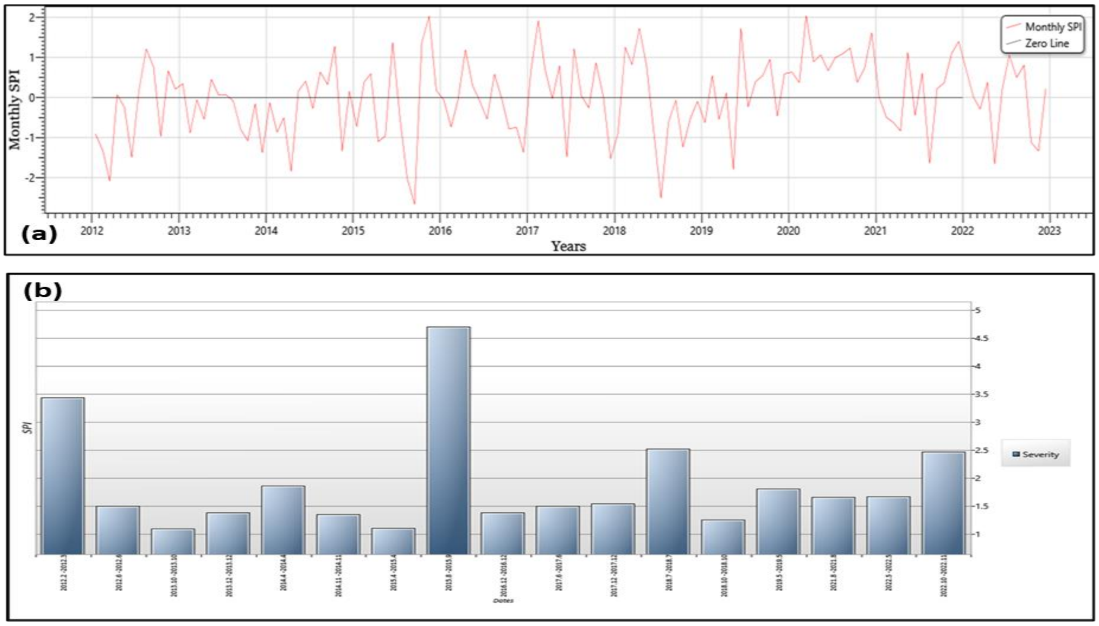

Fig. 8: Monthly Standardized Precipitation Index (SPI) and Drought Severity in Badingilo National Park from 2012 to 2022. (a) Monthly SPI; (b) Dates of Drought Severity

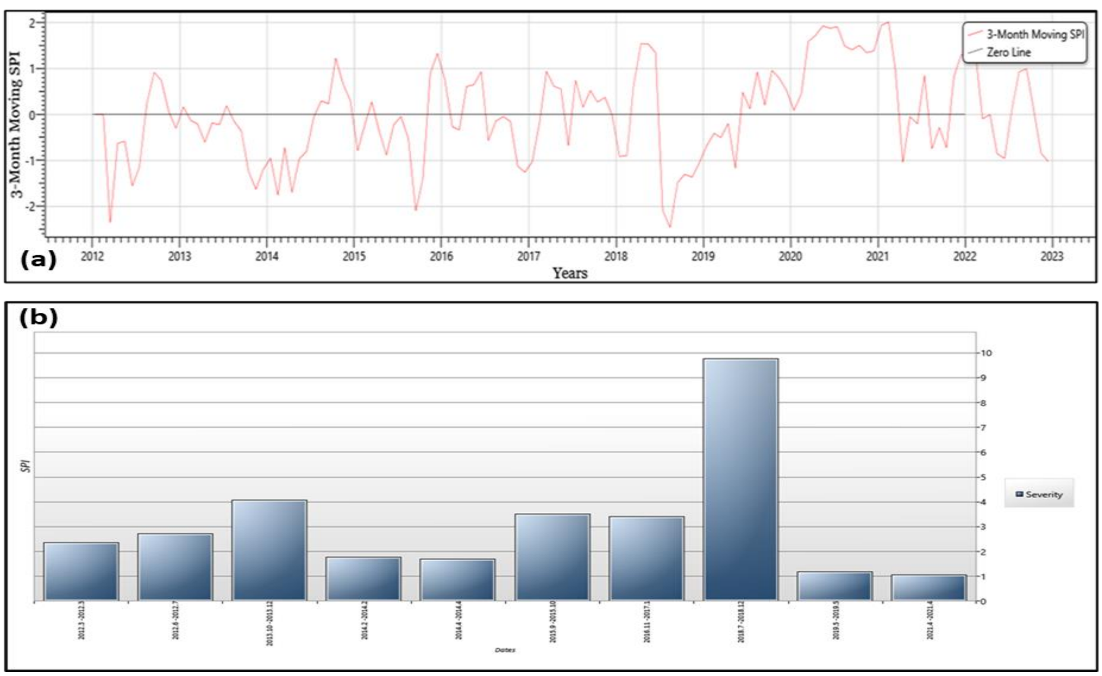

Fig. 9: Three-Month Moving Averages of SPI and Drought Severity in Badingilo National Park from 2012 to 2022. (a) The Three-Month Moving Average of SPI; (b) Three-Month Drought Severity Occurrence

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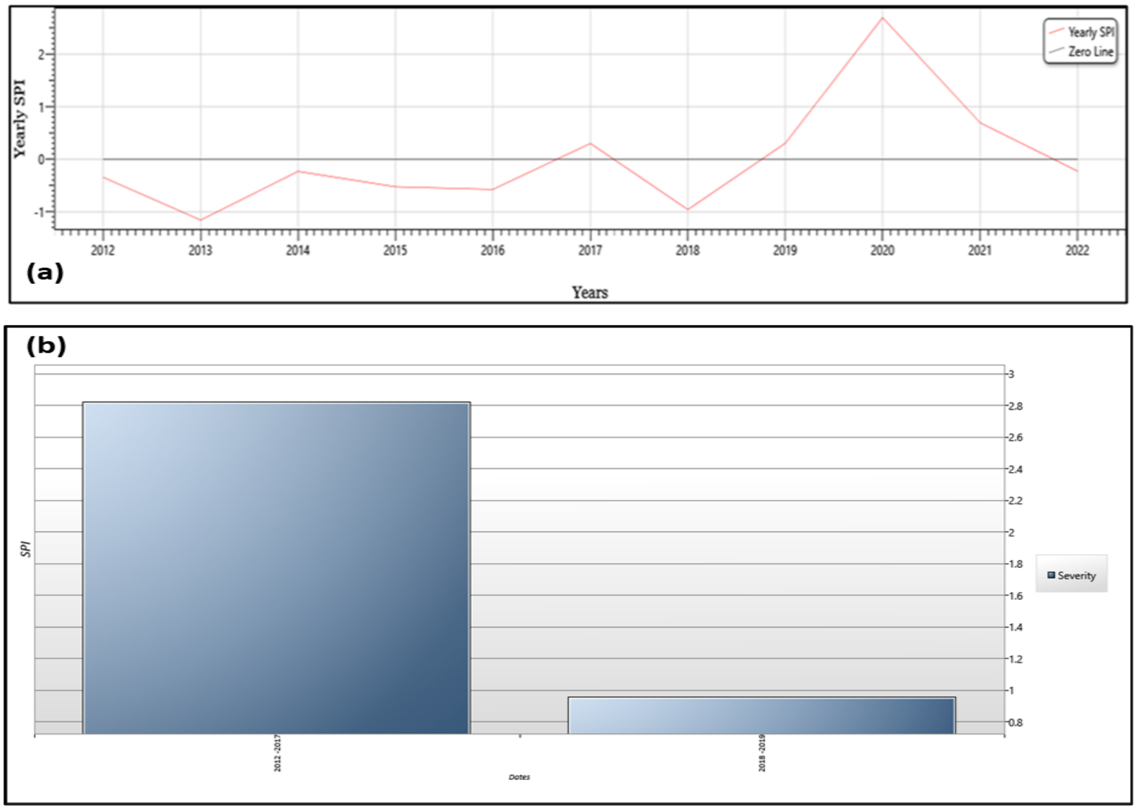

Fig. 10: Annual Rainfall Standardized Precipitation Index and Drought Severity in Badingilo National Park from 2012 to 2022. (a) Annual Rainfall SPI; (b) Date of Annual Drought Severity Occurrence

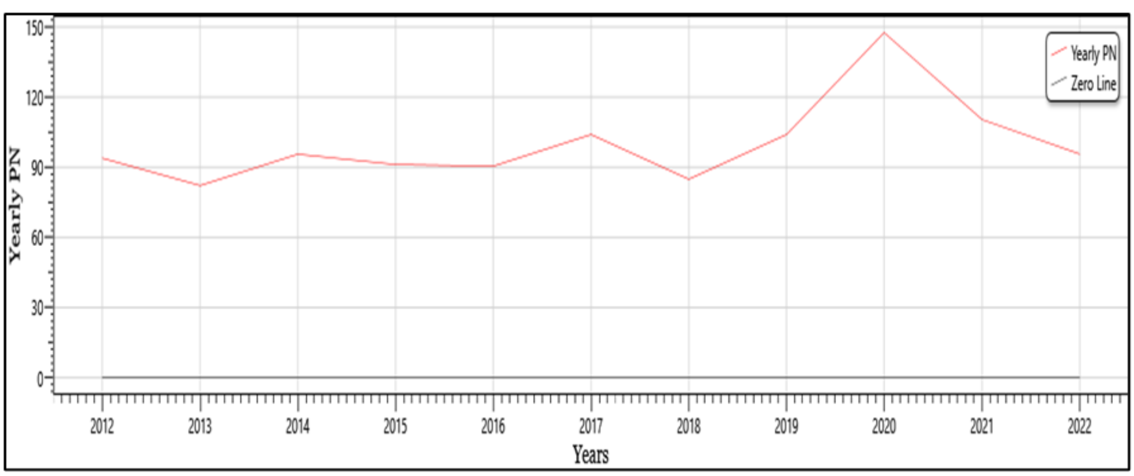

Fig. 11: Annual Percent of Normal Rainfall Distribution in Badingilo National Park from 2012 to 2022

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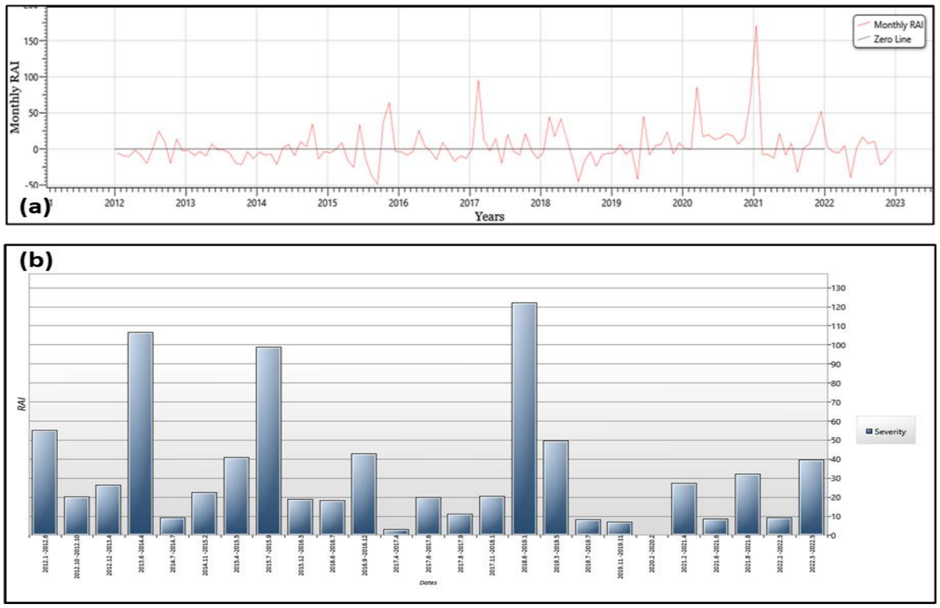

Fig. 12: Monthly Rainfall Anomaly and the Dates from 2012 to 2022 in Badingilo National Park. (a) Monthly Rainfall Anomaly (RAI); (b) The Dates of Rainfall Anomaly in Badingilo National Park

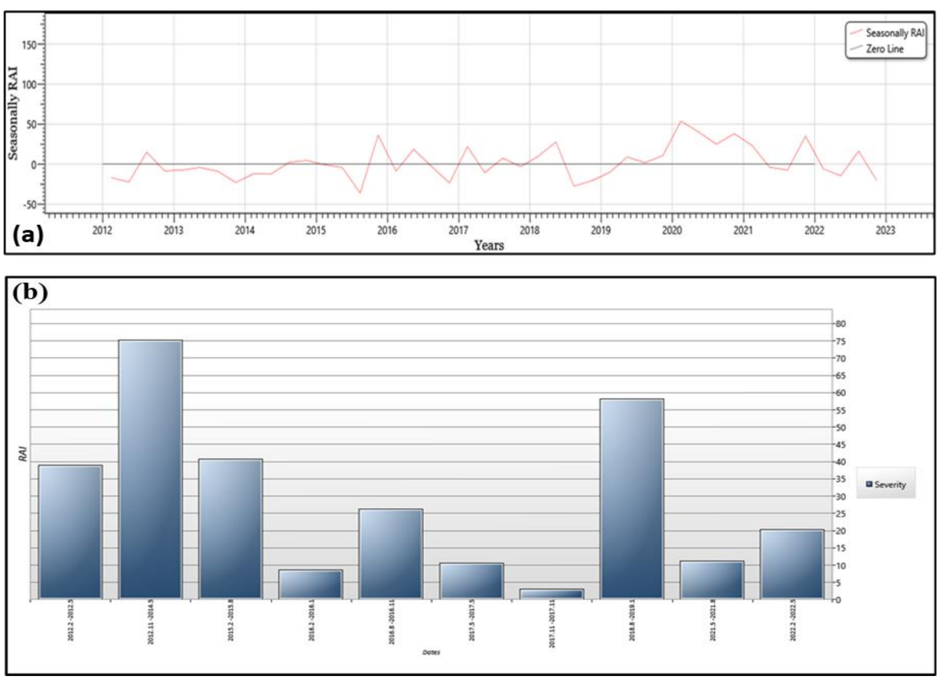

Fig. 13: Seasonal Rainfall Anomaly Index and the Dates between 2012 and 2022 in Badingilo National Park. (a) Seasonal Rainfall Anomaly Index; (b) the Date Seasonal Rainfall Anomaly Index

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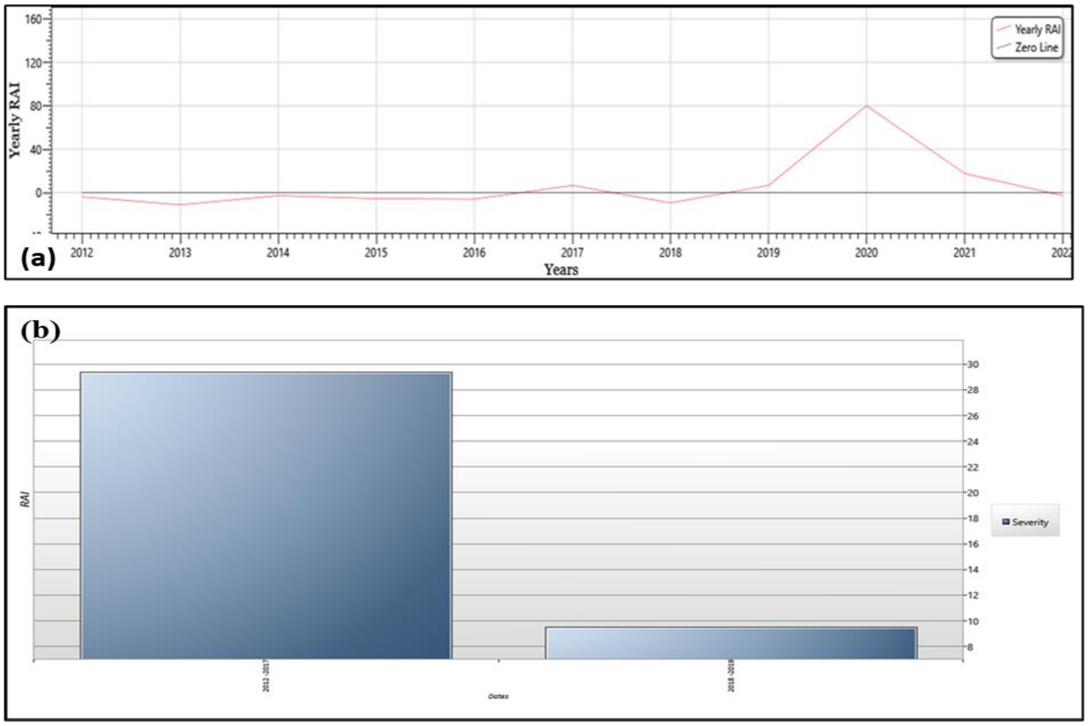

Fig. 14: Annual Rainfall Anomaly Index and the Dates between 2012 and 2022 in Badingilo National Park. (a) Annual Rainfall Anomaly Index; (b) the Dates of Annual Rainfall Anomaly

4.0 DISCUSSION OF RESULTS

4.1 Climate Trends between 2012 and 2022 in Badingilo National Park in South Sudan

Climate change is a deviation from the average weather conditions, or parameters such as rainfall and temperature, over a decade at the national or regional scale (23). Evidently, rainfall trends did not significantly ($P>0.05$) increase, whereas temperature trends did not significantly ($P>0.05$) decrease between 2012 and 2022 in Badingilo National Park in South Sudan. However, the increasing trend in monthly rainfall amounts was observed from January to May, July, and September to December from 2012 to 2022 (2). East African region observed (24) an increase in seasonal rainfall variability from 1982 to 2023 with a dominant pattern of consecutive short wet days lasting three to five days. Importantly, the erratic variability in rainfall distribution from March-May, 1983-2023, is influenced by climate change and anthropogenic activities, including deforestation, urbanization, and extensive agricultural activity. However, this study shows an increase in wet days during dry and wet seasons, between January and May, and from September to December, in Badingilo National Park. This emanated from the changes in seasonal rainfall patterns in the region influenced by local climate drivers such as human activities and orographic

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extreme factors. Similarly, the East African region exhibited bimodal rainfall patterns (25) that emanated from the Indian Ocean Dipole and the El Niño-Southern Oscillation, which cause annual rainfall variability. Indeed, the Indian Ocean Dipole has a strong correlation with October-December rainfall and temperature in East Africa (26). In addition, sometimes the Indian Ocean Dipole (IOD) has a combined effect with El Niño-Southern Oscillation (ENSO), which increases the rainfall amounts, resulting in floods in October-December in the East African region (26). ENSO was observed to have a strong influence on rainfall patterns, surface temperature, and vegetation health because it partially correlates positively with the presence or absence of rainfall and droughts in the East African region (26–29). However, local factors like the presence of forests and mountains, and proximity to coastal areas and swamps, determine local climates in most regions of East Africa, particularly in South Sudan (28). Osman (30) demonstrated that ENSO has a low effect on the equatorial region of South Sudan. This demonstrates that local rainfall regimes and droughts might be influenced by the complex topography composed of mountains, hills, dense vegetation cover, and rivers, and the Sudd wetland systems within the equatorial region in South Sudan (30). Incidentally, floods may be influenced by precipitation amounts received, extensive vegetation, the Sudd wetland systems, and overflow from the River Nile, whereas droughts are influenced by deforestation rates and regional climate drivers such as ENSO in Badingilo National Park in South Sudan.

Further, Palmer (25) showed that short consecutive wet days increased, whereas long consecutive dry days decreased from the 1980s to 2010 in the East African region. This assertion is consistent with this study, which demonstrates a marginal increase in annual rainfall trend and amount of over 120 mm from 2019 to 2020 in Badingilo National Park in South Sudan. Accordingly, a nonsignificant decrease in monthly temperature and annual temperature trends was observed from 2012 to 2022. Although the maximum temperature in July, August, and November, and the average temperature trends from February-April and July-August were positive, the trends were not significant between 2012 and 2022. Indeed, the high precipitation in 2020 resulted in heavy flooding that caused the migration of pastoral communities from Bor County to places with higher ground in Eastern and Western Equatoria in 2020 (9). The 2020 floods culminated in a shortage of natural pasture for livestock and wild animals, and displaced many agro-pastoralists from their homes. Studies have shown that the short rainy season from October to December leads to extreme floods in East Africa (26,28,29,31). This emanated from a southward shift in the Intertropical Convergence Zone (ITCZ) and the Indian Ocean Dipole (4,32,33). In contrast, Muorwel (9) elucidated that the migration of pastoralists from Bor County of Jonglei State occurred in July 2020. The study largely shows insignificant increasing trends in monthly rainfall amount from September to December, and annual rainfall amounts, with insignificant decreasing trends in monthly and annual temperature between 2012 and 2022 at Badingilo National Park in South Sudan.

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4.2 Occurrence of Meteorological Droughts and Floods between 2012 and 2022 in Badingilo National Park in South Sudan

The study shows that droughts occurred between 2012 and 2015 in Badingilo National Park in South Sudan. Indeed, monthly rainfall deficits of 340.0 mm (EDI), 4.7 mm (SPI), and 28.1 mm (annual SPI) were recorded between 2012 and 2018. Similarly, Adhyani (32) demonstrated the occurrence of severe droughts in Indonesia between 2002 and 2003, which was the longest and strongest in recent years. However, the droughts that occurred in 2012 (4) had an annual rainfall amount of less than 90 percent. Kose (34) showed that droughts have caused drying of streams and rivers in South Sudan. Definitely, such drying of streams and rivers can significantly affect livestock and wild animals that depend on them in Badingilo National Park of South Sudan. Ultimately, there were low rainfall amounts between 2012 and 2017. Chobo (33) confirmed that precipitation variability has occurred, with some regions receiving less than 100 mm in recent decades in East Africa. Further, monthly and seasonal rainfall anomalies vary widely between January and March, whereas the annual rainfall anomaly indicates variability of extreme droughts from 2012 to 2018 in Badingilo National Park in South Sudan. Accordingly, the study indicates increased daily, monthly, seasonal, and annual rainfall severity between 2019 and 2022 in Badingilo National Park. The rainfall indices, such as SPI, showed severe flooding (>2.5) in 2020, which was 150 percent above the normal rainfall amount, with an anomaly of 80.0 mm. Similarly, studies illustrate that annual precipitation is expected to increase by 35 percent, while the short rainy seasons from October to December will increase by 38 percent in Ethiopia, Uganda, and Kenya in the Eastern African region by 2040 (24,35). This rainfall phenomenon will have an impact on the rainfall regimes in Badingilo National Park because of the teleconnection between the physical features in those regions and Badingilo National Park in South Sudan. However, increased precipitation has both positive and negative effects on biodiversity, livestock, and human populations. Positively, increased precipitation means greater availability of forage and water for livestock and wild animals, and better crop performance for human consumption. Contrarily, the negative effects of increased precipitation include extreme floods that destroy crops and plant species and kill both livestock and wild animals. Literature showed that extreme floods displaced communities from their places and disrupted people's livelihoods (3,4,36). Evidently, over 18,000 people were displaced by floods in four states: Eastern and Western Equatoria States, Northern Bahr El Ghazal, and Unity State of South Sudan in 2022 (37). Ultimately, the study demonstrated the occurrence of extreme droughts in 2012 and floods in 2020, which require future awareness to reduce the effects of droughts and flooding in Badingilo National Park in South Sudan.

CONCLUSIONS

The monthly rainfall amounts did not significantly increase between January-March, July, and September to December between 2012 and 2022 at Badingilo National Park in South Sudan.

Similarly, there were positive trends in monthly and annual rainfall amounts between 2012 and 2022 that were not substantial. However, the monthly and annual temperature trends decreased non-significantly in the same period. However, meteorological drought indices affirm the occurrence of severe monthly and annual droughts from 2012 to 2019, and above-normal floods of 150 percent in 2020. This requires awareness and preparedness of the pastoral and agro-pastoral communities to extreme droughts and floods around Badingilo National Park in South Sudan.

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CONFLICT OF INTEREST

The authors confirm no conflict of interest exists.

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