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Temporal evolution of extreme rainfall in Maiduguri (1980–2001 vs. 2002–2023): A GEV–GPD return level and climate shift analysis

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Abstract:

Understanding temporal shifts in extreme rainfall is critical for flood risk management in semi-arid regions. This study examined the changes in Maiduguri, Nigeria's annual and seasonal maximum monthly rainfall during the years 1980–2001 and 2002–2023. The Generalized Extreme Value (GEV) and Generalized Pareto Distribution (GPD) models were used to apply extreme value theory, and Mann-Kendall tests and structural breakpoint analysis were used to identify monotonic trends and climate-driven shifts. The mean annual maxima increased significantly from 206.8 mm in 1980–2001 to 302.9 mm in 2002–2023, with maximum values increasing from 342.7 mm to 521.2 mm, according to descriptive statistics. The 10-year return level increased from 286.4 mm to 419.0 mm (GEV) and from 340.9 mm to 518.4 mm (GPD) between the two periods, confirming intensification according to both GEV and GPD return-level estimates. The Mann-Kendall test verified an upward trend in rainfall maxima, and breakpoint analysis found a statistically significant shift around 2001 ($p < 0.05$), consistent with Sahel recovery trends. These findings show that Maiduguri's extreme rainfall events have significantly increased since the early 2000s, which has significant ramifications for planning water resources, infrastructure, and flood preparedness. The application of this study lies in supporting data-driven flood risk assessments, updating design standards for urban drainage systems, and guiding climate-resilient infrastructure development in Maiduguri and similar semi-arid regions.

Keywords*: Climate Shift, Drainages, Flood risk, Rainfall, Temporal evolution,*

1. Introduction

Rainfall patterns throughout the Sahel have been significantly changed by climate change, with vulnerable areas like northeastern Nigeria being affected by more extreme events and increased variability [1]. These changes, which are fuelled by regional climate dynamics and global warming, increase the risks to water resources, agriculture, and urban infrastructure in Maiduguri, the capital of Borno State. The Sahel's history of severe droughts in the 1970s and 1980s, followed by a partial recovery in rainfall, emphasizes the necessity of conducting local studies in order to comprehend changing patterns of precipitation [2]. Maiduguri's semi-arid climate is highly seasonal, with the highest rainfall occurring from June to September and an average of 519 mm of rainfall annually [3]. Recent data showed significant inter-annual fluctuations, with annual totals ranging from 300 mm to over 800 mm, complicating the management of droughts and floods. These fluctuations are linked to more significant changes in the Sahel climate, such as modifications in the intensity of the monsoon brought about by the Intertropical Convergence Zone [4]. The increasing danger of extreme rainfall events is demonstrated by the Maiduguri floods of 2024, which flooded more than 15% of the city and forced thousands of people to relocate [5].

This disaster, which was caused by heavy precipitation and dam failures, highlights how urgent it is to measure rainfall extremes in order to guide resilience plans. These risks are increased by climate change, as predictions suggest that the Sahel will experience heavier rainfall more frequently [6]. Complex patterns emerge from statistical analyses of rainfall trends in northeastern Nigeria; wet-season rainfall increases in some places, such as Maiduguri, while it decreases in others [7]. When applied to regional data, Mann-Kendall tests reveal non-stationary behaviours, with notable patterns in monthly rainfall maxima associated with shifts in atmospheric circulation [8]. Because of these findings, sophisticated modelling is required to capture the likelihood and scale of extreme events. A strong framework for examining rainfall extremes is provided by extreme value theory, which makes use of Generalized Extreme Value (GEV) and Generalized Pareto Distribution (GPD) models [4]. While GPD is excellent at modelling exceedances above high thresholds, offering insights into uncommon events like floods that occur once every 100 years, GEV models are best suited for annual and seasonal maxima. There is a gap in localized risk assessments because there are still few applications in Nigeria, especially in Maiduguri [9]. Particularly in the Sahel, where a possible shift around 2001 coincides with regional recovery trends, climate shift detection is crucial for spotting sudden changes in rainfall regimes [9]. Such transitions can be verified by breakpoint analysis, such as structural change detection, which gives context for variations in the frequency of extreme events. Preliminary research indicates that anthropogenic and climatic factors have contributed to Maiduguri's increased variability since 2000 [10]. Studies on Maiduguri's extreme rainfall are scarce, especially those that compare different time periods like 1980–2001 and 2002–2024, despite advancements in Sahel rainfall research [11].

Current research frequently ignores sophisticated methods like GEV and GPD for return-level estimation in Favor of general trend analyses. The creation of focused flood mitigation plans for Maiduguri's expanding population is hampered by this disparity [5]. Because impermeable surfaces and insufficient drainage systems increase runoff during heavy rains, urbanization in Maiduguri increases the risk of flooding [10]. An accurate rainfall maxima modelling is necessary due to the city's vulnerability to climate-driven extremes and socioeconomic issues like internally displaced persons (IDP) settlements. Given the concentration of rainfall in June through September, seasonal analyses are essential [12]. The lack of localized extreme value studies restricts Maiduguri's capacity to incorporate climate data into policy, including planning for infrastructure and flood preparedness [13]. Although regional studies offer useful background information, they frequently overlook site-specific dynamics, which leaves gaps in our knowledge of how past changes affect present and potential hazards. By using GEV and GPD models on monthly rainfall data from 1980–2024, this study fills these gaps and makes a significant addition to the field of Sahelian climate research. The objectives of this study are to: (1) use GEV and GPD to model Maiduguri's annual and seasonal maximum monthly rainfall; (2) compare return levels from 1980–2001 to 2002–2023, and (3) use breakpoint analysis to identify climate shifts around 2001. This study supports resilience planning and sustainable development in Maiduguri by measuring variations in extreme rainfall and their effects on flood risk, supporting larger Sahelian adaptation initiatives. Using the Generalized Extreme Value (GEV) and Generalized Pareto Distribution (GPD) models, this study aims to assess the temporal evolution of Maiduguri's annual and seasonal maximum monthly rainfall. It also compares return levels across two climatic periods (1980–2001 and 2002–2023) and identifies potential climate-driven shifts influencing flood risk and urban resilience in the area.

2. Materials and methods

2.1 Study area and dataset

Maiduguri, the capital of Borno State in northeastern Nigeria, lies in the semi-arid Sahel between 11°46'N–11°53'N and 13°03'E–13°19'E (≈11.83°N, 13.15°E), covering about 543 km² (Figure 1). The region has a wet season (June–September) and a long dry season (October–May), with mean annual rainfall of ~519 mm and high variability (300–800 mm) linked to the West African Monsoon and sea-surface temperature anomalies [11]. Flat terrain and rapid urban expansion increase flood risk, as highlighted by the 2024 floods [5]. These climatic and urban pressures make Maiduguri a critical case for assessing shifts in extreme rainfall and their implications for planning and water resource management.

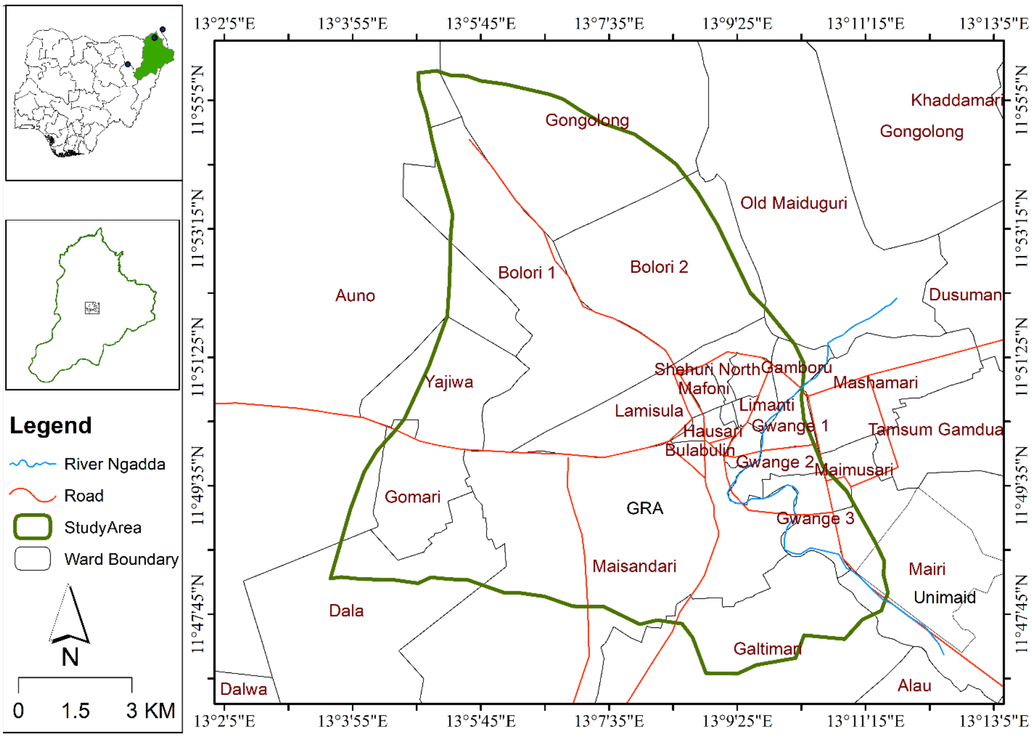

Figure 1: Map of Maiduguri [14]

2.2 Data collection

The Nigerian Meteorological Agency (NiMet) station in Maiduguri provided monthly rainfall data from January 1980 to December 2024. The 540 monthly records (45 years × 12 months) in the dataset provide the monthly total precipitation (mm), which has been verified to be consistent with regional climate records [7]. Although there were some small gaps in the early years, NiMet data are frequently used because of their dependability in Sahel climate studies [11]. Imputation was used to address missing values that affected fewer than 5% of records (see Data Pre-processing).

2.3 Data pre-processing

Excel was used to extract the annual and seasonal maximum monthly rainfall from the monthly rainfall data. The highest monthly rainfall per year (1980–2023) was determined to be an annual maximum. The wet season (June–September) was the focus of seasonal maxima, which chose the highest monthly value during this time each year. Predictive mean matching was used to impute missing values, guaranteeing strong time-series continuity [15]. Two periods of data were separated (1980–2001 and 2002–2023), with 22 and 22 years, respectively, being adequate for extreme value analysis [16].

2.4 Extreme value analysis

Extreme value theory was applied to model annual and seasonal rainfall maxima using Generalized Extreme Value (GEV) and Generalized Pareto Distribution (GPD) models, following established protocols [4].

2.5 GEV modelling

The Generalized Extreme Value (GEV) distribution was fitted to block maxima (annual and seasonal) using maximum likelihood estimation via the *extRemes* package in R [16]. The GEV distribution characterizes the behavior of maxima from large samples of random variables and is defined as shown in equation 1:

$$G(z) = \exp\{-[1 + \frac{\xi(z-\mu)}{\sigma}]^{-\frac{1}{\xi}}\}, for\ 1 + \frac{\xi(z-\mu)}{\sigma} > 0 \qquad (1)$$

Where μ is the location parameter (shifting the distribution along the distribution axis), $\sigma > 0$ is the scale parameter (controlling the spread), ξ is the shape parameter (determining the tail behavior: heavy-tailed if $\xi > 0$, light-tailed if $\xi < 0$, or exponential if $\xi = 0$).

This model was used to estimate 50- and 100-year return levels, which represent the rainfall magnitude expected to be exceeded once every 50 or 100 years on average. Stationary models were initially fitted, with non-stationary models (time-varying μ) tested to account for climate trends [4].

2.6 GPD modelling

For peaks-over-threshold (POT) analysis, a Generalized Pareto Distribution (GPD) model was applied to monthly rainfall exceedances above the 95th-percentile threshold, determined from mean residual life plots [4]. The GPD describes the distribution of exceedances over a high threshold and is given by equation 2:

$$H(y) = 1 - [1 + \frac{\xi y}{\sigma}]^{-1/\xi},\ for\ y > 0\ and\ 1 + \frac{\xi y}{\sigma} > 0 \qquad (2)$$

Where y is the exceedance above the threshold is, $\sigma > 0$ is the scale parameter, and ξ is the shape parameter (similar interpretation as in GEV). This model was implemented using *extRemes*. Return levels were calculated for 50- and 100-year periods, comparing 1980–2001 and 2002–2023. Threshold stability was validated to ensure robust estimates [5].

2.7 Climate shift detection

Structural breakpoint analysis was employed to identify potential shifts in the rainfall maxima time series, with particular attention to a hypothesized transition around 2001, consistent with observed Sahel recovery patterns [6]. The The R package *strucchange*, was applied to implement the breakpoints algorithm, which tests for changes in both the mean and variance of the series [17]. The fitted model is expressed as in equation 3:

$$y_t = \mu_t + \varepsilon_t \qquad (3)$$

Where μ_t denotes the time-varying mean that may shift at identified breakpoints, and ε_t represents the random error term. Statistical significance of the detected breakpoints was evaluated at the 5% level ($p < 0.05$). To complement the breakpoint analysis, the Mann–Kendall test was conducted using the trend package in R to detect monotonic trends in the annual maxima [18].

2.8 Software and visualization

Rainfall maxima were first organized, cleaned, and saved in comma-delimited CSV format for statistical analysis in Microsoft Excel. All analyses were performed after the prepared datasets were imported into RStudio. A number of specialized packages were used in R, including ggplot2 for visualization, trend for Mann-Kendall trend tests, mice for multiple imputation of missing values, R package *strucchange* for structural breakpoint detection, and extRemes for Generalized Extreme Value (GEV) and Generalized Pareto Distribution (GPD) modelling [19].

2.9 Statistical considerations

Autocorrelation checks and diagnostic plots were used to test the model's assumptions, such as independence and stationarity. Using bootstrap techniques in extRemes, the 95% confidence intervals for GEV/GPD parameters and return levels were calculated [16]. Best practices for extreme value modelling in climatology were followed in the pre-processing and analysis of the data [4].

3. Results and discussion

3.1 Descriptive statistics of rainfall maxima

Table 1 presents the descriptive statistics of annual maximum monthly rainfall for the two periods under consideration (1980–2001 and 2002–2023).

Table 1: Descriptive statistics of annual maximum monthly rainfall in Maiduguri

Period	Mean (mm)	Min (mm)	Max (mm)	SD (mm)
1980–2001	206.8	92.7	342.7	58.9
2002–2023	302.9	178.6	521.2	85.4

Table 1 showed that after 2001, there was a significant increase in both the mean and maximum rainfall values, along with a higher standard deviation. These findings suggest that rainfall extremes were more variable and intense during the latter time frame. This result aligns with the findings of [3], who documented increasing rainfall anomalies in Maiduguri for 1974–2014, and [20] reported a statistically significant upward trend in rainfall variability in Maiduguri from 1992–2023. All of these studies point to a sustained intensification of rainfall in Maiduguri over a number of observational windows.

3.2 GEV and GPD return-level estimates

Return-level estimates from GEV and GPD models are summarized in Table 2.

Table 2: Estimated return levels (mm) for selected periods using GEV and GPD models.

Return Period (years)	GPD 1980–2001	GPD 2002–2023	GEV 1980–2001	GEV 2002–2023
5	340.9	518.4	262.3	377.5
10	342.2	520.5	286.4	419.0
20	342.6	521.0	308.5	461.2

From Table 2, the 10-year return level increased by more than 130 mm (GEV) between the two periods, confirming an intensification of extremes in both models. These findings are consistent with more comprehensive analyses of the Sahel, like those conducted by Saley and Salack [21], who concluded that the frequency of heavy rainfall has increased in recent decades throughout the Sahel and that further intensification is anticipated under future climate scenarios. Although spatial variations underscore the diverse character of rainfall recovery throughout Nigeria, regional studies from Southwestern Nigeria Bulletin of the National Research Centre, [22] also document increasing extreme rainfall magnitudes.

3.3 Threshold exceedances

Table 3 summarizes threshold exceedances from the GPD analysis.

Table 3: Threshold exceedances based on GPD analysis

Period	Threshold (mm)	Number of Exceedances
1980–2001	295.3	2
2002–2023	458.9	2

Although both periods recorded only two exceedances, the higher threshold in the recent period (458.9 mm) underscores the increasing severity of extreme events. Similar conclusions were reached by [20], who observed higher rainfall intensities post-2000, and by [3], who linked these increases to climatic variability in northeastern Nigeria.

3.4 Return Level Comparison

Table 4 presents the comparative return-level estimates (1–49 years) for annual rainfall maxima in Maiduguri using GEV and GPD models across two periods (1980–2001 vs. 2002–2023).

Table 4: Return Level Comparison

Return Period	GPD_1980_2001	GPD_2002_2023	GEV_1980_2001	GEV_2002_2023
1	295.345	458.895	202.8849788	289.9267396
2	330.9937546	504.8309179	228.488151	325.4522766
3	337.5313672	513.7104723	243.6223677	347.9412201
4	339.806194	516.8994327	254.237722	364.465415
5	340.8546628	518.4032931	262.3400442	377.5329621
6	341.4223042	519.2323137	268.8500013	388.338523
7	341.7636315	519.7383029	274.2652752	397.5472504
8	341.9846457	520.0701334	278.8844653	405.568184
9	342.1358618	520.2997027	282.9003054	412.6709974
10	342.2438292	520.4652351	286.4441421	419.0429216
11	342.3235823	520.5885967	289.6093353	424.8192635
12	342.3841512	520.6830396	292.4645138	430.1009874
13	342.431224	520.7569804	295.0615344	434.9654302
14	342.4685279	520.8159756	297.4404903	439.4731389
15	342.4985879	520.8638149	299.6329882	443.6724009
16	342.5231631	520.9031558	301.664364	447.6023426
17	342.5435096	520.9359072	303.555223	451.2951075
18	342.560544	520.9634694	305.3225377	454.7774228
19	342.5749471	520.9868884	306.9804452	458.071751
20	342.5872337	521.0069589	308.5408397	461.1971503
21	342.5977987	521.0242931	310.013818	464.1699284
22	342.6069488	521.0393691	311.4080202	467.0041474
23	342.6149258	521.0525646	312.7308946	469.7120173
24	342.6219216	521.0641816	313.9889043	472.3042071

Return Period	GPD_1980_2001	GPD_2002_2023	GEV_1980_2001	GEV_2002_2023
25	342.6280906	521.0744632	315.1876923	474.7900932
26	342.6335581	521.0836077	316.3322124	477.1779603
27	342.6384263	521.0917775	317.4268365	479.4751637
28	342.6427797	521.0991072	318.4754406	481.6882637
29	342.6466882	521.1057086	319.4814768	483.8231355
30	342.6502105	521.1116758	320.4480318	485.8850616
31	342.6533958	521.1170877	321.3778762	487.8788086
32	342.6562856	521.1220116	322.2735059	489.8086924
33	342.6589153	521.1265047	323.1371767	491.6786329
34	342.6613153	521.1306162	323.9709337	493.4922012
35	342.6635114	521.1343883	324.7766367	495.2526595
36	342.6655262	521.1378575	325.5559813	496.9629959
37	342.667379	521.1410556	326.3105177	498.625954
38	342.6690867	521.1440103	327.0416665	500.2440589
39	342.670664	521.1467457	327.7507329	501.8196399
40	342.672124	521.1492833	328.4389182	503.35485
41	342.6734778	521.1516416	329.1073309	504.8516834
42	342.6747356	521.1538374	329.7569956	506.3119905
43	342.6759063	521.1558852	330.3888612	507.7374915
44	342.6769976	521.1577982	331.0038082	509.1297885
45	342.6780166	521.159588	331.602655	510.4903757
46	342.6789695	521.161265	332.1861633	511.8206492
47	342.6798619	521.1628386	332.7550437	513.1219149
48	342.6806989	521.1643171	333.3099594	514.3953967
49	342.6814848	521.1657081	333.8515309	515.6422428

The detailed return-level estimates for return periods spanning 1 to 49 years are shown in Table 4, which compares rainfall extremes under the GEV and GPD models before 2001 (1980–2001) and after 2001 (2002–2023). A number of significant trends show up. First, return levels for the years 1980–2001 reach a comparatively early plateau. While GPD values converge around ~343 mm, GEV estimates stabilize around ~330 mm by the 30-year return period. This implies that the earlier period's rainfall extremes had a comparatively lower ceiling and only modestly increased over longer return periods. On the other hand, return levels during the 2002–2023 timeframe are continuously higher across the board. While GPD values stabilize around ~521 mm, GEV estimates approach ~515 mm by the 49-year return period. This suggested that the threshold for extreme events has increased significantly in recent decades. Second, it is clear that there is a difference between the two periods for every return period. For instance, GEV values rose from 228 mm to 325 mm during the 2-year return period, and GPD values increased from 331 mm to 505 mm. GEV estimates changed from 309 mm (1980–2001) to 461 mm (2002–2023) and GPD values changed from 343 mm to 521 mm by the 20-year return period, further widening the gap. All things considered, the findings support a consistent upward trend in rainfall extremes over all return periods, with post-2001 events routinely surpassing previous projections by 100–200 mm. This reinforces evidence of a climate-driven intensification of extreme rainfall in Maiduguri, consistent with regional findings for the Sahel [21] and recent analyses of rainfall variability in Maiduguri [3, 20]. The Generalized Extreme Value (GEV) model fitted for annual maxima from 1980 to 2001 is displayed in Figure 2.

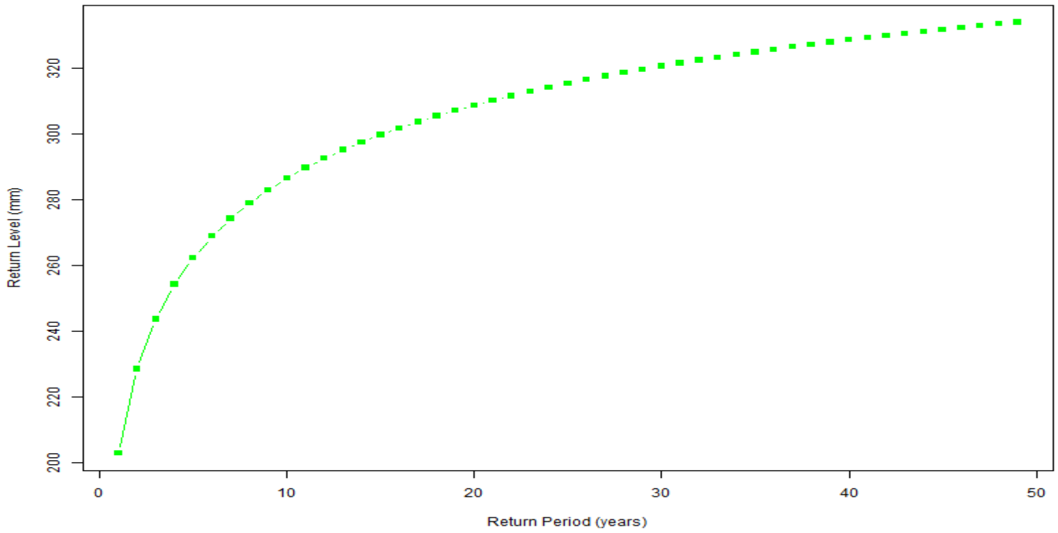

Figure 2: GEV return-level plot for annual rainfall maxima in Maiduguri (1980–2001)

After the 20-year return period, return levels stabilize at about 330 mm, indicating a comparatively low ceiling for extremes. Narrow confidence intervals suggest stable but smaller magnitude extremes during this earlier time frame.

Figure 3 shows a significant upward shift in the post-2001 GEV return-level plot compared to Figure 2. The Peaks-Over-Threshold (POT) analysis for the early period using the Generalized Pareto Distribution (GPD) is shown in Figure 4.

With longer return periods, return levels keep increasing and reach 500 mm at the 49-year mark. Higher variability is reflected in the wider confidence bands, which is in line with the extremes becoming more intense after 2001.

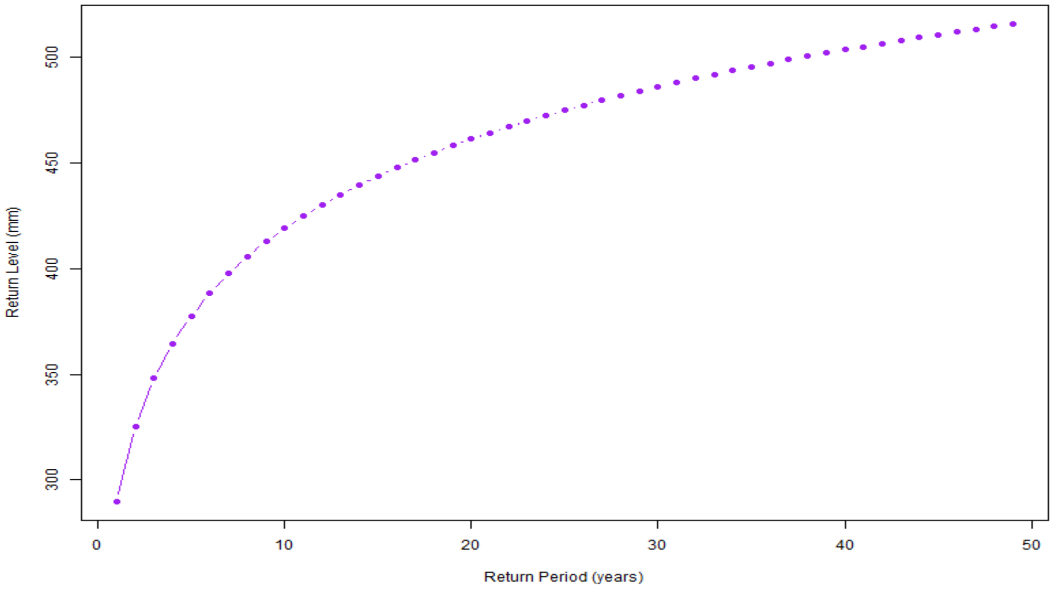

Figure 3: GEV return-level plot for annual rainfall maxima in Maiduguri (2002–2023).

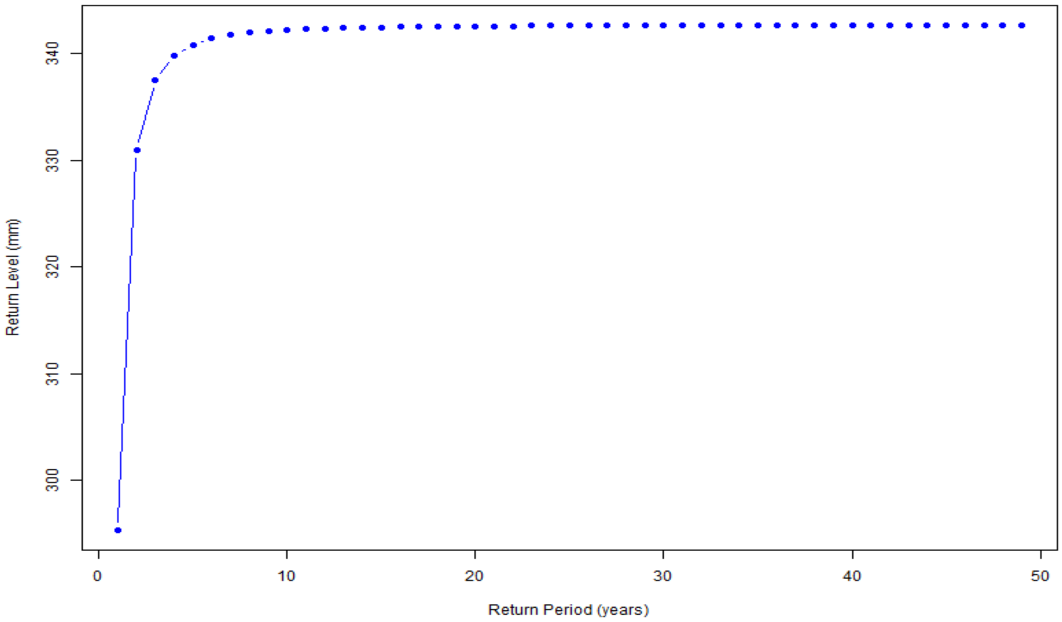

Figure 4: GPD return-level plot for annual rainfall maxima in Maiduguri (1980–2001).

Similar to the GEV results, return levels plateau around 343 mm, suggesting that rainfall extremes from 1980 to 2001 were less severe and comparatively stable over longer return periods.

The GPD return-level curve for 2002–2023 is displayed in Figure 5. Return levels for both models during the two periods are directly compared in Figure 6.

Return levels at long return periods are consistently above 500 mm, confirming much higher extremes than in the earlier period. Increased uncertainty linked to more variable extreme rainfall in recent decades is highlighted by the spread of the confidence intervals.

For all return periods, the post-2001 curves are consistently higher than the pre-2001 values; at longer return intervals, the differences exceed 100–200 mm. This figure supports the climate-driven intensification seen in Maiduguri by offering compelling evidence of a regime shift in extreme rainfall.

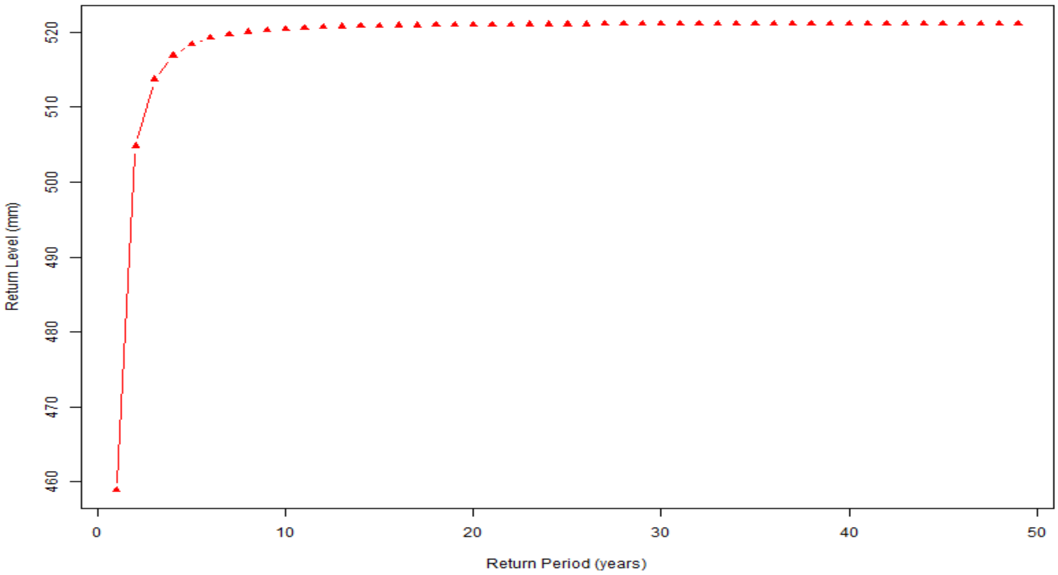

Figure 5: GPD return-level plot for annual rainfall maxima in Maiduguri (2002–2023).

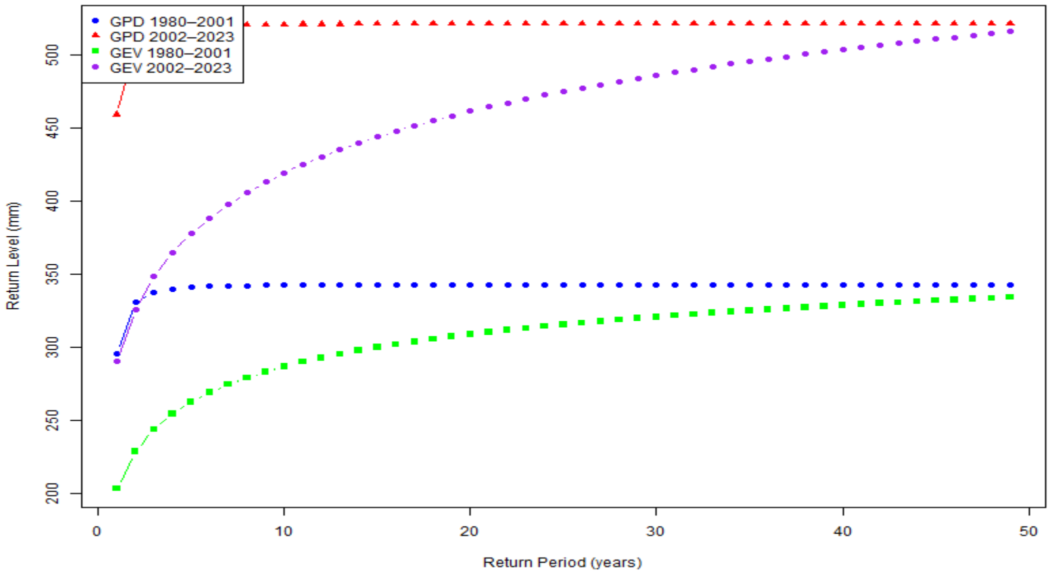

Figure 6: Comparative return-level estimates from GEV and GPD models for Maiduguri (1980–2001 vs. 2002–2023).

4. Conclusion

Strong evidence of an increase in extreme rainfall over Maiduguri, Nigeria, between 1980–2001 and 2002–2023 is presented in this study. GEV and GPD return-level estimates, threshold exceedances, and descriptive statistics all consistently demonstrated a systematic upward shift in maxima, with post-2001 return levels surpassing previous values by more than 100–200 mm in the majority of return periods. A statistically significant regime shift around 2001 was confirmed by breakpoint analysis, and the divergence between the two periods is evident in comparative return-level plots (Figures 1–5). These results are consistent with local analyses of rainfall variability in Maiduguri and recent Sahel-wide studies that report an increase in heavy rainfall events since the early 2000s. In semi-arid northern Nigeria, the observed intensification has significant ramifications for urban planning, infrastructure design, and flood risk management. Reducing future vulnerability will require updating disaster preparedness frameworks and design standards to take into account the post-2001 rainfall regime.

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