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An Analysis of Precipitation Patterns in the Major Cities of Nepal

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Abstract

Climate change has significantly altered precipitation dynamics, increasing the frequency and intensity of extreme rainfall events. However, infrastructure design practices in Nepal still largely depend on stationary assumptions based on historical rainfall records, creating a critical gap between evolving climatic conditions and existing engineering standards. This study evaluates temporal changes in precipitation patterns across eleven major cities of Nepal, representing the Mountain, Hilly, and Terai regions over the period 1981–2024. The objectives were to develop precipitation inventory datasets, estimate 10-year return period storm intensities, and assess variations in design rainfall values over time. Daily rainfall data obtained from the NASA POWER database were analyzed using the Annual Maximum Series (AMS) approach. The dataset was divided into two equal periods: 1981–2002 and 2003–2024. Return periods were estimated using the Weibull plotting position formula, while 10-year storm intensities were derived through logarithmic and linear trendline modeling. Results indicate that 9 of the 11 cities experienced increased rainfall intensity during the recent period. Pokhara exhibited the highest increase (92.834%), followed by Jomsom (82.606%) and Jumla (50.245%). The findings confirm climatic non-stationarity across Nepal and highlight the urgent need to revise rainfall standards and update engineering design codes for climate-resilient infrastructure planning.

Keywords: *Climate change, climate non-stationarity, extreme rainfall events, frequency analysis, return period*

1. Introduction

1.1 Research Background

Rainfall recharges all forms of physical water resources and plays a vital role in sustaining hydrological systems (Bista, 2019). Understanding its spatial and temporal variability is essential for effective water resource management, flood forecasting, and hazard assessment (Thapa et al., 2017). Under changing climatic conditions, the study of evolving rainfall characteristics, particularly extreme precipitation events, has become increasingly important for evaluating environmental and infrastructural impacts (IPCC, 2022).

In Nepal, nearly 80% of annual precipitation occurs during the June–September monsoon season, primarily influenced by moisture originating from the Bay of Bengal (Bista, 2019).

The complex topography of the Hindu Kush Himalayan region causes abrupt orographic lifting, resulting in highly variable wet and dry micro-climatic zones across short distances (Karki et al., 2016a; 2016b). Urban valleys such as Kathmandu are especially sensitive to rainfall variability because of rapid urbanization and increasing impervious surfaces. Across Nepal's approximately 193km south to north elevation gradient, two major precipitation peaks are observed: one between 500–700 masl and another between 2000–2200 masl (Shrestha & Sthapit, 2015; Talchabhadel et al., 2018). Variations in seasonal rainfall patterns contribute to water shortages during dry periods and excessive drainage loading during intense storms, often causing floods and landslides (Tuladhar et al., 2020).

As urban populations continue to grow, flood risk planning has become increasingly necessary for climate resilient development (IPCC, 2022). Studies indicate that extreme rainfall events are becoming more frequent and intense worldwide (Alfieri et al., 2015; Dodman et al., 2022). Developing countries such as Nepal remain particularly vulnerable because of limited adaptive capacity and comparatively weaker infrastructure systems (Nicholas Stern, 2007).

Nepal is highly exposed to riverine flooding and rainfall induced disasters (Alfieri et al., 2017). However, significant research gaps remain. Existing studies are often limited to localized regions such as Kathmandu or the Karnali Basin (Prajapati et al., 2021; Bhattarai et al., 2023), while many engineering design approaches still rely on the assumption of climatic stationarity. Such assumptions may reduce the long-term reliability and resilience of hydraulic structures under changing climatic conditions (Bade et al., 2019). Therefore, a nationwide engineering-focused assessment of changing rainfall extremes is necessary.

Nepal's infrastructure systems are highly sensitive to rainfall variability due to the country's steep topography, intense monsoon climate, and rapid urban expansion. Conventional hydrological and hydraulic design practices are primarily based on historical rainfall records and assume that climatic conditions remain stationary over time. However, recent observations indicate changing rainfall behavior characterized by fewer rainy days but more intense precipitation events. These changes increase the risks of urban flooding, slope instability, drainage failure, and infrastructure damage. As a result, many existing structures may no longer be adequately designed to withstand current and future rainfall extremes.

Although evidence of changing precipitation patterns exists, complete and thorough city-specific comparative studies that measure shifts in design storm intensity are still limited in Nepal. This creates uncertainty for engineers and planners involved in infrastructure development and disaster mitigation. To address this gap, the present study analyzes annual maximum daily rainfall data from major Nepali cities and compares two different time periods to evaluate changes in extreme rainfall intensity and their implications for engineering design.

The primary objectives of this study are to develop a comprehensive precipitation inventory database for major cities of Nepal, estimate storm intensity and frequency corresponding to a 10-year return period, and quantify the observed changes in storm intensity over time. Furthermore, the study aims to evaluate the practical implications of these changing rainfall characteristics on urban infrastructure planning, hydrological design, and climate resilience in the Nepalese context.

The findings are intended to support hydrological design, urban planning, and disaster risk management applications. This study is subjected to certain limitations. The analysis is based on only 44 years of precipitation data, which may not fully capture long term climatic variability and extreme hydrological events. Additionally, all rainfall data used in the study were obtained from secondary sources, specifically NASA POWER, and the accuracy of the dataset was not independently verified through ground based observational records or field validation.

1.2 Literature Review

Climate change has significantly altered global precipitation patterns, with the Intergovernmental Panel on Climate Change (IPCC, 2023) confirming that anthropogenic warming is increasing the frequency and intensity of extreme weather events worldwide. Nepal, due to its complex topography and monsoon-dominated climate, is particularly vulnerable to these changes. Extreme Rainfall Events (EREs) in the country frequently trigger floods, landslides, and debris flows, causing major losses to life, infrastructure, and agriculture. Researchers have highlighted the emerging "climate change paradox," where heavier rainfall events coexist with prolonged drought conditions (Park & Western, 2026). Consequently, the focus of climate studies has shifted from average rainfall toward the analysis of precipitation extremes and storm intensities. Trend line analysis has become a widely accepted method for identifying climatic shifts because of its simplicity and effectiveness in interpreting long-term environmental data. Studies in Nepal by Bista (2019) demonstrated noticeable regional changes in rainfall distribution, while global and regional assessments such as Alfieri et al. (2015) and Zhan (2017) reported increasing flood frequency and intensified precipitation extremes across Europe and the Hindu Kush Himalayan region, respectively. These findings establish that changing rainfall behavior is now a critical concern for hydrological planning and infrastructure design.

Several studies conducted within Nepal further confirm the intensification and uneven spatial distribution of rainfall extremes. Talchabhadel et al. (2018) identified significant regional variability in precipitation trends across the country, while Prajapati et al. (2021) observed a shift toward fewer rainy days but more intense rainfall events in the Kathmandu Valley. Future projections by Shrestha D. et al. (2023) suggested that extreme rainstorms in Kathmandu could intensify by nearly 72% under warming scenarios, whereas attribution studies by Liang (2024) linked recent catastrophic floods in Nepal directly to anthropogenic climate change. Hydrological studies such as "Shifting Mountain Flood Regimes under Global Warming" (Shah et al., 2026) and flood risk assessments in the Indrawati River Basin by (Bade et al., 2019) revealed that warming temperatures are altering runoff mechanisms, increasing flash flood potential, and reducing the reliability of historical return periods used in engineering practice. Furthermore, compound climate risks involving both floods and droughts continue to intensify, challenging existing adaptation strategies and exposing vulnerable communities to greater socio-economic risks. There is an urgent need for localized precipitation analysis, updated hydrological design standards, and climate-resilient infrastructure planning in Nepal.

2. Materials and Methods

2.1 Study Area and Data Source

The study has been conducted for selected major cities of Nepal representing diverse geographical, climatic, and topographical regions of the country. The selection of cities was made to capture rainfall variability across the Mountainous, Hilly, and Terai regions, as well as to reflect both urban and semi-urban settings with engineering significance. The cities were selected for having higher population density than others. The cities included in this study are:

- Kathmandu (27.71° N, 85.32° E) – representing a densely urbanized intermontane valley in central Nepal

- Pokhara (28.21° N, 83.99° E) – representing a high rainfall hilly region influenced by orographic effects
- Namche Bazaar (27.81° N, 86.71° E) – representing high altitude Himalayan climate conditions
- Jumla (29.25° N, 82.17° E) – representing a rain shadow, high altitude mountainous region in western Nepal
- Jomsom (28.78° N, 83.72° E) – representing an arid trans-Himalayan region with distinct precipitation characteristics
- Bharatpur (27.67° N, 84.44° E) – representing the inner Terai region with growing urban development
- Butwal (27.70° N, 83.47° E) – representing a foothill city at the transition between hills and Terai
- Janakpur (26.73° N, 85.93° E) – representing the central Terai plains
- Biratnagar (26.46° N, 87.28°E) – representing the eastern Terai region with monsoon dominated rainfall
- Birendranagar (Surkhet) (28.60° N, 81.63° E) – representing the mid-western inner Terai
- Dhangadhi (28.69° N, 80.62° E) – representing the far-western Terai region

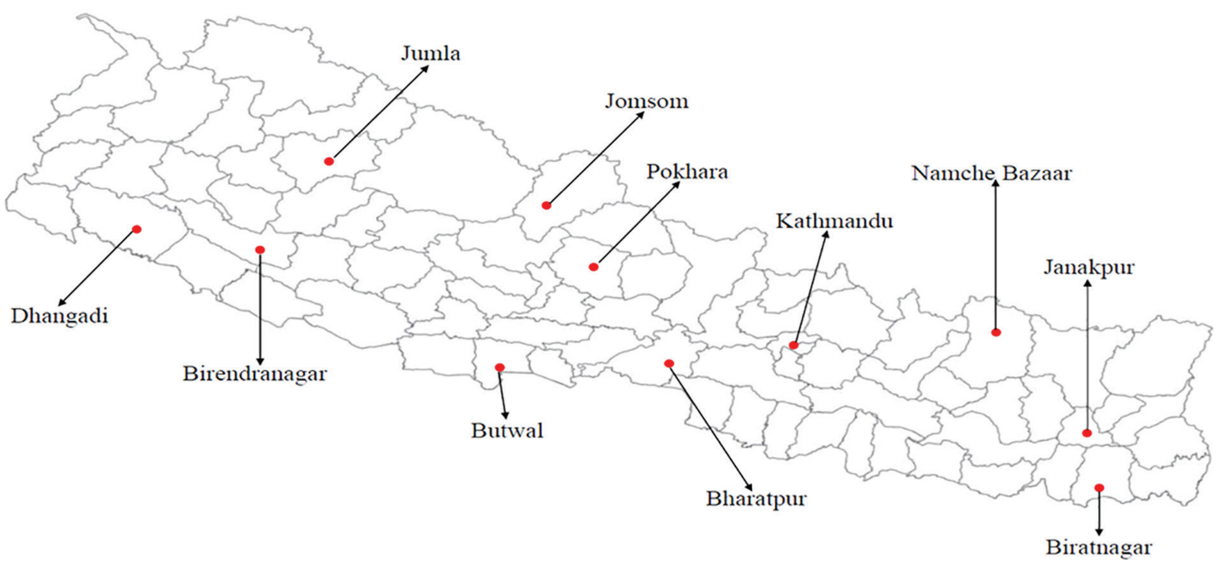


Figure 1: Geographic location of major cities in Map of Nepal.

These cities collectively provide a comprehensive spatial representation of Nepal's rainfall regimes, enabling comparative analysis of extreme precipitation behavior across different climatic zones. Daily rainfall data for the selected cities were obtained from the NASA POWER (Prediction of Worldwide Energy Resources) Data Access Viewer, an open access global meteorological database developed by the National Aeronautics and Space Administration (NASA). The platform provides long term, quality controlled gridded climate datasets derived from satellite observations, assimilation models, and ground based measurements.

Using the NASA POWER data access viewer, daily precipitation data corresponding to the geographical coordinates of each selected city were extracted for the period 1981 A.D. to 2024 A.D., subject to data availability. The extracted daily rainfall records were then processed to generate the Annual Maximum Series (AMS) by identifying the highest daily rainfall value for each year, which forms the basis for the extreme rainfall and return period analysis.

2.2. Data Preparation and Analysis

This study investigates the extreme rainfall events in Nepal by comparing storm intensities between, multiple cities of Nepal, between two time periods. The overall process is divided into five sequential phases as follows:

2.2.1. Data Preparation and Period Depiction

The analysis begins with preparing an Annual Maximum Series (AMS) using historical daily rainfall data. For each year from 1981 to 2024, the maximum 1-day rainfall depth is extracted to form the AMS. To examine how extreme rainfall has changed over time, the dataset is split into two distinct periods:

- Baseline Period or Old Period (1981A.D–2002 A.D): Represents historical climate conditions
- Contemporary Period or New Period (2003 A.D–2024 A.D): Represents recent climate conditions influenced by ongoing climate change

Separating the data in this way allows for a clear comparison of extreme rainfall characteristics across two different climatic windows.

2.2.2. Frequency Analysis and Return Period Calculation

A standard extreme value analysis is performed separately for each period, which establishes the statistical relationship between rainfall magnitude and its expected frequency. The following steps are applied:

- Sorting: Annual maximum rainfall values are arranged in descending order.
- Ranking: Each value is assigned a rank (*m*), with 1 for the highest value, 2 for the next, and so on.

Return Period Estimation: The Weibull plotting position formula has been used to compute the return period

$$(T)=\left(\frac{n+1}{m}\right)$$

Where, n= total number of precipitation data & m= assigned rank

2.2.3. Derivation of Design Storm Intensity

To evaluate changes in engineering-relevant rainfall extremes, the 10-year return-period intensity is derived for each period.

- Graphical Analysis: A scatter plot is generated with Return Period on the X-axis and Rainfall Intensity on the Y-axis.
- Trendline Fitting:
    1. A linear trendline ($y = mx + c$) is first to be applied.
    2. If the fit is weak ($R^2 < 0.7$), a logarithmic trendline is used better to represent the heavier tail of extreme rainfall data.
- Intensity Extraction: Using the trendline equation, the rainfall intensity corresponding to a 10-year return period ($x = 10$) is interpolated. This gives a single design storm intensity for each time window.

2.2.4. Variation of Rainfall

The difference between the two design storm intensities is quantified to measure how extreme rainfall has changed over time.

$$Percentage\ Change = \frac{New\ Period\ Intensity - Old\ Period\ Intensity}{Old\ Period\ Intensity} \times 100\%$$

This provides a clear numerical indicator of how much more intense a 10-year rainfall event has become in recent decades.

2.2.5. Data Analysis

Finally, the results are interpreted in terms of climate non-stationarity. The percentage change in the 10-year storm intensity is to be discussed with respect to:

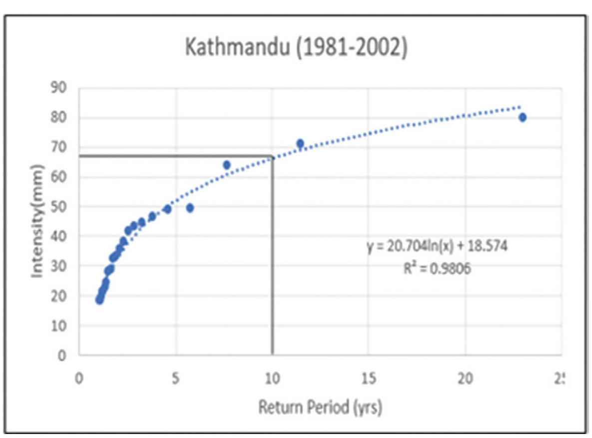
- Comparison between multiple cities of Nepal.
- Implications for hydraulic and drainage infrastructure design.
- Increased flood risk to communities.
- The need to update engineering standards and hydrological models to reflect current and future climate conditions.

3. Results and Discussion

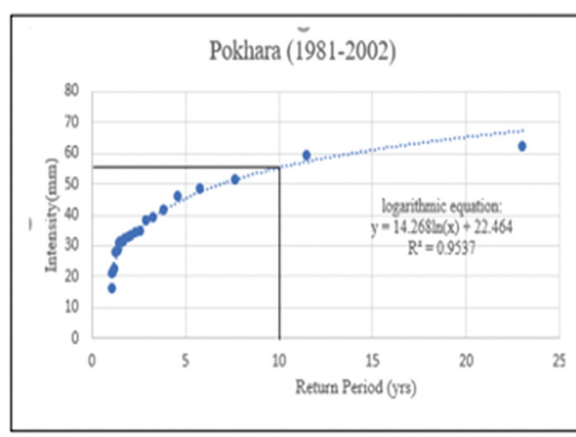
3.1. Intensity–Return Period Relationship

3.1.1. Old Period (1981-2002 A.D.)

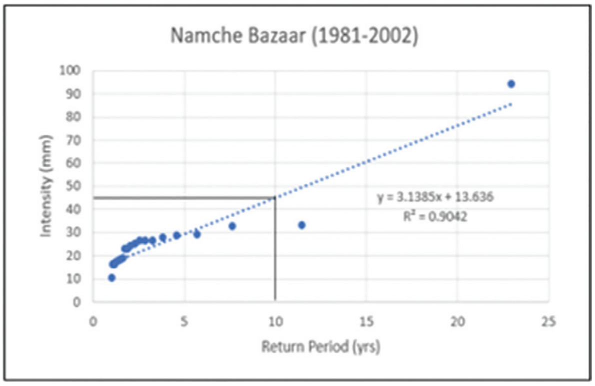
This section analyzes the relationship between rainfall intensity and return period for the old time period, i.e., 1981-2002 A.D. Logarithmic (most commonly used) and Linear (only a few) trendlines were applied to represent extreme rainfall behavior. Rainfall intensity and return period of the old time period of eleven cities, as shown in Figures 2 (a – k).



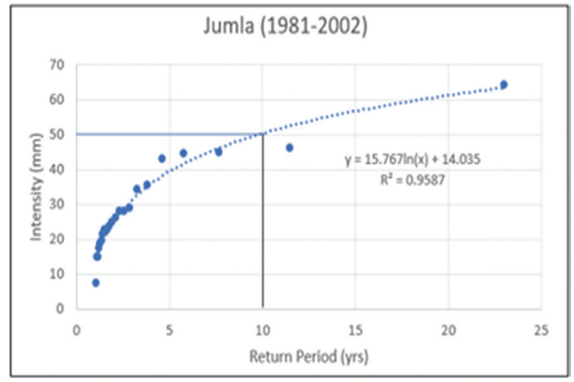
(a) Intensity-Return Period between 1981-2002 in Kathmandu.



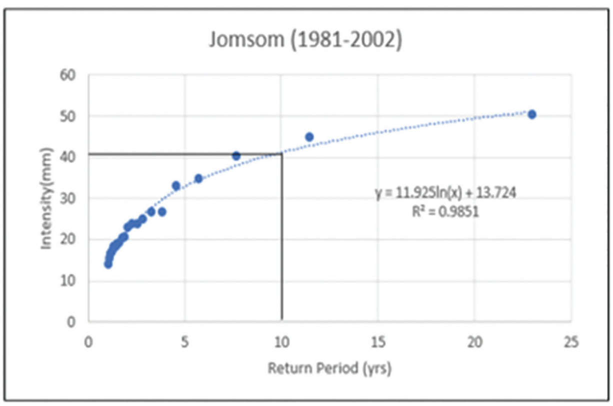
(b) Intensity-Return Period between 1981-2002 in Pokhara.



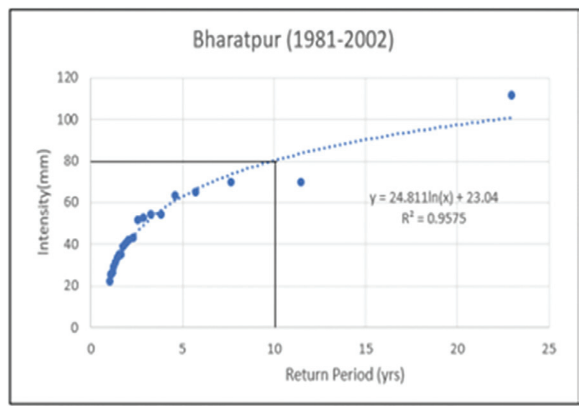
(c) Intensity-Return Period between 1981-2002 in Namche Bazaar.



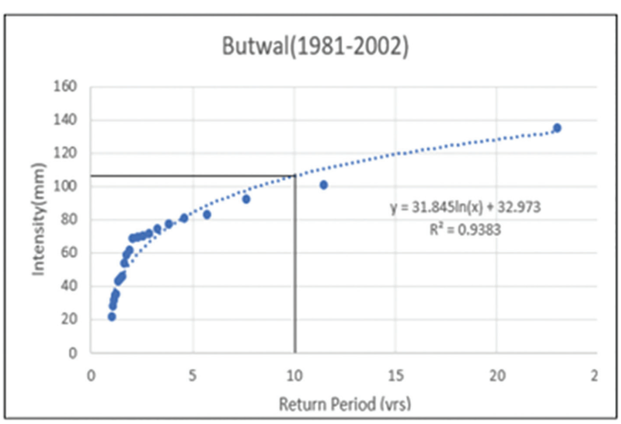
(d) Intensity-Return Period between 1981-2002 in Jumla.



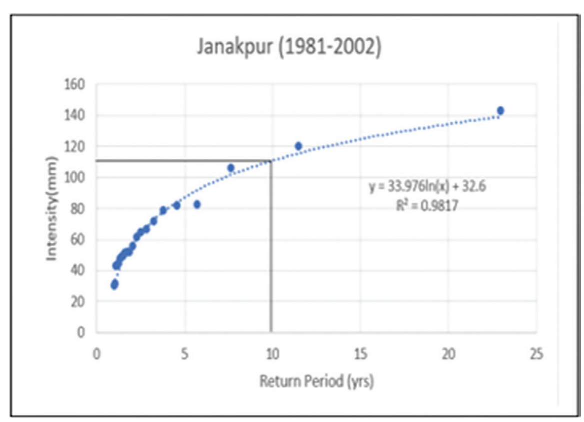
(e) Intensity-Return Period between 1981-2002 in Jomsom.



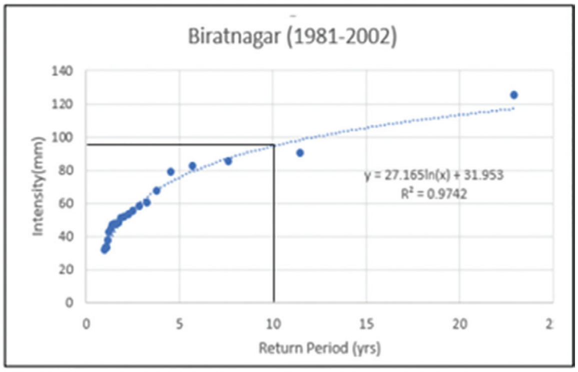
(f) Intensity-Return Period between 1981-2002 in Bharatpur.



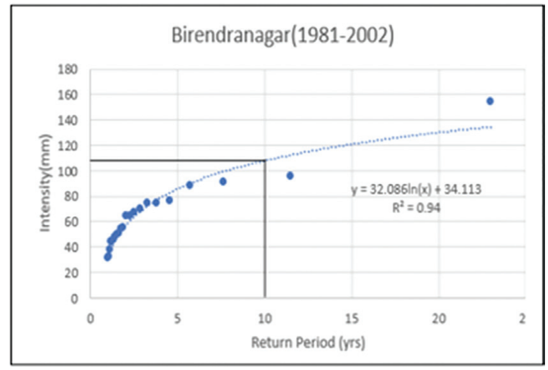
(g) Intensity-Return Period between 1981-2002 in Butwal.



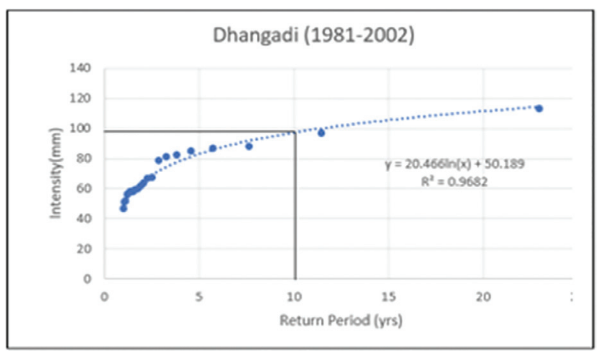
(h) Intensity-Return Period between 1981-2002 in Janakpur.



(i) Intensity-Return Period between 1981-2002 in Biratnagar.



(j) Intensity-Return Period between 1981-2002 in Birendranagar.



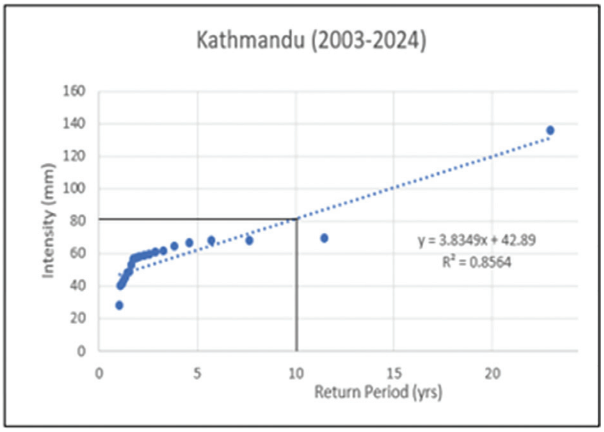
(k) Intensity-Return Period between 1981-2002 in Dhangadi.

Figure 2: Rainfall intensity and Return period at different periods from 1981-2002 at different major cities of Nepal.

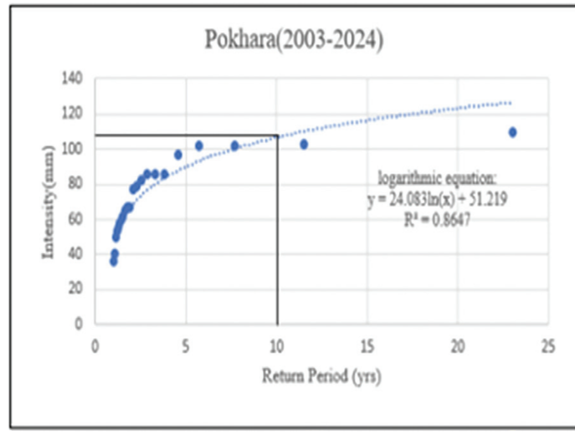
The 10-year return-period storm intensities for the baseline period (1981–2002) were estimated for all eleven cities using logarithmic and linear trendline equations derived from Weibull plotting positions. In Kathmandu (Figure 2.a), the relationship follows $y = 20.70\ln(x) + 18.54$, yielding an intensity of 66.246 mm, while Pokhara (Figure 2.b) follows $y = 14.268\ln(x) + 22.464$, giving 55.317 mm. Namche Bazaar (Figure 2.c) follows a linear trend $y = 3.1385x + 13.636$, producing an intensity of 45.021 mm, and Jumla (Figure 2.d) follows $y = 15.767\ln(x) + 14.035$, yielding 50.339 mm. Jomsom (Figure 2.e), with $y = 11.925\ln(x) + 13.724$, recorded the lowest intensity among mountain cities at 41.182 mm. Moving to the mid-hill and Terai cities, Bharatpur (Figure 2.f) follows $y = 24.811\ln(x) + 23.04$, giving 80.169 mm, and Butwal (Figure 2.g) follows $y = 31.845\ln(x) + 32.973$, yielding 106.298 mm. Janakpur (Figure 2.h), with $y = 33.976\ln(x) + 32.6$, recorded 110.832 mm, while Biratnagar (Figure 2.i) follows $y = 27.165\ln(x) + 31.953$, giving 94.502 mm. Birendranagar (Figure 2.j) follows $y = 32.086\ln(x) + 34.113$, yielding 107.993 mm, and finally Dhangadi (Figure 2.k), with $y = 20.466\ln(x) + 50.189$, recorded an intensity of 97.3137 mm, among the higher baseline values observed in the Terai region.

3.1.2. New Period (2003-2024 A.D.)

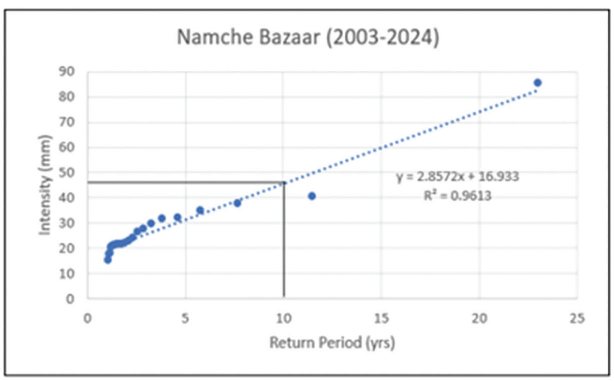
This section analyzes the relationship between rainfall intensity and return period for the new time period, i.e., 2003-2024 A.D. Logarithmic (mostly used) and Linear (only a few) trendlines were applied to represent extreme rainfall behavior. Rainfall intensity and return period of the new time period of eleven cities as in Figures 3 (a- k), have been shown below.



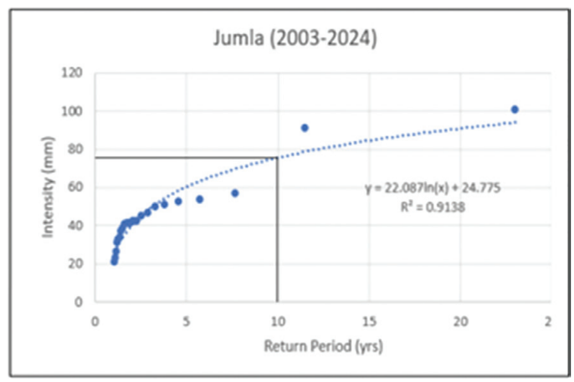
(a) Intensity-Return Period between 2003 - 2024 in Kathmandu.



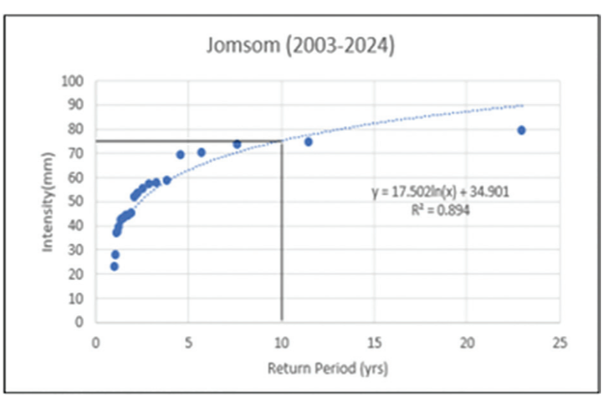
(b) Intensity-Return Period between 2003 - 2024 in Pokhara.



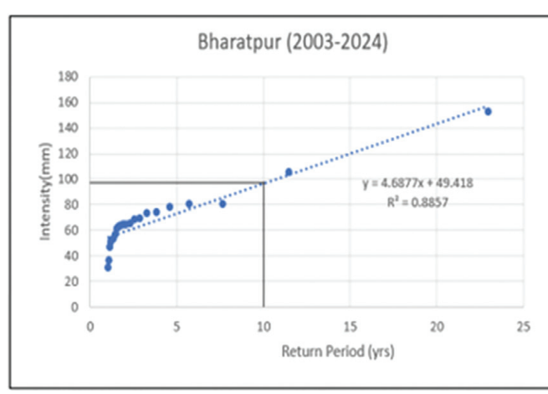
(c) Intensity-Return Period between 2003 - 2024 in Namche Bazaar.



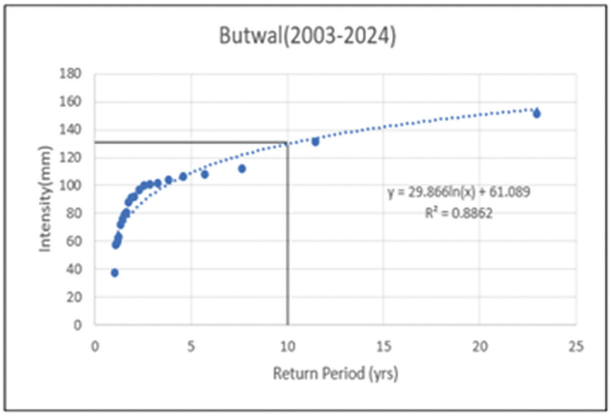
(d) Intensity-Return Period between 2003 - 2024 in Jumla.



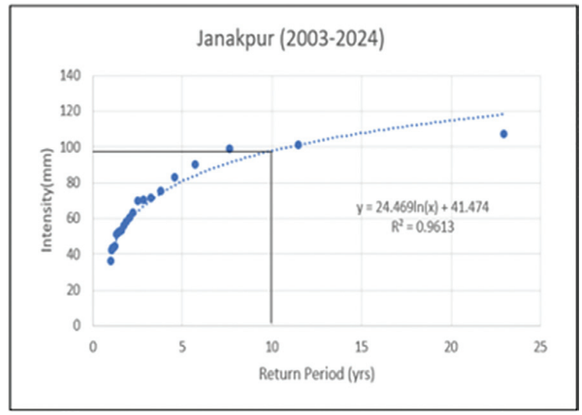
(e) Intensity-Return Period between 2003 - 2024 in Jomsom.



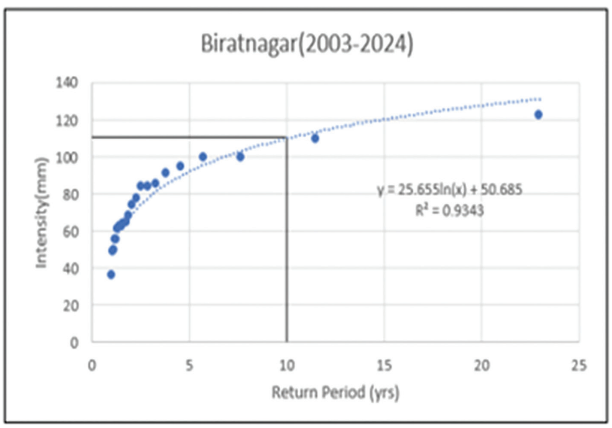
(f) Intensity-Return Period between 2003 - 2024 in Bharatpur.



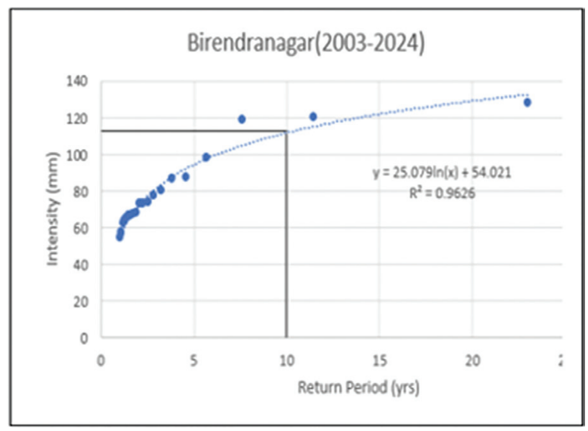
(g) Intensity-Return Period between 2003 - 2024 in Butwal.



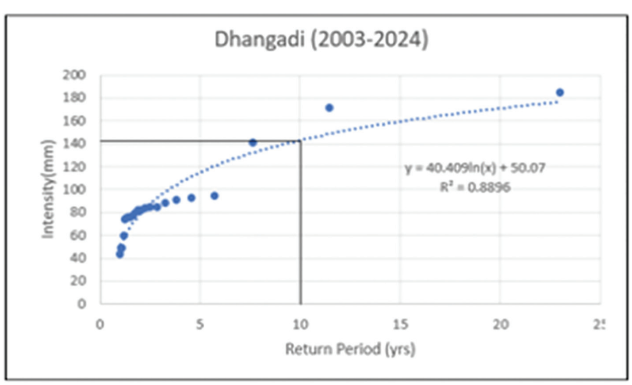
(h) Intensity-Return Period between 2003 - 2024 in Janakpur.



(i) Intensity-Return Period between 2003 - 2024 in Biratnagar.



(j) Intensity-Return Period between 2003 - 2024 in Birendranagar.



(k) Intensity-Return Period between 2003 - 2024 in Dhangadi.

Figure 3: Rainfall intensity and Return period at different periods from 2003 - 2024 at different major cities of Nepal.

The 10-year return period storm intensities for the contemporary period (2003–2024) were similarly estimated across all eleven cities. In Kathmandu (Figure 3.a), the relationship follows a linear trend y =

3.8349x + 42.89, yielding an increased intensity of 81.239 mm, while Pokhara (Figure 3.b) follows y = 24.083ln(x) + 51.219, giving a substantially higher 106.67 mm. Namche Bazaar (Figure 3.c) follows y = 2.8572x + 16.933, producing 45.505 mm, and Jumla (Figure 3.d) follows y = 22.087ln(x) + 24.775, yielding 75.632 mm, a notable rise from its baseline value. Jomsom (Figure 3.e), with y = 17.502ln(x) + 34.901, recorded 75.201 mm, reflecting one of the most dramatic increases among all cities studied. In the mid-hill and Terai cities, Bharatpur (Figure 3.f) follows y = 4.6877x + 49.418, giving 96.295 mm, and Butwal (Figure 3.g) follows y = 29.866ln(x) + 61.089, yielding 129.858 mm. Janakpur (Figure 3.h), with y = 24.469ln(x) + 41.474, recorded 97.816 mm, while Biratnagar (Figure 3.i) follows y = 25.655ln(x) + 50.685, giving 109.757 mm. Birendranagar (Figure 3.j) follows y = 25.079ln(x) + 54.021, yielding 111.767 mm, and Dhangadi (Figure 3.k), with y = 40.409ln(x) + 50.07, recorded the highest contemporary intensity among all cities at 143.115 mm, a striking increase that further underscores the accelerating rainfall trend observed across the Terai region.

3.2. Percentage Change in Extreme Rainfall Intensity

The percentage change in the 10-year return period rainfall intensity between the two periods was calculated to quantify the effect of climate variability.

Table 1: Percentage Change in 10-years return period rainfall intensity in different cities of Nepal.

Cities	% Change	Cities	% Change
Kathmandu	22.63	**Butwal**	22.16
Pokhara	92.83	**Janakpur**	-11.74
Namche Bazaar	1.08	**Biratnagar**	16.14
Jumla	50.25	**Birendranagar**	3.5
Jomsom	82.61	**Dhangadi**	47.07
Bharatpur	20.12		

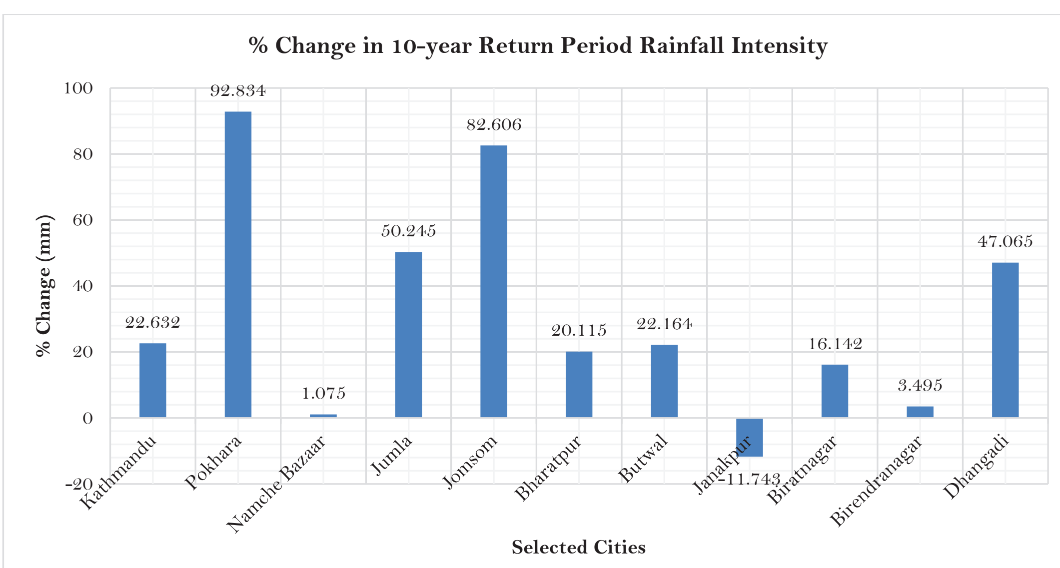


Figure 4: Comparative City-Wise Overview on percentage change in 10-year return period rainfall intensity of each period

3.3. Analysis Overview

3.3.1. City-wise Overview

City-wise analysis shows that the change in 10-year return period rainfall intensity varies significantly across different regions of Nepal. Pokhara recorded the highest increase, with a rise of 92.83%, indicating that the design storm intensity has nearly doubled from 55.32 mm to 106.67 mm. This reflects a strong intensification of extreme rainfall events in the hilly region. Similarly, the mountain stations of Jumla and Jomsom also showed large increases, 50.25% and 82.61% respectively, suggesting that high altitude areas are becoming more vulnerable to intense precipitation events.

In the terai region, Dhangadi experienced a notable increase of 47.07% in 10-year return period rainfall intensity. Bharatpur and Biratnagar showed moderate increases of 20.12% and 16.14%, respectively, indicating a rising trend in extreme rainfall, though less pronounced compared to hilly and mountainous regions. Kathmandu, 22.63% and Butwal 22.16% also exhibited increases greater than 22%, further supporting the overall increasing trend in extreme rainfall intensity across central and western parts of Nepal.

Janakpur was the only city that showed a decrease in 10-year return period rainfall intensity, with a reduction of 11.74%, highlighting the presence of regional variability in rainfall patterns. Additionally, Namche Bazaar,1.075% and Birendranagar,3.495%, showed very small changes ranging from about 1% to 3.5%, indicating relatively stable rainfall conditions in these locations compared to other cities analyzed in this study.

3.3.2 Regional Overview

A) Mountain Region (Jumla, Jomsom, and Namche Bazaar)

The mountain region shows a high level of change in extreme rainfall intensity, with an average increase of about 44.642% in the 10-year return period storm intensity. Among the mountain stations, Jomsom recorded very large increases of 82.606%, followed by Jumla at 50.245%, while Namche Bazaar showed only a small change, of only 1.075%. These results indicate that high altitude regions are highly sensitive to changing climatic conditions, even though the magnitude of change may vary from location to location. The increase in extreme rainfall intensity suggests a growing risk of flash floods, glacial lake outburst floods (GLOFs), and erosion processes in mountain areas. As a result, infrastructure in mountain towns, including roads, bridges, and drainage systems, may require climate-resilient design considerations.

B) Hilly Region (Kathmandu, Pokhara and Butwal)

The hilly region experienced an average increase of approximately 45.876% in 10-year return period rainfall intensity. Although Pokhara recorded a very high increase of 92.83%, which significantly influences the regional average, all selected hill stations showed an overall increasing trend. This indicates that extreme rainfall events are becoming more intense across the hilly regions of Nepal. The rising rainfall intensity increases the likelihood of landslides, urban flooding, and slope instability. Consequently, hill side settlements, road networks, urban drainage systems, and hydropower projects in these areas are expected to face greater hydrological risks in the future.

C) Terai Region (Biratnagar, Bharatpur, Dhangadi, Janakpur, and Birendranagar)

In the Terai region, the average increase in extreme rainfall intensity was about 15.015%, which is lower compared to the mountain and hilly regions. However, significant spatial variability was observed within the plains. Dhangadi showed a relatively high increase of 47.07%, whereas Janakpur recorded a decrease of 11.74% in the 10-year return period rainfall intensity. Biratnagar and Bharatpur showed moderate increases.

These results suggest that changes in extreme rainfall in the terai are more localized in nature. While some areas may experience reduced or stable rainfall intensity, others may face more intense storm events, indicating the need for improved flood management, river training works, and strengthened embankment systems in vulnerable locations.

The results of this study indicate that extreme rainfall characteristics in Nepal have changed noticeably over time, with most cities showing an increase in 10-year return period storm intensity in the recent period. The dominance of increasing trends in nine out of eleven cities suggests that extreme rainfall events are becoming more intense, which is consistent with the influence of climate change on precipitation patterns. Warmer atmospheric conditions can hold more moisture, leading to heavier rainfall events occurring over shorter durations, even if total annual rainfall does not increase significantly. The magnitude of change was found to vary considerably across different physiographic regions. Mountain and hilly regions generally exhibited larger increases in extreme rainfall intensity compared to the Terai region. Stations such as Pokhara, Jumla, and Jomsom showed very high increases, indicating that complex topography and orographic effects may be enhancing rainfall intensity in these areas. These findings align with previous studies conducted in Nepal, which have reported increasing rainfall extremes and higher climate sensitivity in mountainous regions.

In contrast, the Terai region showed relatively moderate changes, with noticeable spatial variability. While cities like Dhangadi experienced substantial increases, Janakpur showed a decrease in extreme rainfall intensity. This suggests that rainfall behavior in the plains is influenced by localized monsoon dynamics and regional atmospheric circulation patterns. Such variability highlights the limitation of applying uniform rainfall design values across different regions of Nepal. The results also provide clear evidence of climate non-stationarity. Traditional hydrological design practices assume that rainfall statistics remain constant over time; however, the observed changes in design storm intensities indicate that this assumption may no longer be valid. If design standards are not updated to reflect current rainfall behavior, infrastructure may face increased risks of failure during extreme events.

4. Conclusions

The analysis of annual maximum daily rainfall across major cities of Nepal reveals a clear and concerning shift in extreme rainfall characteristics between the two study periods. Nine out of eleven cities recorded higher 10-year return period storm intensities in the recent period, confirming that the long-held assumption of climatic stationarity is no longer valid. Mountain and hilly regions, particularly Pokhara and Jomsom, experienced the most dramatic increases, exceeding 80%, while the Terai region showed more moderate but spatially variable changes, with cities like Dhangadi recording significant rises and Janakpur showing a decline. This regional variability underscores that climate change impacts are far from uniform across Nepal. The methodology employed, combining Weibull plotting positions with logarithmic trendlines, proved reliable in quantifying these shifts and deriving updated design storm intensities fit for a changing climate.

The practical implications of these findings are both urgent and far-reaching. Existing engineering standards, hydrological design manuals, and infrastructure built on stationary climate assumptions now carry an elevated risk of underperformance, particularly in mountainous regions where intensifying rainfall has sharply raised the threat of floods and landslides. Existing flood protection structures and drainage systems warrant immediate reassessment, with priority given to retrofitting or upgrading wherever vulnerabilities are identified. In the Terai, localized flood management strategies including river training, embankment strengthening, and improved urban drainage remain essential. Looking ahead, future research should expand observation networks, incorporate shorter-duration rainfall data, and adopt non-stationary frequency analysis methods to build a more complete and accurate picture of Nepal's evolving rainfall behavior. Climate-resilient design is no longer optional; it is a necessity.

References

(IPCC), I. P. (2023). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P. S., . . . Feyen, L. (2017). Global Projections of River Flood risk in a Warmer World. *Earth's Future* , 171-182.

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, 2247-2260.

Bade, B., Gyawali, D. R., & and Timilsina, S. (2019). Assessing The Impacts Of Climate Change On The Hydrology Of The Indrawati River Basin, Nepal. *ISPRS ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences.*

Bhattarai, N., O'Connor, B., Tang, G., & Marahatta, S. (2023). Impact of climate change on flood hazards in the Karnali River Basin, Nepal. *Journal of Hydrology: Regional Studeis* .

Bista, R. B. (2019). Trend and Forecasting Analysis on Climate Variability: A Case of Nepal. *Journal of Advanced Research in Civil and Environmental Engineering*, 1-10.

Dodman, D., Hayward, B., Pelling, M., Castan Broto, V., Chow, W., Chu, E., . . . Ziervogel, G. (2022). *Cities, settlements and key infrastructure. In Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Intergovernmental Panel on Climate Change. (2022). Summary for policymakers. In H.-O. Pörtner, D. C. (2022). *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Karki Ramchandra, T. R. (2016a). New Climatic Classification of Nepal. *Theoretical and Applied Climatology*, 799-808.

Karki, R., Hasson, S. u., Gerlitz, L., Talchabhadel, R., Schenk, E., Schickhoff, U., . . . Böhner, J. (2016b). WRF-based simulation of an extreme precipitation event over the Central Himalayas: Atmospheric mechanisms and their representation by microphysics parameterization schemes. *Atmospheric Journal, Volume-182*, 183-204.

Liang, L. (2024), Climate change amplified the effects of extreme rainfall in Nepal, Eos, 105, https://doi.org/10.1029/2024EO240582. Published on 18 December 2024. *EOS.*

NASA. (2025, 12 4). Retrieved from NASA POWER | Data Access Viewer (DAV): https://power.larc.nasa.gov/data-access-viewer/

Nicholas Stern, C. O.-H. (2007). *The Economics of Climate Change: The Stern Review.* Cambridge, UK ; New York: Cambridge University Press.

Park, S., & Western, A. W. (2026). 'Climate Change Paradox: Worsening Droughts amidst Increasing Average Precipitation across South Korea'. *Journal of Hydrology.*

Prajapati, R., Talchabhadel, R., Silwal, P., Upadhyay, S., Ertis, B., Thapa, B. R., & Davids, J. C. (2021).). Less rain and rainy days—lessons from 45 years of rainfall data (1971 to 2015) in the Kathmandu Valley, Nepal . *Research Square* .

Shah, S., Liu, Y., Kim, S., Sharma, A., & Fischer, S. (2026). Shifting Mountain Flood Regimes under Global Warming. *EGU Gernal Assembly-2025.*

Shrestha, D. &. (2023). Rainfall extremes under future climate change with implications for urban flood risk in Kathmandu, Nepal. *International Journal of Disaster Risk Reduction.*

Shrestha, R. M., & Sthapit, A. B. (2015). Temporal variation of rainfall in the Bagmati River Basin, Nepal. *Nepal Journal of Science of Technology* , 31-40.

Talchabhadel, R., Karki, R., Thapa, B. R., Maharjan, M., & Parajuli, B. (2018). Spatio-temporal variability of extreme precipitation in Nepal. *International Journal of Climatology* , 4296-4331.

Thapa, B. R., Ishidaira, H., Pandey, V. P., & Shakya, N. M. (2017). A multi-model approach for analyzing water balance dynamics in Kathmandu Valley, Nepal. *Journal of Hydrology: Regional Studies*, 149-162.

Tuladhar, D., Dewan, A., Kuhn, M., & Corner, R. J. (2020). Spatio-temporal rainfall variability in the Himalayan mountain catchment of the Bagmati River in Nepal. . *Theoretical and Applied Climatology* , 599-614.

Zhan, Y. &.-Y. (2017). Changes in extreme precipitation events over the Hindu Kush Himalayan region during 1961–2012. *Advances in Climate Change Research.*