Exploring Rainfall Patterns in Diverse Nepalese Regions and Implications: A spatial and Temporal Analysis

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ABSTRACT

This article explores rainfall patterns in diverse Nepalese regions and presents a comprehensive provincial analysis of the spatial and temporal distribution of monsoon rainfall in Nepal during 2021 to 2023. The variation in topography, distinct landscape, and climatic diversity of Nepal significantly influences monsoon rainfall and its rainfall patterns, which are shaped by the completely interactive nature of geographical and meteorological factors. Utilizing data from 47 rainfall stations this study aims to investigate provincial rainfall variability and intensities to assess disaster risks. Present work reflects the spatial distribution of rainfall by showing provincial disparities and we observed that central provinces such as Gandaki received the highest amount of rainfall i.e. near about 2000 mm in monsoon season and exceeding 3000 mm annually in 2021. Meanwhile, western provinces, such as Karnali, experience significantly records the lowest rainfall dropping below 1000 mm in 2023. Altogether the amount of rainfall recorded spatially is declining each year in every province. Similarly, this study highlights the recent temporal distribution of rainfall by comparing the total rainfall of the monsoon season during study period. The analysis reveals that July emerges as the peak month for rainfall in the years 2021, and 2023. However, August also contributes to some provinces. Though the total rainfall fluctuates seasonally, June also shows the highest rainfall in the year 2022 except in Lumbini and Sudurpashchim due to broader climatic variations. We have also analyzed rainfall intensity and found an increase in extreme rainfall events, especially in Gandaki and Bagmati provinces, which poses risks of flood and landslides. Additionally, the increasing number of light rainfall days suggest potential drought conditions in provinces like Karnali and Madhesh. Provincial rainfall analysis provides a crucial insight for disaster risk management, agricultural planning, and water resource management in current socio-economic scenario of Nepal.

Keywords: Monsoon rainfall, Spatial and Temporal variability, Categorization of Rainfall, Climate change

1. Introduction

Rainfall is a crucial constituent in the present-day of climatic and cryospheric studies in present climate change scenario. It plays a vital role in running the water cycle, maintaining water balance which alters the regional and global climate, and determining most of the environmental changes throughout the world(Sharma, Khadka, Hamal, Shrestha, et al., 2020).The spatial and temporal patterns of rainfall frequency can have a significant effect both regionally and globally(Sharma, Khadka, Hamal, Baniya, et al., 2020). Rainfall is a hydrological process by which groundwater recharges, and it is mainly influenced by the spatial distribution of rainfall in Nepal. Higher groundwater extraction rates and surface sealing limited groundwater recharge and the areas with highly porous but less permeable soil show greater fluctuations in groundwater (Prajapati et al., 2021).

Nepal, a landlocked country that lies on the southern edge of the Tibetan plateau experiences approximately 80% of the total annual rainfall between June and September under the influence of the summer monsoon season (Shrestha, 2000). Rainfall analysis shows that southern Nepal experiences heavier rainfall during the summer monsoon which is an important factor for the success of local farming from the agricultural point of view.

Climate change is a crisis that will shift rainfall and contribute to challenges like water scarcity, transportation issues, food insecurity, health risks, economic losses, and damage to ecosystems (Tarmizi et al., 2019). It is a real threat to life on Earth, impacting vital areas such as water resources, agriculture, coastal regions, freshwater habitats, and geological processes such as landslides, desertification and floods and long-term effects on food security as well as human health (Bajracharya et al., 2023).

Exploring rainfall patterns in diverse Nepalese regions both spatially and temporally is crucial due to the country's complex topographic and climate systems. Nepal's geography ranges from the high Himalayan mountains to the flat plains of the Terai which creates contrast differences in rainfall distribution. This diversification when combined with the growing impact of climate change, leads to erratic rainfall patterns which makes it crucial to understand these changes. These patterns not only impact but also increase the risk of floods and landslides.

The rationale behind this study is based on the increasing frequency of extreme weather events caused by changing rainfall patterns. Our country Nepal has to face floods and landslides every year and many people lost their lives. For instance, two passenger buses were swept away in Trishuli due to landslides on

July 12, 2024, Floods in the Melamchi and Indrawati rivers two years ago displaced more than 500 families in 2023, and so on. Likewise, many accidents take place every year which affects both the social and economic health of our country. Existing previous studies on rainfall patterns in Nepal, Shrestha et al. (2000), and Prajapati et al. (2021) have mainly focused on long-terms averages and utilize satellite-based precipitation data. Similarly, Sharma et al. (2020) assess the accuracy of two satellite-based precipitation products i.e. TRMM and IMERG between 2001 to 2018. While all the studies provide valuable insights, they lack detailed breakdown at provincial level analysis using manual gauge precipitation data. Moreover, limited research, especially post 2020 across province and absence of rainfall intensity categorization are found. Our study is among the first to conduct comparative province wise analysis using ground-based station data (2021-2023) from 47 DHM stations and introduce a categorization of rainfall intensity offering insights into the frequency of extreme events such as floods, landslides and so on. Previous studies (Khadgarai S., Yatagai, A., & Masuda, M. 2019, Nepal B. et al., 2021) mainly focused on the satellite-based data such as APHRODITE, IMERG and TRMMM and comparative studies of it and lack detailed breakdown of provincial analysis using ground truth. So, the recent three years data analysis is very useful to understand the provincial pattern.

This comprehensive understanding of rainfall patterns not only contributes to scientific research but also informs policy formulation, guiding investments in climate resilience and sustainable development.

The specific objectives of the present study are:

- To explore and analyze the spatial and temporal trends of rainfall across seven provinces of Nepal over the past three years 2021, 2022, and 2023 focusing on monsoon season variability in rainfall amounts using ground-based rainfall data.
- To categorize rainfall intensity levels and assess disaster risk implications.

2. Data and Method

2.1 Study Area

For the study of rainfall patterns in Nepal, the entire country has been selected as the focus area of Nepal. Nepal extends between latitudes 26º22´N and 30º27´N and longitudes 80º40´E and 30º27´E with a total area of 1,47,516 square kilometers which is shown in (Figure 1). The study area is subjected to the influences of the South Asian Summer Monsoon (SASM) and westerly winds which dominate the seasonal variability with maximum rainfall during the

summer monsoon seasons. The SASM contributes approximately 80% of the annual rainfall, with varying rainfall patterns significantly between different provinces. The rest of the rainfall spread across the pre-monsoon and post-monsoon. The blue dotted points are the location of stations of the study area that we had chosen in our research which are shown in Figure 1 given below:

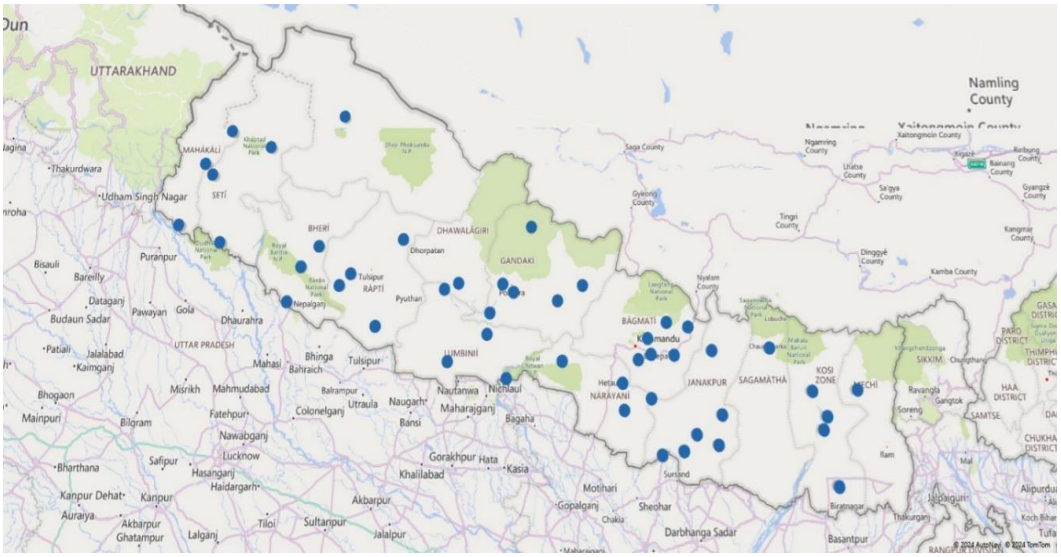


Figure 1: Study Area, Nepal.

2.2 Data and Sources

The daily gauge observed precipitation data of 47 manual gauging stations from 2021 to 2023 were obtained from the Department of Hydrology and Meteorology (DHM), Nepal (www.dhm.gov.np) accessed on 1 April 2024. These manual stations report past 24-hour rainfall accumulated at every 0300UTC, making the end of the observation day (EOD). In the present study 47 ground-based rain gauge station data is used. Province-wise station distribution are as follows.

Table 1: Province-wise station distribution:

Province	**No. of Stations**
Koshi	6
Madhesh	5
Bagmati	11
Gandaki	8
Lumbini	8
Karnali	3
Sudurpaschim	6
Total	47

The primary criteria for the selection of stations for seven provinces were:

1. Geographical Distribution: Stations were selected to make sure complete spatial coverage across all seven provinces featuring various topographical features (Terai, Hilly, and Mountain regions).
2. Data Availability: The stations with consistent daily (24 hour) precipitation data available from 2021 to 2023 were only included.
3. Operational Reliability: Preference was given to manual gauge stations that are operated and maintained by the Department of Hydrology and Meteorology (DHM), Nepal.

2.3 Methodology

The methodology is precisely designed to explore analysis in hydrological and meteorological, rainfall patterns and have been used to identify whether a change in the patterns significantly decreases or increases with space or time. Data preprocessing involved identifying missing values, which are marked as "NaN" to ensure integrity instead of filling the gap. Basic quality checks ensured data consistency and outlier detection are performed. Then data was processed for statistical analysis, focusing on calculating key standards such as monthly calculation of the total rainfall per station and standard deviation per station of monsoon season (June to September). Then we imported the data into the origin for a more sophisticated visualization including error bars to depict variability. To intensify the clarity of data representation, we showed standard deviation as error bars, providing a visual indicator of the variability around the total rainfall values.

Further, Rainfall intensity was categorized into five groups based on DHM thresholds limit. The intensity of rainfall plays vital role in hydrological and meteorological study.

Table 2: Categorization of Rainfall

Category of Rainfall	**Rainfall Intensity of 24hr (mm)**
Light rain	≤2.5
Moderate rain	2.6-7.5
Moderately heavy rain	7.6-50
Heavy rain	50.1-100
Extreme rain	>100

3. Results and Discussion

3.1 Categorization of Rainfall

By examining all the stacked columns of all provinces by comparing it to the different years, the data reveals an increase in extreme rainfall events across the past three years, especially in 2023. Analysis indicates increasing extreme rainfall events, particularly in Gandaki, Bagmati, and Koshi provinces. These shifts increase the risk of floods and landslides and waterlogging particularly in the Terai region. Light rainfall days are also rising, notably in Madhesh and Karnali provinces, suggesting high lightened risks of both floods and droughts which gives signals of water scarcity and challenges for agriculture in upcoming days. Provincial distribution of different categories of rainfall over the three years is shown in Figure (2-8).

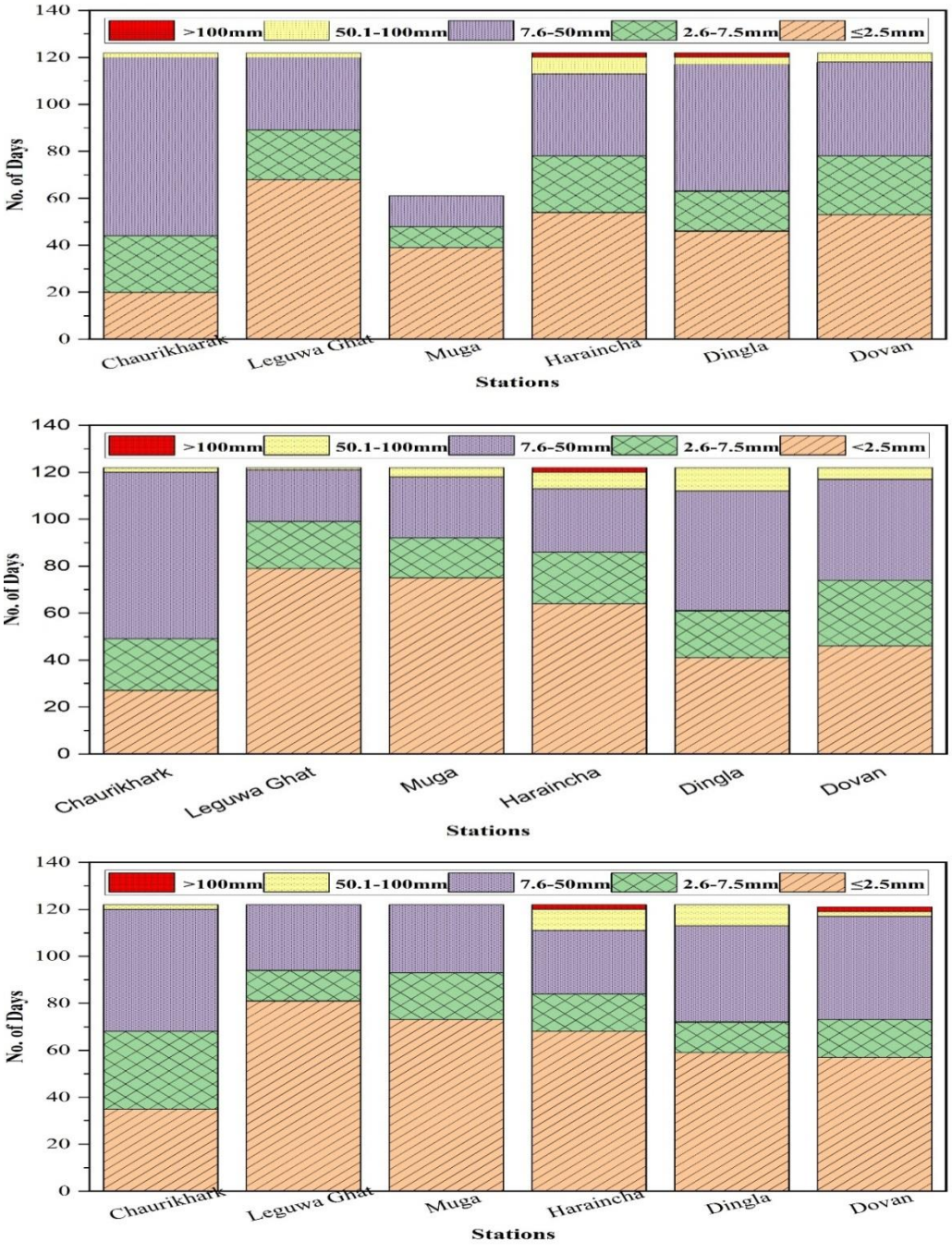


Figure 2: Categorization of Rainfall of Koshi province stations for the year 2021**,** 2022, and 2023 (Up to Down).

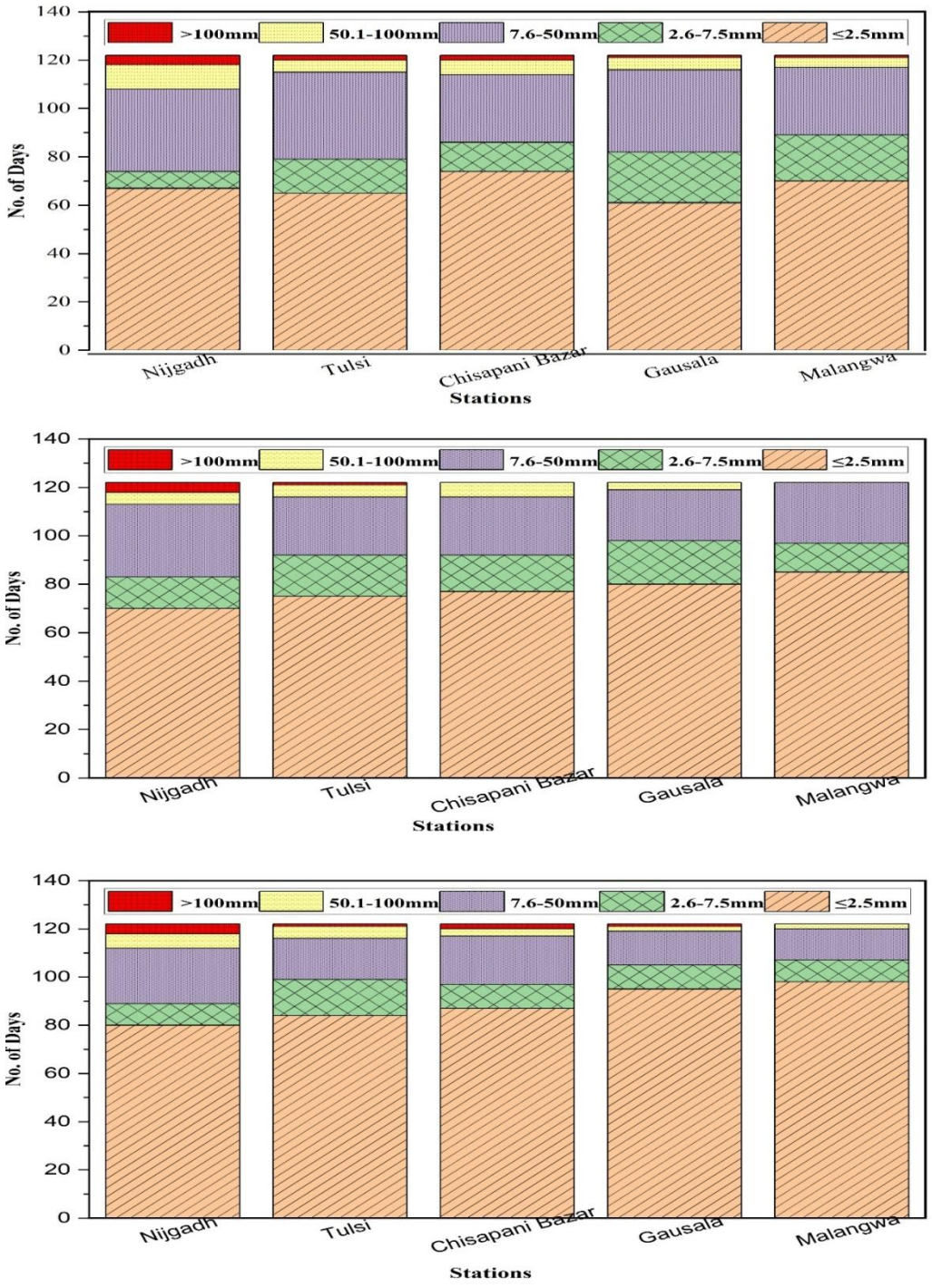


Figure 3: Categorization of Rainfall of Madhesh province Stations for the years 2021, 2022, and 2023 (Up to Down).

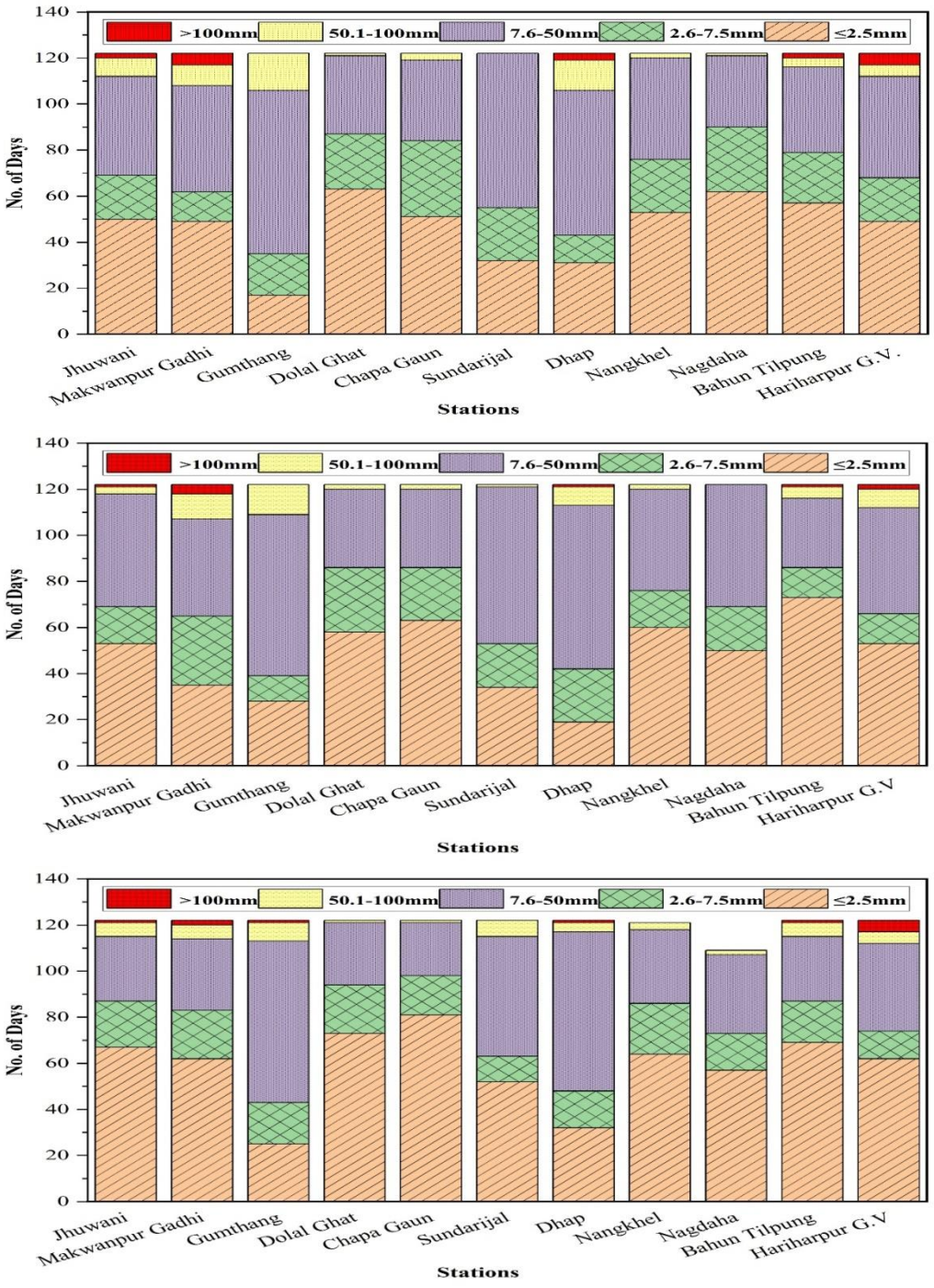


Figure 4: Categorization of Rainfall of Bagmati province Stations for the years 2021, 2022, and 2023 (Up to Down).

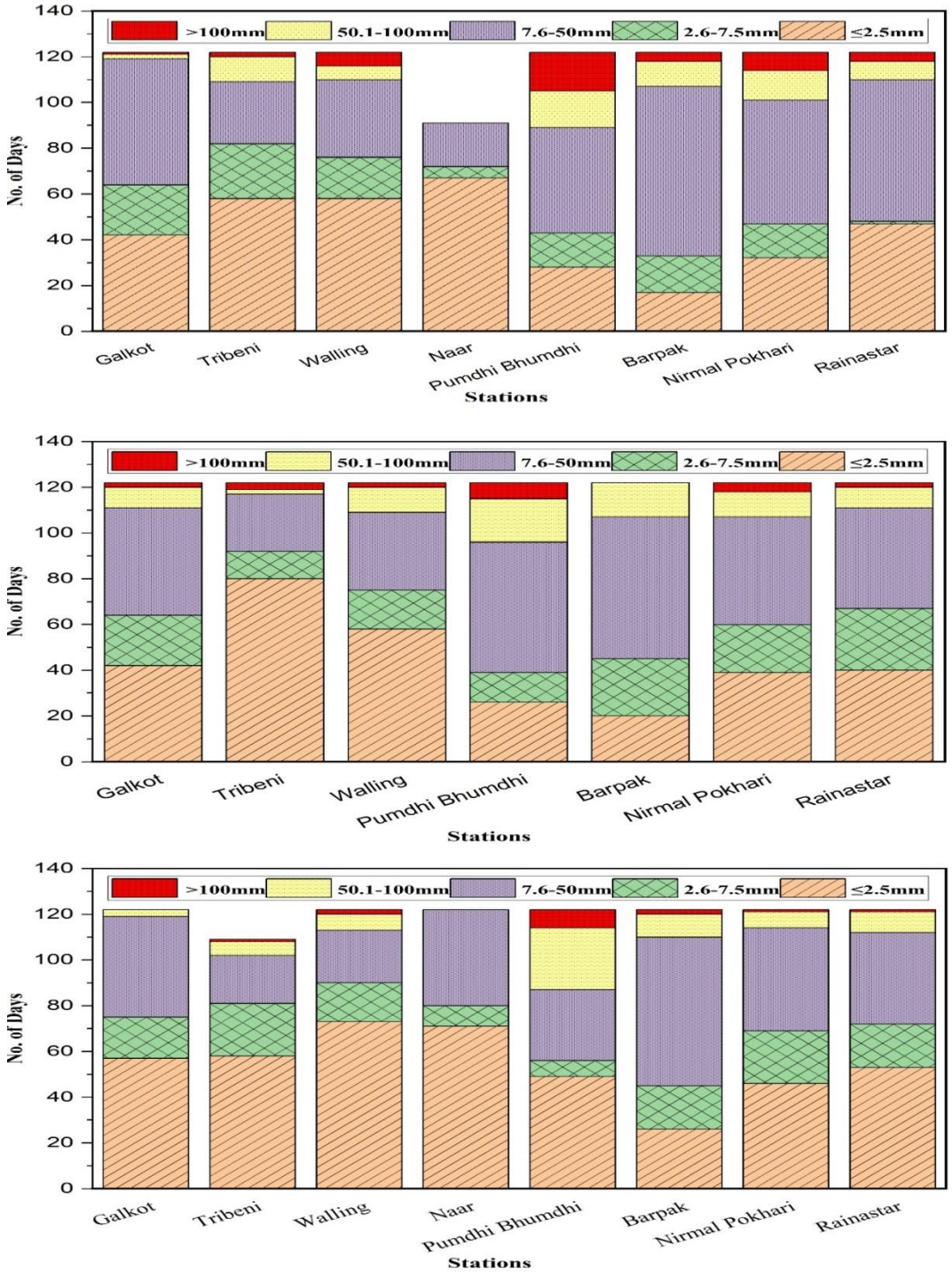


Figure 5: Categorization of Rainfall of Gandaki province Stations for the years 2021, 2022, and 2023 (Up to Down).

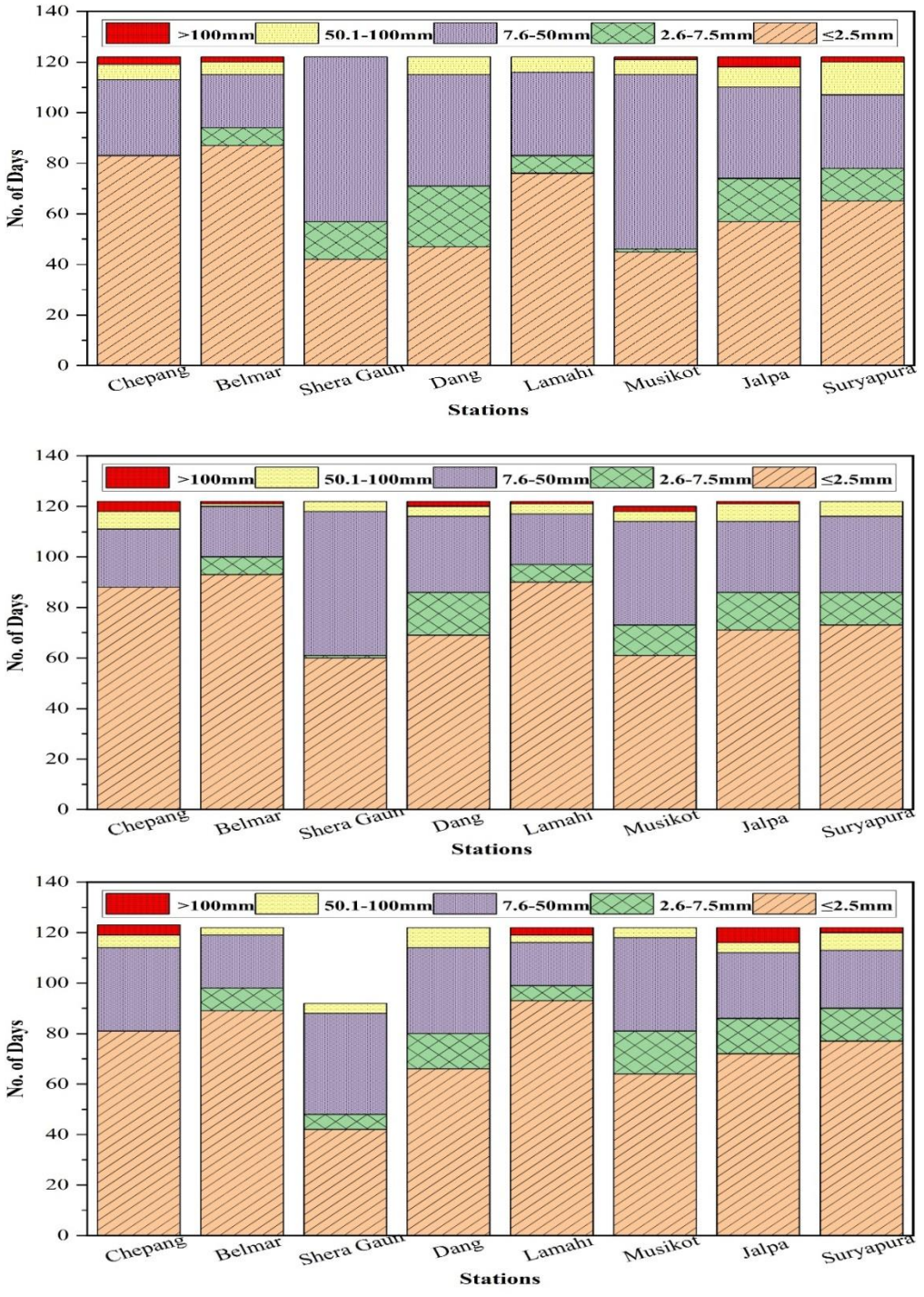


Figure 6: Categorization of Rainfall of Lumbini province Stations for the years 2021, 2022, and 2023 (Up to Down).

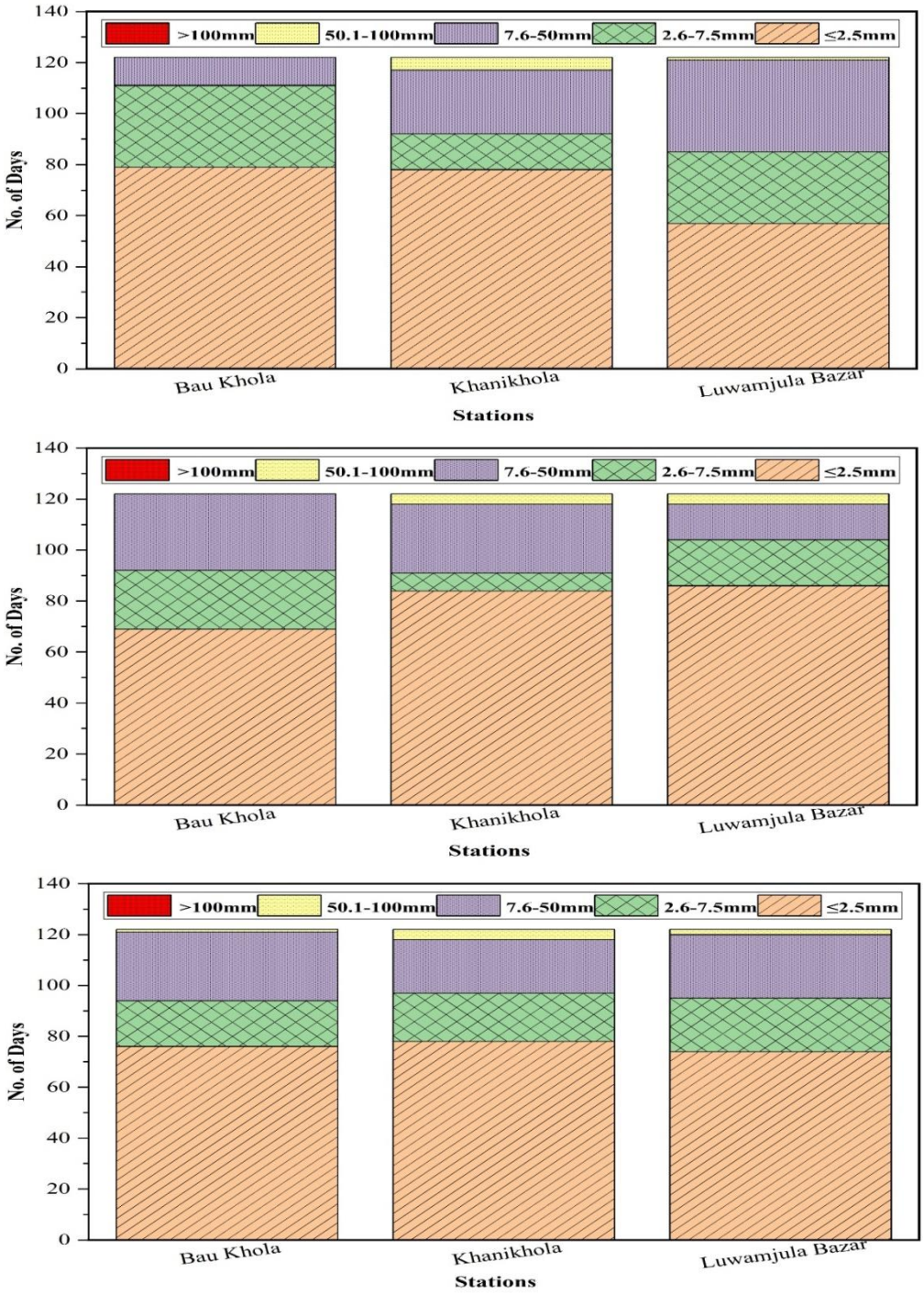


Figure 7: Categorization of Rainfall of Karnali province Stations for the years 2021, 2022, and 2023 (Up to Down).

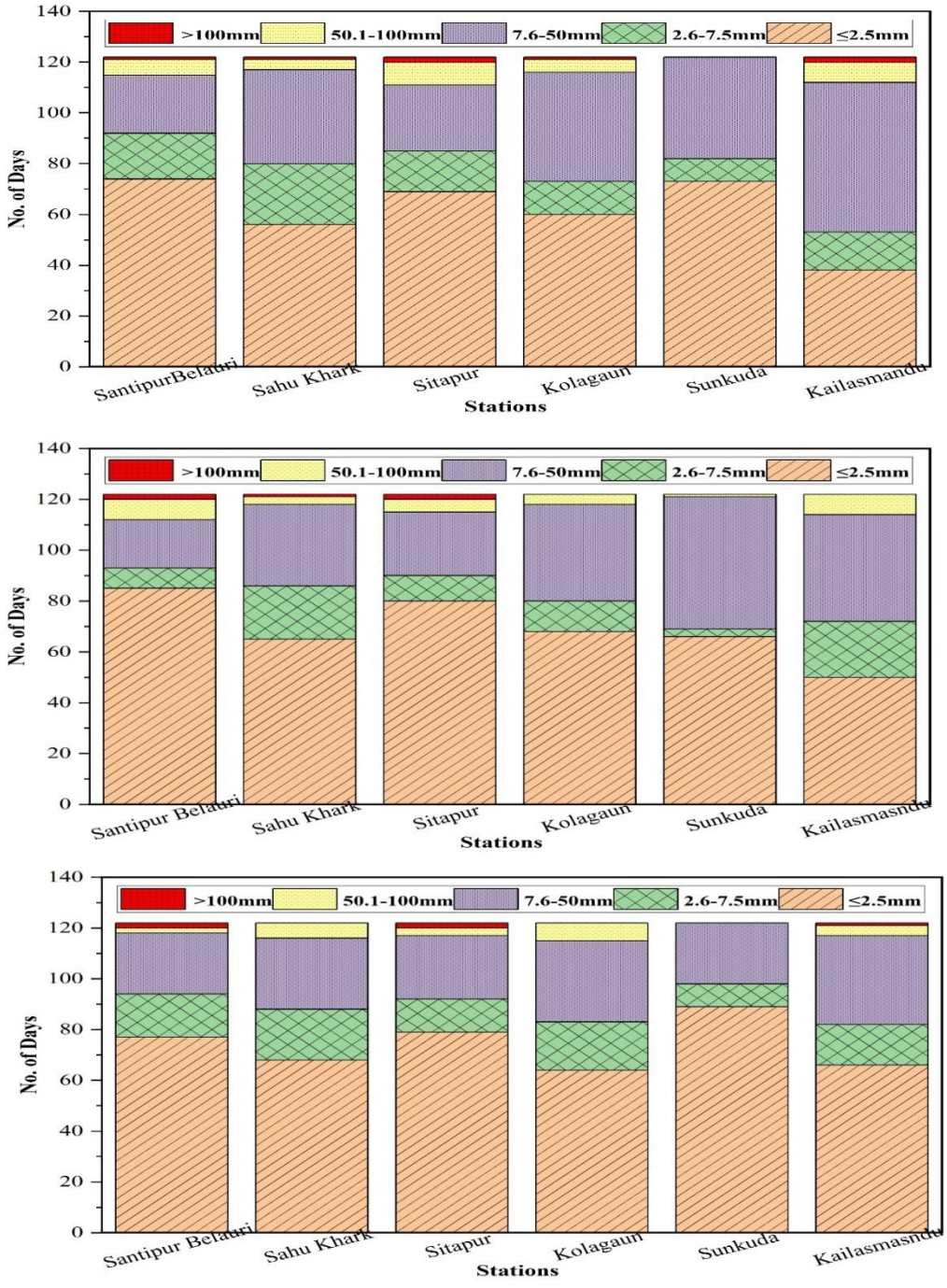


Figure 8: Categorization of Rainfall of Sudurpaschim province Stations for the years 2021, 2022, and 2023 (Up to Down).

3.2 Temporal Variability

The temporal analysis across the different provinces reveals that the monsoon season in Nepal exhibits considerable fluctuations in both the timing and amount of rainfall. A common pattern is observed in many provinces, where July consistently dominated especially in Koshi, Madhesh, Bagmati, Gandaki, and Sudurpashchim provinces in the years 2021 and 2023, somehow August also received highest rainfall in few provinces. But June received the highest rainfall in all provinces except Lumbini and Sudurpashchim in the year 2022. However, the intensity and distribution of rainfall during this peak month of peak rainfall vary significantly from year to year.

These observed decrements in total rainfall over the years, especially the lower total observed in 2023 compared to 2021, indicate a drying trend or cessation of rainfall and increase the variability in the pattern of the monsoon season. The error bar in graphs also indicates the variability and uncertainty which emphasize the complex and unpredictable nature of the monsoon necessities for adaptive strategies and planning. Temporal analysis (monthly) for seven provinces of Nepal for the three years is shown in Figure (9-15).

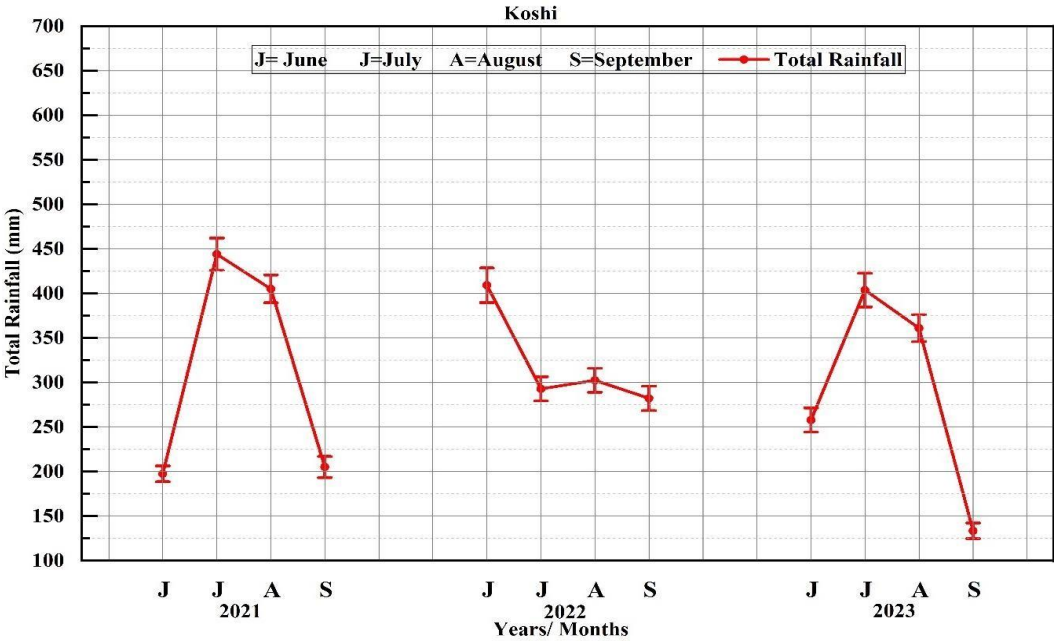


Figure 9: Temporal Distribution of Monsoon Season Rainfall Over Koshi Province

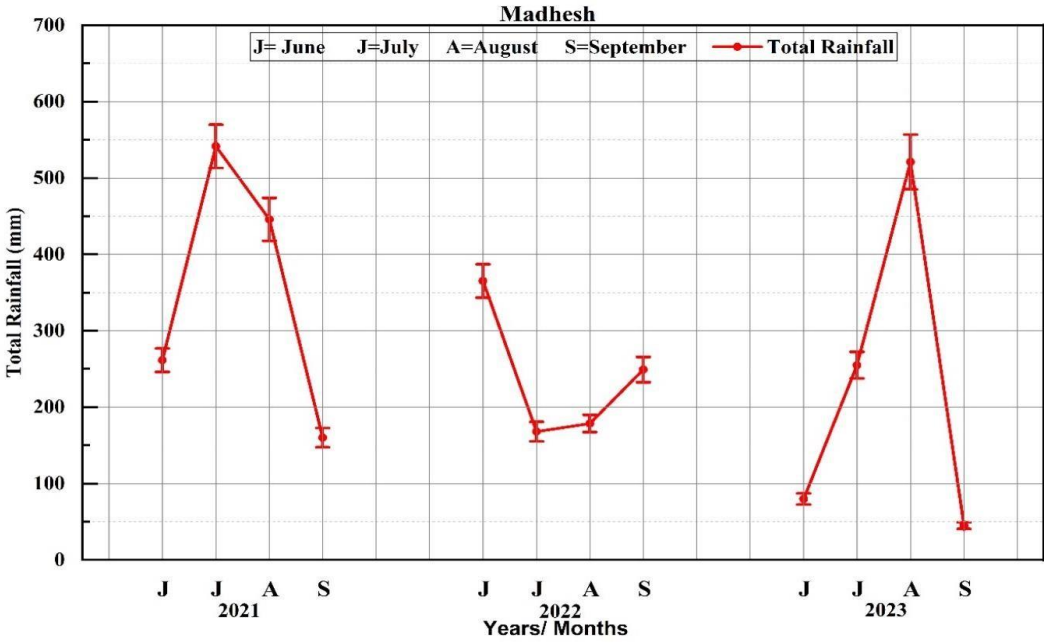


Figure 10: Temporal Distribution of Monsoon Season Rainfall Over Madhesh Province

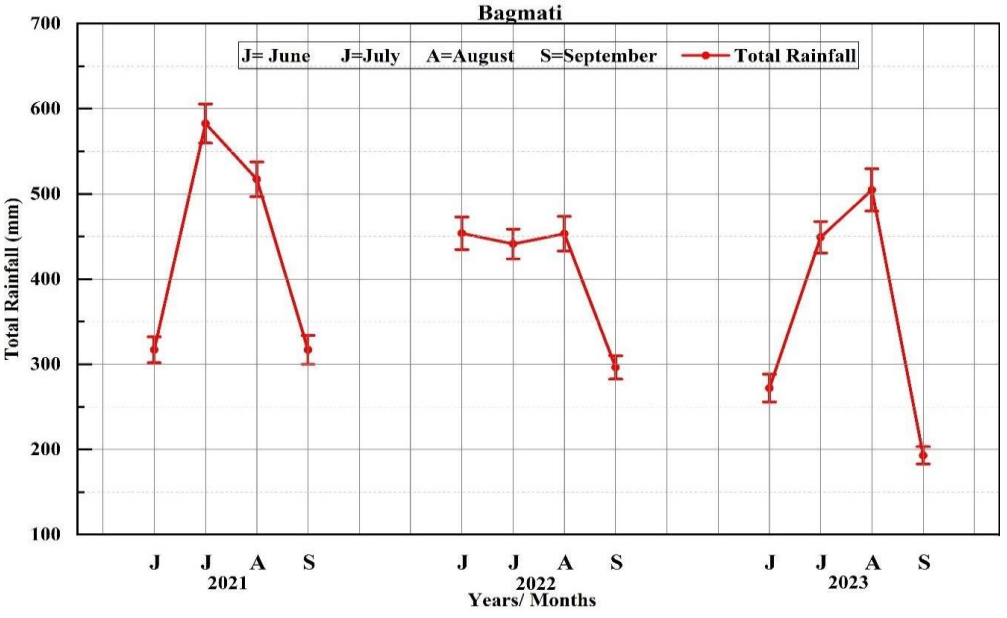
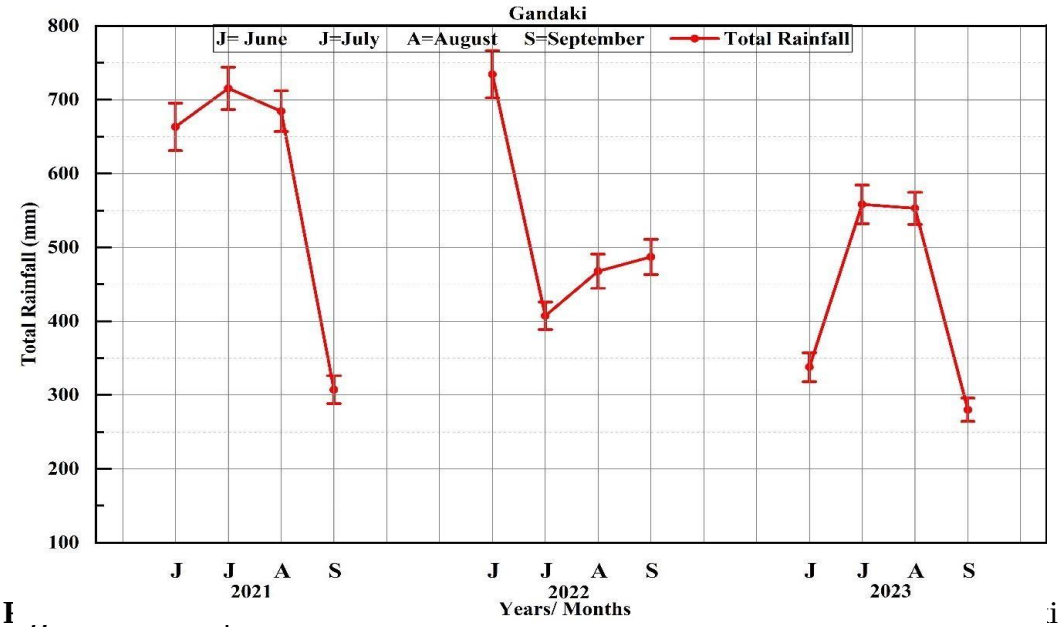


Figure 11: Temporal Distribution of Monsoon season Rainfall Over Bagmati Province



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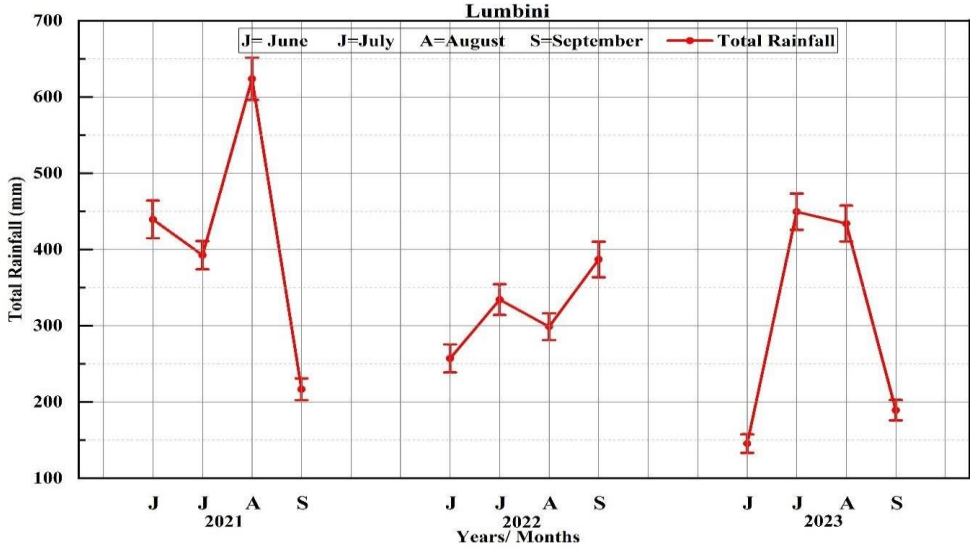

Figure 13: Temporal Distribution of Monsoon Season Rainfall Over Lumbini Province

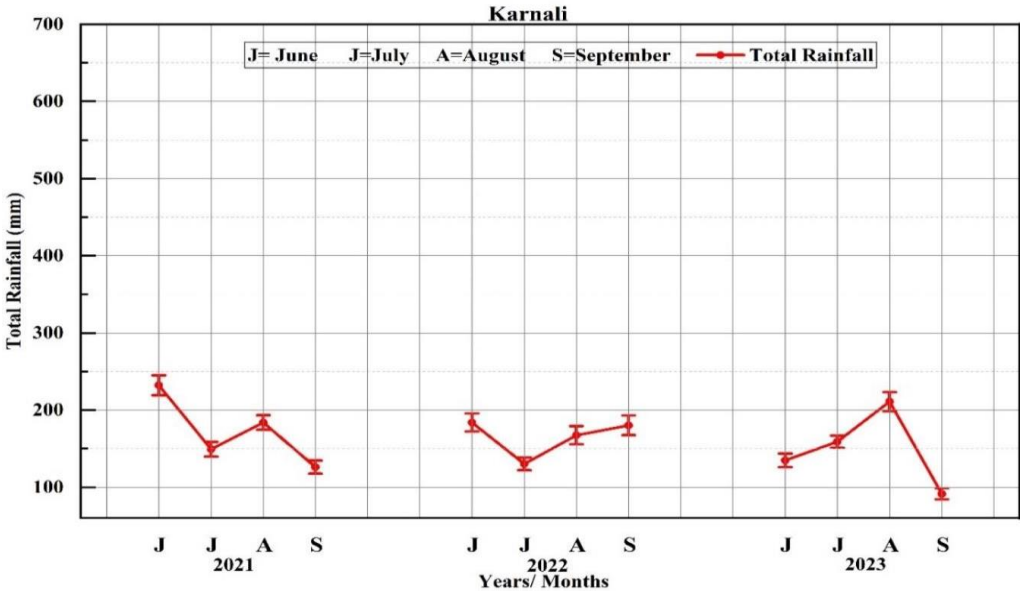

Figure 14: Temporal Distribution of Monsoon Season Rainfall Over Karnali Province

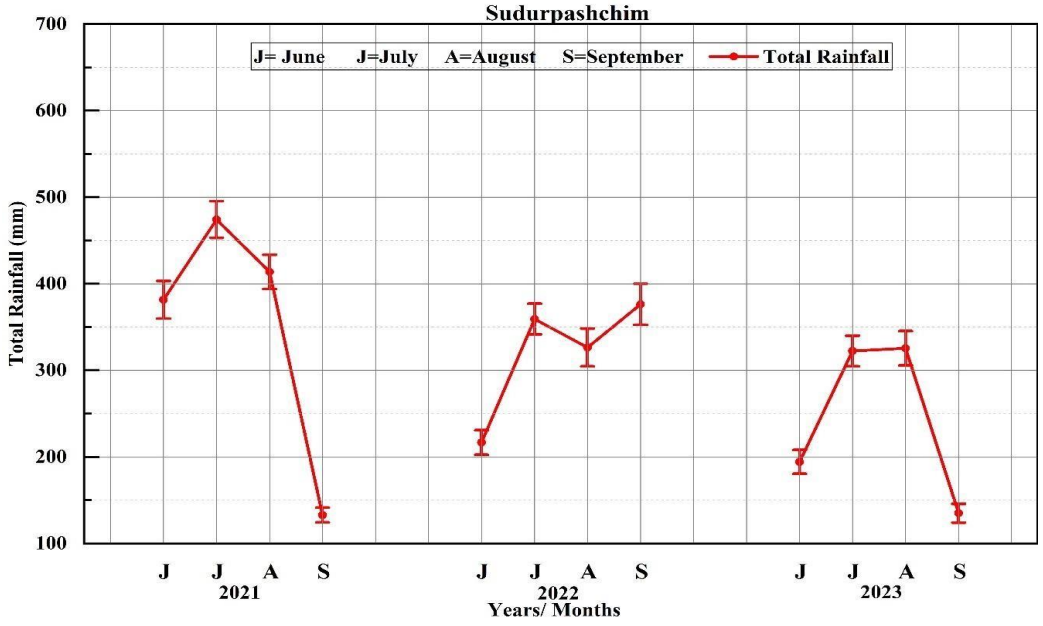

Figure 15: Temporal Distribution of Monsoon Season Rainfall Over Sudurpashchim Province.

It is found that in the year 2021, The monsoon onset and retreat were relatively normal with the historical average pattern. Due to favorable monsoon conditions and orographic features provinces like Gandaki, Bagmati, and Koshi received higher total rainfall compared to other regions. Likewise, Karnali recorded the lowest one. July emerged as several instances of heavy and extreme rainfall days, especially in Gandaki province. In 2022**,** an irregular pattern was observed. June recorded the highest rainfall in several provinces deviating from typical July peak whereas, September reflected in Lumbini and Sudurpashchim provinces. Again, Karnali province experienced long dry spells and Gandaki followed by intense rainfall days, reflecting increasing climate variability. Rainfall pattern in 2023 shows a noticeable year to year fluctuation. Extreme rainfall days increased significantly in central provinces such as Bagmati and Gandaki while Western provinces such as Karnali and sudurpashchim recorded comparatively lower rainfall. As well as light rainfall days were unusually frequent in provinces like Madhesh and Karnali, indicating a potential shift which causes drought in upcoming time series.

3.3 Spatial Variability

Spatially, the monsoon rainfall shows marked differences across the provinces. Gandaki Province consistently recorded the highest rainfall among all provinces (i.e. >3000 mm annually), especially in 2021. In contrast, Karnali province consistently received the least rainfall (i.e.<1000mm annually), particularly in 2023. This spatial disparity highlights the diverse and non-homogenous nature of the monsoon system in Nepal.

The sharp decline in rainfall from Gandaki to Karnali, followed by a slight recovery in Sudurpashchim, indicates a complex interaction between geographic factors and monsoon dynamics. From this analysis, we can point out that, the provinces in the central region of Nepal, especially, Gandaki and Bagmati generally receive more rainfall, possibly due to the orographic effect, while the provinces in the western region are drier and the provinces in the eastern region receive the near sufficient amount of rainfall which helps in cultivation of seasonal crops.

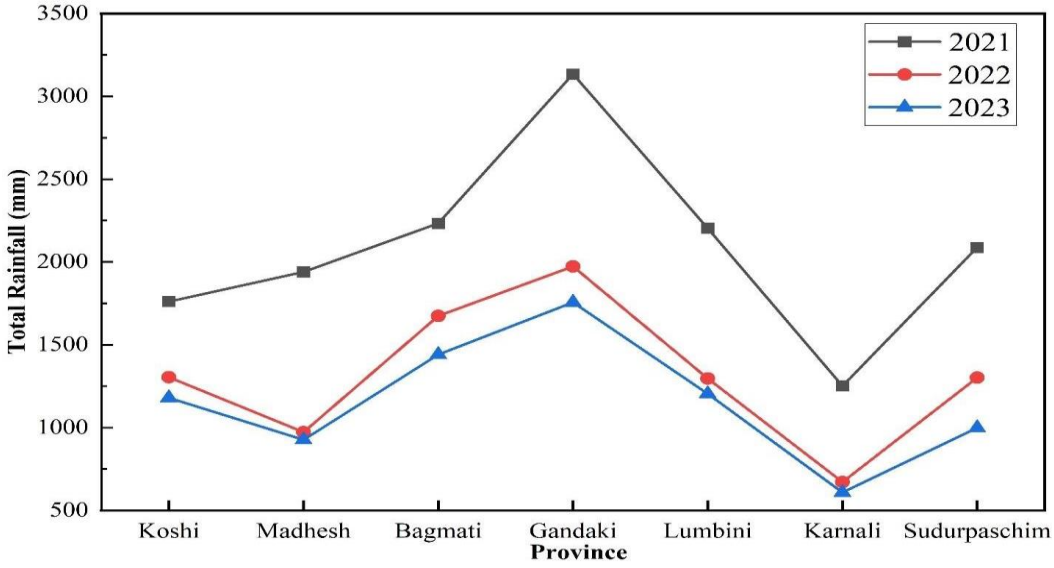

Figure 16: Spatial Distribution of monsoon season rainfall of the year 2021, 2022, and 2023.

The average monsoon rainfall (June to September) for the 7 provinces of Nepal during the study was tabulated below. These values have been calculated based on the daily station data obtained from the DHM.

Table 3. Total monsoon rainfall (Based on station taken in in present study)

	Rainfall/mm		
Province/Year	2021	2022	2023
Koshi	1279	1304	1180
Madhesh	1441	972	926
Bagmati	1770	1674	1441
Gandaki	2412	1973	1756
Lumbini	1706	1296	1247
Karnali	702	671	608
Sudurpashchim	1431	1301	998

3.4 Policy Management and Implications:

The above rainfall patterns from the analysis emphasize the need for adaptive and flexible water management plans and strategies that can defend or face the increasing variability and unpredictability of the monsoon. Central provinces need infrastructure to mitigate excess rainfall, while western provinces must prioritize water conservation. Policymakers must be focused on the predictive modelling and integrated station-satellite data which can enhance future planning.

Moreover, the year-to-year fluctuations suggest that relying solely on past data averages for planning may no longer be sufficient and effective. Addressing these challenges will require a combination of advanced predictive modeling, and infrastructure development that can respond to the increasingly erratic nature of the monsoon.

4. Conclusions and Discussion

4.1 Conclusion

Based on the analysis of the rainfall patterns conducted in this research, we have widely examined the spatial and temporal distribution of monsoon season rainfall across various provinces of Nepal over the years 2021, 2022, and 2023. Spatial analysis indicates that Gandaki province consistently experienced the peak rainfall (i.e.>2000mm in monsoon season) every year and >3000mm annually in 2021, while the province like Karnali recorded the lowest rainfall (i.e. <1000mm every year in 2021, 2022, and 2023) exploring the diverse rainfall patterns within Nepal.

Temporal analysis indicates that July is typically the peak month of rainfall in 2021 and 2023 except in few provinces in which August received the highest one. While, June dominated in 2022 (except in Lumbini and Sudurpashchim where September received most rainfall) reflecting the complex dynamics of monsoon behavior. Moreover, the study underscores the potential impacts of broader climatic changes, as evidenced by the irregular variability and unpredictable rainfall patterns observed in the three years.

Rainfall categorization analysis indicates that the extreme rainfall events increased in Koshi, Bagmati and Gandaki province suggesting risks of flood, landslides and so on. On the other side Light rainfall days noticeably increasing in Madhesh and Karnali provinces highlighting the risk of drought. So, that, there is a high possibility of facing flood, landslides, and drought in the same year in different part of country These studies help in adaptive water resources management strategies to overcome the impacts of such variable patterns on agriculture, disaster preparedness, and overall socio-economic stability in Nepal.

4.2 Discussion

This article is unique in its approach to examining rainfall patterns utilizing a combination of spatial and temporal ground-based rainfall data from various provinces over a three-years span. This approach allows for a more in-depth and detailed understanding of monsoon patterns in Nepal that has been less explored in previous studies. Our findings align with the existing literature who reported that higher rainfall in central province of Nepal such as Bagmati and Gandaki due to the Himalayan orographic influence. This research also highlights the regional disparities with our observation of lower rainfall amount in Karnali and Sududrpaschim province and adding new insights into climatic trends after the post pandemic. Present work significantly contributes to national prosperity by providing important data and highlights that can enhance Nepal's

quick recovery from climate variability and change. The obtained rainfall patterns are essential for improving agricultural practices, which are crucial for the nation's economy. Additionally, this research helps in the groundwork for more resilient infrastructure, adaptive policies, and sustainable development practices essential for long-term national prosperity against climate change.

5. Limitations and Recommendation

5.1 Limitations

- The analysis covered only a three years span (2021-2023), which limits the ability to identify long term precipitation trends and variability.
- Although 47 stations were used in the study covering all provinces but remote areas and high-altitude areas are lack of manual gauge stations especially in Karnali and Sudurpashchim provinces. So, the data could not offer high spatial coverage.
- Missing data gaps are handled properly by marked them as ("NaN") instead of filling it but it slightly influences on some calculated averages, particularly in provinces with fewer stations like Karnali.

5.2 Recommendation

- In future studies we should consider a longer temporal dataset, preferably covering at least 10-15 years to capture long term trends and its influence on rainfall and climate change.
- Combining satellite-based precipitation data (IMERG and TRMM) with ground-based station data to improve spatial coverage especially in the area where limited density of stations is available and to check the accuracy of manual stations data.
- Further, our research should focus on assessing the impacts of rainfall variability on key sectors of Nepal such as agriculture sector, water resources management, disaster and risk management and so on.

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