



## SPATIOTEMPORAL ANALYSIS AND FUTURE PROJECTIONS OF PRECIPITATION USING CMIP5 IN MAJOR CITIES OF NEPAL

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### ABSTRACT

Climate change has triggered extreme precipitation events that have increasingly affected urban areas. This study investigates precipitation events across ten major cities using daily data collected from DHM from 1981 to 2022. The Mann-Kendall test and Sen's slope were applied to assess the precipitation trend, while Surfer software 19.1.189 was utilized for spatial precipitation mapping based on data obtained from 32 stations. For extreme precipitation, seven extreme precipitation indices developed by ETCCD in ClimPACT version 3.1.6 were employed. Results indicate that Pokhara had the highest annual precipitation (5454.26 mm), while Dunai recorded the lowest annual precipitation (750.642 mm). Precipitation displayed an increasing trend for Kathmandu (5.38 mm yr<sup>-1</sup>;  $p=0.072$ ), Pokhara (0.33 mm yr<sup>-1</sup>;  $p=0.965$ ), and Gorkha (0.1 mm yr<sup>-1</sup>;  $p=1$ ), whereas Birgunj (-18.88 mm yr<sup>-1</sup>;  $p=0.005$ ) and Illam (-11.85 mm yr<sup>-1</sup>;  $p=0.0013$ ) showed a significant decreasing trend. Extreme precipitation demonstrated substantial decreases in Illam and Bhadrapur, suggesting a drying trend, while Kathmandu, Gorkha, and Pokhara exhibited increasing trends. Spatially, the average annual and monsoonal rainfall varied at the city scale. CMIP5 model projections (2024-2100) under RCP 2.6, 4.5, and 8.5 scenarios show that future precipitation will likely change more than in past years. Extreme precipitation events have led to urban pluvial flooding in many cities and are likely to increase further in the future.

**Keywords:** Cities, CMIP5, Extreme precipitation, ETCCDI, Future projection

### INTRODUCTION

Climate change has intensified the hydrological cycle, leading to changes in precipitation patterns and an increase in extreme precipitation events (Trenberth et al., 2011). Persistent global warming and the onset of El Niño conditions in the first half of 2023, following a transition from La Niña conditions, were major contributors to the record-high global surface temperature observed worldwide, which further intensified precipitation trends (Adler & Gu, 2024). Globally, changes in precipitation patterns have been observed, resulting in wet regions becoming wetter and dry regions becoming drier (Dore, 2005; Adler & Gu 2024). The impact of climate change and extreme precipitation events are particularly pronounced in urban areas, especially those experiencing rapid population growth, leading to increase urban flooding (Zeng et al., 2021). Nepal's complex topography contributes to highly variables precipitation patterns

(Dhar & Nandargi, 2005). Monsoon precipitation dominates the country's annual rainfall regime. When moisture-laden monsoon winds approach Nepal, precipitation generally increases with elevation on the windward slopes up to a certain altitude and then decreases rapidly on the leeward side and within river valleys (Nayava, 1980a; Talchabhadel et al., 2018). In Nepal, maximum precipitation is primarily observed between June and September, particularly in the northwestern region of Pokhara, the northeastern region of Kathmandu, and eastern Nepal (Bohlinger & Sorteberg, 2018). In contrast, the lowest precipitation occurs in Mustang, Manang, Dolpa, and the Everest region (Karki et al., 2017). The precipitation pattern is observed to be more in Central Nepal than in Eastern Nepal, followed by Western Nepal (Khadka et al., 2020a). Nepalese cities are increasingly facing challenges associated with heavy precipitation events and rapid urban growth, particularly during the

monsoon season when roads are frequently inundated (Khadka et al., 2020b). Flooding generally increases due to the expansion of impervious surfaces, which reduces infiltration and enhances surface runoff. As urbanization continues, the volume of surface runoff has increased dramatically because of growing imperviousness (Basnet et al., 2020). Advanced modelling tools are required to integrate complex urban systems, climate variables, and hydrological processes to assess the impacts of future urban development and climate change scenarios on runoff patterns (Willuweit et al., 2016). Numerous climate models are available for generating future climate change scenarios. These models are mathematical representations of the global climate system and vary in size, scope, scale, and complexity (Fenech et al., 2002). According to Pradhan Salike and Raj Pokharel, (2017), Kathmandu Metropolitan City had approximately 25% area of imperviousness, which increased to about 75% by 2010, placing substantial pressure on the urban drainage system. On 28<sup>th</sup> September 2024, several districts including Kathmandu, Lalitpur, Bhaktapur, Kavrepalanchok, Argakhanchi, Chitwan, Dhading, Jhapa, Makwanpur, Nuwakot, Palpa, Panchthar, Sindhupalchok, Tanahun recorded extreme precipitation events. Daman recorded the highest three-day accumulated rainfall of 517.0 mm. This event resulted in more than 200 fatalities and caused significant economic losses

and property damage, particularly affecting communities within the Bagmati, Narayani, and Koshi river basins (Department of Hydrology and Meteorology, 2024). Similarly, in Lamachaur, Pokhara, roads frequently turn into streams during periods of intense rainfall. The maximum daily rainfall recorded during the period 2002–2017 was 314 mm in 2007 (Basnet et al., 2020). Therefore, this study focuses on the temporal and spatial characteristics of extreme precipitation and its future projections in ten major cities of Nepal.

## MATERIALS AND METHODS

### Study area

Geographically, Nepal extends from 26°22' to 30°27' N latitude and 80°04' to 88°12' E longitude, covering an area of 147,516 km<sup>2</sup> (Fig. 1). The country is divided into three major physiographic regions: the Mountains, Hills, and Terai, each characterized by distinct climatic conditions and diverse ecosystems. Nepal experiences four climatological seasons: pre-monsoon (March–May), summer monsoon (June–September), post-monsoon (October–November), and winter (December–February) (Nayava, 1980b). For this study, ten major cities representing seven provinces and three geographical regions (Mountain, Hill, and Terai) of Nepal were selected. These cities also represent diverse climatic conditions across the country. The selected cities are presented in Table 1.

**Table 1.** List of meteorological stations in different geographical regions at near 10 cities in Nepal

SN	Major cities	Provinces	Precipitation Stations	Longitude	Latitude	Elevation (m)
1	Bhadrapur	Koshi	Bhadrapur	88.0615	26.56389	90
2	Birendranagar	Madesh	Birendranagar	81.63516	28.58787	720
3	Birgunj	Lumbini	Birgunj	84.8782	27.0232	67
4	Dhangadhi	Sudurpaschim	Dhangadhi	80.6	28.68333	187
5	Dunai	Karnali	Dunai	82.89605	28.95065	2098
6	Gorkha	Gandaki	Gorkha	84.58944	27.97139	724
7	Illam	Koshi	Illam Tea State	87.92308	26.90964	1208
8	Kathmandu	Bagmati	Kathmandu airport	85.35625	27.70383	1337
9	Pokhara	Gandaki	Pokhara airport	83.97952	28.20018	827
10	Taulihawa	Lumbini	Taulihawa	83.06717	27.57108	106

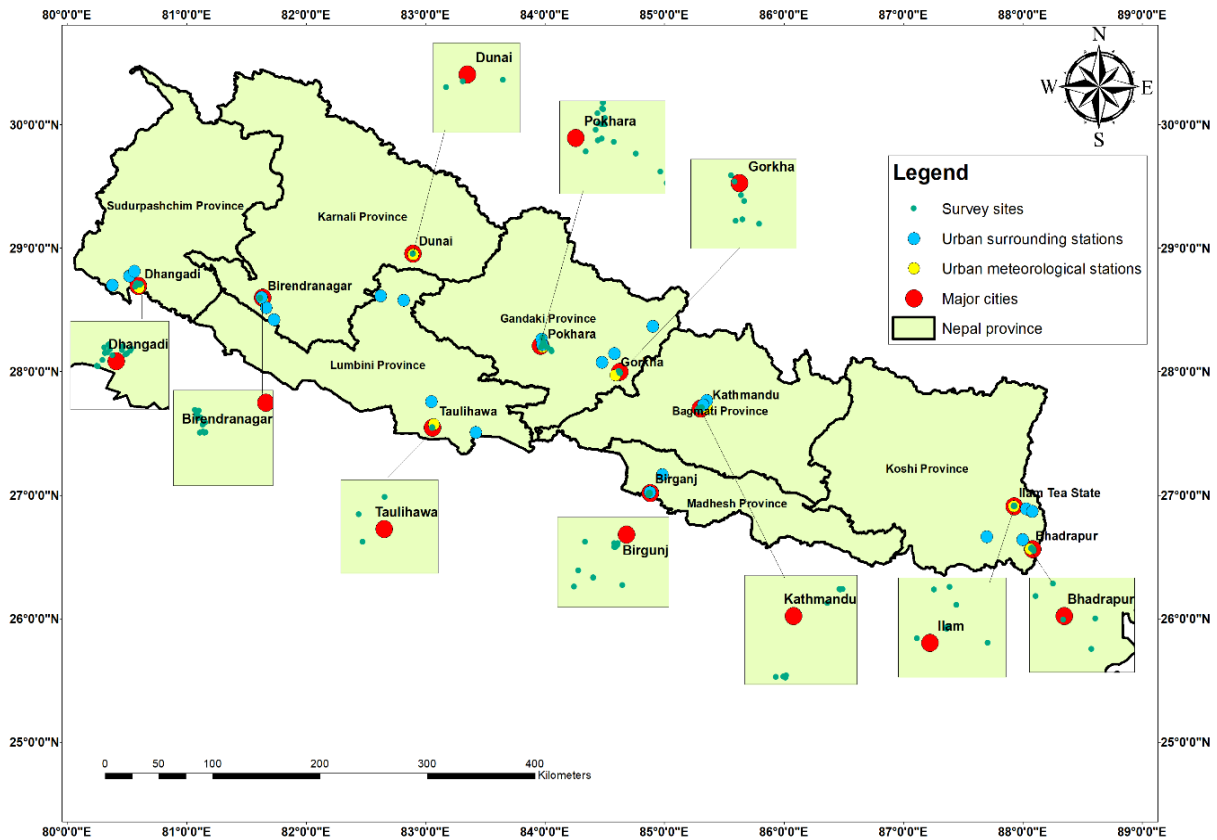


Figure 1. Map of the study area including major cities, precipitation stations and observed drainage sites

**Data used**

The daily precipitation data from 1981 to 2022 of meteorological stations located within the cities were collected from the Department of Hydrology and Meteorology.

**Analysis of precipitation trends**

The Mann-Kendall test is a non-parametric statistical technique utilized to assess the presence of trend in time series data (Mann, 1945; Kendall, 1948). For the trends, the Sen's slope method was applied (Sen, 1968). The missing data were filled up using average weighted methods in XLSTAT software.

**Analysis of extreme precipitation indices**

The extreme precipitation indices were calculated based on obtained daily precipitation data of Department of Hydrology and Meteorology (DHM) through ClimPACT version 3.1.6 based on the RCLIMDEX software developed by the WMO CCI/WCRP Expert Team on Climate Change Detection and Indices (ETCCDI). The ETCCDI seven extreme precipitation indices listed were calculated as in Table 2 to detect changes in climate extremes for this study (Table 2).

Table 2. Description of ETCCDI (Expert Team on Climate Change Detection and Indices)

Category	ID	Name of Index	Definition	Unit
HIP	R95	Very Wet days	Annual total precipitation of days in the 95th percentile	mm
HIP	RX1day	Max 1-day precipitation amount	Annual maximum 1-day precipitation	mm
HIP	RX5day	Max 5-day precipitation amount	Annual maximum consecutive 5-day precipitation	mm
HIP	R99	Extremely wet days	Annual total precipitation of days in >99 <sup>th</sup> percentile	mm

FP	R10	Number of heavy precipitation days	Annual count of days when precipitation is $\geq 10\text{mm}$	days
FP	R20	Number of very heavy precipitation days	Annual count of days when precipitation is $\geq 20\text{mm}$	days
DWS	CWD	Consecutive wet days	Maximum number of consecutive wet days (precipitation $\geq 1\text{mm}$ )	days

*Note: HIP: High Intensity related precipitation extreme; FP: Frequency-related precipitation extreme; DWS: Dry and wet spell or duration*

### Spatial analysis of precipitation

Spatial mapping of the extreme precipitation was done through kriging on Surfer software by using the data obtained from DHM. Surfer is a decent interpolation program for two-dimensional data processing. When utilizing the Surfer program to plot contour maps, three types of data files were introduced: contour data file, figure border blank file, and base map file. The plotting method is broken into four stages: data input, gridding, blanking, and overlay maps. Term-wise contour, mark, color, and coordinate axis attribute parameters were built up in this method (Zheng et al., 2010). Altogether, 32 stations were used for the spatial mapping of precipitation. The stations used for the mapping included both the major stations situated in the study areas as well as their surrounding stations, where each study area consisted of precipitation data from at least three stations, elevation, longitude, and latitude for the formulation of potential precipitation in the study areas, which was illustrated with the contour maps in Surfer gridded software

### CMIP5 GCM climate model for future precipitation

The Statistical Downscaling Model (SDSM) was used in this study to downscale the outputs of the CMIP5 GCM model under the representative concentration pathway (RCP) scenarios in 2024 to 2100, with the period of 1981–2016 serving as the baseline for ten cities across Nepal. With the use of a statistical model and data from a GCM, the Statistical Downscaling Model (SDSM) replicates the local climate. Usually, this involves two steps; first, an empirical comparison of local climate variables such as rainfall and large-scale predictors like the mean sea-level pressure was produced. The relationship was then used to simulate local climate variables using GCM simulation data (Wilby & Dawson, 2004). The GCMs data are predictors, and local station data are predictands. The predictors were selected based on significance level

and correlation coefficient. The predictors were selected based on highly correlated predictands during statistical downscaling. The data was downloaded (Predictors) from Canadian Climate Change Scenario network (CCSN); CanESM2 predictors: CMIP5 experiments Link which is best fit in context of Nepal.

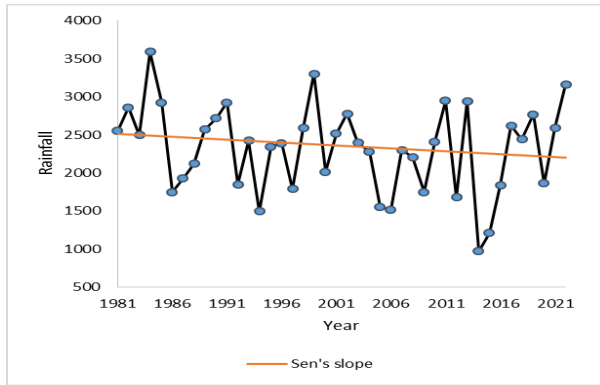
## RESULTS

### Temporal precipitation trend

Based on Sen’s slope and Mann Kendall’s test along with maximum annual precipitation, the study of ten meteorological stations, it was found that Birgunj (Sen’s slope =  $-18.880 \text{ mmyr}^{-1}$ ,  $p\text{-value} = 0.005$ ) and Illam (Sen’s slope =  $-11.850 \text{ mmyr}^{-1}$ ,  $p\text{-value} = 0.013$ ) had a significantly decreasing trend of precipitation. During the chosen timeframe, the results show a relevant correlation or trend in precipitation patterns for Birgunj and Illam, which are both negative in trend. The remaining stations show no apparent trends since their  $p$ -values exceed the set threshold of 0.05. Kathmandu and Pokhara have positive slopes. Sen’s slope values were found to be  $5.382 \text{ mm yr}^{-1}$  for Kathmandu,  $0.100 \text{ mm yr}^{-1}$  for Gorkha, and  $0.337 \text{ mm yr}^{-1}$  for Pokhara, although they were not statistically significant ( $p > 0.05$ ). This generally shows an increasing trend in the data for these sites, implying a rise in precipitation throughout the period. Whereas, in the rest of the study areas, a negative trend is observed, which implies a decreasing trend from 1981 to 2022 (Fig. 2).

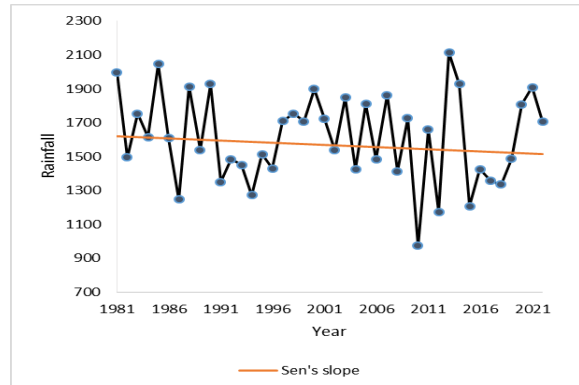
Positive Kendall tau values of 0.001, 0.194, and 0.006, respectively, were found in Gorkha, Kathmandu, and Pokhara. These findings generally indicate an increasing trend in precipitation for both sites throughout the studied period. The results also show a positive relationship between time and precipitation, supporting the concept of a growing trend in the meteorological data for Gorkha, Kathmandu, and Pokhara.

Sen's slope =  $-7.686 \text{ mm yr}^{-1}$ ,  $p = 0.423$



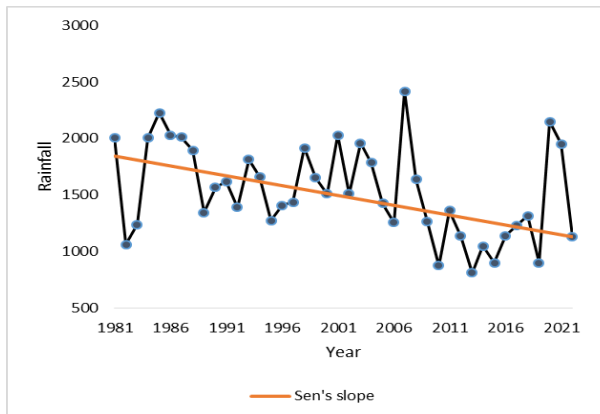
**Bhadrapur**

Sen's slope =  $-2.637 \text{ mm yr}^{-1}$ ,  $p = 0.423$



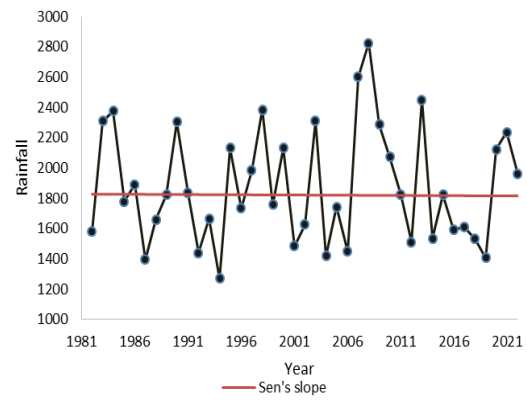
**Birendranagar**

Sen's slope =  $-18.880 \text{ mm yr}^{-1}$ ,  $p = 0.005$



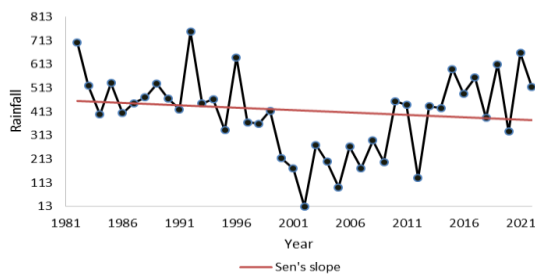
**Birgunj**

Sen's slope =  $-0.355 \text{ mm yr}^{-1}$ ,  $p = 0.938$



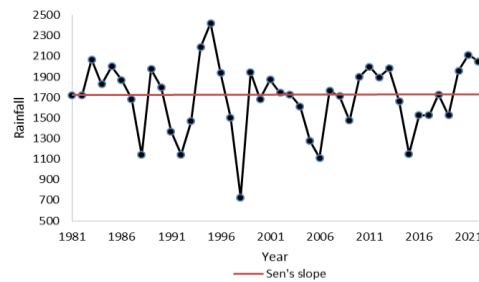
**Dhangadhi**

Sen's slope =  $-1.998 \text{ mm yr}^{-1}$ ,  $p = 0.365$



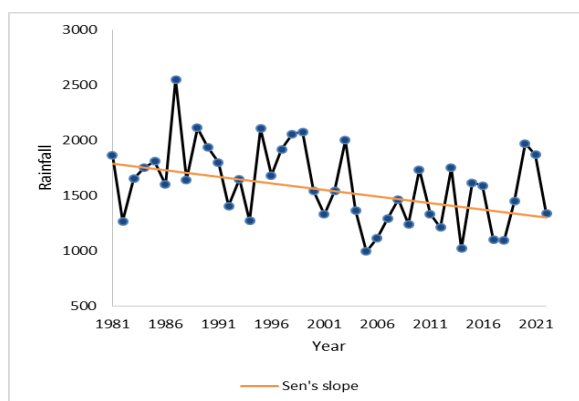
**Dunai**

Sen's slope  $0.100 \text{ mm yr}^{-1}$ ,  $p = 1.00$



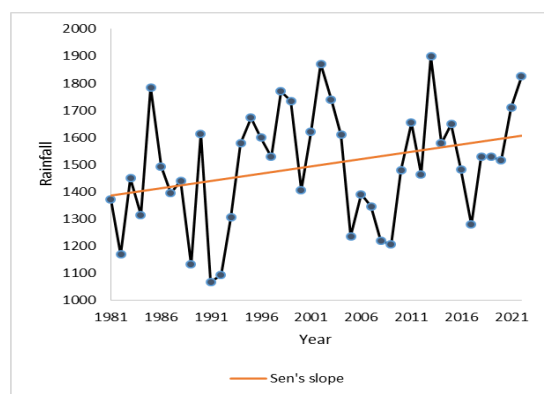
**Gorkha**

Sen's slope =  $-11.850 \text{ mm yr}^{-1}$ ,  $p= 0.013$



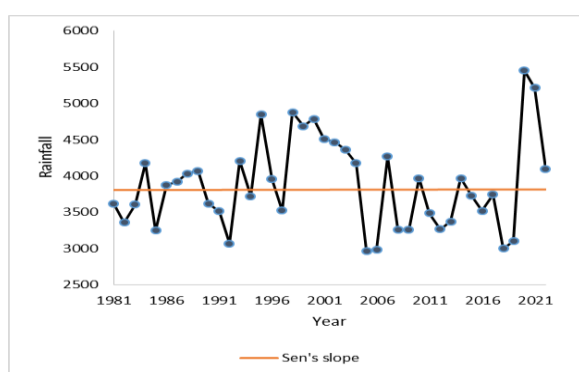
Illam

Sen's slope =  $5.382 \text{ mm yr}^{-1}$ ,  $p= 0.072$



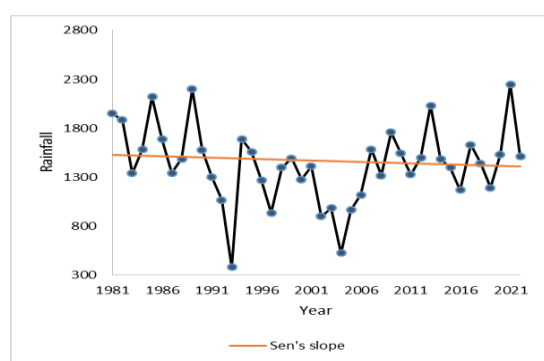
Kathmandu

Sen's slope =  $0.337 \text{ mm yr}^{-1}$ ,  $p=0.965$



Pokhara

Sen's slope =  $-2.950 \text{ mm yr}^{-1}$ ,  $p=0.573$



Taulihawa

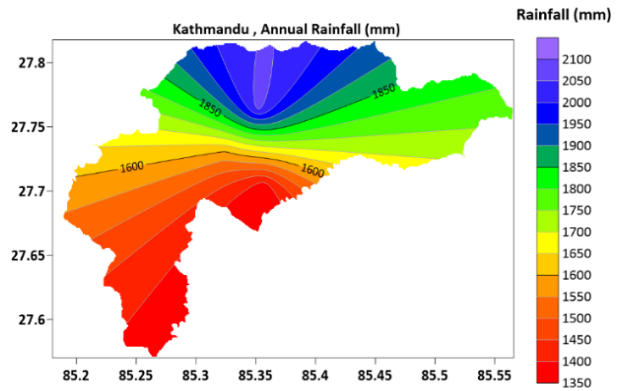
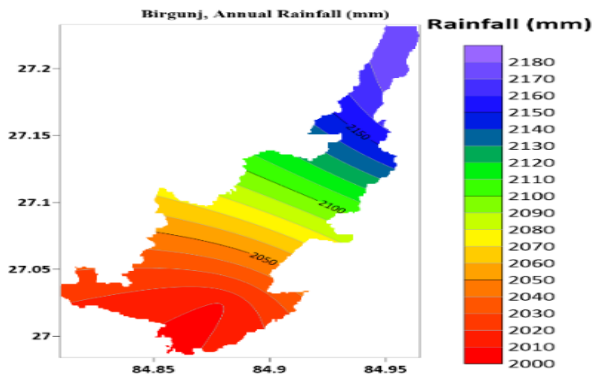
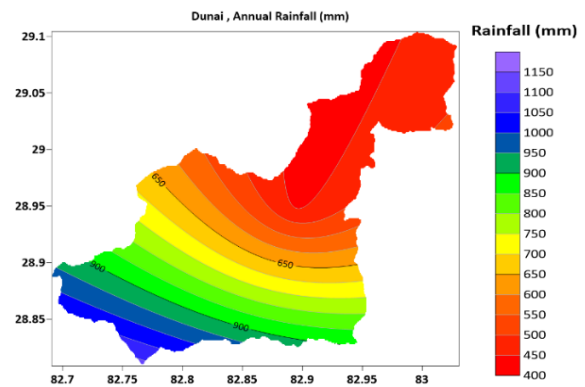
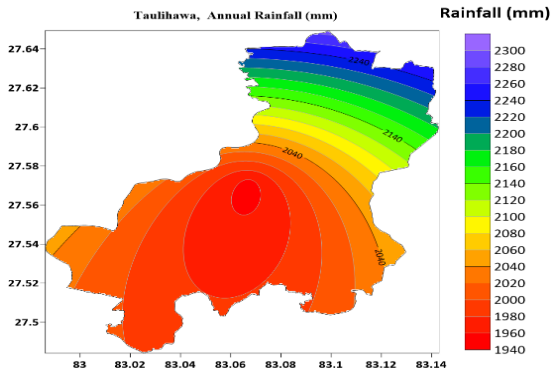
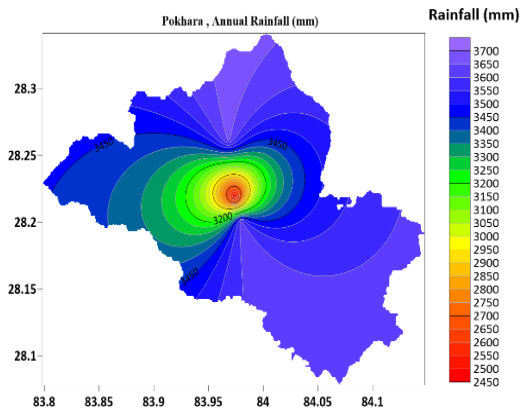
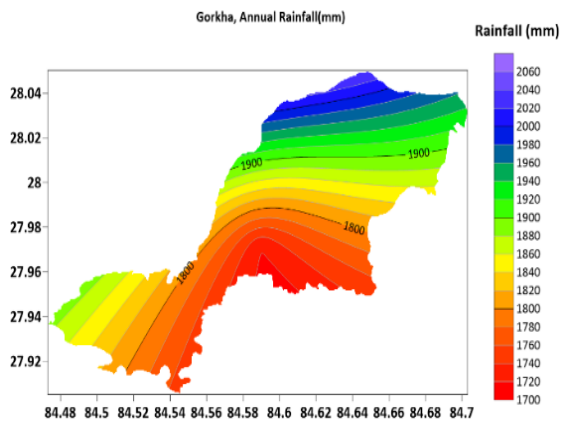
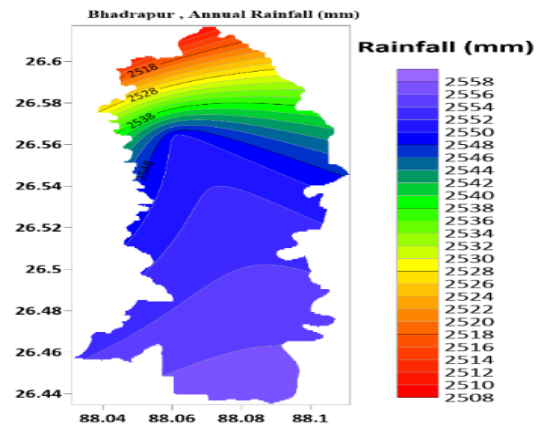
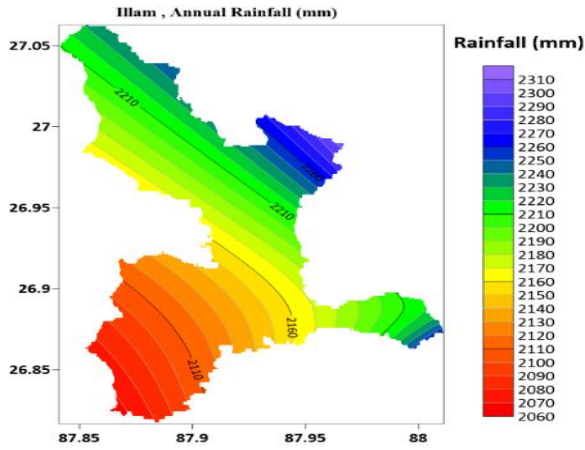
**Figure 2.** Annual precipitation trends obtained from Sen's slope and MK test during 1981 to 2022 in 10 major cities of Nepal (X- axis represent years, and Y-axis represents rainfall in mm)

### Spatial precipitation patterns

In the eastern hilly region of Nepal, Illam recorded the highest monsoon precipitation, reaching 3541.2 mm in 1987, and the highest annual precipitation, with 4283.7 mm in the same year. On average, Illam received 2299.281mm of annual precipitation. In contrast, Bhadrapur experienced its maximum monsoon precipitation of 3156 mm in 1984, with a peak annual precipitation of 3658.341 mm in 2020. The average annual precipitation in Bhadrapur is 2415.728 mm, whereas Gorkha and Pokhara had maximum precipitation of 3252.6mm and 4528.25 mm in the monsoon season, respectively, in the same year, 2020. The maximum annual precipitation of Gorkha was 4477.782 mm again in the year 2020, with an average of 2108.739 mm, and Pokhara experienced a maximum yearly precipitation of 5997.755 mm in

1998, with an average rainfall of 4051.175 mm. Taulihawa had a maximum monsoon precipitation of 3032.3 mm and an annual precipitation of 3524.4 mm in 1998. On average, Taulihawa received 1785.613 mm annually (Fig. 3).

Dunai has received an average rainfall of 1243.907 mm between the years 1981 to 2022. The other region, Birendranagar, had a maximum monsoon precipitation of 1778.7mm in 2000 and a maximum annual precipitation of 2113.5 mm in 2013, with an average of 1492.755 mm from 1981 to 2022. The western part, Dhangadhi, had a maximum monsoon precipitation of 2345.7 mm in 2008 and a maximum annual precipitation of 2823.3 mm in the same year. On average, Dhangadhi has received 1710.19 mm annually.



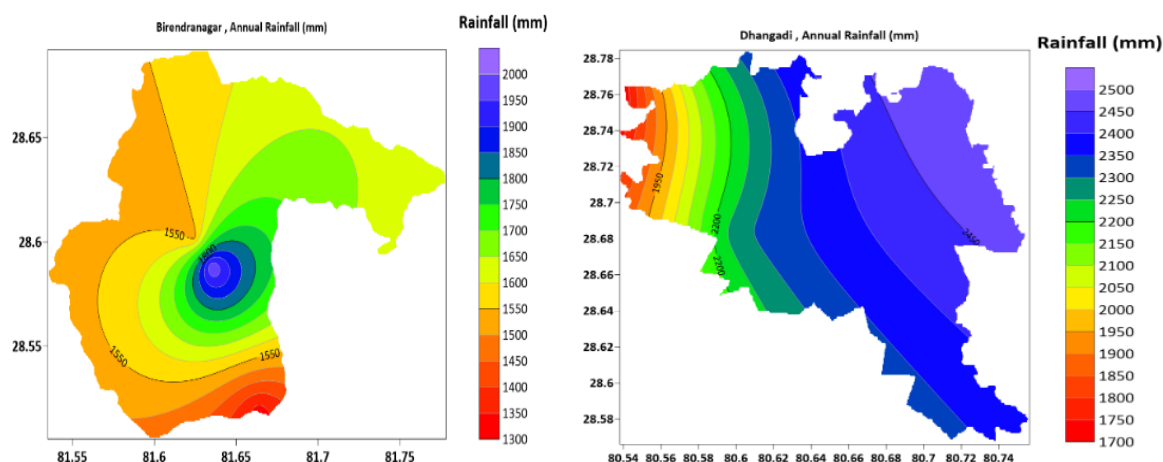


Figure 3. Spatial variation of precipitation in 10 major cities from 1981 to 2022

### Extreme precipitation indices in major cities

In Bhadrapur, a decreasing trend of extreme indices was observed except for the insignificant rise of R20mm (0.043 mm yr<sup>-1</sup>, *p*=0.688). Similarly, Birendranagar also showed a decrease in the extreme indices except for the RX1 day with an increasing trend (0.415mm yr<sup>-1</sup>, *p*=0.288), although not significant. Birgunj has shown a decline in the extreme precipitation indices, indicating a fall in extreme precipitation. Dhangadhi, Dunai, and Illam have, however, shown significantly decreasing negative trends such as Dunai for R10mm (-0.242 mm yr<sup>-1</sup>, *p*=0.01), R95mm (-4.124 mm yr<sup>-1</sup>, *p*=0.001) and RX1 day (-0.6415 mm yr<sup>-1</sup>, *p*=0.011) and Illam for R20mm (-0.259 mm yr<sup>-1</sup>, *p*= 0.011) and RX1 day (-1.014 mm yr<sup>-1</sup>, *p*=0.05). Conversely, Kathmandu has shown significantly increased extreme precipitation indices except for the CWD index, which has significantly decreased (-0.103 mm yr<sup>-1</sup>, *p*= 0.018). Gorkha has shown a decline in the indices with insignificance. Pokhara and Taulihawa, though, have shown variations such as a significant rise in RX1 day (1.584 mm yr<sup>-1</sup>, *p*=0.008) and an insignificant

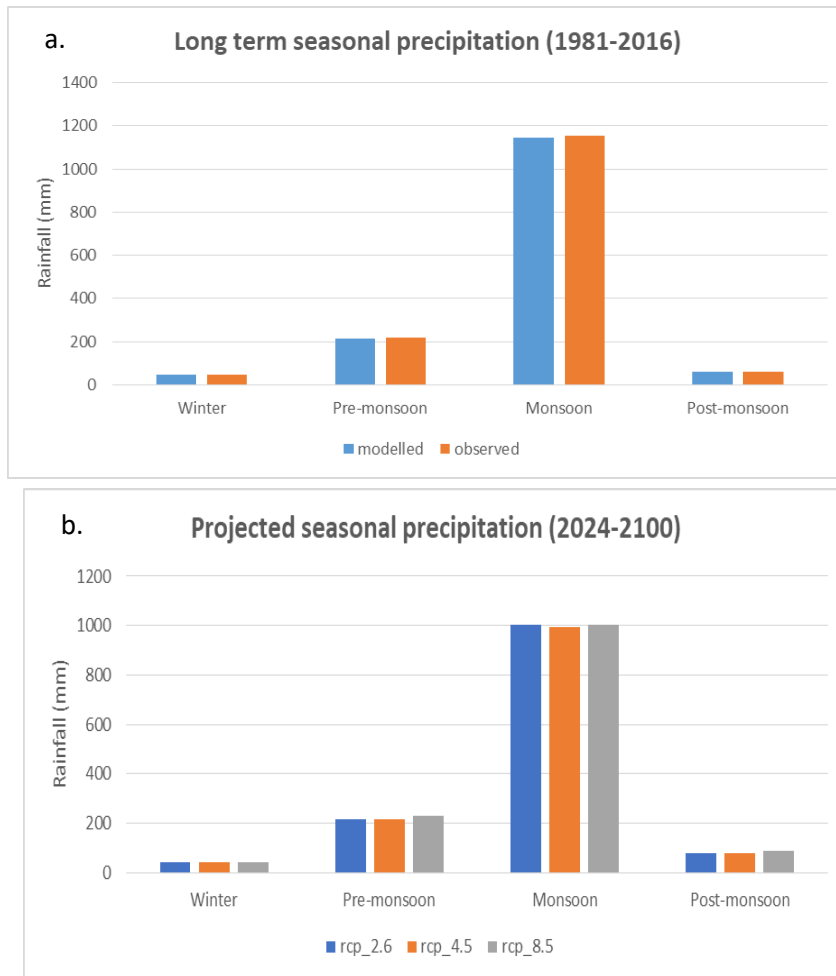
decrease in R10mm, R20mm, and CWD. Whereas, Taulihawa has shown a significant decrease for R20mm (-0.158 mm yr<sup>-1</sup>, *P*= 0.068) and a rise of R95 and RX1 day. The remaining indices showed stability.

### Projected precipitation in major cities

The variance between historical precipitation (1981-2016 AD) and projected precipitation (2024-2100 AD) of both monsoon seasons is generally minimal, with a few exceptions for certain cities. However, the 24-hour intensity, duration, and frequency of the varied rainfall have the potential to impact different cities in the future. Compared to the historical precipitation, the projected precipitation based on RCP 2.6, RCP 4.5, and RCP 8.5 was the highest in Pokhara, exceeding 3000mm, followed by Birgunj and Bhadrapur, exceeding 16000mm. Birendranagar, Dhangadhi, Illam, Kathmandu, and Taulihawa also have variations in the projected monsoonal precipitation (Fig. 4). However, Gorkha and Dunai, with the lowest projected precipitation, have been predicted (Table 3).

Table 3. Historical and projected scenarios of the precipitation (mm) in major cities of Nepal

Name of Cities	Precipitation (mm)		Projected scenarios of precipitation (mm)		
	Modelled	Observed	RCP2.6	RCP4.5	RCP8.5
Bhadrapur	1822.07	1854.67	1736.58	1718.35	1692.13
Birendranagar	1261.93	1326.05	1325.22	1357.11	1409.74
Birgunj	1194.42	1232.36	1849.442	1888.949	2092.033
Dhangadhi	1088.8	926.68	1262.98	1327.29	1438.83
Dunai	244.46	247.66	236.8	238.71	237.28
Gorkha	775.33	950.04	712.81	687.86	680.64
Illam	1047.23	1046.98	1127.26	1157.96	1217.96
Kathmandu	1143.9	1155	1001.52	995.14	1004.06
Pokhara	3089.86	3068.77	3137.64	3155.55	3260.87
Taulihawa	1031.3	1221.85	1008.45	1012.3	1009.06



**Figure 4.** Example of modelled, observed and projected precipitation of Kathmandu (a) Long-term modeled and observed seasonal rainfall of Kathmandu (1981-2016) and (b) Projected seasonal rainfall for Kathmandu under different RCP scenarios

Kathmandu had modeled a value of 1143.90 mm from 1981 to 2016 showing good alignment with the observed value. On the other hand, the future projection according to the model is 1001.517 mm for RCP2.6, 995.136 mm for RCP4.5, and a slight increase to 1004.064 mm for RCP8.5. There is consistency and biased corrections for the RCP scenarios.

## DISCUSSION

The study of precipitation patterns and extreme indices across Nepal revealed spatial and temporal variability due to the country's diverse topography and climatic influences. Among the ten cities, Pokhara had the highest annual precipitation of 5454.26 mm, which can be attributed to its orographic setting, as the hills act as a barrier, and the windward side falls on the valley, resulting in maximum precipitation (Nayava, 1980b). The annual rainfall is then followed by Bhadrapur, Illam, Gorkha, and Taulihawa, exceeding 2200 mm. This trend of maximum precipitation pattern is consistent with the observations reported by DHM (Department of Hydrology and Meteorology, 2017). The precipitation pattern of higher rainfall in Central Nepal and then in

Eastern Nepal, followed by Western Nepal, aligns with the previous studies (Khadka et al., 2020a). In contrast, Dunai of Western Nepal has a minimum annual precipitation of only 750.642 mm as it lies in the rain shadow area of the Annapurna range (Karki et al., 2016). The trend analysis of the precipitation of ten cities showed significantly increasing trends for Kathmandu, Pokhara, and Gorkha. An earlier study of rainfall from 1991 to 2020 showed a similar trend in the region (Kansakar et al., 2004; Kharel & Basnet, 2022). Except for these three stations, all the others have shown a negative trend in Sen's slope. Birgunj and Illam revealed a negative trend, which indicates a decrease in the precipitation pattern from 1981 to 2022. A DHM report reveals a negative trend of 7.5mm per year between 1971 to 2014 in Illam, which supports the present findings (Department of Hydrology and Meteorology, 2017). Furthermore, Eastern Nepal showed a pattern between the years 1996 to 2016, where the average annual precipitation was found to be decreasing at the rate of 20mm per year (Subba et al., 2019). Extreme precipitation indices were declining in the lower eastern region, particularly in Bhadrapur and Illam where R10mm, R20mm, R95p, R99p, RX1, RX5, and CDW all

showed negative trends. A similar decrease in the trends of extreme precipitation resulted in a study done between 1997 to 2016, except for the CWD index (Subba et al., 2019). This decrease in trends of extreme precipitation indices leads to dryness in the region. However, a study from 2001 to 2016 showed an increase in Province 1 of R10mm and R20mm indices, indicating heavy and extreme precipitation. Furthermore, high fluctuation in the CWD index was observed in Province 1 (Khadka et al., 2020a). Another region of Province 2, Birgunj, a region with hot temperatures, showed a negative trend, with some showing significance and no record of extreme heavy precipitation by analyzing the R10mm, R20mm, R95p, R99p, RX1, RX5, and CWD indices but also, heavy precipitation is observed in Birgunj and the other nearby stations from 1985 to 2022 over 15 times with an excess of 200mm rainfall (Ghimire, 2023). The most precipitation-receiving region was found in the central region of Kathmandu, Gorkha, and Pokhara. In Kathmandu, all the indices showed a positive trend except for the CWD index, and this indicates an increase in extreme precipitation events and a decrease in consecutive wet days. A similar result was revealed by a study done with data from 1975 to 2015, showing a decrease in Kathmandu cold spell days (Awasthi & Owen, 2020). Similarly, Gorkha showed a positive trend for all indices except for R10mm and R20mm.

Pokhara showed a positive trend for R99p, R95p, RX1, and RX5 and a negative trend for the remaining indices. From 1971 to 2010, the analysis of percentiles showed positive responses indicating heavier precipitation, which could potentially lead to disastrous flood events in Pokhara (Bohlinger & Sorteberg, 2018). All three areas of Central Nepal indicate higher extreme precipitation events than Nepal's western region (Shrestha et al., 2020). However, overall decreasing trends for the precipitation indices were observed from 1981 to 2010 for the central middle regions (Karki et al., 2017). The lower Terai region, Taulihawa, has shown variations in the indices, where the R10mm, R20mm, R99p, RX5, and CWD showed a decrease in the precipitation trends, and R95p and RX1 indices showed a positive but insignificant trend. According to (Karki et al., 2017), RX1 day was recorded as lowest in the central highlands but was highest in the central lowlands, along with eastern and western lowlands. The extreme precipitation event was recorded in 1998, but a study also revealed heavy precipitation in 2022. The maximum 24-hour daily precipitation in Taulihawa was recorded on 30<sup>th</sup> June 2024, exceeding 200mm (Department of Hydrology and Meteorology, 2024). The results illustrate that there is a slight trend of extreme precipitation events in comparison to the historical period. In contrast, Dunai has shown a negative trend for all the indices except for the CWD index, which is rising. This indicates the area to

experience wet spell days. Conversely, Birendranagar showed a negative trend for all the indices except for the RX1 index. This indicates that a single day has received maximum precipitation. Dhangadhi, which lies at the lowest elevation, showed a positive trend for the R10mm, R95p, and RX5 but no trend for the R20mm, R99p, and CWD, and a negative trend for RX1. This result indicates a slight increase in the precipitation, but no extremely heavy precipitation. A similar rise of R95p, RX1, and RX5 was observed in the western region of a study done from 1981 to 2010 (Karki et al., 2017). A study also showed an increase in the extreme precipitation indices in the western mountains of Nepal for the period between 1966 and 2015.

Across Nepal, several extreme precipitation events have been recorded in recent decades. Notably, in Kathmandu, 2002 with 1955.4 mm monsoonal precipitation and 2014 with 2661.01 mm have been observed. The Kathmandu extreme precipitation event of 2002, resulting in disastrous urban flooding, occurred, with the death of 27 people (Dangol & Bormudoi, 2017). Other remarkable instances of extreme precipitation include Dhangadhi in 2008 with 2345.7 mm monsoonal and 2823.3mm annual precipitation, Birendranagar in 2013 with 2113.5mm annual precipitation, and Gorkha in 2020 with 3252.6mm monsoonal and 4477.782mm annual precipitation (Niraula & Pokhrel, 2022). Birgunj also has records of urban flooding in the roadways due to extreme precipitation events, which also triggered the Sirsiya River (Ghimire, 2023). Kathmandu, on the other hand, with rapid population growth and urbanization, also has a record of inundation and urban pluvial flooding in the roadways due to its reduced natural infiltration rate and small drainage canals (Bajracharya et al., 2016). According to Paudel & Prasad (2022), the core of Pokhara city experiences a rainfall intensity of 103.4mm/hr and 50% of the drainage pipes have exceeded their capacity. Poor drainage systems and unplanned urbanization contribute to the severity of inundation during heavy rainfall (Karki et al., 2017). The CMIP5 model has shown accuracy for the baseline period for all the cities. The model has shown higher predictions for Pokhara, Illam, Dhangadhi, and Birendranagar. The CMIP5 model predictions on growing precipitation extremes throughout Nepal highlighted an increase in precipitation trends, especially during extreme weather events, which are predicted to become more frequent and intense in the country's western area (Karki et al., 2017). Nepal is projected to see a 19.5% increase in precipitation by the end of the 21<sup>st</sup> century. This increase will be particularly pronounced in the western region during winter, alongside a rise in summer monsoon precipitation. The changes in precipitation are anticipated to differ across various regions of Nepal, with the western regions likely to

experience more substantial increases (Almazroui et al., 2020).

## CONCLUSION

This study highlights the spatiotemporal variation of precipitation and its extreme indices across ten major cities of Nepal from 1981 to 2022, with Pokhara receiving the maximum annual precipitation of 5454.260mm, and Dunai the lowest annual precipitation with 750.642 mm. A positive trend was found in Kathmandu, Gorkha, and Pokhara, where the precipitation has increased. The cities Birgunj and Illam found negatively significant trends. In the eastern regions of Bhadrapur and Illam, precipitation indices such as R10mm, R20mm, R95p, R99p, RX1, RX5, and CWD indicated a significant drying. Birgunj also showed a negative trend in precipitation indices with no extreme events. Conversely, Kathmandu exhibited an increase in extreme precipitation events across nearly all indices except CWD. Gorkha and Pokhara showed positive trends for extreme precipitation indices but declined in R10mm, R20mm, and CWD. Dhangadhi showed slight increases in some precipitation indices, but no significant trends overall. Despite that, the CMIP5 model demonstrated good alignment between the modeled and observed precipitation of the ten cities. Compared to the historical precipitation, the projected precipitation based on RCP 2.6, RCP 4.5, and RCP 8.5 was found to be higher in major cities. This study encourages the development of mitigation measures for urban flooding caused due to extreme precipitation and poor drainage structures.

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## AUTHORS CONTRIBUTION

Conceptualization: JK; Methodology: JK, AT; Validation: BB; Investigation: JK; Data analysis: JK, AT, MS; Writing-original draft: JK; Writing-review & editing: JK, BB; Supervision: BB; Funding acquisition: JK

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## ETHICAL STATEMENT

We declare that it is our original work and has not been previously published or submitted for publication elsewhere.

## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

## DATA AVAILABILITY STATEMENT

The data are available upon request to first and corresponding authors.

## SUPPLEMENTARY INFORMATION

None.

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