Spatial and Temporal Variation of Precipitation Extreme in the Kathmandu Valley During Last Three Decades

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ABSTRACT

Changes in the severity, duration, and frequency of various meteorological fundamentals are thought to be the primary source of the world's changing climate. Precipitation extremes are one of significant events triggered by changes in the climate system. The Mann-Kendall Trend test was used to analyze the precipitation trend, and ClimPACT2, an R software package, was used to calculate sector specific climate indices for the daily precipitation data from 1990 to 2022. The data set used in this study included daily precipitation data from 5 weather stations in the Kathmandu valley. The result showed that monsoon precipitation contributing to 70-80% of average annual rainfall in which the monsoon precipitation was found the highest in Godawari and lowest in Khumaltar. The annual rainfall variability in the valley found to be 847-2367 mm. Godavari and Bhaktapur has decreased rainfall at the rate of -12.59 mm and 4.57 $mmyr^{-1}$ respectively. The Kathmandu airport, Khumaltar and Panipokhari shows an increasing trend with average annual rainfall increasing by 4.45 $mmyr^{-1}$, 1.95 $mmyr^{-1}$ and 2.63 $mmyr^{-1}$, respectively during 1990-2022. The average monthly precipitation in the Kathmandu Valley ranged from 4.09 to 454.29 mm received maximum rainfall by the Godavari. Spatially, the maximum rainfall reached to 1971 mm during monsoon especially in the Godawari and Panipokhari area. The heavy precipitation days (R10mm) and very heavy precipitation days (R20mm) was higher in Godawari (70 days) and Panipokhari (42 days) and lowest in Khumaltar (9 days). In Panipokhari, the maximum lengths of consecutive wet and dry days were observed over 32 days and 202 days respectively. The highest annual maximum values of 1-day and 5-day precipitation amount within a year was highest in Godawari in the range of 52 to 225 mm, and 121 to 476 mm and the annual total precipitation over the certain long-term 95th & 99th percentile was also highest for Godawari station. These varied results in the range, duration, and frequency of precipitation patterns could be due to the changing climate.

Keywords: Extreme precipitation, Precipitation indices, Trend analysis and Kathmandu Valley

1. Introduction

Changes in the severity, duration, and frequency of various meteorological fundamentals are primary source of the world's changing climate (Lamichhane et al., 2020). Likewise, extreme weather events are driven by changes in the climate system brought on by increasing temperatures (Abdila and Nugroho, 2021). Precipitation extremes are one of significant events triggered by changes in climate system. According to the Intergovernmental Panel on Climate Change (IPCC) special report on extreme events and the fifth assessment report, both the intensity and frequency of precipitation extremes have been rising globally (Subba et al., 2019). Precipitation extremes are one of the major leading factors of natural catastrophic events such as floods, landslides, droughts, and glacier lake outburst flood (GLOF), impairing societal and economic progress (Karki et al., 2017; Karl and Knight, 1998; Sheikh et al., 2015). Extreme weather events with substantial precipitation can be considered the root triggering of natural disasters in Nepal (Chalise and Khanal, 2002). Flash floods, landslides, GLOF, and dam breaks are the most frequent disasters linked to excessive precipitation (Bohlinger, 2018; Chalise and Khanal, 2002). The cloudburst that occurred in the northern Himalayas near the Nepalese border from June 14 to 17, 2013, killed about 5700 people and injured over 100,000 others, causing substantial property damage (Karki, 2017). Likewise, a severe downpour on August 14-16, 2014, also caused a series of landslides and catastrophic flooding, affecting over 35,000 homes and claiming many lives (Karki et al., 2017). Melamchi is one of the recent examples of flash flood which occurred in Nepal Himalaya in response to monsoon cloud burst, where the monsoon cloud burst in 2021 was more than national average. The rainfall pattern of Nepal is erratic (Sigdel and Ikeda, 2010). Southern parts of the country faced moderate and severe drought condition in June, 2023 where the percentage of

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normal precipitation is less than 50%. However, some parts of center Nepal have experienced more than normal precipitation in June-September, 2023 (DHM, 2023). During 2020, the summer monsoon has increased and became the wettest year (Sharma et al., 2023). Overall, the precipitation trend in Nepal has decreased in national and provincial scales (Sharma et al., 2020). The time-series winter precipitation anomalies revealed the winter precipitation are varied (Dawadi et al., 2023) and the years 1996, 1998, 2000, 2005, 2007, and 2008 as precipitation deficit years and 1988, 1995, 1997, 2002, 2012, and 2014 as the wet years (Hamal et al., 2020).

Nepal is more vulnerable to the development of extreme precipitation and drought events (Lamichhane et al., 2020). According to a study based on meteorological stations, the distribution of monsoon precipitation patterns over Nepal encloses a similar distribution to that of 80% of the average yearly precipitation (Bohlinger et al., 2017; Karki et al., 2017; Lamichhane et al., 2020; Nayava, 1980) followed by 8% during post-monsoon and 12% during pre-monsoon (Chalise and Khanal, 2002). The precipitation pattern differs with a regional and temporal variation heavily influenced by the Indian summer monsoon (Bohlinger and Sorteberg, 2018). The central Terai region of Nepal recorded its highest rainfall event in 2003, totaling 456.8 mm, as measured at Hetauda station. Between 1971 and 2015, there were 1023 extremely heavy precipitation events occurrences with more than 150 mm of precipitation per day, where 60% and 40% of rainfall occurred after the 1990s and 2000s, respectively. Likewise, there have been 411 instances in Nepal where daily rainfall exceeds 200 mm. Up until the foothills of the mountains, Terai and Siwalik experienced the majority of the extreme precipitation, which resulted in catastrophic floods, landslides, and other significant environmental degradation) (Awasthi and Owen, 2020). Extreme rainfall events are frequently observed in the western region of the country including Hetauda (456.8 mm in 2003, 405.4 mm in 2006), Malepatan (445.7 mm in 2007), and Surkhet all recorded daily events higher than 400 mm (423.1 mm in 2014) (Awasthi and Owen, 2020). The high-intensity precipitation (greater than 100 mm in 24 hours) is becoming increasingly common (Devkota and Bhattarai, 2018). The poor resist communities and physical infrastructure are affected by heavy rainfall events, which result in to flooding, drought, and prolonged dry spells (Awasthi and Owen, 2020; Devkota and Bhattarai, 2018). These previous climate data analyses have revealed that the temperature has increased and precipitation decreased (Baniya et al., 2019). Extreme weather occurrences are becoming more uncertain in terms of location and time (Awasthi and Owen, 2020).

The trend of extreme precipitation is crucial for determining the precipitation threshold in an area, the successive review of the threat to the region, and its possible preventive measures (Gentilucci et al., 2019). Precipitation extremes are one of the major leading factors of natural catastrophic events. With the increasing temperature and changing climate, precipitation extremes are globally becoming more severe (Karki et al., 2017). Recent studies assume that the extreme precipitation is increasing on a global, continental, and regional scale, but its patterns in Nepal are still unclear and sporadic (Bohlinger, 2018; Lamichhane et al., 2020). Likewise, observed precipitation extremes across Nepal, compared with the rest of South Asia, are also sparse, limited, and inconsistent, with contradictory findings (Karki et al., 2017). During 1961 to 2006, majority of the stations out of 26 study stations indicated an increasing trend of extreme precipitation (Baidya et al., 2008). The extreme precipitation indices from 1975-2010 within the Koshi basin showed increase in frequency and amount of precipitation with statistically insignificant trends (Karki, 2017; Shrestha et al., 2017). Thus, these contradicting findings in precipitation extremes over Nepal may be attributable to differing data spanning different periods centered on a definite study area (Karki et al., 2017). The extreme rainfall events and their intensity, duration and frequency are increasing (Sigdel and Ma, 2016). Numerous disasters, including floods, landslides, and stormwater flooding, were caused by extreme precipitation (Bohlinger, 2018; Chalise and Khanal, 2002). Kathmandu valley is one of the worst cities of storm water flooding during monsoon period (MoUD, 2017). After 2000, the average annual rainfall and number of rainy days found decreased in Kathmandu valley (Prajapati et al., 2021). In this context, our study attempts to find the extreme rainfall in Kathmandu valley using data from in-situ observations which is very essentials to know about the rainfall threshold and possible mitigations for rainfall induced extreme disaster in the valley.

2. Materials and Methods

2.1. Study Area

Kathmandu Valley, the home to the three largest cities, Lalitpur, Bhaktapur, and Kathmandu itself, is located in the Bagmati province of central Nepal with an area of about 665 km^2 and an average elevation of 1350 m above sea level. Four mountain ranges surround the valley: Shivapuri, Nagarjun, Phulchowki, and Chandragiri. Bagmati is a significant flowing river that drains out of the Kathmandu Valley. Kathmandu Valley usually has a moderate, warm, and temperate climate in which the summers are significantly wetter and rainier than winters (Haffner, 1981). The usual monsoon regime regulates precipitation receiving approximately 80% of total annual rainfall (Nayava, 1980). This study was carried out using five meteorological stations of Panipokhari, Kathmandu airport, Bhaktapur, Godawari and Khumaltar along the Kathmandu Valley (Fig. 1)

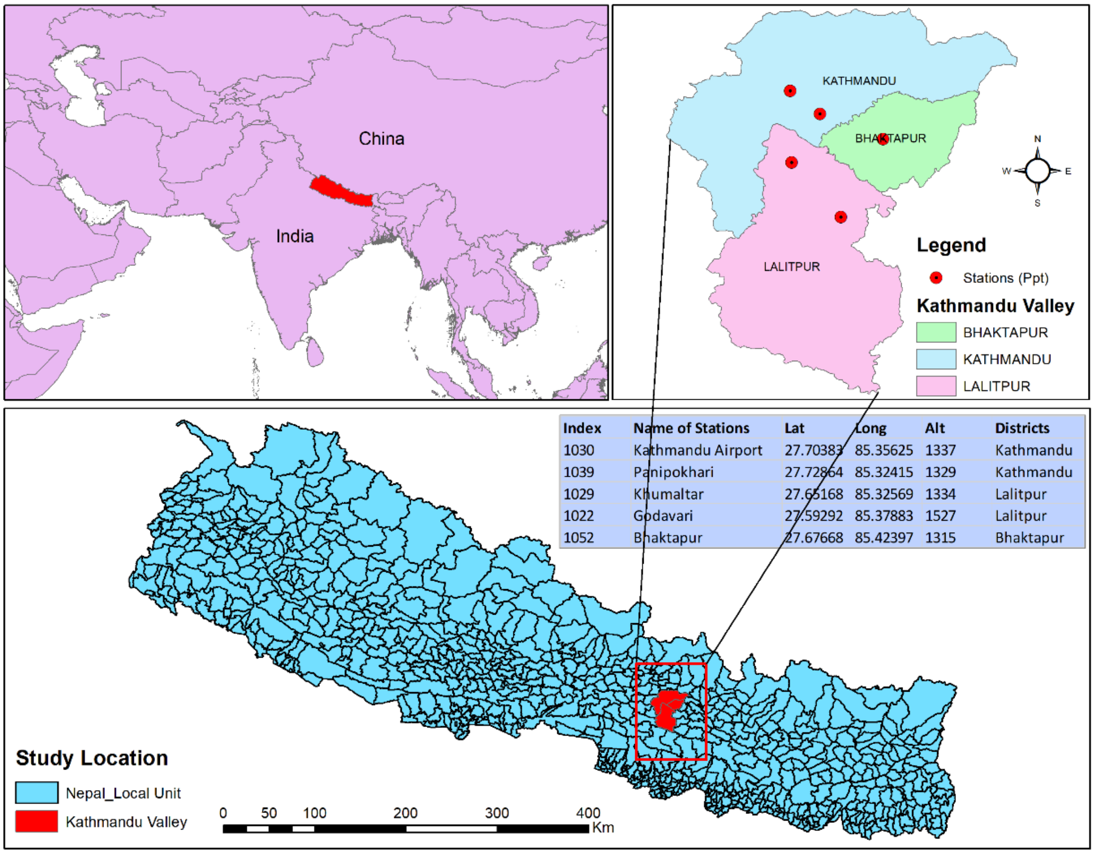

Figure 1. Location map of the study area with five meteorological stations' records during 1990-2022 in the Kathmandu Valley.

The Bagmati River Basin (BRB), a significant river system coursing through the Kathmandu valley, holds crucial importance for various purposes. However, a significant trend of precipitation could not be observed where the annual average and monsoon average rainfall of the catchment area are 1800 mm and 1500 mm respectively and the mean annual temperature varies between 10–30 °C (Dhital et al., 2013). The river system in the Bagmati basin possesses the potential to fulfill approximately 82% of the valley's drinking water requirements (Dahal et al., 2011). In accordance with a study focused on the BRB, significant floods occurred in 1993 and 2002, affecting communities residing along the banks of the Bagmati River and its tributaries (Dahal et al., 2011). The risk to individuals living in close proximity to rivers remains consistently high mostly on monsoon seasons (Gautam and Kharbuja, 2005).

2.2. Data

The data set used in this study included daily precipitation data during 1990-2022 from 5 weather stations in the Kathmandu Valley. Fig. 1 depicts the distribution of meteorological stations across the valley managed by the Department of Hydrology and Meteorology (DHM) Nepal. The obtained raw data was prepared in an Excel sheet and analyzed. The auxiliary data of GIS layers was collected from the Department of Survey, Government of Nepal.

2.3. Methods

2.3.1. Mann-Kendall Trend

The MK trend test (Kendall, 1975; Mann, 1945) is a notable non-parametric test for determining the relevance of a trend in a time series since it does not require normally distributed data sets and can handle missing data records and extremes (Yadav et al., 2014). The Mann-Kendall Test determines whether a time series consistently trends upward or downward over time. The information does not have to be uniformly distributed or linear. The Mann-Kendall test statistic S is calculated using the formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{Sgn}(x_j - x_i) \tag{1}$$

where x_j and x_i are the annual values in years j and i (where $j > i$), respectively. The application of the trend test is done to a time series x_i that is ranked from $i = 1, 2, \ldots, n-1$ and x_j, which is ranked from $j = i+1, 2, \ldots, n$. Each of the data points x_i is taken as a reference point, which is compared with the rest of the data points x_j so that:

$$\text{Sgn}(x_j - x_i) = \begin{cases} 1, & \text{if } x_j - x_i > 1, \\ 0, & \text{if } x_j - x_i = 0, \\ -1, & \text{if } x_j - x_i < 0. \end{cases} \quad (2)$$

It has been documented that when $n \geq 8$, the statistic S is approximately normally distributed with a mean of $E(S) = 0$. The variance of the statistic is given by:

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18} \quad (3)$$

where t_i is considered as the number of ties up to sample i. The test statistic Z_c is computed as:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0. \end{cases} \quad (4)$$

The test statistic Z_c here follows a standard normal distribution. A positive (negative) value of Z signifies an upward (downward) trend. A significance level α is also used for testing either an upward or downward monotone trend (a two-tailed test). If Z_c appears greater than $Z_{\alpha/2}$, where α depicts the significance level, then the trend is considered significant.

2.3.2. Sen's slope

Sen's slope is a non-parametric test for determining the true slope of existing trend, if a time series consist of linear trend (Sen, 1968). It is used extensively as it is less susceptible to the outliers and missing data (Karki et al., 2017). The magnitude of trend is predicted by the Sen's estimator. Here, the slope T_i of all data pairs is computed as (Sen, 1968)

$$T_i = \frac{x_j - x_k}{j - k} \qquad for\ i = 1, 2, \ldots\ldots, N \quad (5)$$

where, x_j and x_k are considered as data values at time j and k (j>k) correspondingly. The median of these N values of T_i is represented as Sen's estimator of slope which is given as:

$$Q_i = \begin{cases} T_{(\frac{N+1}{2})} & \text{N is odd,} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & \text{N is even.} \end{cases} \quad (6)$$

Sen's estimator is computed as Qmed=T(N+1)/2 if N appears odd, and it is considered as Qmed=[TN/2+T(N+2)/2]/2 if N appears even. At the end, Qmed is computed by a two-sided test at 100 (1-α)% confidence interval and then a true slope can be obtained by the non-parametric test. Positive value of Qi indicates an upward or increasing trend and a negative value of Qi gives a downward or decreasing trend in the time series.

2.3.3. Analysis of extreme precipitation indices

The extreme precipitation indices were calculated through ClimPACT2 version 1.2.8 based on the RClimDEX software developed by the WMO CCI/WCRP Expert Team on Climate Change Detection and Indices (ETCCDI). Firstly, the data was loaded and validated for quality control before calculating the indices. The loaded data should meet some requirements: the file must be in CSV file format, and columns in the data should be in the sequence of year, month, day, rainfall (mm), minimum temperature, and maximum temperature. Missing data was be coded as -99.99, and data records was be in calendar order (Alexander and Herold, 2016). The ETCCDI-recommended 10 extreme precipitation indices which were calculated to detect changes in climate extremes for this study (Table 1).

The expert team define HIP represents high intensity related precipitation extreme; FP is frequency related precipitation extreme; DWS is dry and wet spell or duration and EX represent extra.

3. Results

3.1. Precipitation Trend and Extreme Variation

The trend analysis of annual rainfall of the Kathmandu valley-based stations depicts the rainfall variability from 847-2367 mmyr^{-1}. The Kendall's tau value was -0.28 for Godawari station showing the decreasing rainfall trend. Similarly, Sen's slope value determines that average annual rainfall decreases by -4.58 mmyr^{-1}. However, the positive value of Kendall's tau for Kathmandu airport (0.06), Khumaltar (0.07), and Panipokhari (0.11) station shows an increasing trend with average annual rainfall increasing by 4.45 mmyr^{-1}, 1.95 mmyr^{-1}, and 2.63 mmyr^{-1}, respectively. Similarly, Sen's slope value determines that average annual rainfall decreases by -12.59 mmyr^{-1} at Godavari station (Fig. 2).

The average monthly precipitation in the Kathmandu Valley ranged from 4.09 mm to 454.29 mm. The Godawari station received the maximum amount of rainfall, whereas the Khumaltar station received the minimum amount of precipitation compared to the overall five stations as shown in Fig. 2. July and August are recorded as the highest precipitation month for all stations, followed by November as the lowest precipitation month for all the stations. Nepal's rainfall pattern typically varies from 70-90% in the summer monsoon, and less rainfall occurs elsewhere. Spatially, the

Table 1. Summary of precipitation indices and definitions.

Category	ID	Name of Index	Definition	Unit
HIP	R95	Very Wet Days	Annual total precipitation on days > 95th percentile	mm
HIP	RX1day	Max 1-day Precipitation	Annual maximum 1-day precipitation	mm
HIP	RX5day	Max 5-day Precipitation	Annual maximum 5-day precipitation	mm
HIP	R99	Extremely Wet Days	Annual total precipitation on days > 99th percentile	mm
FP	R10	Heavy Precipitation Days	Annual count of days with precipitation ≥ 10 mm	days
FP	R20	Very Heavy Precipitation Days	Annual count of days with precipitation ≥ 20 mm	days
DWS	CDD	Consecutive Dry Days	Max number of consecutive dry days (precipitation < 1 mm)	days
DWS	CWD	Consecutive Wet Days	Max number of consecutive wet days (precipitation ≥ 1 mm)	days
EX	PRCPTOT	Annual Total Wet Day Precipitation	Annual total precipitation from days with ≥ 1 mm precipitation	mm
EX	SDII	Simple Daily Intensity Index	Ratio of annual total to wet days in a year	mm/day

distribution of extreme precipitations records varied seasonally in the Kathmandu valley during last three decades (Fig. 3).

The maximum precipitation records were observed 1971 mm in Monsoon, 435 mm during Pre-Monsoon, 200 mm in post-monsoon and 153 mm in winter season as shown in Figure 3. It has shown that extreme precipitation is observed higher in the Godavari and lower in the Khumaltar during all the season. In Kathmandu Valley, extreme monsoon precipitation is generally recorded from 1326 to 1971 mm during last three decade.

3.1.1. Extreme Precipitation Indices

The maximum 1-day, and 5-day precipitation for Godawari station was found in the range of 52 to 225 mm, and 121 to 476 mm respectively each year. Likewise, the maximum 1-day and 5-day precipitation was found in the range of 45.2 to 177 mm and 95.3 to 262 mm for Kathmandu airport station, 41 to 260 mm and 95 to 512.8 mm for Bhaktapur station, 34.2 to 135.4 mm and 76.2 to 240 mm for Khumaltar station and 43.5 to 151 mm and 117 to 277 mm for Panipokhari station. All stations, except Godawari station, experienced a positive RX1 and RX5 trend. However, this trend is not statistically significant. Similarly, the amount of precipitation falling above the 95th and 99th percentile was found in the range of 55.3 to 843.5 mm and 82.5 to 431.2 mm for Godawari station, 74.2 to 712.7 mm and 72.2 to 212.9 mm for Kathmandu airport station, 67.2 to 948.5 mm and 70 to 530 mm for Bhaktapur station, 36.4 to 626.5 mm to 62.4 to 239.4 mm for Khumaltar station and 43.5 to 521.6 mm and 69.8 to 307.5 mm for Panipokhari station. Except for all stations, Godawari station experienced a negative RX1day precipitation index (Fig. 4).

Frequency-related precipitation extreme represents number of heavy precipitation days (R10mm) and very heavy precipitation days (R20mm). The highest number of heavy (R10mm) precipitation days was observed in Godawari (70days) whereas lowest number of heavy precipitation days was observed in Khumaltar station. Likewise, the highest very heavy (R20mm) precipitation days were observed in Panipokhari station (42days) whereas lowest number of very heavy precipitation days was also observed in Khumaltar station (9days). All stations, except Godawari station and Khumaltar station, experienced a positive R10 trend. However, this trend is not statistically significant (Fig. 5).

Dry and wet spells or duration represents the periods of consecutive wet days (CWD) or dry days (CDD). The highest number of dry days was observed in Panipokhari station (202days) whereas the lowest number of dry days was observed in Bhaktapur and Godawari stations (22days). Likewise, the highest number of wet days was observed in Panipokhari station (32days) whereas lowest number of wet days was observed over a week in all of the stations. All stations, experienced a positive CDD trend. However, this trend is not statistically significant. Similarly, all stations experienced a negative CWD trend but this trend is not statistically significant. Extra other indices represent the annual total wet day precipitation (PRCPTOT) and simple daily intensity index (SDII). The PRCPTOT and SDII are found in the range of 816.7 to 2360. 6 mm and 8.24 to 20 mm/day respectively. All stations, except Godawari

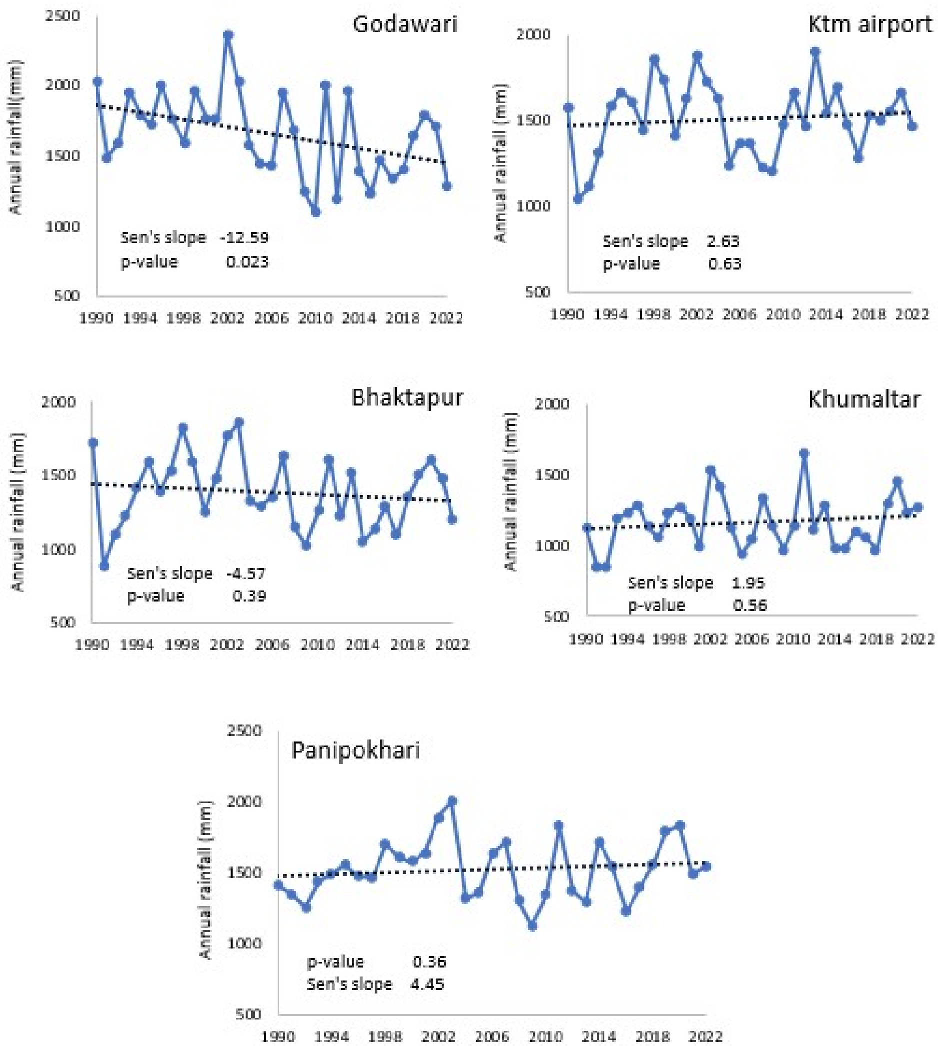

Figure 2. Mann Kendel test and Sen's slope of the annual precipitation in different five stations in the Kathmandu Valley.

station, experienced a positive PRCPTOT and SDII trend. However, this trend is not statistically significant (Table 2). This analysis shows that the consecutive dry days (CDD) have increased in all the stations in the valley. Conversely, wet days are decreased. The high-intensity precipitation extreme has been found to increase in majority of the stations i.e. in the Panipokhari and Khumaltar followed by the Bhaktapur and Kathmandu airport except RX1 indices. In Godavari, high intensity and frequency-related precipitation extremes have not increased during the last 32 years (Table 2). However, the CDD has increased by 0.8 mmyr^{-1} as it has also increased in other stations.

4. Discussion

4.1. Precipitation trends and extreme threshold in the Kathmandu valley

This study has analyzed annual/monthly precipitation trends and mapped spatially extreme precipitation in four different seasons of the Valley. All the stations of the valley were not having equal trends in which Godawari and Bhaktapur found decreasing and Panipokhari, Kathmandu Airport and Khumaltar found increasing trends during 1990-2022. Spatially, Godawari showed high rain shower in the Valley. Previous study of extreme precipitation for 35 years in Nepal showed that the frequency of the extreme precipitation is increased over the southern central Himalaya regions (Sigdel and Ma, 2016). The shift in the inter-annual precipitation threshold which may be caused by a combina-

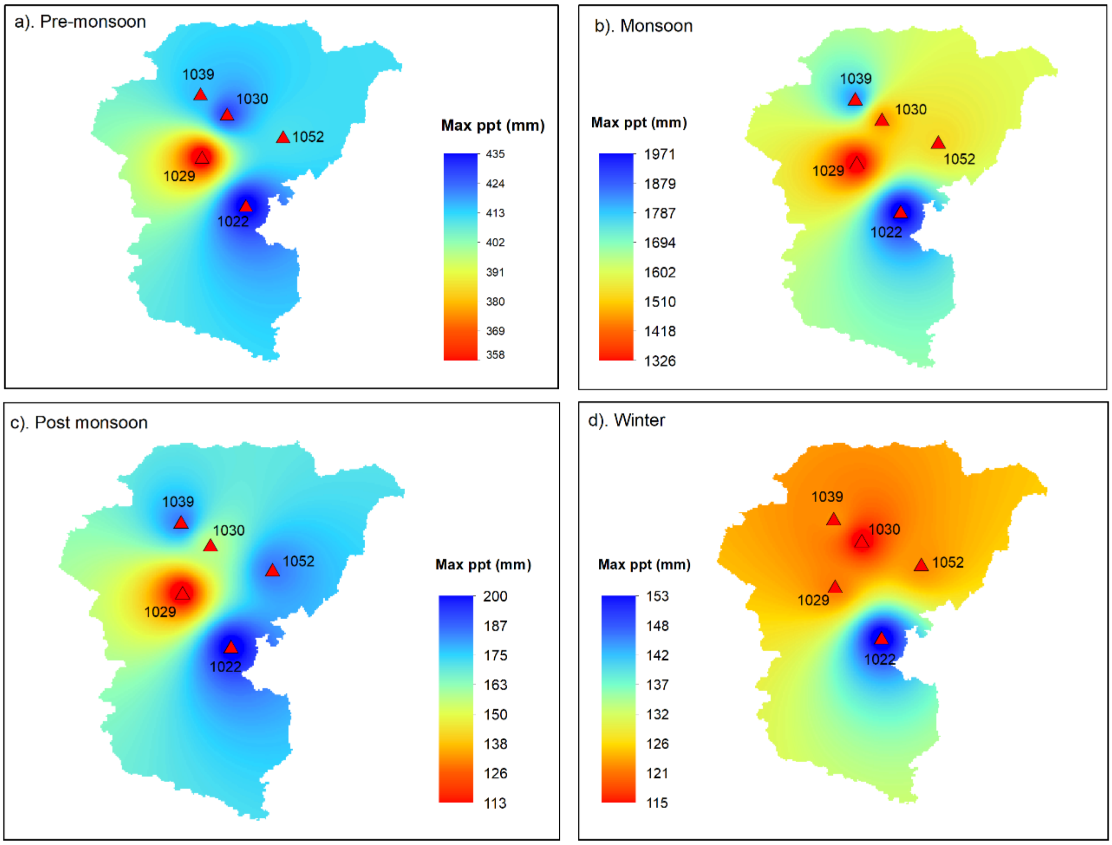

Figure 3. Maximum precipitation extreme in four different seasons in the Kathmandu Valley during 1990-2022.

Table 2. Sen's slope of extreme precipitation indices during 1990-2022 for five stations in the Kathmandu valley.

Name of Stations	Change in high intensity precipitation extremes (mm yr^{-1})				Change in frequency related precipitation extremes (mm yr^{-1})		Change in Dry/Wet spell duration (mm yr^{-1})		Change in other indices (mm yr^{-1})	
	RX1	**RX2**	**R95**	**R99**	**R10**	**R20**	**CDD**	**CWD**	**PRCPTOT**	**SDII**
Godavari	-0.72	-1.19	-4.28	-2.49	-0.26	-0.18	0.80	-0.06	-10.80	-0.05
Kathmandu Airport	-0.47	0.64	0.91	0.66	0.06	0.00	0.55	-0.07	2.77	0.00
Bhaktapur	-0.75	1.04	4.80	0.00	0.10	0.09	0.78	-0.09	5.47	0.05
Panipokhari	0.32	0.94	1.66	0.00	0.00	0.11	0.74	-0.06	5.86	0.05
Khumaltar	0.66	0.68	4.20	3.00	-0.07	-0.05	1.29	-0.00	0.81	-0.03

tion of natural variability, anthropogenic change, localized effects, and their interactions, among other factors. The reasons for this shift are extremely intricate (Karki et al., 2017). In our study, we observed the precipitation trends inside the valley with July and August are recorded as the highest precipitation month for all stations, followed by November as the lowest precipitation month for all the stations. The summer monsoon influences 81% of the annual precipitation in Kathmandu between June and September (Fig. 6).

The effect of orographic contributes in areas with short distances between sharp topographical variations. As shown in Fig. 3, the threshold of the maximum cumulative precipitation was found 435 mm, 1971 mm, 200 mm and 153 mm during Pre-monsoon, Monsoon, post-monsoon and winter seasons respectively during 1990-2022. During this study period, the extreme precipitation records of 260 mm average daily rainfall were found in Bhaktapur on August-12, 1990. In the meantime, the extreme daily precipitation records in Godawari were 225.2 mm and in Kathmandu airport was 177 mm on July 23, 2002. In the Panipokhari and Khumaltar the maximum daily records were found 151 mm and 136 mm on August 8, 2022, and July 23, 2002. It can be said that the years 2002, 1990 and

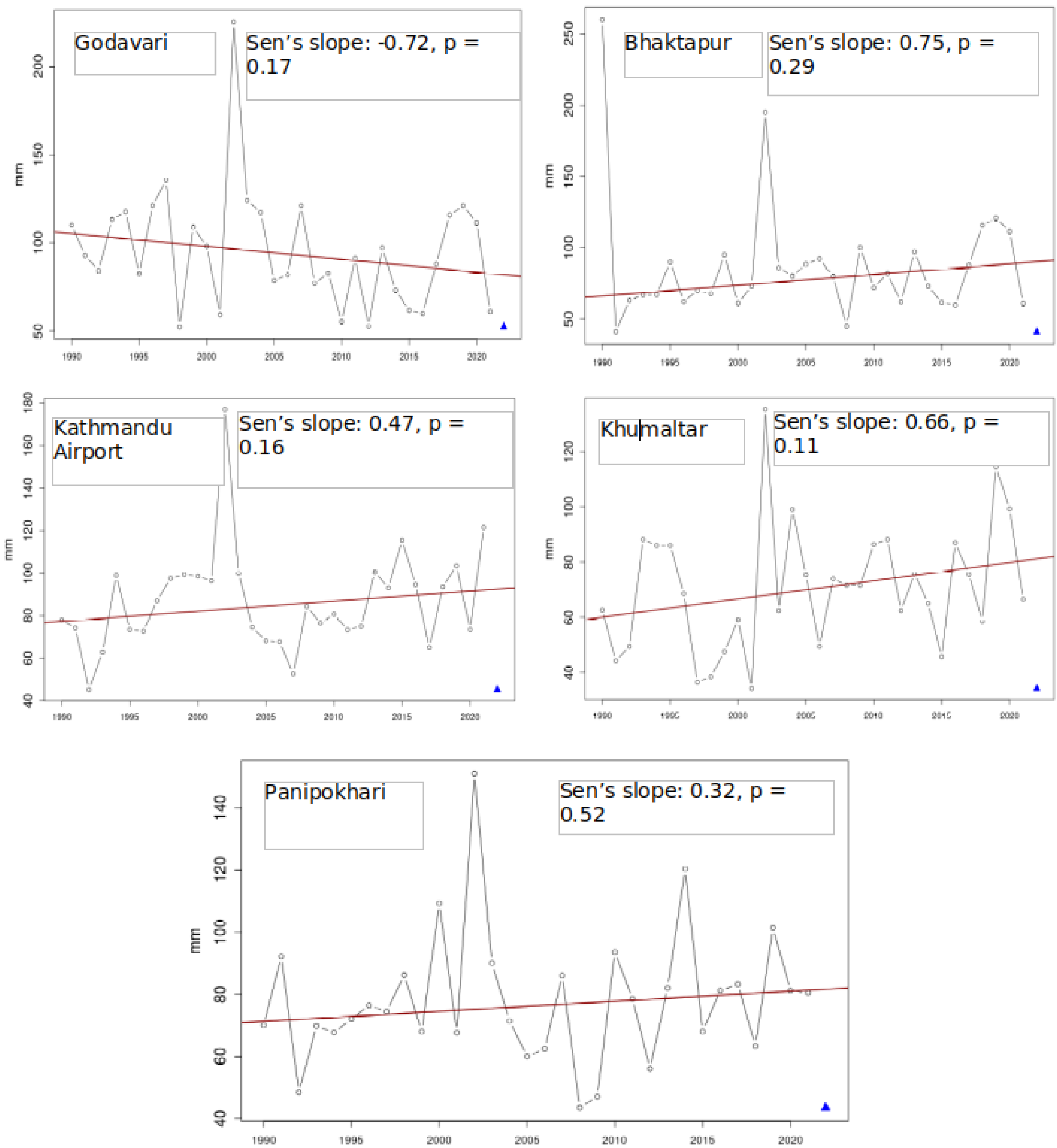

Figure 4. RX1day precipitation indices (Max 1-day precipitation amount) during 1990-2022 for five stations in the Kathmandu valley.

2022 are considered as the high precipitated year of the record during 1990-2022.

4.2. Extreme Precipitation in the Kathmandu Valley

The high Intensity related precipitation extreme represents annual maximum values of 1-day (RX1day) and 5-day (RX5day) precipitation amount within a year and the annual total precipitation over the certain long-term 95th & 99th percentile (R99 & R95). At Godawari station, annual 1-day precipitation ranged from 52 to 225 mm, while the 5-day values varied between 121 and 476 mm. Similar trends emerged at other stations like Kathmandu airport,

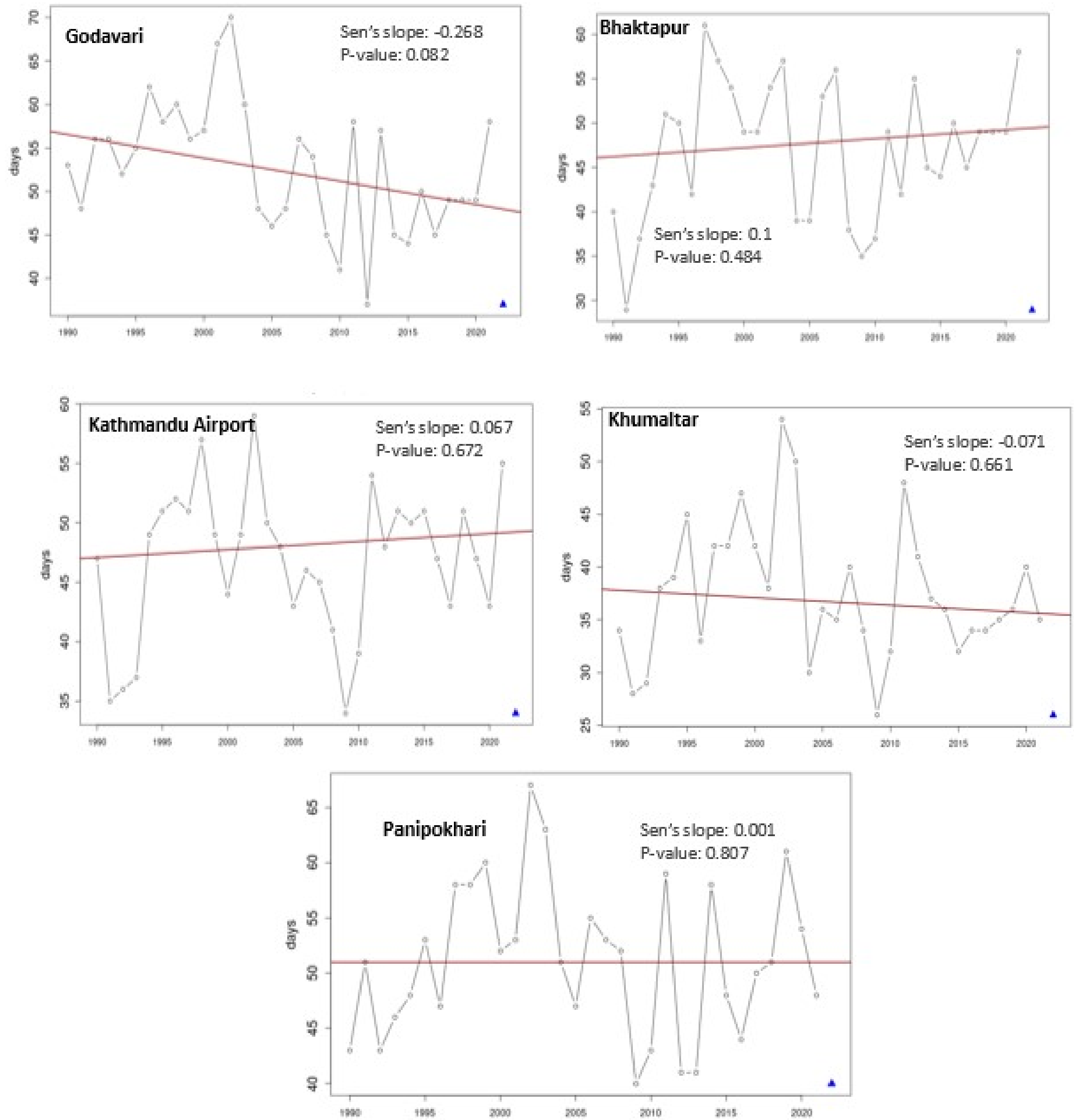

Figure 5. R10 precipitation indices (Annual number of days when precipitation is ≥10mm) during 1990-2022 for five stations in the Kathmandu valley.

Bhaktapur, Khumaltar, and Panipokhari, reflecting diverse extreme precipitation patterns. Positive but statistically insignificant trends were observed in RX1 and RX5 at most stations. Furthermore, an analysis of precipitation beyond the 95th and 99th percentiles indicated positive yet non-statistically significant trends in R95 for different stations. The seasonal extreme precipitation map of the Kathmandu valley that appeared in our study is also similar to the previous studies for all of Nepal (Duncan et al., 2013; Panday et al., 2015; Yu et al., 2008). With increased extreme precipitation days, the duration of monsoon has also changed. In 2022, the duration of monsoon was 134 days, which was twenty-two days longer than normal monsoon period (112 days) (DHM, 2022). Based on the observation from 96 stations, Nepal received more than 80% normal precipitation in June Month, 2023 (DHM, 2023)).

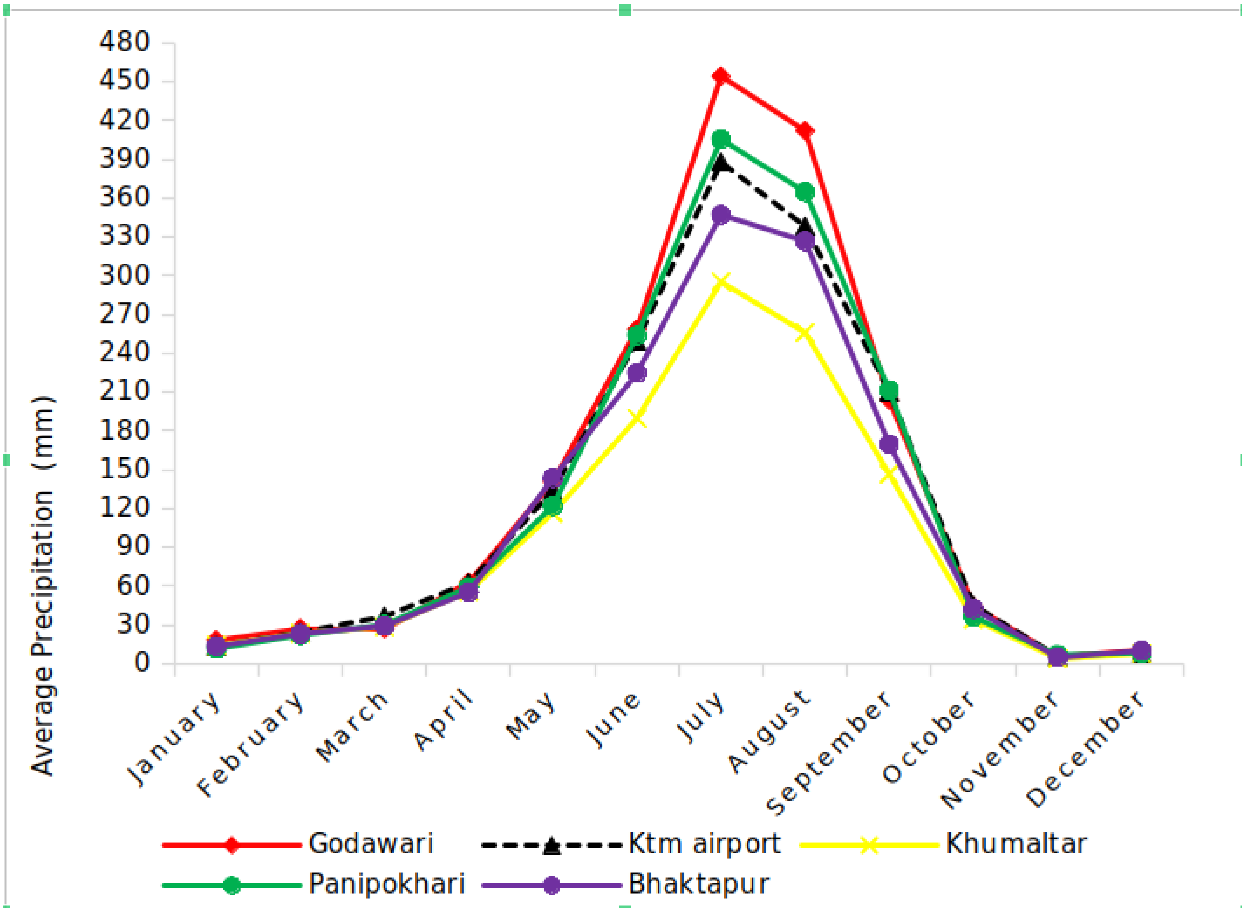

Figure 6. Average Monthly Precipitation (mm) in the Kathmandu Valley during 1990-2022.

The frequency-related extremes represent heavy precipitation days (R10mm) and very heavy precipitation days (R20mm). The outcomes unveiled fluctuations in occurrences, with Godawari exhibiting the highest number of heavy precipitation days and Panipokhari recording the most instances of very heavy precipitation. However, positive trends in R10 and R20 lacked statistical significance. The number of heavy precipitation days is higher in all the stations but the general trends of frequency of heavy precipitation events are not significantly increased with a decrease in Godawari stations. In Godawari, the number of higher precipitation days is higher but the frequency of heavy precipitation trends decreased during 1990-2022. Instead, the trends of frequency of consecutive dry days (CDD) are increased in all the stations. Similar kind of heavy precipitation days are observed in the Central Himalaya (Sigdel and Ma, 2016). The dry and wet spell durations involve consecutive wet days (CWD) and dry days (CDD). Remarkably, Panipokhari registered the highest number of dry days, while the same station recorded the peak count of wet days. Despite the observed trends in CWD and CDD, they did not achieve statistical significance consistently.

Pre-monsoon and post-monsoon rainfall in Kathmandu result from thermal convection, orographic uplift, and a shift in Nepal's circulation. While winter brings snow to higher peaks due to westerly disturbances, summer monsoons lead to increased rainfall on the windward side with altitude-dependent variations and reduced rainfall on the leeward side (Nayava, 1980). Moist air masses transported from the Bay of Bengal rise up the southern slopes of the Himalayas and fall as orographic rain (Yu et al., 2008). Our results collaborated with previous findings as the change in precipitation extremes appears statistically insignificant to temperature extreme (Klein Tank et al., 2006). The trend of precipitations lacks consistent patterns (Panday et al., 2015) which indicates that the number of extreme rainy days could be higher but the frequency of extreme precipitation may be negative or positively insignificant as we observed in Godavari. In central Himalayan regions, R10 and R95p precipitation indices indicated a period of more intense precipitation (Duncan et al., 2013) which also supports to our results. Thus, the high intensity related precipitation extreme (1day, 5day extreme, 95th, 60th percentile threshold is relatively more intense however the frequency is not positively significant.

5. Conclusion

In this study, we have examined the precipitation extreme and their intensity, duration and frequency of the extreme precipitation using observed precipitation data in Kathmandu Valley. There was no significant trend observed in average annual rainfall over the stations. Kathmandu airport, Panipokhari, and Khumaltar depicted positive trend i.e. increased by 2.63 mmyr^{-1}, 0.36 mm yr^{-1} and 1.95 mmyr^{-1} respectively. However, Godawari and Bhaktapur observed decreasing in trends i.e. decreased by -12.59 mmyr^{-1} and -4.57 mmyr^{-1} respectively during 1990-2022. The CDD are also increased more in Godavari (0.8 mmyr^{-1}) and Bhaktapur (0.78 mmyr^{-1}) compared to other stations. Monsoon season typically contributed to 70-80% of the annual precipitation with extreme precipitation records from 1326-1971 mm during monsoon season in the valley. The highest annual average record of 1668.9 mm was observed in the Godawari and lowest 1162.4 mm found in the Khumaltar during 1990-2022. Extreme precipitation indices show that the core city in the Panipokhari observed higher dry days where 32 maximum lengths of consecutive wet days (CWD) and 202 consecutive dry days (CDD) were observed. The annual total wet day precipitation (PRCPTOT) and simple daily intensity index (SDII) are found in the range of 816.7 to 2360.6 mm and 8.24 to 20 mm/day respectively. All the observed stations experienced a positive PRCPTOT and SDII trend except Godavari. However, the heavy precipitation days (R10mm) and very heavy precipitation days (R20mm) were higher in Godawari (70 days) and Panipokhari station (42 days) and lowest in Khumaltar station (9 days). The highest annual maximum values of 1-day and 5-day precipitation amount in Godawari station range from 52 to 225 mm, and 121 to 476 mm respectively with the higher annual precipitation of long-term 95th & 99th percentile. The results show that Kathmandu Valley has had frequent experience of extreme precipitation events during last three decades.

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