Spatio-Temporal Variability of Rainfall Over Kathmandu Valley of Nepal

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ABSTRACT

The present study used and analyzed rainfall data from 18 meteorological stations from 1971 to 2013 to examine the spatial and temporal variability of seasonal and annual rainfall based on rain gauge measurements. The monthly to annual rainfall analysis was carried out for each site of Kathmandu Valley. Rainfall amounts in Kathmandu Valley vary considerably in space and time. The minimum mean monthly rainfall is observed in November which is 6.5 mm and maximums of 447.8 mm in July. Monsoon is the main contributor of the rainfall which is 80% followed by pre-monsoon with 13.6%, post-monsoon with 3.6% and winter with 2.8%. Spatial interpolation was used to explore spatial variability of seasonal and annual rainfall over Kathmandu Valley. There is large spatial variability of monsoon rainfall; generally, the upper parts of the Kathmandu Valley received the heavy monsoon rainfall than the lower parts of the Valley floor. The rainfall of Kathmandu has marked decreasing in recent a couple of decades. Annual rainfall has decreased by 0.96 mm/year observed in Kathmandu Valley.

Keywords: Rainfall variability, Seasons, Trends, Kathmandu.

1. Introduction

Rainfall is one of the key climatic variables that affect both the spatial and temporal patterns of water availability. One of the challenges posed by climate change/climate variability is the ascertainment, identification and quantification of rainfall and its trends (De Luis et al., 2000). Rainfall in Asia varies sharply over a wide range of periods (Yao et al., 2010). The fluctuations in the Asian monsoon circulation have long been thought to be related to the intra-seasonal and inter-annual variability of the rainfall (Webster et al., 1998; Yao et al., 2010; Wang et al., 2020). It is also linked to the variations of sea surface temperature (SST) over the Pacific and Indian Ocean (Wu and Qian, 2003; Varikoden et al., 2015), Eurasian land surface process (Wu and Qian, 2003; Yasunari, 2007), and large-scale atmospheric circulation patterns such as El Nino southern oscillation (ENSO) (Fan et al., 2017; Wang et al., 2020), the Arctic Oscillation and westerly circulations (Wang et al., 2020) have been considered important factors contributing to the year to- year variability of rainfall over Asia. Strong El Niño/ La Nino episodes develop into weak/strong monsoon and drought/flood in the South Asian region (Fan et al., 2017). In South Asia monsoon rainfall has decreased in the past couple of decades (Kumar et al., 2013). El Niño characterized by the warming of surface temperatures in the Pacific Ocean as well as the Indian Ocean, is associated with the weak monsoon in South Asia (Varikoden et al., 2015; Wang et al., 2020). South Asian countries are strongly affected by the Indian summer monsoon. It has large inter-seasonal rainfall variability links with the ENSO (Bhalme and Jadhav, 1984; Webster et al., 1998). In recent decades the monsoon rainfall has marked decreasing in India, Bangladesh, and Nepal (Ahasan et al., 2010; Varikoden et al., 2015; Bagale et al., 2023).

Nepal observes almost 80% of the annual rainfall received within the monsoon months of June to September and faces scarcity of rainfall in the rest 8 months of the year (Ichiyanagi et al., 2007). A comparison of the precipitation time series with the ENSO 3.4 index reveals a strong correlation between ENSO and the variability in monsoon precipitation (Bohlinger and Sorteberg, 2018; Bagale et al., 2021). Some studies exist concerning Nepalese rainfall variability (Shrestha et al., 2000; Kansakar et al., 2004; Baidya et al., 2008; Sigdel and Ikeda, 2012; Shrestha et al., 2012; Karki et al., 2017). However, there are countable rainfall studies examined in Kathmandu Valley (Nayava, 1981; Devkota, 2005). Nayava (1981) used less than 10 years of data from 11 stations and identified the seasonal and annual rainfall. Devkota (2005) was studied using 14 stations including Kakani station's monthly rainfall. It was taken and analyzed only three stations of Thankot, Godawari and Kathmandu Airport for long-term annual variations of rainfall. The rainfall analysis information provides insight into the availability of water. The availability of water sufficient to meet the water needs or scarcity in the

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region is the one of important local issues of Kathmandu Valley, where more than 2.5 million people live. Through this study, an attempt has therefore been made to study the mean monthly rainfall variability, seasonal rainfall totals and percent-wise different location's rainfall in monsoon and annual rainfall trends of the Valley from long-term climatic data series (1971 to 2013). This study also examines relatively drier, wet and normal locations of the Valley. However, this is the study that has taken as long-term data as possible to quantify and map the seasonal rainfall, percent-wise monsoon rainfall over different stations, and spatial annual rainfall trends of 18 stations over Kathmandu Valley.

The main objective of the study is to investigate the spatial and temporal variability of rainfall over Kathmandu Valley. The specific objectives are to (i) Identify the percent-wise monsoon rainfall variability; and (ii) study of decreasing/increasing trends of annual rainfall in Kathmandu Valley.

2. Materials and Methods

2.1. Study Area

Kathmandu Valley is surrounded by hills with forest on all sides. The study area of the Valley is around 932 km^2. The Valley floor is relatively flat. Kathmandu experiences the monsoon rainfall from June to September. Most of the days are cloudy with heavy rainfall, and incessant rains are common during these months. About 80 percent of the annual precipitation in the Valley was observed from June to September under the influence of the monsoon circulation (Nayava, 1981). The amount of rainfall varies considerably from place to place because of topographic variations. During October the Valley receives a few spells of post-monsoon thunder showers similar in character to the pre-monsoon. The winter months are dry with clear sky. However, few spells of rain do occur during December, January and February. From March to May the Valley experiences pre-monsoon thunder showers. The spatial distributions of the meteorological stations are shown in Figure 1 and details are tabulated in Table 1.

2.2. Data Used and Methodology

The daily rainfall of 18 weather stations which have continuous data series as long as possible were taken from time period 1971 to 2013 and shorter not less than 14 years in the study acquired from the Department of Hydrology and Meteorology, Government of Nepal. Monthly total rainfall values were obtained by summing up daily rainfall data. Annual, seasonal, and monthly means were calculated for all stations using the arithmetic mean method. Similarly, the annual total rainfall data were calculated by adding monthly total rainfall data from January to December. Furthermore, monthly rainfall was divided into four seasons: monsoon (June to September), post-monsoon (October and November), pre-monsoon (March to May) and cold winter (December– February). Rainfall analysis at each station was computed after completing the missing data. Stations were selected based on less than 10% missing records. We have adopted the Normal ratio method (NR) to estimate missing rainfall values of climate datasets from nearby three weather stations. The NR method was selected to estimate the missing daily rainfall values since similar studies have found that it outperformed other daily rainfall infilling methods during the use of two to five index gauges (Mair and Fares, 2011). The missing data are estimated by:

$$P_x = \frac{1}{n}\sum_{i=1}^{\cdot} n\left[\frac{N_x}{N_i}\right] P_i \tag{1}$$

where
P_x = estimate of the missing value
P_i = rainfall values of rain gauges used for estimation
N_x = mean annual precipitation of X station
N_i = mean annual precipitation of surrounding station
n = number of surrounding stations

Seasonal and annual rainfall was interpolated and visualized by using inverse distance weighted (IDW) technique (Patel et al., 2007). We have used the IDW interpolation technique to explore the spatial variability of seasonal and annual rainfall over a basin by using a Geographic Information System (GIS). The Student's t-test was used to test the significance of the rainfall data series. The nonparametric rank-based Mann-Kendall test was performed to check the trends of the time series dataset.

2.3. Mann-Kendall Test (MK)

MK test is the rank-based non-parametric test and has recently been used by several researchers to detect trends in rainfall data (Taxak et al., 2014; Subash and Ram Mohan, 2011).

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} Sgn(x_j - x_k) \tag{2}$$

Test statistic S is defined as:

$$S = Sgn(x_j - x_k) \tag{3}$$

where n is the length of the data set. X_j and X_k are the annual values in years j and k, j>k respectively.

$$\mathrm{Sgn}(x_j - x_k) = \begin{cases} 1, & \text{if } x_j - x_k > 1, \\ 0, & \text{if } x_j - x_k = 0, \\ -1, & \text{if } x_j - x_k < 0. \end{cases} \tag{4}$$

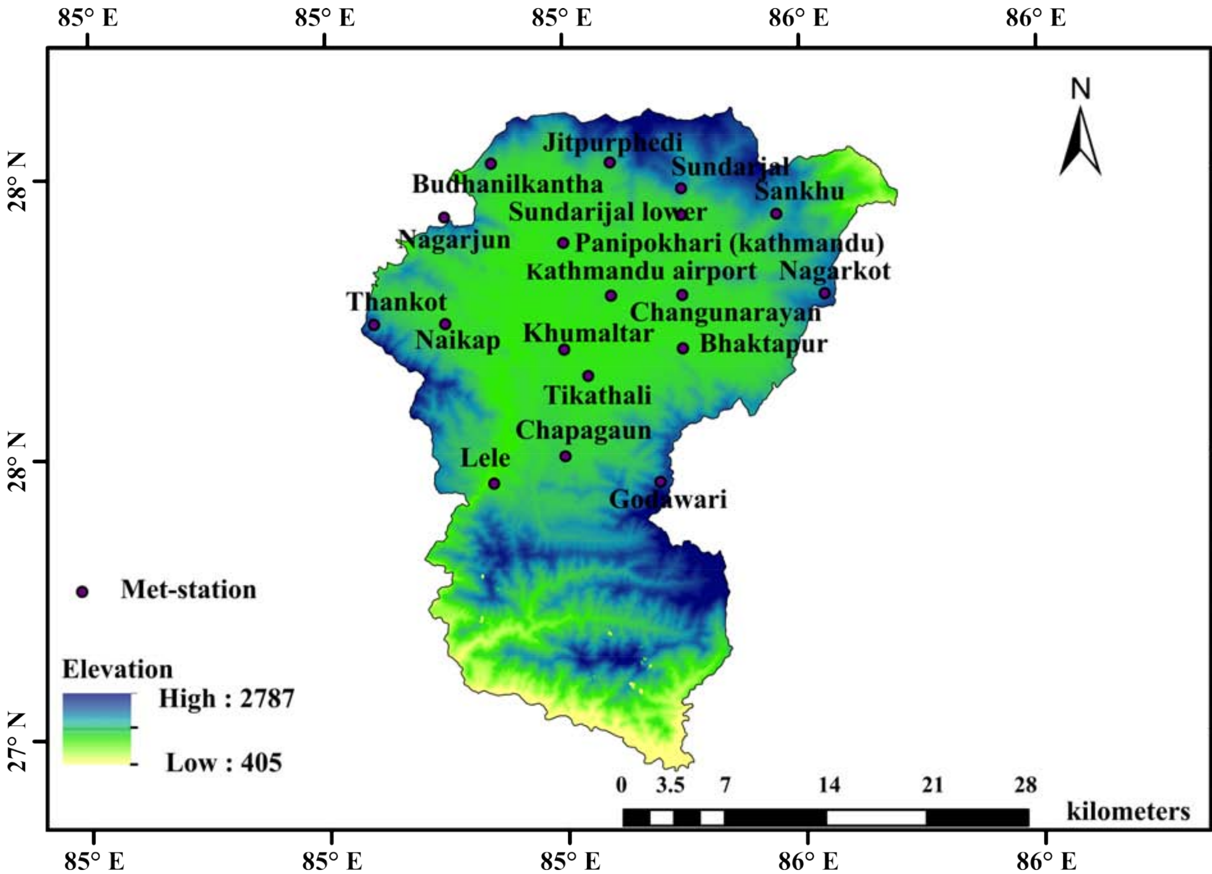

Fig. 1. Location map of the study area along with rainfall stations used in this study.

Table 1. List of Meteorological stations used in this study.

Index No.	Station name	Latitude ($^\circ N$)	Longitude ($^\circ E$)	Altitude (m.a.s.l.)	Data periods in years
1015	Thankot	27.68	85.20	1630	43
1022	Godawari	27.58	85.40	1360	42
1029	Khumaltar	27.67	85.33	1050	39
1030	Kathmandu airport	27.70	85.37	1037	43
1035	Sankhu	27.75	85.48	1449	43
1039	Panipokhari	27.73	85.33	1335	43
1043	Nagarkot	27.70	85.52	2163	43
1052	Bhaktapur	27.67	85.42	1330	43
1059	Changunarayan	27.70	85.42	1543	40
1060	Chapagoan	27.60	85.33	1448	38
1071	Budhanilkantha	27.78	85.37	1350	26
1074	Sundharijal	27.77	85.42	1490	20
1075	Lele	27.62	85.28	1590	20
1076	Naikap	27.68	85.25	1520	17
1077	Sundharijal lower	27.50	85.42	1360	17
1079	Nagarjun	27.75	85.25	1690	16
1080	Tikathali	27.65	85.35	1341	14
1081	Jitpurphedi	27.783	85.28	1320	14

It has been documented that when N≥10, the statistic S is approximately normally distributed the variance as

$$\mathrm{VAR}(S) = \frac{1}{18}\left[n(n-1)(2n+1) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)\right] \tag{5}$$

Here, q is the number of tied groups and t_p is the number of data values in the pth group. The standard test statistic Z is computed by

$$Z = \begin{cases} \frac{S-1}{\mathrm{VAR}(S)}, & \text{if } S > 0, \\ 0, & \text{if } S = 0, \\ \frac{S+1}{\sqrt{\mathrm{VAR}(S)}}, & \text{if } S < 0. \end{cases} \tag{6}$$

3. Results

3.1. Rainfall Statistics

The monthly precipitation Metrics from 1971 to 2013 revealed that the rainfall strongly increased from May, with the highest in July due to the influence of summer monsoon rainfall while the lowest recorded in November is clearly shown in (Figure 2). However, winter precipitation (December-February) is significant as it accounts for approximately 2.8% of Kathmandu's total annual rainfall. The rainfall of Kathmandu is primarily dominated by the monsoon from June to September, with about 80% received in monsoon seasons characterized by high rainfall followed by pre-monsoons with 13.6%, and post-monsoons 3.6%. The mean seasonal rainfall of the Kathmandu Valley is shown in the pie chart of Figure 2.

3.2. Annual Average Rainfall and its Trends

Monsoon is the main contributor to the total annual rainfall. There is large spatial variability of mean annual rainfall varies from place to place; the highest rainfall received was 2,234 mm in Godawari station and the second in Sundarijal 2,214.97 mm. However, the Northeast part of the Valley received more rainfall than the Valley floor. Similarly, the lowest rainfall was received at 1,222.6 mm in Khumaltar; the remaining stations mean annual rainfall (mm) is clearly depicted in Table 2. However, the spatial distribution of the total mean annual rainfall was observed clearly on the isohyetal map (Figure 3a). Generally, the upper parts of the Kathmandu Valley received heavier annual rainfall than the lower parts of the Valley floor.

Using the MAKESENS Template, Non-parametric Mann-Kendall trend identified the increasing or decreasing annual rainfall trends depending on the Z value of individual stations over different regions of Kathmandu Valley is tabulated in Table 2. For this, we have used annual rainfall for the time period (1971 to 2013). Annual rainfall trends over Kathmandu identified most of the regions showed a decreasing trend (Figure 3b).

Overall eighteen stations, our results exhibited five stations showing increasing trends and thirteen stations showing decreasing trends in Kathmandu Valley (Table 2). However, one station shows a significant increase, and five stations show a significant decrease in different regions over Kathmandu. Most of the Valley's stations showed a decreasing annual rainfall trend. Out of them, Sundharijal observed the largest decreasing significant trend. This study identified the average annual rainfall decreased by 0.94 mm/year during the period 1971 to 2013.

3.3. Average Seasonal Rainfall

The winter season mostly affects the western parts of the Valley and results in snowfall in the high mountains and cold situations happening in the valley. Winter (December - February) is the driest season contributing 2.8% of the total annual rainfall. Winter rainfall is very important for the winter crops and tunneling vegetable farming over the valley. The spatial variations of rainfall are clearly shown in the isohyetal map (Figure 4a). In this season, the highest rainfall received in Thankot was 61.84 mm and the lowest rainfall received in was Panipokhari 36.37 mm.

During the pre-monsoon (March to May), the valley occurrences thundershowers and hailstorm activity associated with thermal convection due to an increase in solar insolation combined with the orographic effect. Premonsoon season received 13.6% of the total annual rainfall which is the second highest rainfall season after the recorded monsoon season during the study period. The highest rainfall received in was Sundarijal 304.42 mm and the lowest rainfall was received in Chapagoan 176.36 mm. Spatial variability of pre-monsoon rainfall is depicted as shown in the isohyetal map (Figure 4b).

Monsoon season is the wettest and is the main source of rainfall in Kathmandu Valley. The highest rain occurs during monsoon and comes from the southwest Indian monsoon originating from the Bay of Bengal. Monsoon contributes on average 80% of the total annual rainfall. The highest rainfall was received in Sundarijal station at 1803.85 mm, and the lowest rainfall was received in Khumaltar at 929.04 mm. Spatial variation of rainfall during the monsoon is clearly shown in the isohyetal map (Figure 4c).

During the post-monsoon season (October and November), Kathmandu Valley has received an average of 3.6% of the total annual rainfall. The character of the rainfall is similar to the pre-monsoon rainfall. November receives the lowest rainfall of the year. The spatial distribution of post-monsoon rainfall is similar to the pre-monsoon and monsoon seasons. In this season Panipokhari received the highest rainfall 89.95 mm and Chapagoan received the lowest rainfall 48.06 mm. The spatial variation of post-monsoon rainfall is shown in the isohyetal map (Figure 4d).

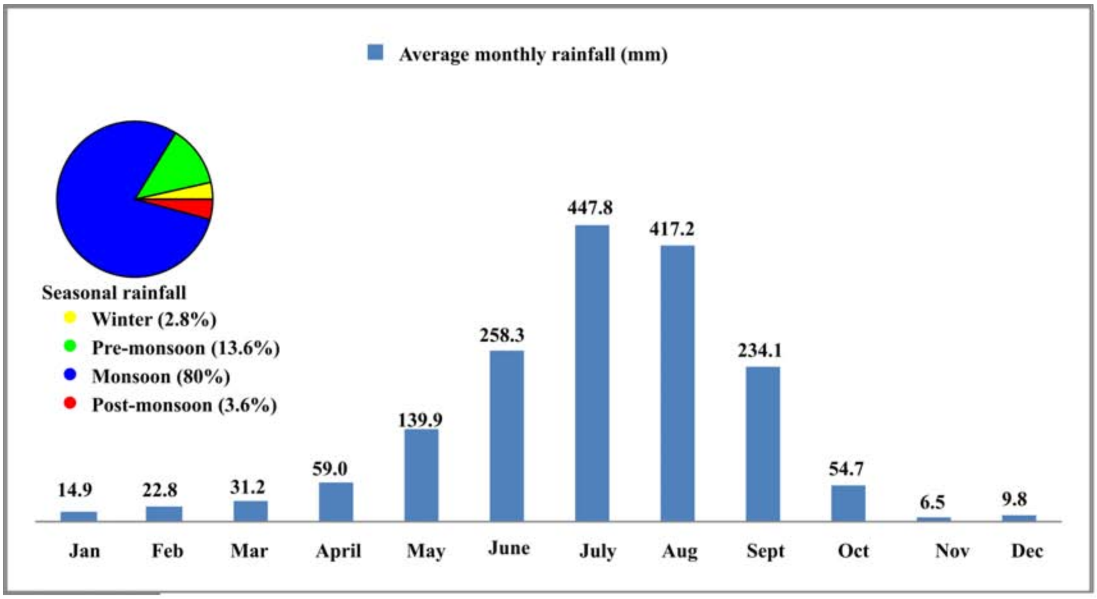

FIG. 2. Variability of (a) Monthly rainfall (mm) averaged from 1971 to 2013 and Pie chart shows the seasonal amount of rainfall (%).

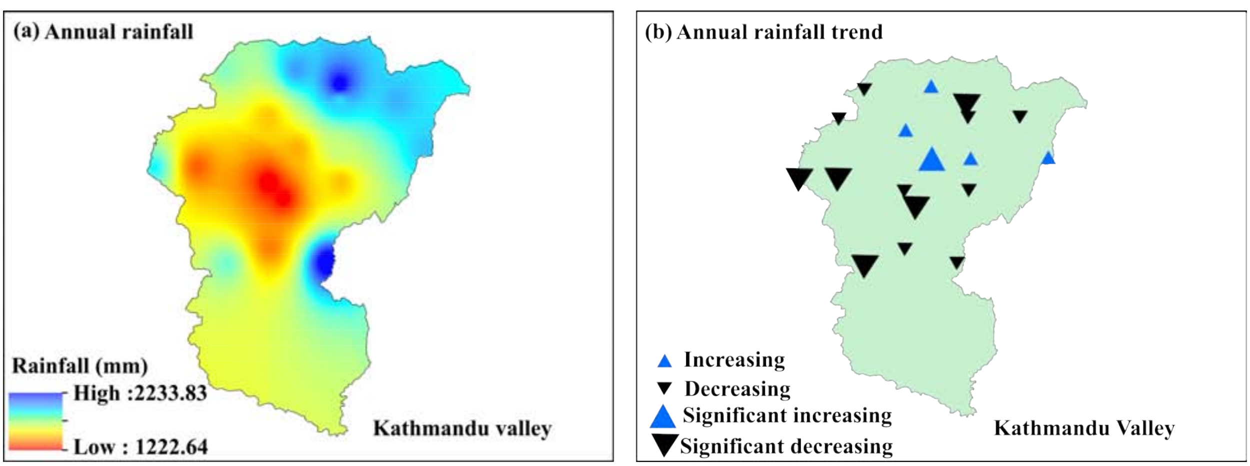

FIG. 3. Annual rainfall trends mm/year from 1971 to 2013.

3.4. Spatial Distribution of Percent Rainfall During Monsoon

The monsoon rainfall for each of the stations has been expressed as a percent of annual rainfall. Sankhu, Sundharijal, Nagarkot, Jitpurphedi and Nagarjun of Kathmandu receive about 81% of the annual rainfall during the monsoon which is the highest over Kathmandu and lowest about 75% of annual rainfall during the monsoon occurs at Tikathali and Khumaltar about 79% Bhaktapur, Changunarayan, Naikap and Thankot. An average of about 80% of the annual rainfall is received over Kathmandu during the monsoon season. The spatial distribution of this monsoon rainfall in percent over Kathmandu is clearly shown in (Figure 5). This study indicates that Kathmandu is getting the major portion of the annual rainfall during the monsoon. With some exceptions, rainfall slightly increases with height.

3.5. Temporal Variability of Seasonal and Annual Average Rainfall

This study used 18 stations for average rainfall to produce the temporal variability of seasonal and annual rainfall (Figure 6). The average seasonal (monsoon and winter) rainfall of the valley is 1357.4 mm/monsoon and 47.1 mm/winter from long-term climatology for the period 1971–2013. Similarly, the average annual precipitation of

Table 2. Non-parametric Mann-Kendall trend gives Z value of different stations annual rainfall of different duration's. (Negative Z value indicates decreasing trend of rainfall, ** Represents 0.01 level of significance, * Represents 0.05 level of significance, + Represents 0.1 level of significance, Blank represents level of significance greater than 0.1).

Station	First Year	Last Year	Data Year	Z Test	Significant	Annual mean rainfall (mm)
1015	1971	2013	43	-1.99	*	1859.33
1022	1971	2012	42	-1.26		2234.02
1029	1975	2013	39	-0.02		1222.55
1030	1971	2013	43	1.72	+	1453.23
1035	1971	2013	43	-1.53		1948.13
1039	1971	2013	43	0.28		1486.75
1043	1971	2013	43	0.59		1930.01
1052	1971	2013	43	-1.19		1478.02
1059	1974	2013	40	0.62		1682.10
1060	1976	2013	38	-1.16		1387.05
1071	1987	2012	26	0.22		1975.16
1074	1994	2013	20	-2.82	**	2214.97
1075	1994	2013	20	-1.85	+	1795.68
1076	1997	2013	17	-1.77	+	1345.97
1077	1997	2013	17	-1.52		1901.62
1079	1998	2013	16	-1.22		1602.93
1080	2000	2013	14	-2.41	*	1239.97
1081	2000	2013	14	-1.53		1773.46

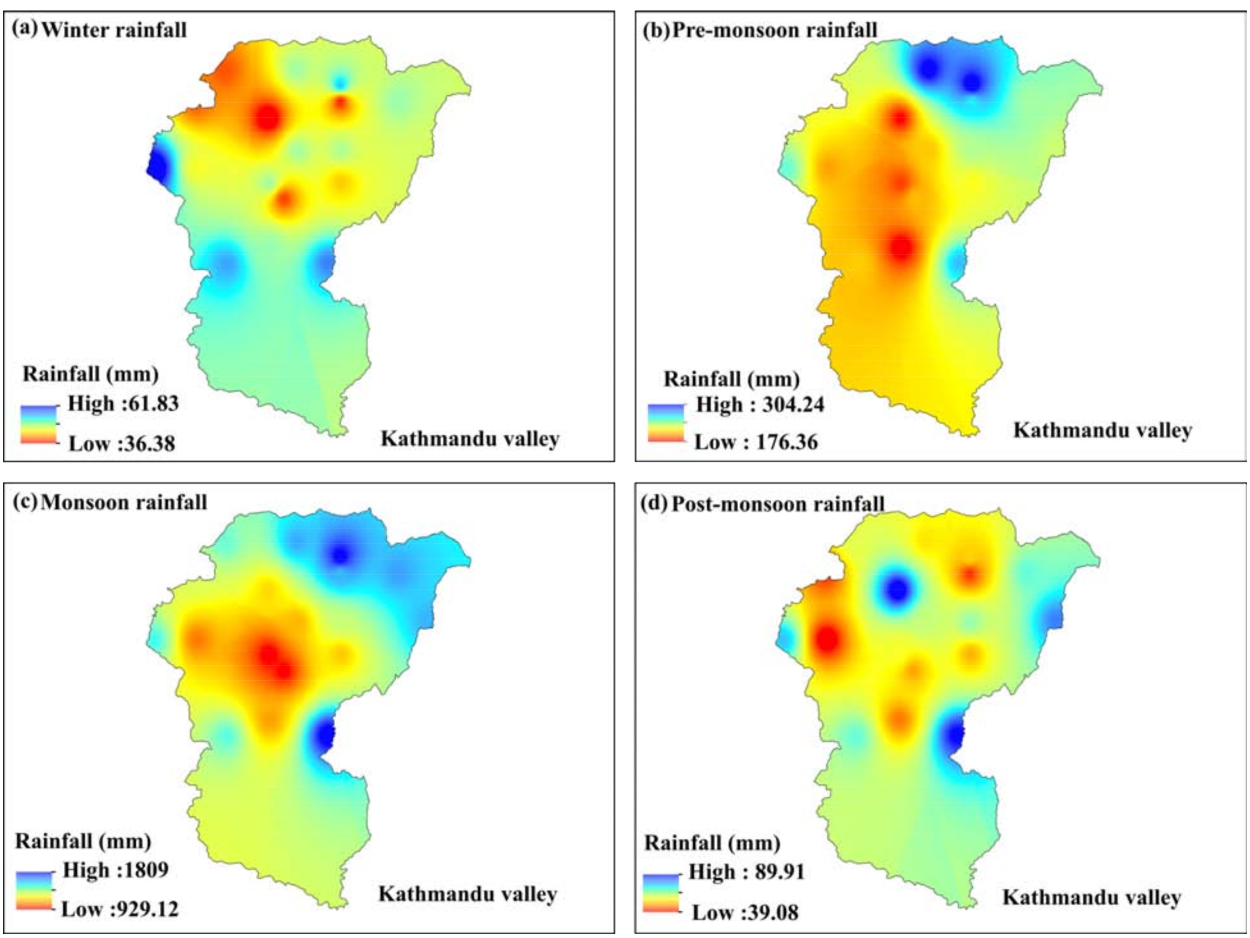

Fig. 4. Spatial distribution of mean seasonal precipitation (mm) for winter season (a); pre-monsoon (b); monsoon (c); and post-monsoon (d) season over period of 1967 to 2013. Note legend scales of all four seasonal maps are different.

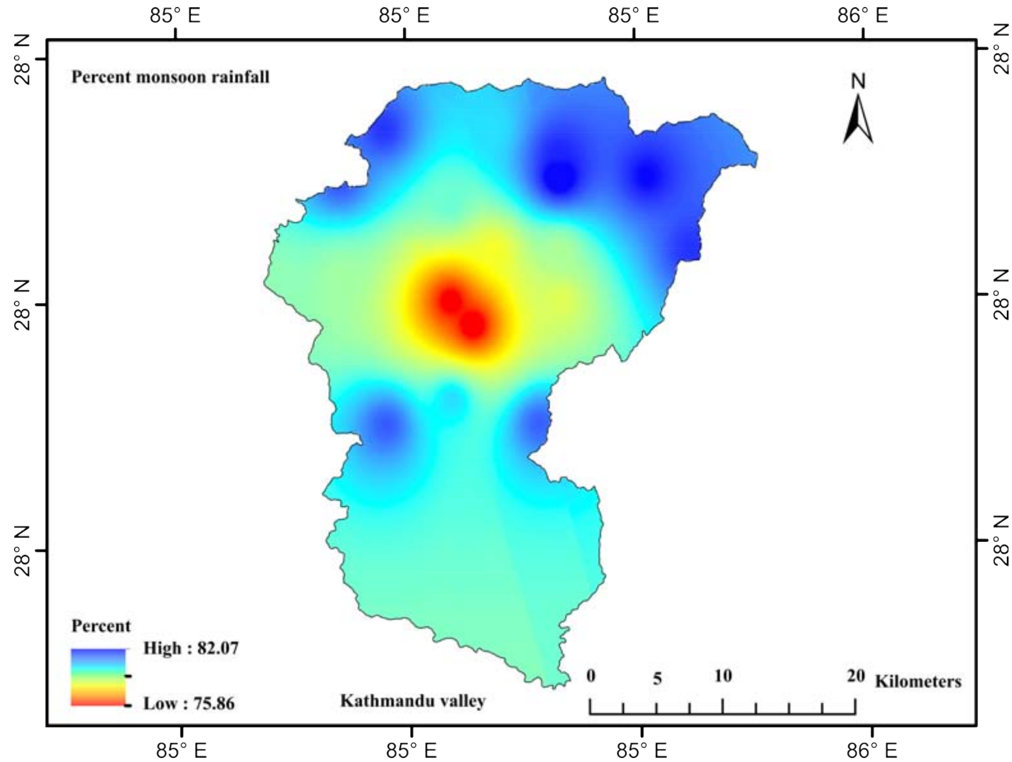

FIG. 5. Spatial distribution of percent monsoon rainfall in different locations of the valley.

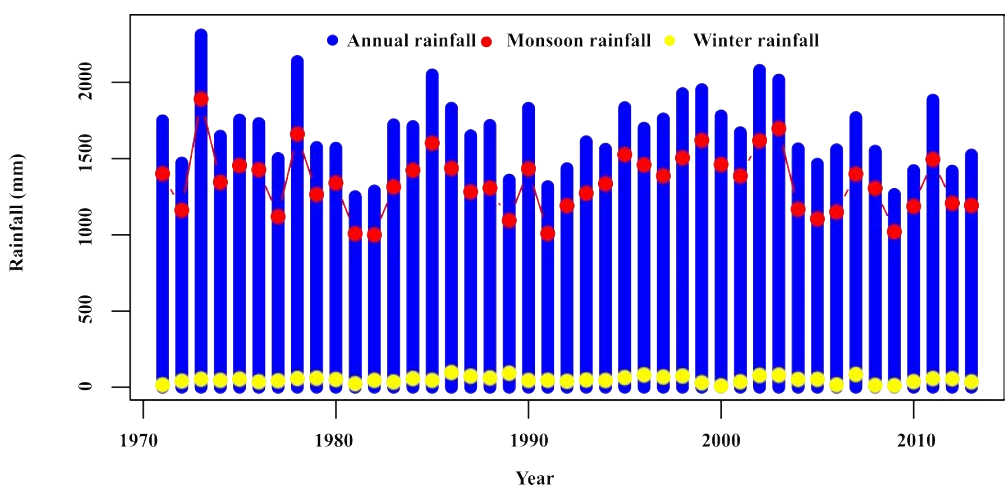

FIG. 6. Temporal variability of seasonal and annual rainfall in Kathmandu from 1971 to 2013 averaged from 18 stations.

the valley is 1696.2 mm/annual from long-term climatology. There is a large intra-seasonal variation between summer and winter seasons. During the monsoon season, the temporal variability varies from minimum rainfall in year the 1982 and maximum in the year 1973. Similarly, the variability of winter rainfall was observed at a minimum in the year 2009 and a maximum in the year 1989. Generally, the monsoon rainfall dominates the annual rainfall, with the maximum annual rainfall observed in the year 1973 and the minimum rainfall observed in 1981. The temporal variability of seasonal and annual rainfall during the study period is clearly shown in Figure 6.

3.6. Wet and Dry Areas

The long-term annual average rainfall was high at the Godawari station and minimum at the Khumaltar. Figure

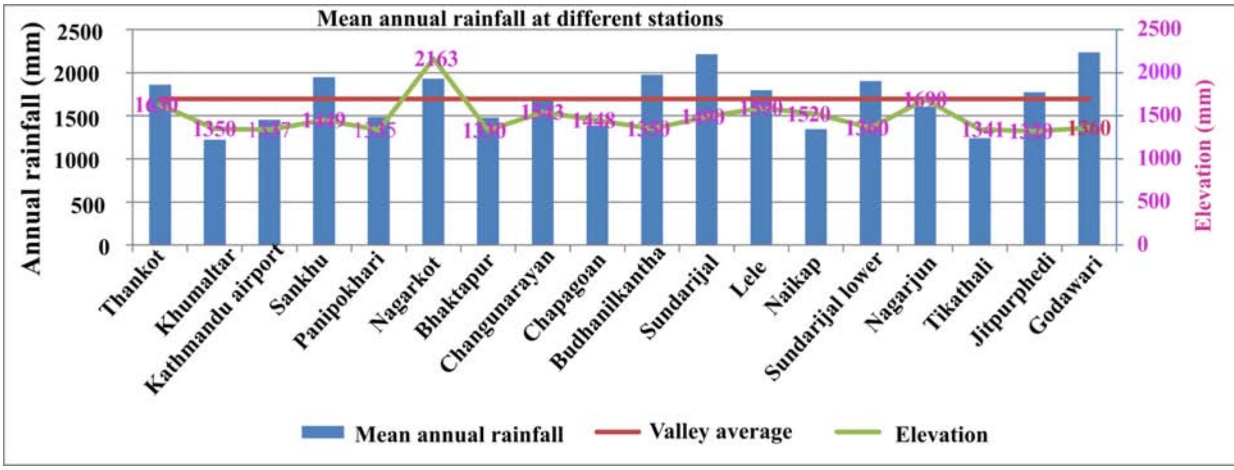

Fig. 7. Annual average rainfall of different locations of the valley 1971-2013.

7 shows the clear spatial variation of rainfall on different stations in the Valley. Godawari, Jitpurphedi, Sundarijal, Lele, Buddhanilkantha, Nagarkot, Sankhu and Thankot are the wet regions of the valley. Similarly, Khumaltar, Kathmandu airport, Panipokhari, Bhaktapur, Chapagoan, Naikap, Nagarjun and Tikathali are the relatively drier locations and the rest of them are the normal locations of the Valley. Generally, the higher elevations of the Kathmandu Valley received heavier rainfall than the lower flat parts (Figure 7).

4. Discussions

Almost 80% of the annual rainfall is received within the monsoon months; followed by pre-monsoons at 13.6%, post-monsoons at 3.6% and winters at about 2.8%. Kathmandu is flooded with rain in monsoon and faces rain scarcity or drought in the rest 8 months of the year. A similar result was identified from the previous study (Nayava, 1981). Similarly, Ichiyanagi et al. (2007) noticed Nepal flooded during monsoon months and faced water scarcity for the rest eight months.

The trend analysis identified that annual rainfall has decreased (0.96 mm/year) in Kathmandu Valley during the study periods. A similar result was identified that the seasonal and annual rainfall has been decreasing in Nepal for a few decades (**?**). Likewise, according to Ahasan et al. (2010) monsoon rainfall has decreased (0.53 mm/year) in Bangladesh during the study period 1961 to 2010. The region behind the decreasing rainfall was the weakening of monsoon rainfall in summer and westerly in winter.

A previous study Taxak et al. (2014) examined long-term spatial and temporal rainfall trends in the Waingana Basin of central India which concluded that annual and monsoon rainfall decreased during the study period from 1901 to 2012. The results of the present study have indicated that after 1990 the rainfall was remarkably decreasing (Figure 6). The region behind this may be the monsoon of Kathmandu is greatly affected by the southwest Indian monsoon system which has been decreasing in recent decades (Kumar et al., 2013; Varikoden et al., 2015). Similar results presented by Kumar et al. (2013) in South Asia the monsoon rainfall has been shown to decrease during a couple of recent decades.

There are different rainfall dynamics in different seasons in Kathmandu Valley. There was large temporal variability in seasonal and annual rainfall clearly shown in (Figure 6). The year 1978 was the wettest in monsoons and 1982 was the driest. Likewise, 1973 was the wettest episode in winter and 2009 was the driest episode. Moreover, rainfall has been decreased in Kathmandu after 1980. In the El Nino years 1982, and 2009, Nepal was dominated by deficit monsoon rainfall (Bagale et al., 2023). Similar results indicated by Acharya et al. (2011) in India, 2009 was the strong dry event. Furthermore, in recent decades, some researchers identified in their studies that the interdecadal weakening of the South Asian Summer Monsoon frequently after 2000 in South Asian countries (Fan et al., 2017; Varikoden et al., 2015; Kumar et al., 2013). Those studies support the findings of temporal variations of rainfall as reported in the present study.

5. Conclusion and Recommendation

This study provided concise knowledge about the temporal and spatial variability of seasonal and annual rainfall in Kathmandu during the past few decades (1977–2013). July is the wettest month and November driest. Kathmandu is flooded during the monsoon season and the rest of the eight months faces water scarcity. There is a large spatial variability of rainfall in Kathmandu Valley. The upper parts of the Kathmandu Valley received more seasonal and annual rainfall than the lower parts. The average annual rainfall of the Kathmandu Valley was 1696.2 mm/year during the study period. The year 1982 received the least monsoon rainfall. Likewise, the worst winter rainfall was recorded in 2009. The deficit rainfall has been recorded frequently after 1980 both in summer and winter seasons. The seasonal and annual rainfall quantification identified that in recent decades the rainfall is markedly decreasing. The present study concluded that annual rainfall decreased by 0.96 mm/year during the period 1971 to 2013.

We suggest that further study of extreme events and their linkage with atmospheric circulation will be useful to flood and drought assessment.

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References

Acharya, N., S. C. Kar, U. Mohanty, M. A. Kulkarni, and S. Dash, 2011. Performance of gcms for seasonal prediction over india—a case study for 2009 monsoon. *Theoretical and applied climatology*, 105, 505–520.

Ahasan, M., M. A. Chowdhary, and D. Quadir, 2010. Variability and trends of summer monsoon rainfall over bangladesh. *Journal of Hydrology and Meteorology*, 7 (1), 1–17.

Bagale, D., M. Sigdel, and D. Aryal, 2021. Drought monitoring over nepal for the last four decades and its connection with southern oscillation index. *Water*, 13 (23), 3411.

Bagale, D., M. Sigdel, and D. Aryal, 2023. Influence of southern oscillation index on rainfall variability in nepal during large deficient monsoon years. *Journal of Institute of Science and Technology*, 28 (1), 11–24.

Baidya, S. K., M. L. Shrestha, and M. M. Sheikh, 2008. Trends in daily climatic extremes of temperature and precipitation in nepal. *Journal of Hydrology and Meteorology*, 5 (1), 38–51.

Bhalme, H., and S. Jadhav, 1984. The southern oscillation and its relation to the monsoon rainfall. *Journal of climatology*, 4 (5), 509–520.

Bohlinger, P., and A. Sorteberg, 2018. A comprehensive view on trends in extreme precipitation in nepal and their spatial distribution. *International Journal of Climatology*, 38 (4), 1833–1845.

De Luis, M., J. Raventós, J. González-Hidalgo, J. Sánchez, and J. Cortina, 2000. Spatial analysis of rainfall trends in the region of valencia (east spain). *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 20 (12), 1451–1469.

Devkota, L. P., 2005. Rainfall analysis of the kathmandu valley. *Journal of Hydrology and Meteorology*, 2 (1), 34–40.

Fan, F., X. Dong, X. Fang, F. Xue, F. Zheng, and J. Zhu, 2017. Revisiting the relationship between the south asian summer monsoon drought and el niño warming pattern. *Atmospheric Science Letters*, 18 (4), 175–182.

Ichiyanagi, K., M. D. Yamanaka, Y. Muraji, and B. K. Vaidya, 2007. Precipitation in nepal between 1987 and 1996. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 27 (13), 1753–1762.

Kansakar, S. R., D. M. Hannah, J. Gerrard, and G. Rees, 2004. Spatial pattern in the precipitation regime of nepal. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 24 (13), 1645–1659.

Karki, R., S. u. Hasson, U. Schickhoff, T. Scholten, and J. Böhner, 2017. Rising precipitation extremes across nepal. *Climate*, 5 (1), 4.

Kumar, K. N., M. Rajeevan, D. Pai, A. Srivastava, and B. Preethi, 2013. On the observed variability of monsoon droughts over india. *Weather and Climate Extremes*, 1, 42–50.

Mair, A., and A. Fares, 2011. Comparison of rainfall interpolation methods in a mountainous region of a tropical island. *Journal of hydrologic engineering*, 16 (4), 371–383.

Nayava, J. L., 1981. Areal rainfall in the kathmandu valley. *Mausam*, 32 (4), 343–8.

Patel, N., P. Chopra, and V. Dadhwal, 2007. Analyzing spatial patterns of meteorological drought using standardized precipitation index. *Meteorological Applications: A journal of forecasting, practical applications, training techniques and modelling*, 14 (4), 329–336.

Shrestha, A. B., C. P. Wake, J. E. Dibb, and P. A. Mayewski, 2000. Precipitation fluctuations in the nepal himalaya and its vicinity and relationship with some large scale climatological parameters. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 20 (3), 317–327.

Shrestha, D., P. Singh, and K. Nakamura, 2012. Spatiotemporal variation of rainfall over the central himalayan region revealed by trmm precipitation radar. *Journal of geophysical research: atmospheres*, 117 (D22).

Sigdel, M., and M. Ikeda, 2012. Summer monsoon rainfall over nepal related with large-scale atmospheric circulations. *J Earth Sci Clim Change*, 3, 112.

Subash, N., and H. Ram Mohan, 2011. Trend detection in rainfall and evaluation of standardized precipitation index as a drought assessment index for rice–wheat productivity over igr in india. *International Journal of Climatology*, 31 (11), 1694–1709.

Taxak, A. K., A. Murumkar, and D. S. Arya, 2014. Long term spatial and temporal rainfall trends and homogeneity analysis in wainganga basin, central india. *Weather and climate extremes*, 4, 50–61.

Varikoden, H., J. Revadekar, Y. Choudhary, and B. Preethi, 2015. Droughts of indian summer monsoon associated with el niño and non-el niño years. *International Journal of Climatology*, 35 (8), 1916–1925.

Wang, B., X. Luo, and J. Liu, 2020. How robust is the asian precipitation–enso relationship during the industrial warming period (1901–2017)? *Journal of Climate*, 33 (7), 2779–2792.

Webster, P. J., V. O. Magana, T. Palmer, J. Shukla, R. Tomas, M. Yanai, and T. Yasunari, 1998. Monsoons: Processes, predictability, and the prospects for prediction. *Journal of Geophysical Research: Oceans*, 103 (C7), 14 451–14 510.

Wu, T.-W., and Z.-A. Qian, 2003. The relation between the tibetan winter snow and the asian summer monsoon and rainfall: An observational investigation. *Journal of Climate*, 16 (12), 2038–2051.

Yao, C., W. Qian, S. Yang, and Z. Lin, 2010. Regional features of precipitation over asia and summer extreme precipitation over southeast asia and their associations with atmospheric–oceanic conditions. *Meteorology and Atmospheric Physics*, 106, 57–73.

Yasunari, T., 2007. Role of land-atmosphere interaction on asian monsoon climate. . *2* , 85, 55–75.