Less rain and rainy days - lessons from 45 years of rainfall data (1971 to 2015) in the Kathmandu Valley, Nepal

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Abstract

Understanding spatio-temporal variability in rainfall patterns is crucial for evaluating water balances needed for water resources planning and management. This paper investigates spatio-temporal variability in rainfall and assesses the frequency of daily rainfall observations from seven stations in the Kathmandu Valley, Nepal, from 1971–2015. Daily rainfall totals were classified into five classes, namely, A (light rain, daily rainfall < 10 mm in a day), B (between 10–50 mm), C (between 50–100 mm), D (between 100–150 mm) and E (> 150 mm). The relationship between daily rainfall and rainfall frequency of various rainfall rate classes were analysed. Kriging method was used for interpolation in interpreting seasonal and annual rainfall data and spatial maps were generated using QGIS. The Mann-Kendall (MK) test was performed to determine the temporal trends and Theil-Sen's (TS) slope estimator was used in quantifying the magnitude of trends. Mountain stations showed a decreasing trend in rainfall for all seasons, ranging from − 8.4 mm/year at Sankhu to -21.8 mm/year at Thankot, whereas, a mixed pattern was found on the Valley floor. Mean annual rainfall in the Valley was 1610 mm. Both annual rainfall and the number of rainy days decreased in the Kathmandu Valley over the study period. The study indicated a significant reduction in rainfall after 2000. Since springs and shallow groundwater are the primary sources of water supply for residents in the Kathmandu Valley, it is apparent that decreasing rainfall will have (and is already having) an adverse impact on domestic, industrial, and agricultural water supplies, and the livelihoods of people.

1. Introduction

Rainfall, one of the major components of the hydrological cycle, influences life on earth (Shrestha and Sthapit 2015). A sound understanding of spatio-temporal rainfall variability is vital for evaluating water balances at various scales, which in turn are prerequisites for effective water resources planning and management (Wong et al. 2009; Thapa et al. 2017). An assessment of rainfall variability is a frequent practice in hydrology and has important applications in hydrologic modeling, water resource assessments, agricultural planning, flood frequency analysis (Buytaert et al. 2006), flood hazard mapping, climate change impacts and other environmental assessments (Ngongondo et al. 2011).

In particular, studies on rainfall variability have significant roles in urban hydrology, where the hydrologic response is sensitive to rainfall distribution in both space and time, due to the dominant impervious surfaces, medium-sized catchment and high spatial heterogeneity of urban land use (Emmanuel et al. 2012; Cristiano et al. 2017). Further, the study of rainfall variability in urban areas is necessary to learn about the impact of global climate change as well as the influence of local urbanization and development on rainfall (Karki et al. 2017).

In Nepal, the summer monsoon rainfall (from June to September), which accounts for approximately 80% of the total annual rainfall, is governed by the South Asian Monsoon originating from the Bay of Bengal (Panthi et al. 2015). Significant spatio-temporal variations in the rainfall pattern have been illustrated in previous studies (Ichiyanagi et al. 2007; Karki et al. 2017; Bohlinger and Sorteberg 2018; Dahal et al. 2019). The summer monsoon is more active in eastern and central Nepal, whereas winter rainfall, caused by western disturbances originating from the Mediterranean Sea (Shrestha and Sthapit 2015; Talchabhadel et al. 2018a), is more active in western Nepal (Ichiyanagi et al. 2007; Sigdel and Ikeda 2012). The climatic regime varies from subtropical near Nepal's southern border, to warm and cool in the hills, to cold on the mountains; this climatic variability occurs in less than 200 km moving from India-Nepal border northward (Shankar and Shrestha 1985; Chalise 1994; Karki et al.

2016). Diverse topography over the latitudinal distance of 193 km causes a high variation of rainfall throughout Nepal due to intense orographic lifting and subsequent rain shadowing. Interestingly, two significant rainfall peaks appear over the southern slope of the Himalayas across Nepal due to its unique topographical setting; the first peak appears along 500 – 700 meters above sea level (masl), and the second peak appears along 2000–2200 masl (Shrestha and Sthapit 2015; Talchabhadel et al. 2018a). The substantial fluctuation in rainfall is the reason for the water crisis during the drier months and extreme precipitation events resulting in floods, landslides, and other water-induced disasters in monsoon months (Tuladhar et al. 2020).

To date, perhaps due to limited data availability, only a few studies have analyzed observed rainfall data in Nepal (Shrestha and Aryal 2010). Dhital and Kayastha (2013) performed frequency analysis of future rainfall and peak flood events in the Bagmati catchment. A study on rainfall intensity of the Kathmandu Valley was done by Pokharel and Hallet (2015). Bohlinger and Sorteberg (2018) analyzed the trends in monsoon rainfall and extreme events in Nepal. Shrestha and Sthapit (2015) identified the temporal trend of rainfall in Bagmati River basin using time series data for the period of 1981-2008. Karki (2015) studied the daily rainfall pattern of summer monsoon in the Kathmandu Valley. Tuladhar et al. (2020) analyzed local variability in rainfall distributions as well as long-term trends of monthly and annual rainfall in the Bagmati River catchment.

The Kathmandu Valley (Valley) is the most populated urban center in Nepal. Uncontrolled urban expansion in the Valley has increased water demand and also reduced groundwater recharge potential by lowering surface infiltration capacities (Davids et al. 2018). Springs originating from the upper portions of the mountainous watersheds surrounding the Valley along with groundwater are the primary sources of freshwater supply in the Valley. Summer monsoon rain is the main source of these springs, surface water, and groundwater recharge (Shrestha and Sthapit 2015). Degradation of both quality and quantity of surface water supplies led to excessive extraction of groundwater (Shrestha et al. 2012). To deal with the current water crisis, the Kathmandu Valley Water Supply Management Board (KVWSMB), a government agency responsible for water supply and sanitation management in the Valley, is planning to augment groundwater recharge in the Valley. Urban flooding due to short-duration intense rainfall coupled with increased built land use has become an emerging issue in the Valley. Improving the understanding of temporal and spatial structures of rainfall is, therefore, integral to the sustainable livelihood of people. Variation in rainfall patterns may significantly affect the springs, streams, and groundwater of surrounding headwater catchments, the lifeline of water supplies for downgradient urban dwellers, industry, and agriculture. Thus, the assessment of the annual rainfall pattern and its seasonal variations is critical for sustainable water resource management and planning. The major objective of our study was to improve our understanding of the rainfall in the Valley by:

1. Assessing the frequency of rain events and rainfall accumulated by events of various intensity
2. Investigating and quantifying the spatial and temporal trends in annual and seasonal rainfall variability

The present study includes an investigation of spatio-temporal variability of rainfall in the Kathmandu Valley from 1971 to 2015, using data available from the Department of Hydrology and Meteorology (DHM), Government of Nepal.

2. Study Area

The Kathmandu Valley lies between 27°32'13" - 27°49'10"N latitude and 85°11'31" - 85°31'38" E longitude (Fig. 1). The Kathmandu Valley watershed has an area of approximately 587 square kilometers (km^2) (Davids et al. 2018). The Valley is surrounded by hills: Phulchowki in the South East, Chandragiri/Champa Devi in the South West, Shivapuri in the North West, and Nagarkot in the North East. The Valley is a roughly circular intermontane basin with an approximate diameter of 25 km and an average altitude of 1350 meters above sea level (masl) while the surrounding hills reach as high as approximately 2800 masl in elevation (Shrestha et al. 2016; Thapa et al. 2017). The Valley consists mainly of alluvial plains, alluvial and colluvial fans, fluvial and lacustrine terraces, and steep to very steep sloping mountains. The Valley lies in a semi-tropic zone and is characterized by a warm and temperate climate (Karki et al. 2016) having a rainy season from June through September.

3. Methods

3.1 Data

Daily rainfall data for the period between 1971 and 2015 were obtained from the Department of Hydrology and Meteorology, Government of Nepal (DHM 2019). Although there are 20 rainfall stations in the Kathmandu Valley with elevation ranging from 1212 m at Khokana, Lalitpur to 2163 m at Nagarkot, Bhaktapur, the present study considered the daily rainfall data only for seven spatially distributed stations due to incomplete time-series data for the study period in other stations. Additionally, available data of the Bagmati River Basin (BRB) for the period 1986-2015 of 41 stations, including those stations that lie in the Valley, were analyzed for a broader perspective on basin level seasonal and annual rainfall series. Table 1 provides a brief description of the rainfall stations used, including their location, elevation, mean annual rainfall, standard deviation and year of installation. Missing data were replaced with the daily rainfall data of the nearest station.

3.2 Spatial and temporal characteristics

3.2.1 Distribution pattern of daily rainfall

Rainfall was classified into five rainfall rate classes based on the amount of daily rainfall (Table 2). The amount of rainfall contributed in percentage (% of total rainfall) by various rainfall rate classes for various stations of the Kathmandu Valley was calculated. Similarly, the frequency of rainy days in percentage (% of total rainy days in a year) by various classes of rainfall rate was also calculated. A combo-chart of a bar graph and a line graph was prepared to demonstrate the relationship between daily rainfall and rainfall frequency of various rainfall rate classes. Further, the temporal distribution of rainfall amount of various rainfall rate classes was analyzed for five sub-periods.

3.2.2 Local and Valley-wide rainfall distribution

The total rainfall days were categorized into two major categories: (a) Local rainfall and (b) Valley-wide rainfall. When all the rainfall stations record daily rainfall > 0.1 millimeters (mm) per day, it is termed as Valley-wide rainfall. When some rainfall stations record daily rainfall > 0.1 mm per day but remaining stations record rainfall < 0.1 mm per day, it is termed as Local rainfall. When all the stations record 0 mm rainfall per day, it is termed as Dry and the number of maximum consecutive dry days is termed as Maximum Consecutive Dry Days (MCDD). The number of maximum consecutive rainfall days were classified into Maximum Consecutive Local Rainfall Days (MCLRD) and Maximum Consecutive Valley-wide Rainfall Days (MCVRD). Local Rainfall Index (LRI) is the ratio of rainfall contributed by Local rainfall to the annual rainfall whereas Valley-wide Rainfall Index (VRI) is the ratio of rainfall contributed by Valley-wide rainfall to the annual rainfall. Local and Valley-wide rainfall distribution was analyzed using line plots.

3.2.3 Annual and seasonal rainfall series

The average daily rainfall was split per month and then per season. The seasons considered were March to May as pre-monsoon, June to September as monsoon, October to November as post-monsoon and December to February as winter. The time series was divided into five sub-periods: (a) 1971-1980, (b) 1981-1990, (c) 1991-2000, (d) 2001-2010, and (e) 2011-2015. However, depending on the availability of data, the time series were divided into four sub-periods for the Bagmati River Basin i.e. 1986-1990, 1991-2000, 2001-2010, and 2011-2015. The average values for different sub-periods for different seasons were then calculated. Kriging method was used for the interpolation of the seasonal and annual rainfall average as it is an advanced, computationally intensive, geostatistical estimation method (Buytaert et al. 2006). Spatial maps for different seasons for each sub-period were prepared using the Quantum Geographic Information System (QGIS). A box-plot of mean annual rainfall (1971-2015) was prepared to analyze the temporal variation of rainfall in the Kathmandu Valley. The same analyses were repeated for the Bagmati River Basin with data from 1986-2015.

3.3 Trend analysis

Mann−Kendall (MK) test was used to determine the significance of temporal trends whereas Theil−Sen's (TS) slope estimator was used to quantify the magnitude of trends (Mann 1945; Kendall 1975; Talchabhadel et al. 2018b). The World Meteorological Organization (WMO) recommends the non-parametric MK test for assessment of trends in meteorological data as it is simple, robust and insensitive to missing data and outliers (Ngongondo et al. 2011).

4. Results And Discussion

4.1 Spatial and temporal characteristics

4.1.1 Distribution pattern of daily rainfall

Our study showed two distinct types of daily rainfall distributions (mountain and valley) in the Kathmandu Valley. The amount and frequency (number of days) of rainfall contributed in percentage (% of total annual rainfall) by various rainfall rate classes is shown in Fig. 2 for all stations. Although 60% of total rain events were of class 'A', these events contributed only 17% of total rainfall. The frequency of class 'B' was about 37%, but it contributed around 63% of total rainfall. While class 'C' only had a frequency of around 3%, it contributed about 15% of total rainfall. Extreme rainfall events of classes 'D' and 'E' were very infrequent (< 0.5%) contributing about 2% to total rainfall.

The result shows that more than half of all rainy days were class 'A' (light rain), but its contribution was less than one-fifth of total rainfall. Around 80% of total rainfall was contributed by classes 'B' and 'C' whereas the frequency of these classes was about 40% of the total number of rainy days.

The frequency of class 'B' was almost equal to the frequency of class 'A' in mountain areas, while on the valley floor, the frequency of class 'B' was lower than the frequency of class 'A'. The frequency of class 'C' is higher in mountain areas (4.5%) than on the valley floor (2.5%). Similarly, the rainfall contribution of class 'C' is higher in mountain areas and lower on the valley floor than class 'A'. These results show a higher frequency of heavy rainfall events and fewer light rainfall events in mountain areas, resulting in a higher amount of rainfall in mountain areas than on the valley floor.

In a study by Karki (2015), 51% of total rain events had rainfall rates between 0.1-10 mm/day (Class A) which accounted for just 13% of the total rainfall. On the contrary, the frequency of rainfall events declined to 17% for rainfall rate between 30-90 mm/day (class B and C) but contributed to 46% of the total rainfall. Heavy rainfall events i.e. rainfall rate more than 90 mm/day (class D and E) were less frequent and contributed to less than 2% of the rainfall received. The findings from the study are similar to what we observed i.e. higher amounts of rainfall were received in the mountain parts (higher frequency of rainfall events i.e. between 10-100) compared to the Valley floor which might be because of the orographic effect.

4.1.2 Annual rainfall series

Annual rainfall had high spatial variation across the Kathmandu Valley. The mean annual rainfall was 1610 mm (1880 mm in mountain areas and 1410 mm on the valley floor) for the study period. Along with spatial variability, the temporal variation was also substantial. The highest observed rainfall was 3425 mm in Sankhu station in 1978 where the mean annual rainfall was 1865±247 mm for 1971-2015. And, the lowest observed rainfall was 827 mm in Khumaltar station in 1992 where the mean annual rainfall was 1237±67 mm for the study period. Despite a substantial year to year variation, we observed spatial and topographical insights that the mountains tended to receive higher rainfall than the valley floor, meaning the valley is drier than mountains. Sankhu station, located in the north-eastern part of the valley at the elevation of 1449 m, received the highest annual mean of 1946 mm, whereas, Khumaltar station, located in the central part of the valley at the elevation of 1350 m, received the lowest annual mean of 1228 mm (Fig. 4). Similar findings were observed in a study by Karki (2015), where the stations located in the mountains received an average of 1978 mm rainfall while that of the valley floor received 1151 mm on average. The northern part of the Valley receives most of the rainfall; when the moisture-laden air entering the Valley sinks into the southern part of the Valley floor, the air warms resulting in less rainfall in that area compared to the mountainous northern parts (Karki 2015).The nature of rainfall distribution in the valley suggests that local factors like topography, elevation, etc. play an important role in the spatial distribution of rainfall.

4.1.3 Seasonal rainfall series

Around 80% of the total annual rainfall occurs in the monsoon season from June to September. Pre-monsoon contributes around 14% and post-monsoon and winter contribute around 6% of the total annual rainfall. The pattern of the spatial distribution of seasonal rainfall was similar to the annual rainfall as mountains received more rainfall than the valley floor. The difference of monsoonal rainfall among the time series spatial maps (Fig. 4) for different sub-periods indicated a significant reduction in rainfall after 2000. The reduction of rainfall in mountain areas is quite higher compared to the valley floor. Similarly, Fig. 4 showed a decrease in post-monsoon rainfall with time. The decrease in monsoon precipitation and subsequent increase in evapotranspiration results in low flow in rivers (Sharma and Shakya 2006). In a study by Sharma and Shakya (2006), the river flow decreased in the monsoon season; however, there was no significant change in the pre- and post-monsoon.

4.1.4 Local and Valley-side rainfall distribution

Fig. 5 shows the temporal distribution of Local rainfall days (LRD) and Valley-wide rainfall days (VRD) in the Kathmandu Valley. For the first two decades (1971-1980 and 1981-1990), the average VRD was 52 and it increased to 63 during 1991-2000. Then, it decreased to 47 and 40 in 2001-2010 and 2011-2015, respectively. For the first two decades (1971-1980 and 1981-1990), the average dry days (DD) was around 165 which increased to 181 in 1990-2000. Then, it decreased to 171 and 178 in 2001-2010 and 2011-2015, respectively. Although there was some decrease in LRD (120) in 1991-2000, the average LRD remained almost constant in other decades (146). But, the average VRD was decreasing and the average DD was increasing with time with an exception in 1991-2000.

The average MCVRD decreased from 7.5 (in 1971-1980 and 1981-1190) to 6.5 (in 2000-2010 and 2011-2015) with an exceptional increase up to 10 in 1991-2000. The average MCDD was increasing in the last few decades. The average VRI decreased from 0.59 in 1971-1980 to 0.52 in 2000-2015 with an exception of 0.69 in 1991-2000. The average LRI increased from 0.41 in 1971-1980 to 0.48 in 2000-2015 with an exception of 0.31 in 1991-2000. It shows that the contribution of valley-wide rainfall to the annual rainfall is decreasing with time whereas the contribution of local rainfall to the annual rainfall is increasing with time. The results indicate a micro-climatic feature is more pronounced in recent times.

4.2 Trend analysis

The MK test was used to test the significance of monotonic trends in the whole time series to the rainfall frequency and rainfall amount for annual rainfall, different rainfall rate classes and seasonal rainfall. The test was performed at 10% significance level. Spatial distribution of long-term rainfall trends and their magnitudes based on the MK test and Sen’s slope for annual rainfall is shown in Fig. 6. All stations (except Kathmandu Airport) showed a falling trend for annual rainfall. All the mountain stations showed falling trends, ranging from 8.4 mm/year at Sankhu to 21.8 mm/year at Thankot, though the trend at Sankhu was not significant. A rising trend of 4.3 mm/year was observed at Kathmandu Airport station located at the central part of the Kathmandu valley. The magnitude of falling trends in the valley floor is lower compared to the mountain areas. Panipokhari and Khumaltar showed falling trends of 0.5 mm/year and -1.3 mm/year respectively. Sankhu (-0.7 count/year), Panipokhari (-0.9 count/year) and Godavari (-0.9 count/year) stations showed statistically significant falling trends whereas Bhaktapur and Kathmandu Airport station had a statistically insignificant falling trend of -0.2 count/year for annual rainfall frequency. Thankot (0.1 count/year) and Khumaltar (0.3 count/year) stations which are located at the western part of the Kathmandu valley showed rising trends for annual rainfall frequency; however, only the rising trend at Khumaltar station was statistically significant. The trend of rainfall frequency is mostly dependent on the rainfall frequency of class ‘A’ whereas rainfall amount of classes ‘B’ and ‘C’ dominates the trend of total annual rainfall.

The spatial distribution of trend results of rainfall frequency and rainfall amount of different rainfall rate classes are shown in Fig. 6. In the rainfall frequency of class ‘A’, statistically significant trends were identified in five stations with two rising (Sankhu and Khumaltar) and three falling trends (Godavari, Panipokhari and Kathmandu Airport). The rainfall frequency of class ‘A’ at Sankhu station showed a falling trend (-0.3 count/year) whereas Bhaktapur station had a constant trend. The falling trends in rainfall frequency (ranging from -0.3 count/year to -0.6 count/year) and rainfall amount (ranging from -13.9 mm/year to -6 mm/year) of class ‘B’ in mountain stations were statistically significant. Two stations (Bhaktapur and Khumaltar stations) in the valley floor had a falling trend in rainfall frequency (-0.2 count/year and -0.1 count/year) and rainfall amount (-6.1 mm/year and

-0.5 mm/year) of class ‘B’ whereas Kathmandu Airport station had no trend in rainfall frequency (but rising trend of 2.3 mm/year in rainfall amount). Panipokhari station had a rising trend in rainfall frequency (0.1 counts/year) and a statistically significant rising trend in rainfall amount (4.5 mm/year) for rainfall class ‘B’. All the stations in the Valley floor had no trends for rainfall frequency of class ‘C’. Thankot and Godavari stations showed statistically significant decreasing trends but Sankhu station showed a statistically insignificant rising trend for rainfall frequency and rainfall amount of class ‘C’. However, mixed patterns were found in the trend of rainfall amount of class ‘C’ on the valley floor. Rainfall classes of ‘D’ and ‘E’ had negligible trends for both rainfall frequency and rainfall amounts in all stations. For total annual rainfall, all the stations (except Kathmandu Airport station) showed a falling trend of which 3 stations were statistically significant. Godavari station located at the southern part of the valley showed a statistically significant consistent falling trend for both rainfall amount and frequency of rainfall classes ‘A’, B’, ‘C’ and for annual rainfall.

The MK test was employed to test the significance of monotonic trends of seasonal rainfall for the study period. All the mountain stations showed a falling trend (average 14 mm/ year) for rainfall in the monsoon season of which 2 stations (Thankot and Godavari) were statistically significant. For the monsoon season on the valley floor, half of the stations (Panipokhari and Kathmandu Airport) showed a rising trend (0.8 mm/year and 2.9 mm/year) and rest (Bhaktapur and Khumaltar) showed a falling trend (6.1 mm/year and 2.9 mm/year). Similarly, a mixed pattern was found for winter and pre-monsoon season. Interestingly, all stations showed a falling trend ranging from 0.2 mm/year to 1.2 mm/year for the post-monsoon season. All the mountain stations showed a falling trend for rainfall in all seasons (except Godavari in pre-monsoon season and Sankhu in winter season) whereas a mixed pattern was found on the valley floor. Kathmandu Airport station showed a rising trend for all seasons except post-monsoon season. Significant falling trends in monsoon season have resulted in a significant falling annual trend at Thankot, Godavari and Bhaktapur stations. In the analysis of rainfall data from 1989 to 2009 by Dhital eta al. (2013), in the pre-monsoon, an increasing rainfall trend was observed for almost all stations of the Bagmati river basin, including Godavari and Kathmandu Airport, which lies particularly in the Kathmandu Valley. Similar falling trend was observed during the post-monsoon period (Dhital et al. 2013). Even when we see the findings of time-series rainfall analysis for the countrywide rainfall by Karki et al. (2017) using data from 1970-2012 and Duncan et al. (2013) from 1951-2007, similar trends were witnessed except for a few areas which might be because of differences in the data analysis methods used. Analysing rainfall trends is essential in decision-making for water resources management and agriculture, devising flood forecasting and early warning systems, designing reservoirs for hydropower projects, and sustaining livelihoods of people in the mountainous river basin of Nepal (Duncan et al. 2013).

The analysis of rainfall trends for different seasons revealed that monsoon rainfall is decreasing in the mountain region. It showed that the recent decades are drier than in earlier decades. The falling trend of 11 mm/year of class ‘B’ contributed much to the decreasing monsoonal rainfall. The natural springs of mountains are the major source of water supply in the Kathmandu Valley. The decreasing trends of monsoon rainfall along with total annual rainfall in mountain areas may have a significant impact on these spring sources, resulting in reduced flow and even drying up of springs. The northern part of the valley floor showed an increasing trend of monsoon rainfall. Similarly, the rainfall frequency and rainfall amount of classes ‘B’ and ‘C’ were in a rising trend but class ‘A’ was in a falling trend in the northern part of the valley floor. This part of the valley is mostly covered by high built land-use with a lower water infiltration rate. The analysis indicated that heavy rainfall was more frequent than light rain, which might cause high surface run-off in the urban area. The falling trend of rainfall frequency or the number of rainy days might affect the livelihood of the people as a result of increased temperature. In

Kathmandu Airport station, the annual rainfall is increasing but the number of rainy days is decreasing, indicating more heavy rainfall events. Similar findings were revealed in a study by Dhital et al. (2013), where a decreasing trend in the frequency of rainfall days was observed while intensity of maximum precipitation was increasing in the Kathmandu Airport station. Alteration in the rainfall pattern, accompanied by changes in temperature and discharge, might result in water quality deterioration, decline in agricultural yield and hydropower generation, effect in aquatic biodiversity, etc. (Dhital et al. 2013). Furthermore, the decreasing post-monsoon and winter rainfall might have a negative impact on seasonal agricultural production like paddy rice, wheat, barley, potato, etc. (Panthi et al. 2015).

4.3 Seasonal and annual rainfall series for the Bagmati River Basin

Similar seasonal and trend analyses were performed for a larger scale i.e. in the BRB, analysing data from 41 stations. The basin is divided into three parts, covering Kathmandu Valley in the upper, mountain and hills in the middle and Terai plain in the lower parts of the basin (Babel et al. 2014). In the upper part of the basin, there is a critical water quality and quantity issue year-round, especially in winter, moving downward into the middle and lower part, landslides and monsoonal floods are prevalent, respectively.

In between 1986-2015, the average rainfall was found to be 1676 mm. The highest observed rainfall was 3746 mm in Makwanpur gadhi (Index No. 919) in the year 1999. From Figure 8, it can be clearly seen that the annual rainfall has been decreasing over time with 1775 mm between 1986-1990 and 1505 mm between 2011-2015. In the pre-monsoon season, precipitation patterns are almost constant and haven't varied significantly over years. However, the monsoonal rainfall has increased from around 1390 mm between 1986-1990 to 1463 mm between 1991-2000. In recent years (2011-2015), the average rainfall dropped below 1200 mm. Since the lower part of the basin is Terai plain and has high agricultural potential, most of the people’s livelihood is connected to crop production. The declining monsoonal precipitation directly affects the river flow impacting the irrigation systems present. In the study by Sharma and Shakya (2006), due to less water availability in the lower part of the basin, the yield of crops, particularly rice and wheat, declined. In the BRB, the winter season received the least rainfall followed by post-monsoon, pre-monsoon, and monsoon seasons. On average, the driest month seen in the study period was November, while the wettest months were July and August. Also, it is clearly observed from Fig. 8 that recent years are dryer compared to past decades.

The findings in our analysis showed an alike trend with other basin studies of the country. A study by Dahal et al. (2019) showed alteration in precipitation patterns in the Rosi river basin and witnessed effects on the river flow and water insecurity in the river basin. Unlike the BRB, in the Gandaki basin, the monsoon precipitation increased with time. However, no significant trend was observed which suggests that the basin has a high annual and seasonal rainfall variability. Due to an increase in rainfall in the monsoon season, the basin is likely to face water-induced disasters (Panthi et al. 2015). On the other hand, decreasing post-monsoonal and winter rainfall affected winter crops production due to soil moisture deficiency (Panthi et al. 2015). In a study by Khatiwada et al. (2016), in the Karnali Basin, the average rainfall declined by 4.91 mm/year and similar effects on food and livelihood of people were observed. Similar effects might be observed in the mountainous part of the Bagmati river basin.

Analysing seasonal rainfall patterns, particularly in the BRB as illustrated by Shrestha and Sthapit (2015), is essential in circulating data-driven findings to relevant authorities like government and non-government institutions for constructing water infrastructures like barrage wherever required, initiation for flood control or evacuation, irrigation purposes, etc. The aforementioned water-induced disasters are major threats to infrastructure, agricultural land, and livelihoods throughout the basin. Therefore, it is crucial to cope with the hydro-climatic variability to minimize livelihood impacts and improve water security.

5. Conclusions And Recommendations

The study investigated the spatial and temporal characteristics of rainfall at seven stations in the Kathmandu Valley. We performed the trend analysis of daily, seasonal and annual rainfall patterns using the MK test. Daily rainfall analysis over the Kathmandu Valley clearly indicated the higher frequency of heavy rainfall events (rainfall class 'B' and 'C') and fewer light rainfall events (rainfall class 'A') in mountain areas resulting in higher rainfall amount of rainfall in mountain compared to the valley floor. The trend of rainfall frequency is mostly dependent on the rainfall frequency of class 'A' whereas rainfall amount of classes 'B' and 'C' dominates the trend of total annual rainfall. Annual rainfall had high spatial variation across the valley with higher rainfall in the mountains compared to the valley floor. The observations of this study depict a falling trend of an average of 14 mm/year in both monsoonal as well as annual rainfall in the mountains. In the valley floor, half of the stations showed a rising trend and rest showed a falling trend in monsoon season whereas all the stations except Kathmandu Airport showed a falling trend for annual rainfall.

The study showed that both annual rainfall and the number of rainy days decreased in the Kathmandu Valley over the study period. Our current study considered seven rainfall stations (1971 - 2015) which seem insufficient to assess the rainfall variability at small-scales. Monitoring and understanding spatio-temporal rainfall distribution at small-scales is vital for local and regional water resource management; this study only represents an initial step towards evaluating this in the Kathmandu Valley.

New technologies and practices have been developed to monitor the spatio-temporal variability of rainfall patterns at a higher resolution. Satellite-based rainfall estimation (Talchabhadel et al., 2021) and use of the citizen science approach (Davids et al. 2018; Davids et al. 2019) in rainfall measurement can be an alternative way to fill the spatial gaps and to cover the spatial heterogeneity. However, evaluation of the performance of satellite-based rainfall estimates is vital and these products can be blended with the rainfall data from rain gauges to improve the overall accuracy. In particular, rainfall monitoring networks in urban areas in valleys such as Kathmandu and Pokhara have some limitations due to strong microclimatic variation, highlighting the need for dense monitoring networks. Installation of highly technical X-radar is quite demanding. Most importantly, citizen science may be considered as a suitable approach to address such issues at the present time. At the same time, the quality assurance of citizen science-based data should also be considered. The current study could be replicated to the other river basins to assess the spatio-temporal rainfall variability. The study of long-term rainfall trends in conjunction with other meteorological parameters like temperature would be our future work. We believe such studies could be useful to understand the impact of climate change in the mountains.

Declarations

Not applicable

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Tables

Table 1
Summary information on rainfall stations used in the study

S.N.	Station name	Index No.	Type of station	District	Long.	Lat.	Elevation (m)	Installation Year
1	Thankot	1015	Precipitation	Kathmandu	85.2	27.68	1630	1967
2	Sankhu	1035	Precipitation	Kathmandu	85.48	27.75	1449	1971
3	Bhaktapur	1052	Precipitation	Bhaktapur	85.42	27.67	1330	1971
4	Godavari	1022	Precipitation	Lalitpur	85.4	27.58	1400	1953
5	Kathmandu Airport	1030	Aeronautical	Kathmandu	85.37	27.7	1337	1968
6	Khumaltar	1029	Agrometeorology	Lalitpur	85.33	27.67	1350	1967
7	Panipokhari	1039	Climatology	Kathmandu	85.33	27.73	1335	1971

Table 2
Classification of rainfall rate based on rainfall amount per day (mm)

Rainfall rate class	Rainfall amount per day (mm)
A	0.1–10
B	10–50
C	50–100
D	100–150
E	> 150

Figures

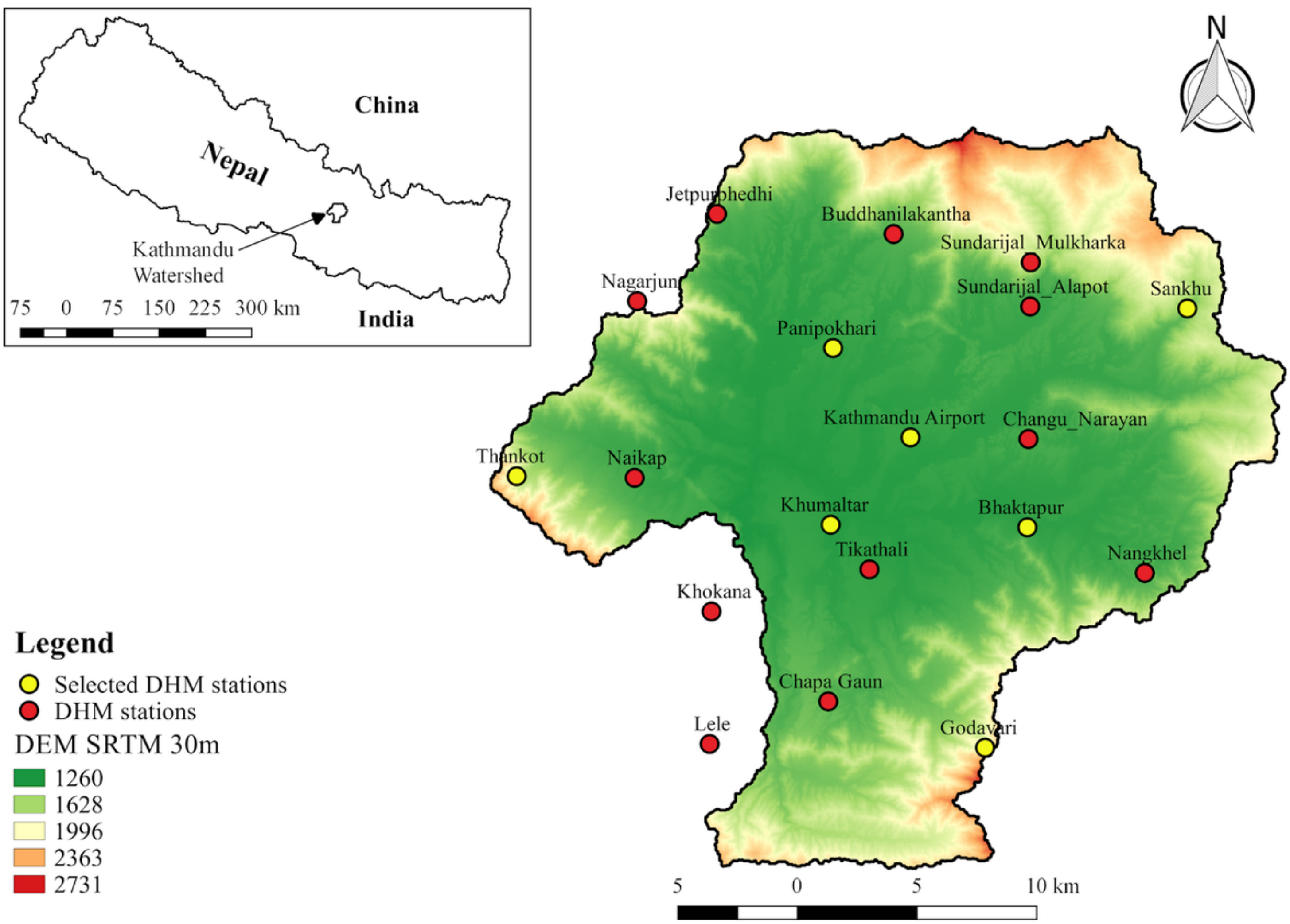

Figure 1

Kathmandu Valley Watershed with SRTM DEM at 30-meter resolution and rainfall stations of Department of Hydrology and Meteorology, Nepal. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

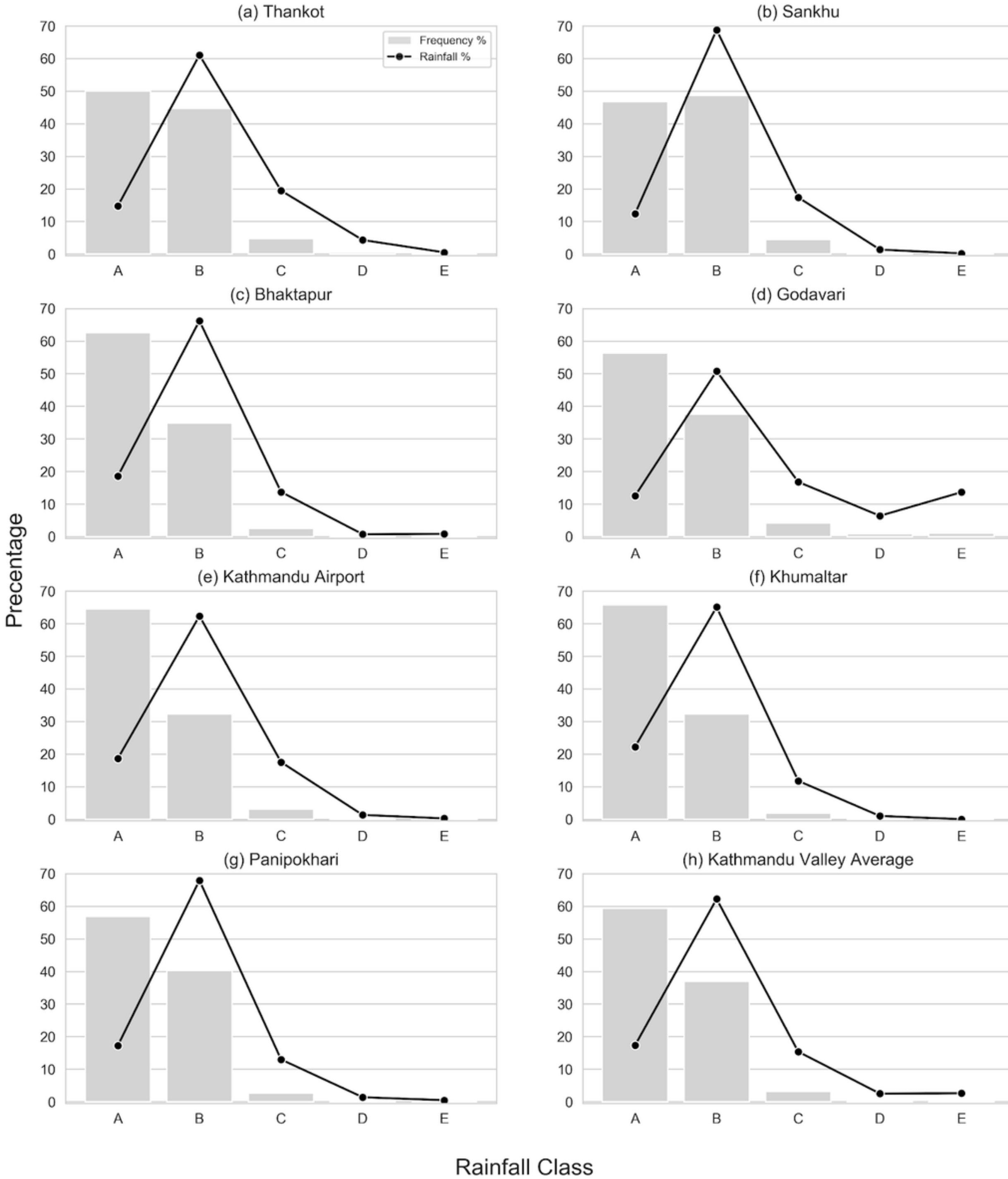

Figure 2

Contribution of rainfall frequency (%) and cumulative rainfall (%) for various classes of rainfall rate at different station locations, a) Thankot, b) Sankhu, c) Bhaktapur, d) Godavari, e) Kathmandu airport, f) Khumaltar, g)

Panipokhari, and h) areal average across the Kathmandu valley (The areal average value was computed using Thiessen weightage method). A description of different classes is shown in Table 2

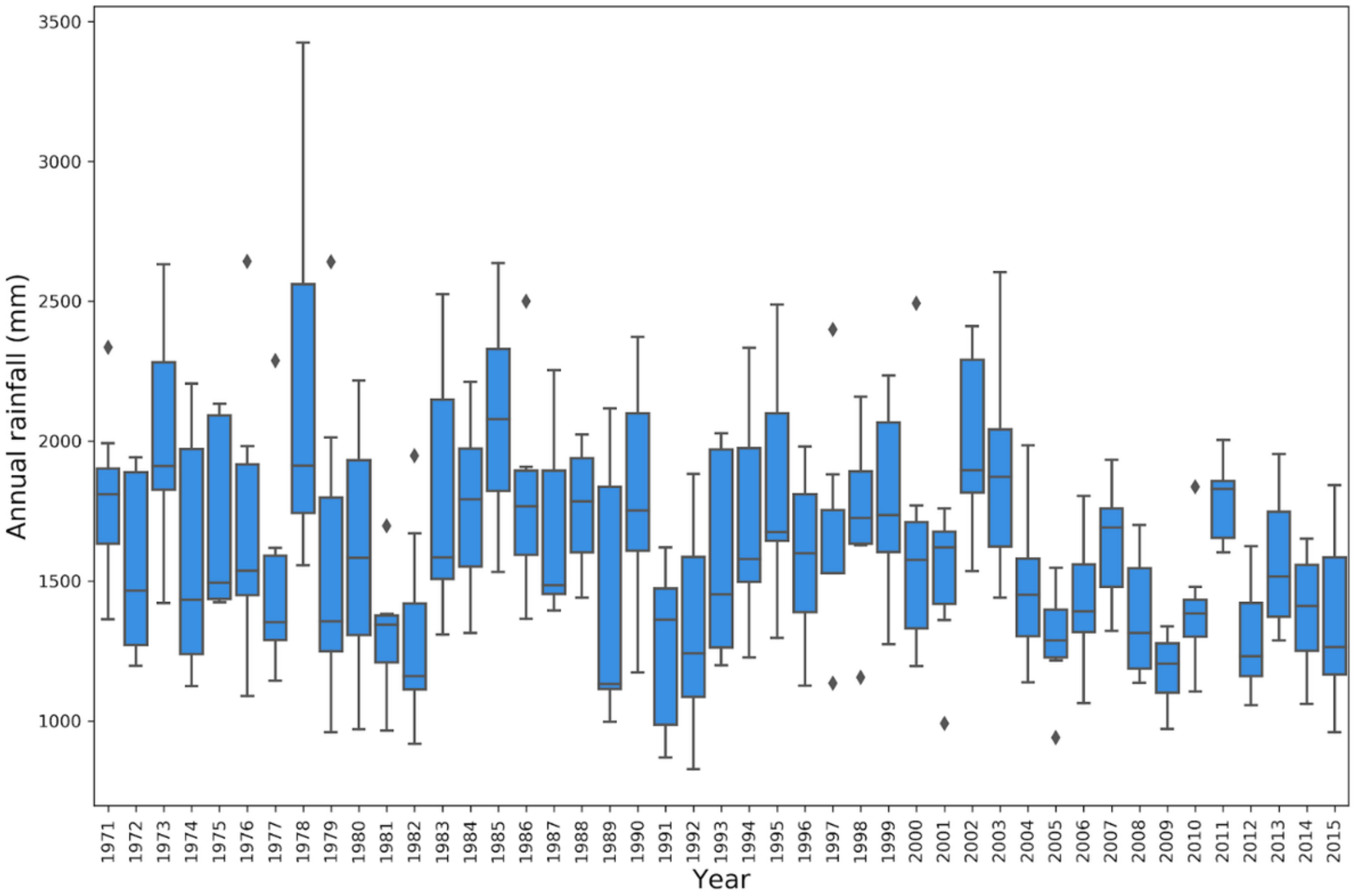

Figure 3

Box plot showing medians, first and third quartiles, and spatial distributions of annual rainfall (mm) distributed across the study area. We show temporal variation of annual precipitation for the period of 1971 – 2015

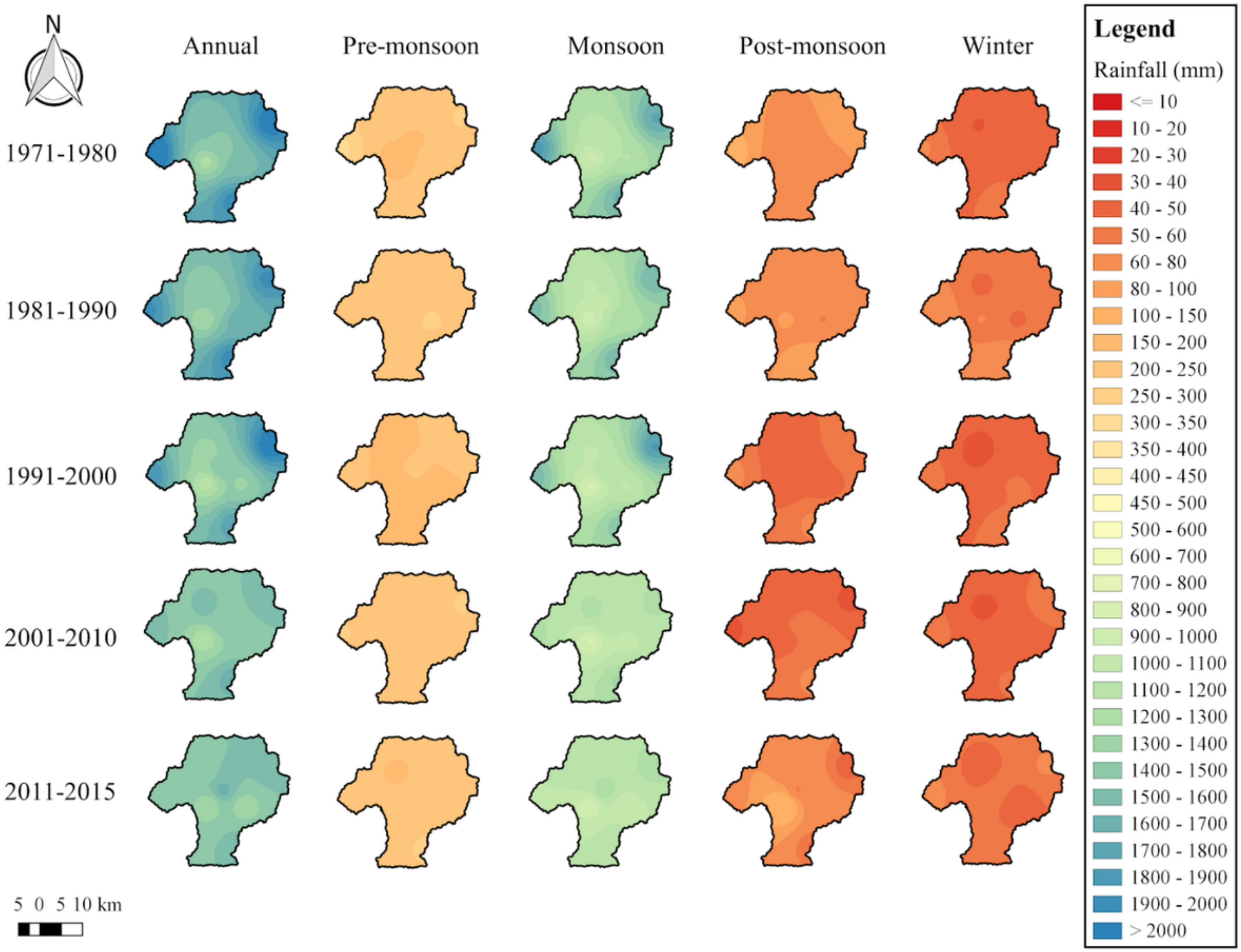

Figure 4

Annual and seasonal rainfall distribution in different time periods. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

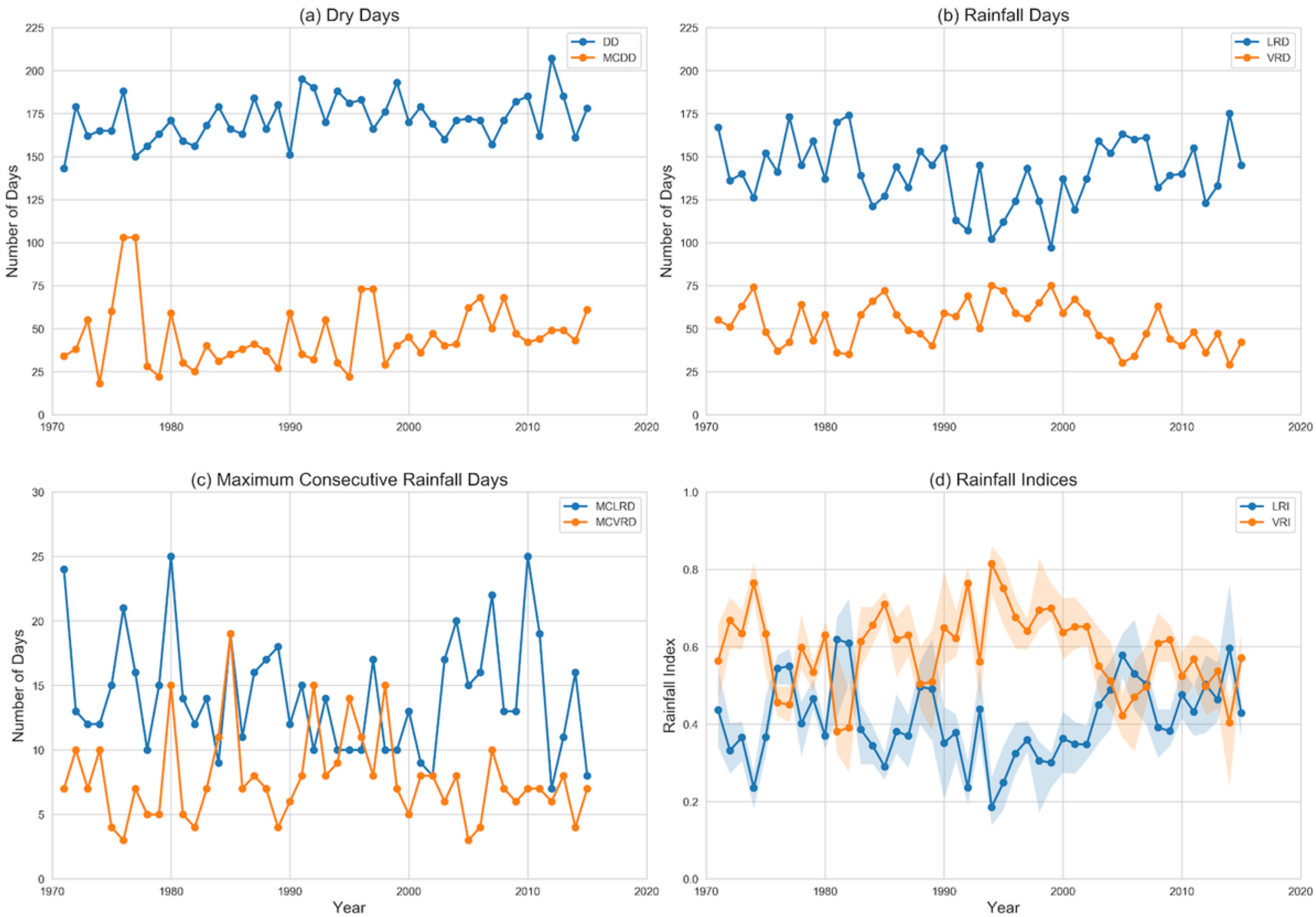

Figure 5

Line plots of temporal distribution (1971-2015) of a) Dry Days (DD: blue) and Maximum Consecutive Dry Days (MCDD: orange), b) Local Rainfall Days (LRD: blue) and Valley-wide Rainfall Days (VRD: orange), c) Maximum Consecutive Local Rainfall Days (MCLRD: blue) and Maximum Consecutive Valley-wide Rainfall Days (MCVRD: orange), and d) Local Rainfall Index (LRI: blue) and Valley-wide Rainfall Index (VRI: orange)

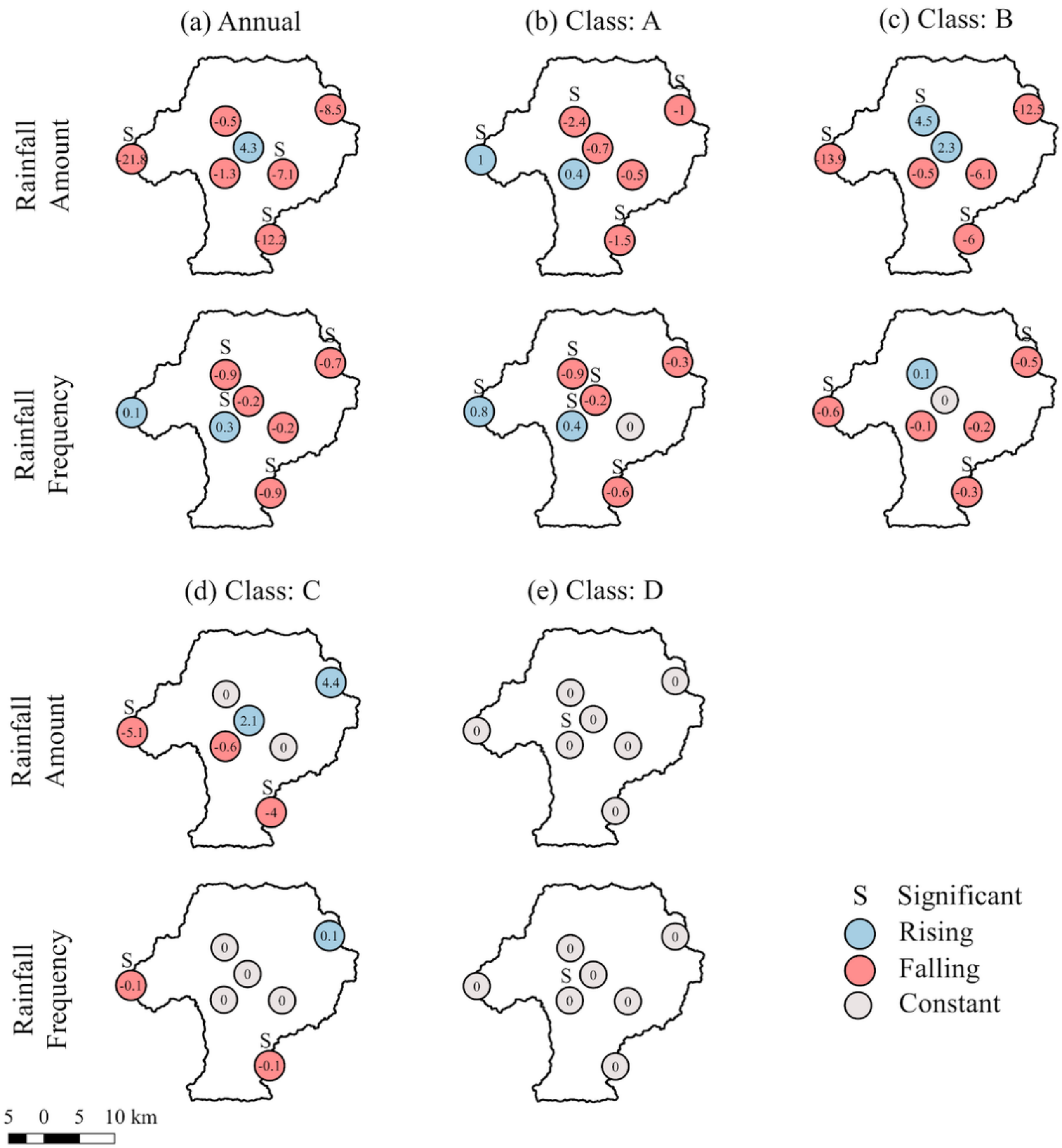

Figure 6

Station-wise trends for rainfall frequency, and rainfall amount for (a) Annual rainfall, (b) Rainfall class ‘A’, (c) Rainfall class ‘B’, (d) Rainfall class ‘C’, and (e) Rainfall class ‘D’ over the period of 1971–2015 (significance at 0.1). The unit of trend is mm/year and count/year for rainfall amount and rainfall frequency respectively. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

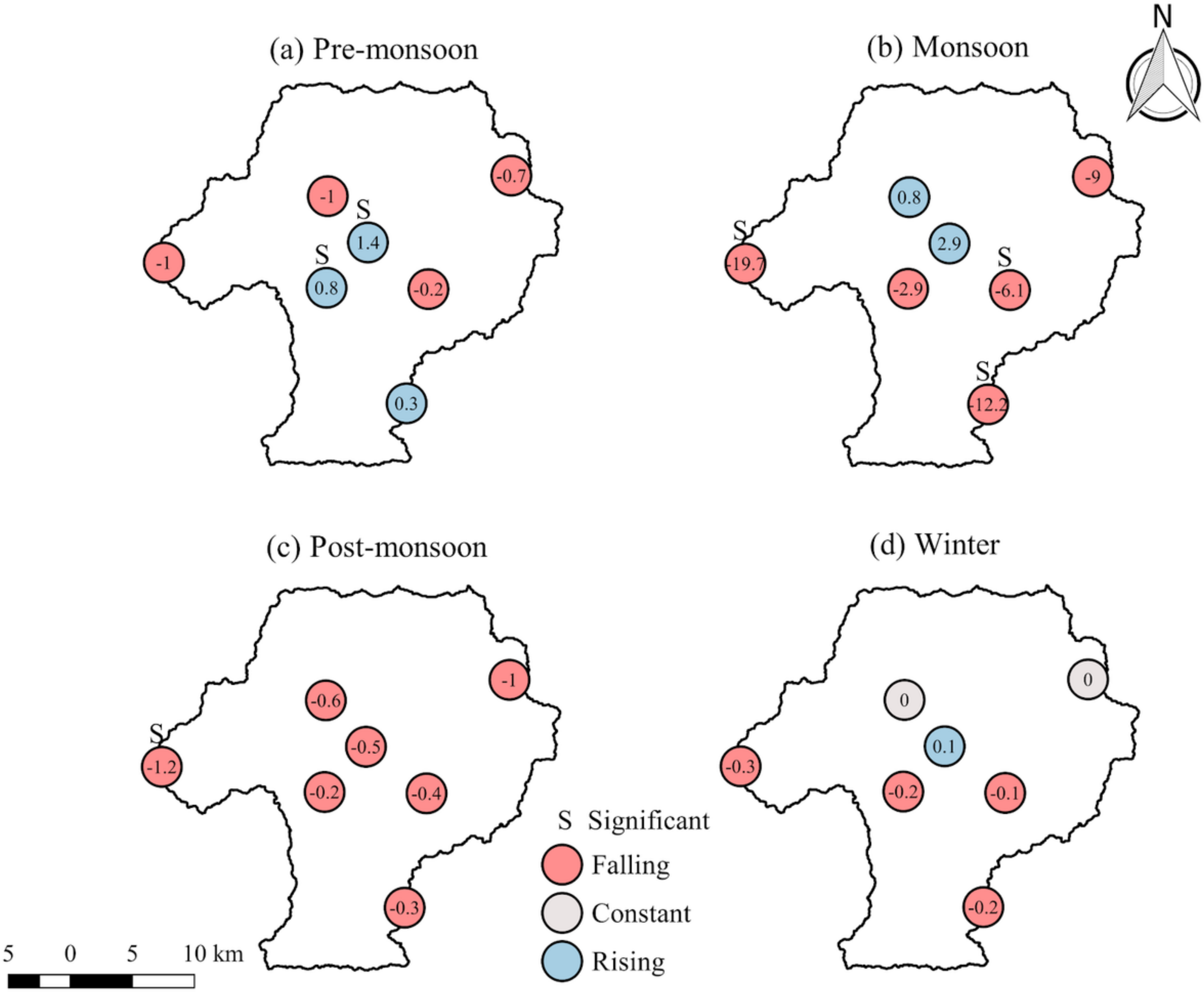

Figure 7

Spatial distribution of long-term seasonal rainfall trend at stations in the Kathmandu valley over the period of 1971–2015 (significance at 0.1). The unit of rainfall trend is mm/year. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

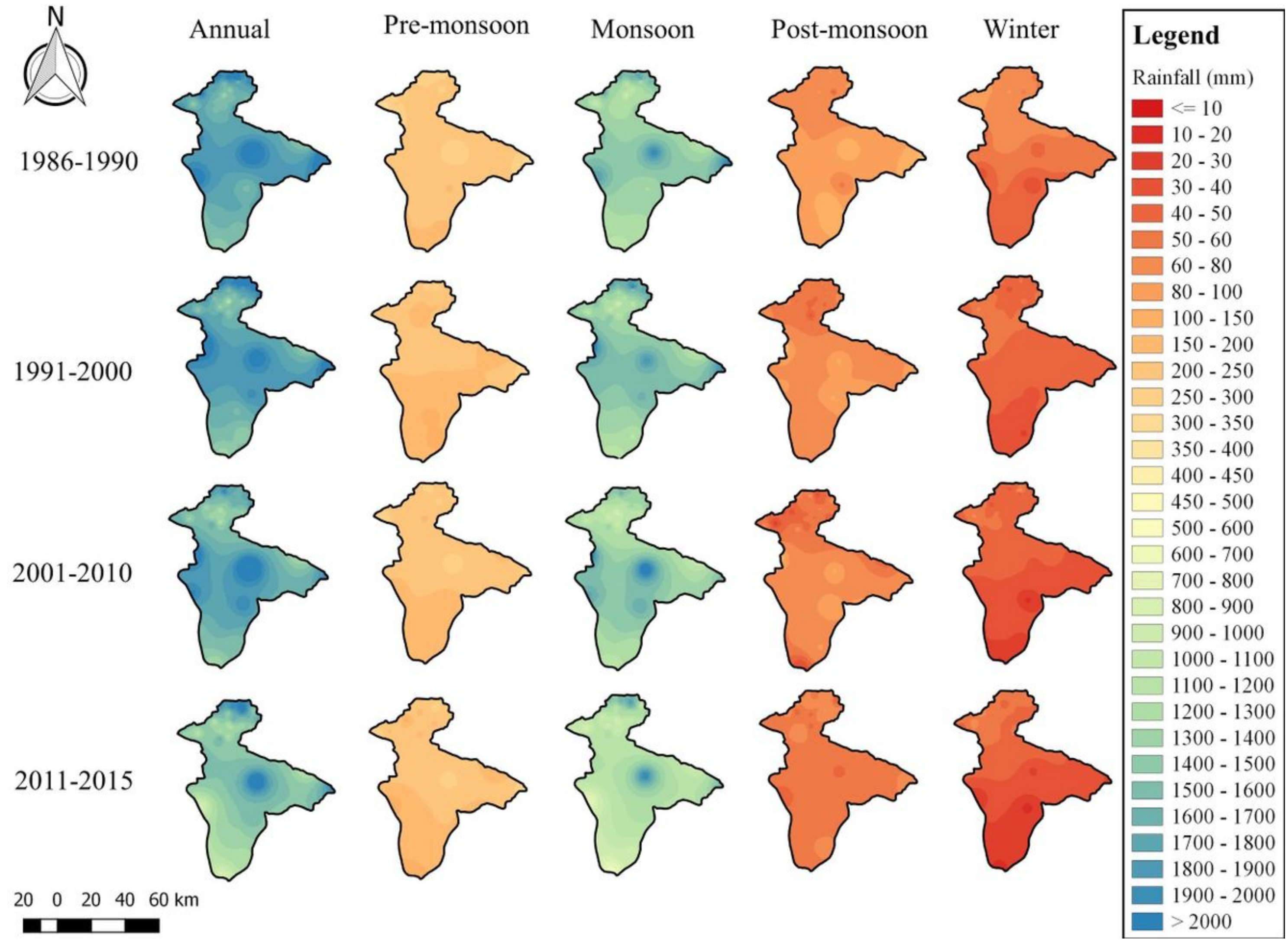

Figure 8

Annual and seasonal rainfall distribution in different time periods (1986-2015) for the Bagmati River Basin. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.