OBSERVED TRENDS AND SPATIAL DISTRIBUTION IN DAILY PRECIPITATION INDICES OF EXTREMES OVER THE NARAYANI BASIN, NEPAL

A Dissertation work submitted to:

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Declaration

I confirm that the work "**Observed Trends and Spatial Distribution in Daily Precipitation Indices of Extremes over the Narayani Basin**" is my own work and has not been submitted elsewhere for the requirement of degree program. The use of all material from other sources has been properly and fully acknowledged and listed in the references.

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Abstract

Climate change is one of the biggest environmental challenge that plays out through changing intensity, duration, and frequency of extreme events. To fulfill the research gap in understanding and quantifying the recent changes in precipitation extremes over the Narayani river basin of central Nepal, the long-term daily precipitation data from 1980 to 2018 were run in ClimPACT2 an R software package to calculate ET-SCI extreme precipitation indices. In this study physically relevant 14indices obtained from 23 stations were examined for their spatial and temporal variation. Before the calculation of indices data quality and homogeneity test was performed. The results suggest that the variations of extreme indices throughout the study area are quite different from that of seasonal and annual patterns to some extent. The monsoonal precipitation was mostly concentrated in the central part of the basin within the Middle Mountain region (Lumle and its surroundings). Especially the lowlands (Terai and Siwaliks) and including some parts of middle mountains the precipitation intensity-based indices like as, percentile indices (R95p) and absolute indices (RX1day, RX3day, RX5day) were in the increasing trends, but the frequency of precipitation like threshold indices (R1mm, R10mm, R20mm) along with the duration of precipitation seemed to be decreasing. This implies that the lowlands regions bringing about rainfall related hazards like floods and soil degradation with inundation and may cause possible impact on agriculture and livelihood due to intense rainfall and prolongation of dry spells with the weakening of rainfall duration (days/year). However, the light to moderate precipitation and associated days over the high altitude and that could be the possible cause of landslides. This study also highlights the suggestion that there may be a possible impact on agriculture facilities, food security, and water scarcity in the eastern part of the basin due to the significant decreasing trend of annual total wet days precipitation (PRCPTOT)

Keywords: *climate change, Narayani river basin, ClimPACT2, ET-SCI precipitation indices*

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List of Acronyms

CCl	Commission for Climatology
CMA	Meteorological Administration
DHM	Department Of Hydrology and Meteorology
ENSO	El Nino Southern Oscillation
EP	Extreme Precipitation
ETCCDI	Export Team on Climate Change Detection and Indices
ET-SCI	Expert Team on Sector-Specific Climate Indices
GDP	Gross Domestic Product
GLDP	Global Land Daily Precipitation
GLOF	Glacier lake outbrust flood
GNU	General Public License
HKH	Hindu Kush Himalaya
IPCC	Inter Governmental Panel on Climate Change
mm	milli meter
MOHA	Ministry of Home Affairs
TP	Tibetan Plateau
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WRRB	West Rapti River Basin

Chapter 1

1.1 Introduction and Background

Climate change is the biggest environmental challenge attracting global attention and takes the planet into 'uncharted territory' with the announcement of 2016 as the warmest year ever(*WMO*, 2017). As a result, heat waves, cold waves, droughts, and floods which used to be occasional events are becoming more regular than in the past(WMO,2020). Nepal is a Mountainous country situated in Northern limit of tropics (South Asia), it is surrounded by India in the south, east and west and China in the north. The country having the total area 147181 km^2 and lies coordinates within $26^o12'$ to $30^o27'$ North latitude and 80^o $04'$ to $88^o12'$ East longitude. Nepal is divided into five different physiographic regions ranging from the low lying sub-tropical Terai through the Siwaliks, the Middle Mountains and the High Mountains to the snow-covered High Himalayas. Nepal has three categories of rivers, first categories originates from the glacial source and cross the mountains in deep gorges and flow south through the middle hills, It includes the major rivers such as, Koshi, Narayani, Karnali, and Mahakali, Second categories rise in the middle hills and Mahabharat range, it includes, Mechi, Kankai and kamala lies in south of the Koshi, the Bagmati lies between Koshi and Narayani, and Babai lies in between Gandaki and Karnali without glacial source, third categories rise in the outermost Siwalik and these rivers are mostly seasonal. The distance from north to south is only 150 to 250 km, within this short distance there is a large altitudinal and climatic variation from tropical in the low land (Terai) to polar tundra (Karki et al., 2016) in the higher altitude (8848 Mount Everest, the highest peak in the world). Due to the short North-South distance and large altitudinal variation it is very sensitive to climate change and facing hydro-meteorological disasters, such as drought, heat waves, cold waves, temperature extremes, precipitation extremes, wildfires, flood and the flow frequency is very high in the rivers.

Nepal receive about 80% of the total annual rainfall from june to September (Shrestha, 2000). The country is dominated by the Asian monsoon system. The main occupation is agriculture, largely based on rain-fed farming practice and tourism based on high altitude adventures is one of the major sources of income for the country (Shrestha & Aryal, 2011). Nepal is one of the most vulnerable countries to climate change impacts. Extreme weather events associated with heavy precipitations are the principal causes of landslides, debris flows and all types of floods disasters in the country, which by causing losses of life and property affects the socio-economic development (Talchabhadel et al., 2018) . The large number of human lost in these recent years because of hydro-meteorological disasters. The human losses due to the hydro-meteorological disasters in Nepal (1971-2018) shown in the table below.

Table- The human losses due to the hydro-meteorological disasters in Nepal

S. N	Type of disasters / years	Number of human losses in different years			
		1971-2012	2013-2014	2015-2016	2017-2018
1	Flood	4079	260	101	183
2	landslide	4511	200	276	161
3	Thunderbolt	1200	242	185	160
4	Cold wave	515	2		48
5	Snow storm		28		10
6	Wind storm		8	2	19
7	Heavy rainfall		10	9	30
8	avalanche		17		1

Source: Nepal disaster report 2013, 2015, 2017, 2019

Narayani basin contains 1710 glaciers with an area of 2285 km^2 (Bajracharya & Shrestha, 2011) The basin already experienced the GLOF event, such as; Setikhola (Machhapuchare lake), Kaligandaki,Trisuli (Langada lake), Trisuli (Zanaco lake) outburst flood (Bajracharya, 2009). There are many hydropower projects has been established in the basin and some are in establishing stage. The Narayani Basin is one of major development hubs of Nepal, contributing about 50% of the total hydropower production of the country (Authority, 2008). Downstream agriculture activities are vulnerable to the impact of flash floods. It is the home of endangered species like red panda, snow leopard and Himalayan black beer. So, it has high biodiversity value and rich in natural resources.

The summer season of 2004, 2005, 2006, 2009 and winters 2006, 2008 and 2009 were the worst widespread droughts, these dry periods have a serious impact on agriculture–livestock production of central Nepal (Dahal et al., 2016). In 1993 July 19-20, a large flood occurred in south central Nepal with record high rainfall of 540 mm in 24 h and intensity exceeding 70 mm/h, during which more than 1050 people lost their lives (Dhital et al., 1993) In 1998 August 30, more than 238mm of rainfall in 24 hrs with spatial coverage of 55 km^2 occurred at Adhikhola, and many landslides were initiated. In some sub drainage basins up to 28% of the hill slope were affected by landslides. Flood height increased up to 6.2 m and channel width increased from 10 m to 120 m destroying houses and agricultural land along the rivers. Fifty-five persons were killed and 640 houses were destroyed. The estimated total loss was 335.794 million Rupees (Khanal, 1999).

According to Nepal's Ministry of Home Affairs (MOHA, 2017) Hydro-meteorological stations in Banke, Chitwan and Makwanpur recorded the heaviest rainfall in 60 years. As of 16 August, 18,320 families are confirmed to have been displaced, and 75,000 families are affected by the flooding. More than 100,000 people have been rescued by formal and informal search and rescue. There have been 123 recorded deaths.

In the Narayani river basin, most of the livestock keepers had observed the variation on weather patterns and experienced increased temperature, decreased but erratic precipitation and delayed summer monsoon. The result revealed that highly impoverished livestock keepers from the fragile mountain with limited access to basic services, wealth and assets, are most vulnerable to extreme climatic events than those with better access to services and wealth (Dhakal et al., 2013). Nature based tourism plays an important role in improving economic conditions and, it is one of the principal sources of optimism for the country’s economic development, however, the tourism industry is challenged by global climate change (Nyaupane & Chhetri, 2009), in this contest Narayani basin has unique natural features, including three peak above 8000m, biodiversity and natural landscape, lakes have made the basin a major tourist destination.

Thus, it is necessary to evaluation of how the impact of precipitation extremes effect on human lives and the environment. The Narayani basin has been selected as a major river basin for studies to improve understanding of changes and trend in extreme precipitation indices. This study aims to comprehensive analysis of extreme precipitation indices from 1981 to 2018 in Narayani basin, to measure these indices, daily precipitation observations data were subjected to calculate the extreme precipitation indices using Climpact2 software platform

1.2 Objective of the study

The general objective of this study is to analyze the precipitation extreme in the Narayani basin. To fulfill the above mention objective, the following specific objectives are being set up.

1. To calculate the ET-SCI precipitation indices in different altitude
2. To calculate and analyze the distribution and trends of each indices
3. To compare effect each indices in different sectors

1.3 Research questions

The research questions that are made for this research are given below:

- Is the Narayani basin affected by precipitation extremes?
- Which area is most influence to precipitation extremes?
- Which sector is most affected by precipitation extremes indices?

1.4 Study area

1.4.1 General features

Narayani river basin is transboundary river basin, also known as Gandaki river basin. It covers the three countries China in the northern part, Nepal in the middle part and India in the southern part, it is located between longitudes 82.88° to 85.70°E and latitudes 27.36° to 29.33°N having the total drainage area of 46300 km^2, among which 72% lies in Nepal alone, remaining 18% and 10% lies in India and China respectively. Narayani River includes seven tributaries namely, Marsyandi, Daraudi, Seti, Madi, Kali Gandaki, Budhi Gandaki, and Trishuli. The basin has high topographic variation with elevation ranging from 60 m in the south to higher than 8000 m in the north where it passes through the high Himalayas, which contain the Dhaulagiri (8167 m) and Annapurna (8091 m) peaks (Shrestha et al., 2011). The Narayani basin contains all five climatic zones of Nepal mainly by elevation (Khanal, 1999; Shrestha et al., 2017), which is presented in Figure 2. Agriculture is the main occupation of people in Narayani river basin. Around 40 % of the land of basin is covered by agricultural land. Most of the agricultural land is rain-fed and only few irrigated croplands are present in the lowlands (Dahal et al., 2016). The upper part of the basin is covered with snow and ice.

1.4.2 Climate

The general climatology of the Narayani river basin is presented in Figure 1.The upstream areas have a mainly temperate or subalpine climate; the mid-stream areas a subtropical to temperate climate, and the downstream areas a more tropical climate. The climate in the basin varies from humid tropical in the low altitude of the southern part to polar tundra in the higher altitude northern belt (Karki et al., 2016).The basin experienced four seasons, namely, winter (December-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-November). Winter is a cold season with the precipitation over the basin is received by the western disturbances. Pre-monsoon is characterized by hot, dry and westerly windy weather with mostly localized precipitation in a narrow band. The monsoon is characterized by moist southeasterly monsoonal winds coming from the Bay of Bengal and occasionally from the Arabian Sea. Post-monsoon is a well-known dry season with the driest month, November. The spatial distribution of precipitation in the basin is highly heterogeneous.

For instance, the annual precipitation varies from less than 270mm for the driest regions (Mustang, Manangand Dolpa, located at the leeward-side north of the Annapurna) to above 5401mm in and around the Lumle region. Precipitation patterns in the basin are directly associated with the summer monsoon, with about 78% of the annual precipitation falling between June and September. July is the highest precipitation month, Lowest precipitation is observed for driest regions including Mustang and Manang located at the leeward-side north of the Annapurna and Lumle receive the highest precipitation (Karki et al., 2017a).

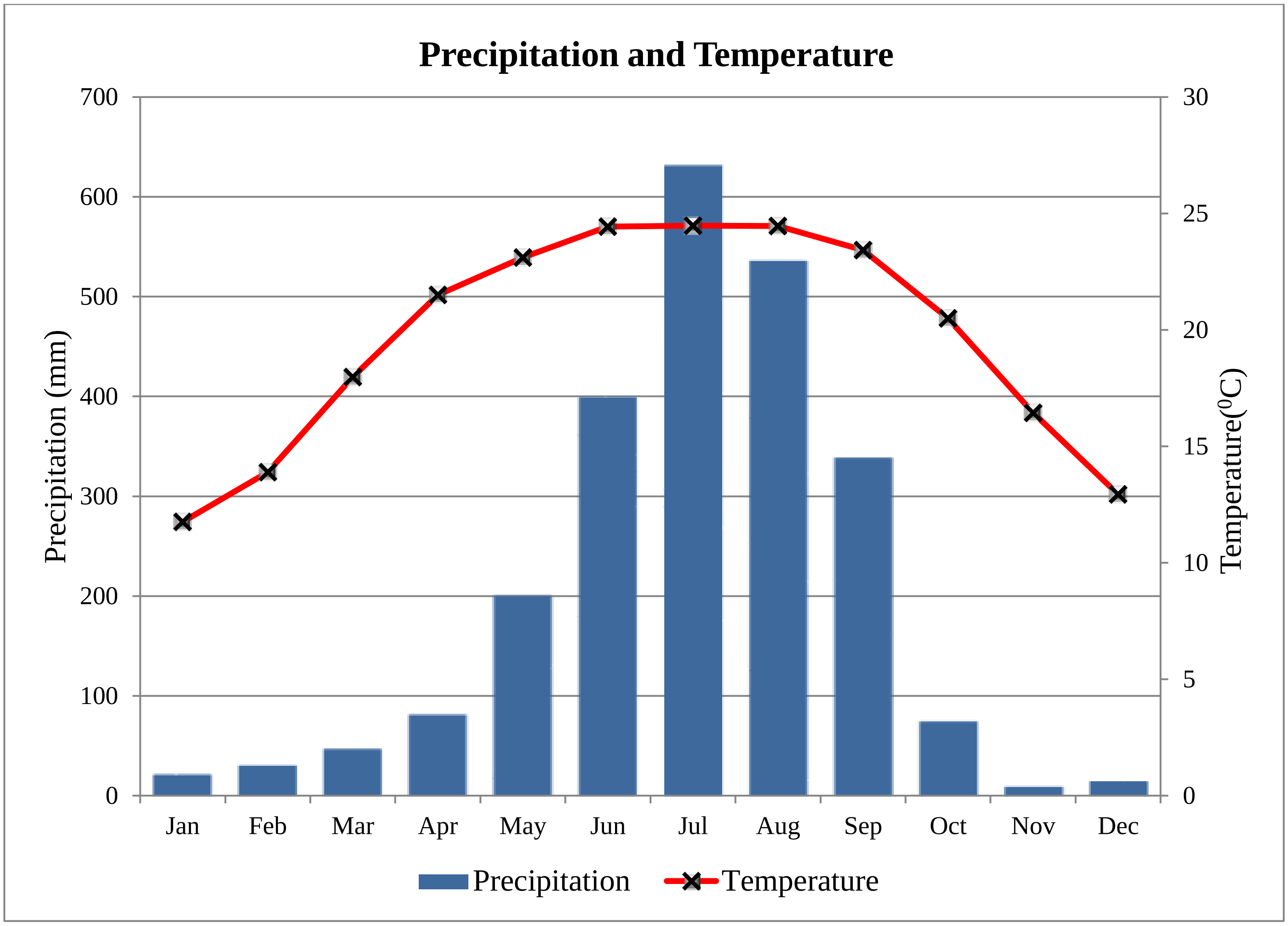


Figure 1: Precipitation and temperature characteristics over Narayani basin

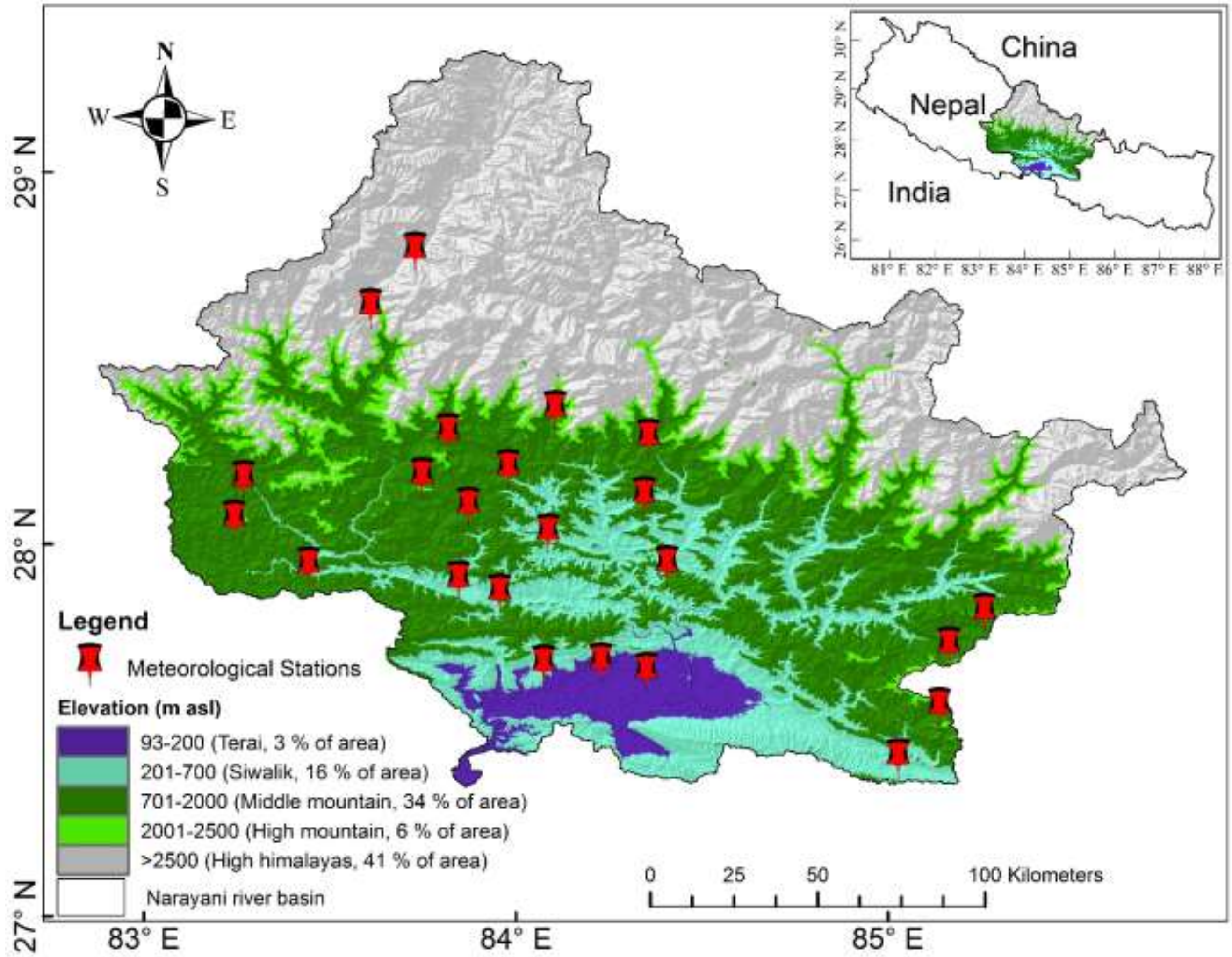


Figure 2: Location of the Narayani river basin with the meteorological stations used in the study, representing different elevation zones based on Shuttle Radar Topography Mission Digital Elevation Model

Chapter 2

Literature review

2.1 Defining extremes

Precipitation is the most important climate element directly affecting the availability of water resources (Randall et al., 2007). Precipitation is one of the most important environmental elements to diagnose climate change (Cannarozzo et al., 2006), which could also specify the eco-environmental response to climate change in regional scale as well. (Alexander et al., 2006) indicate that the extreme precipitation eventually favors natural disasters like floods, landslides etc, which in turn disfavors the socioeconomic development of the region. As with global mean precipitation, climate model projections indicate that extreme precipitation will also increase. It is widely expected that global warming will lead to increased evaporation hence a higher intensity of water cycling. A warmer atmosphere is able to hold more water vapor and has a higher energy potential, implying that the intensity and frequency of extreme rainfall events will increase (Meehl et al., 2007). A Common understanding of an extreme event is based on the assumption that a “normal” state exists which is generally derived from a temporal series of observed conditions (Dankers & Hiederer, 2008). A changing climate leads to change in the frequency, intensity spatial extent, duration and timing of extreme weather and climate event and can result in unexpected extreme weather and climate events (Field et al., 2012).

Generally speaking, indices that characterize aspects of the far tails of the distribution tend to be more relevant to society and natural systems than indices that characterize aspects of the distribution that occur more frequently. This is because the more extreme an event, the more likely it is to cause societal or environmental damage (Zhang et al., 2011). Figure 3, shows the representation of extreme precipitation and extreme temperature.

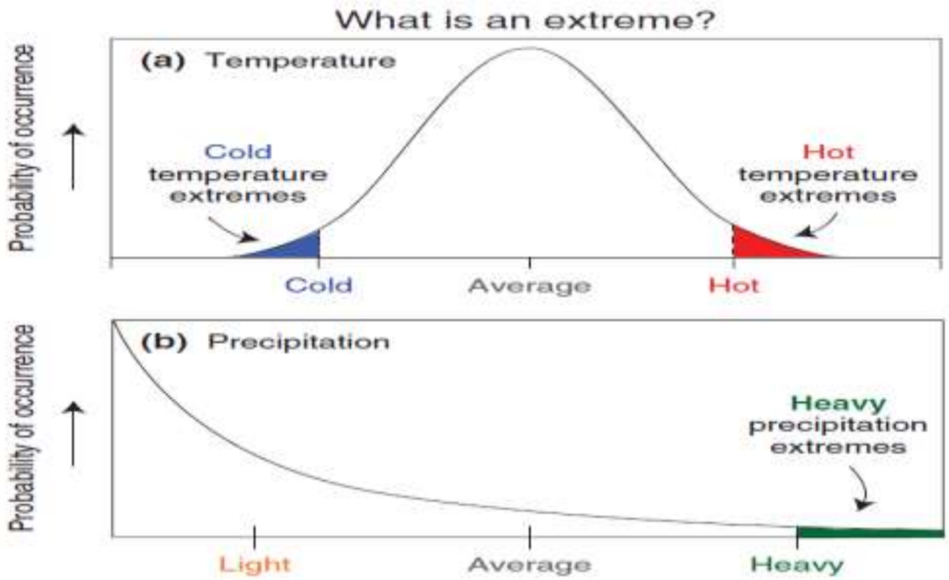


Figure 3 : Probability of daily temperature and precipitation, the higher the black line, the more often weather with those characteristics occurs. The shaded areas denote extremes (Zhang et al., 2011)

2.2 Changes in extremes precipitation

From droughts to flooding rains and damaging frosts to heat- waves, there is no doubt that climate extremes are of substantial societal importance. Observations provide a key foundation for understanding their long-term variability and change and for providing the underpinning for climate model evaluation and projections (Alexander, 2016). In recent years, the impacts of extreme climate have been increasing, such as increases in extreme high temperatures, decreases in extreme low temperatures, and increases in intense precipitation events, However, results on a regional scale differ from region to region (Easterling et al., 2000).

Flooding is the most common type of natural disaster worldwide, accounting for an estimated 40% of all-natural disasters. Extreme precipitation associated with the flooding can directly affect overall public health. For example, water sources can become contaminated with fecal materials or toxic chemicals, wounds may go uncared for or be exposed to contaminated water, water or sewer lines may become disrupted, access to safe and adequate nutrition and basic health care may be impossible (Howard et al., 1996). Donat et al., (2016) outline that, extreme precipitation is expected to increase as global warming intensifies the global hydrological cycle. Thereby, single precipitation events are expected to increase at a higher rate than global mean changes in total precipitation. (Eckstein et al., 2018) analyzed the global climate risk index (CRI) on the basis of following indicators

1. Number of deaths,

2. Number of deaths per 100 000 inhabitants,

3. Sum of losses in US$ in purchasing power parity (PPP) as well as

4. Losses per unit of Gross Domestic Product (GDP), and found that, People all over the world have to face the reality of climate change – in many parts of the world manifesting as increased volatility of extreme weather events. Between 1998 and 2017, more than 526 000 people died worldwide and losses of US$ 3.47 trillion (in PPP) were incurred as a direct result of more than 11 500 extreme weather events. The climate risk index for 2017, Nepal is ranked 4th most affected country. Nepal experienced flash floods and landslides in August 2017 across the southern border, amounting to US$ 600 million in damages. Nearly 250 people were killed by collapsed buildings or drowning in regions of India, Nepal and Bangladesh. 950 000 houses were damaged or destroyed in the floods.

Zhan et al., (2017) analyzed the China Meteorological Administration (CMA) Global Land Daily Precipitation dataset V1.0 (CMA GLDP-V1.0) from 1961-2012 and found that, significant increase in the amount of light and moderate precipitation and number of associated days over the various parts of Indian and northern Tibetan plateau but the intensity of light precipitation decreased significantly in the Hindu Kush and central India, and regional average intensity also decreased. He also found that the amount and frequency of intense precipitation mostly increased significantly on the Tibetan plateau, but there was a heterogeneous change over the remainder of the HKH and regional average annual intense precipitation amount and frequency significantly increased over the HKH. Thirdly, regional average of absolute precipitation indices such as RX1DAY, RX3DAY, and RX5DAY all shows significant upward trend, and there was significantly increased tendency of consecutive wet-days in most part of the region, however trends of consecutive dry-days mostly opposite to those of consecutive wet-days, with regional averaged consecutive dry-days showing no noticeable trend. (Tank et al., 2006) analyze the climate extremes on the basis of daily series of precipitation observations from 116 stations in central and south Asia and found that, no consistent pattern of changes in precipitation extremes could be detected for the majority of precipitation indices The only significant (5% level) regional trend in extreme precipitation indices is the increase in the amount on very wet days. Also, the increase in the contribution of very wet days to the total amounts between 1961 and 2000 is significant at the 5% level, implying disproportionate changes of the precipitation extremes. For precipitation, most regional indices of wet extremes show little change in this period as a result of low spatial trend coherence with mixed positive and negative station trends. Changing patterns of rainfall or melting snow and ice are altering freshwater systems, affecting the quantity and quality of water available in many regions, including South Asia, Climate change will have widespread impacts on South Asian society and South Asians' interaction with the natural environment, the impacts of climate change will influence flooding of settlements and infrastructure, heat-related deaths, and food and water shortages in South Asia (IPCC fifth assessment). Most areas of the Asian region lack sufficient observational records to draw conclusions about trends in annual rainfall over the past century. Rainfall trends, including extremes, are characterized by strong variability with both increasing and decreasing trends observed in different parts of Asia (Field, 2014) . The number of rain days (with at least 2 mm of rain) has decreased significantly throughout Southeast Asia and the western and central South Pacific. The proportion of annual rainfall from extreme events has increased at a majority of stations. The frequency of extreme rainfall events has declined at most stations (Manton et al., 2001) Based on daily precipitation from 12 meteorological stations over the high land of the Tibetan Plateau (TP) observed by the China Meteorological Administration in 1960-2012, changes in ten selected indices of precipitation extremes are investigated. The results demonstrate that very wet day precipitation, extremely wet day precipitation, simple daily intensity index, wet day precipitation, heavy precipitation days, and heavier precipitation days over the "Three-River Headwaters" region exhibit increasing trends during the study period, with wet day precipitation statistically significant. However, non-significant decreasing trends are found for other indices, including maximum 1-day precipitation, maximum 5- day precipitation, and consecutive wet days with the exception of consecutive dry days. Additionally, the stations with significant variations are mainly distributed over the northern "Three-River Headwaters" region (Cao & Pan, 2014)

It is quite amazing that within the span of 200 km from north to south, the climate of Nepal varies from artic to tropical. Nepal also enjoys the four normal seasons: spring, summer, autumn and winter. The annual mean temperature is about 15°C and increases from the north to south with exceptions in valleys. The annual mean precipitation is around 1800 mm in Nepal but because of greatly diverse topography it ranges from more than 5000 mm in the south to less than 250 mm in the north. Spatial distribution of rainfall is also of great concern regarding the occurrence of floods, landslides and other extreme events. Most floods occur during the monsoon season when heavy precipitation coincides with snowmelt in the mountains. (Rai, 2007). Nepal's economy is largely based on agriculture, predominantly small-scale farming, and about half of which is dependent on natural rainfall. In Nepal, agriculture is a highly climate sensitive sector. Historically, the sector has been affected by floods, droughts and erratic rainfall (Devkota et al., 2017). Baidya et al., (2008) used the 26 stations to calculate the extreme precipitation across Nepal during period 1971-2006, and found that the increasing trend in the total and heavy precipitation events at most of the stations. However, the systematic difference is not observed in extreme precipitation trend between hills and low land southern plains of Terai. The evidence suggests complex processes in precipitation extremes, but at the same time there is indication that more weather-related extreme events like floods, landslides can be expected in the future. Similarly, Karki et al., (2017) analyzed the data from 210 stations for the period 1981-2010 across Nepal and a found significant positive trend in consecutive dry days (CDD) but the negative trend in wet days (WD) are observed across the country, suggesting the prolongation of the dry period. pre-monsoon precipitation features a significant positive trend over the central high mountain region (CH) and over all lowland regions. On the other hand, winter precipitation features a decreasing trend over most of Nepal; however, such a trend is significant only over the western middle mountains and hills (WM). Similarly, a significantly decreasing trend in the post-monsoonal precipitation has also been observed across Nepal, except over CH and WL. Long-term trends in the monsoonal and annual precipitation (PRCPTOT) indicate their significant increases over the middle mountains and hills within the western region (WM), and over the high mountains within the central region (CH). In contrast, decreasing trends in the annual precipitation, wet days (WD) and high-intensity-related precipitation extremes (R95, RX1day), together with an increasing trend in the consecutive dry days (CDD) over the central and eastern middle mountains and hills reveals weakening of the intense precipitation extremes.

Bohlinger & Sorteberg, (2018) analyzed the precipitation events of 98 meteorological stations of Nepal during the period 1971-2010 and found that the number of occurring extremes and the amount of precipitation is controlled by the Indian summer monsoon and amount of precipitation and number of extreme events per station are neither significantly increasing nor decreasing between 1971 and 2010. However, on a regional scale they identify areas with positive and negative trends. A comparison of the combined precipitation time series with the ENSO index reveals a connection between ENSO and the variability in monsoon precipitation. The correlation with the number of monsoon extremes vanishes for increasing percentiles. Talchabhadel et al., (2018) analyzed the Spatio-temporal variability of extreme precipitation in Nepal and found that peak annual precipitation elevation between 2,000 and 3,500 m above sea level, while in contrast 1-day extreme precipitation peaks are found at lower elevation in the southern foothills with its highest intensity in a central region of the country. A station-wise trend clearly shows the increase in extreme precipitation events in western mountainous regions in recent decades. In other locations, the mixed patterns of station-wise increasing and decreasing trends are found. When the moisture bearing monsoonal wind approaches Nepal from the southeast in SM season, heavier precipitation falls in the southern foothills of the country resulting in the high intensity of EP therein. The precipitation amount contributed by relatively low-intensity precipitation increases with elevation on the wind-wards side up to certain elevation and sharply decreases in the lee-wards side and river valleys. Tree ring based precipitation studies also showed the frequency of drought event is increasing in the recent decades in the western Himalaya (Yadav, 2011) as well as the northern and southern slope of central the Himalayan region (Dawadi et al., 2013; Huang et al., 2019; Liang et al., 2019). Sigdel & Ma, (2017) assessed Variability and trends in daily precipitation extremes on the northern and southern slopes of the central Himalaya from 1975 to 2009 and found that, all indices increased, apart from the maximum 1-day precipitation (RX1) and simple daily precipitation intensity (SDII) indices on the southern slopes, his result suggest that increases in precipitation has been accompanied by an increasing frequency of extremes over the southern central Himalaya. Nonetheless, no relation could be established between the precipitation extreme indices and circulation indices for higher altitudes.

Shrestha et al., (2017) investigated the Observed trends and changes in daily precipitation extremes over the Koshi river basin 1975–2010. They found that, at most of the stations the number of heavy precipitation days R10mm and the number of very heavy precipitation days R20mm shows increasing, the SDII slightly increasing, rainfall. Consecutive dry days (CDD) increased in high rate (6.7 days decade$-^{1}$) at most stations, and much higher than the number of consecutive wet days (CWD) (0.5 days decade$-^{1}$).There was an increase in total annual rainfall and rainfall intensity, although no clear long-term linear trend, whereas the number of consecutive dry days increased at almost all stations. A recent study by Dahal et al., (2019) in the koshi basin shows that the increasing trend in consecutive dry days, decreased trend in heavy rainfall days R5D and precipitation intensity on wet days (SDII), he also shows that the changes in precipitation pattern have affected the stream flow of the koshi river in the observed decline in annual and seasonal stream flows. The dry spell as represented by the maximum length of the dry spell (CDD) and the magnitude of dryness (AII) has become more pronounced, while the wet spell as represented by the number of heavy rainfall days (R5D) and the precipitation intensity on wet days (SDII) has diminished significantly. Our analysis shows that recent changes in precipitation patterns have affected the stream flow of the Koshi river as manifested in the observed decline in annual and seasonal stream flows. A study by Subba et al., (2019) also analyzed the Spatial and temporal changes of precipitation extremities of Eastern Nepal in the last two decades (1997–2016). They found that solo increase trend of consecutive dry days (CDD) and all the intensity indices of extreme precipitation showed (mostly significant) decreasing trend. he concludes that Eastern Nepal has witnessed some significant drier days in the last two decades, as the events of heavy, very heavy, extremely heavy precipitations events, and annual wet days precipitations (PRCPTOT) were found to be decreasing. A study done by Devkota & Bhattarai, (2018) in the west Rapti river basin (WRRB) found that maximum 1 day precipitation RX1day was found to be increasing in two stations and decreasing in the other four stations and consecutive wet days shows increasing trend in four stations. He also found that the consistent positive trend in the number of consecutive dry days CDD in all stations, being statistically significant in four of the six stations, and the number of extremely wet days (R99p) and the PRCPTOT decreased in most of the stations.

In Kali Gandaki river basin, the maximum number of consecutive dry days (CDD) was increased trend at all stations. A significant increasing trend in consecutive wet days (CWD) was observed at Lete. The simple daily intensity index (SDII) decreased at the most of the stations. Very wet days (R95p) and extremely wet days (R99p) decreased at most of the stations, this was highly correlated with the increasing trend in CDD. Annual total wet-day precipitation (PRCPTOT) decreased at 4 out of 7 study stations and a very significant decrease was recorded at Ridibazar.

Overall, the precipitation indices SDII, R95p, R99p, PRCPTOT and RX1day decreased, while CDD and R10mm increased at many stations (Manandhar et al., 2012).

Based on the above-mentioned research findings, there has not been a recent and specific assessment of observed changes in climate extremes over the Narayani River basin of central Nepal, where meteorological observing systems are among the best in Nepal. The study by (Panthi et al., 2015) analyzed the spatial and temporal trend of precipitation and leaves a gap in understanding and quantifying the recent precipitation extremes over the basin. Therefore, the present study will evaluate the details of precipitation extremes changing in terms of spatial and trend features including intensity, frequency, and duration by the nature of occurrence from the basin and fulfill the regional gap in the climatic extremes focusing on precipitation.

Chapter 3

Data and methodology

3.1 Data

The data set used in this work included daily precipitation data from 74 weather stations from the lowland < 200m asl to the high Himalaya > 2500m asl with the aim to capture different climatic zones. The distribution of Meteorological stations across the basin with the different topographical features is shown in Figure 2, and type of the station is shown in Table 1,Most of the stations are located in the south and central part of the basin. These stations are managed by the Department Of Hydrology and Meteorology (DHM) Nepal. For this study, data for the period 1980-2018 were employed. Within this period, the stations having the data gaps more than 3 days in a month, more than 2 weeks within a year, 3 consecutive and six year in total were excluded from the analysis.

3.2 Quality control

The data quality control is a prior condition for the indices calculation. Quality Control procedures are applied to detect and identify the errors made in the process of recording, manipulating and collecting data. All the data are processed through a series of quality control procedure to ensure invalid values; such as negative daily precipitation amount have been identified. The simple quality control consists; correct format, impossible values, identify potential outliers, then the Climate data were loaded to further quality check and control using Climpact2 software. The Climpact2 software conducts quality control following the procedure.

1. It replaces all missing values.

2. It replaces all unreasonable values into NA. It also finds the duplicate dates, potential outliers etc.

Table 1: list of stations with type, latitude, longitude and elevation in the study area

S.N	Region	Index. No	Stations Name	Station Type	Elevation (M)	Latitude	longitude
1	High Himalayas	601	Jomson	Climatology	2744	28.78	83.73
2	High mountain	607	Late	precipitation	2384	28.63	83.61
3		1007	Kakani	Agrometeorology	2064	27.81	85.26
4	Middle mountain	824	Siklesh	Precipitation	1820	28.36	84.11
5		904	Chisapani Gadi	precipitation	1729	27.56	85.14
6		814	Lumle	Agrometeorology	1740	28.29	83.82
7		613	Karki Neta	Precipitation	1720	28.18	83.75
8		725	Tamghas	Climatology	1530	28.06	83.24
9		722	Musikot	Precipitation	1353	28.17	83.27
10		1038	Dhunibesi	Climatology	1085	27.72	85.16
11		808	Bandipur	Climatology	965	27.94	84.41
12		805	Syangja	Climatology	868	28.09	83.87
13		807	kunchha	Precipitation	855	28.13	84.34
14		804	Pokhara Airport	Aeronatical	827	28.20	83.98
15		802	Khudi Bazar	Climatology	823	28.28	84.36
16	Siwalik	815	Khairani Tar	Agrometeorology	515	28.02	84.08
17		726	Gandkot	Precipitation	500	27.86	83.96
18		906	Hetauda N.F.I	Climatology	474	27.42	85.03
19		810	Chapkot	Climatology	460	27.89	83.85
20		701	Ridi Bazar	Precipitation	442	27.94	83.44
21	(Terai)	704	Balewa girwari	Precipitation	150	27.67	84.07
22		706	Damkauli	Agrometeorology	183	27.68	84.23
23		902	Rampur	Agrometeorology	189	27.65	84.35

3.2 Homogeneity Test

Homogeneity of climate data is the basis for quantitative assessment of climate change, it is necessary to test and correct its homogeneity so as to be able to objectively reflect the true processes of climate change (Shen et al., 2018). The RHtes**t**V4 software package without reference series was used for the homogeneity test. This software package can be used to detect the multiple change points in precipitation and temperature data (Wang & Feng, 2013). In our study penalized maximal F test (Wang, 2008) was performed, which allows the time series being tested to have a linear trend throughout the whole period of the data record. The inhomogeneity of the station has been decided based on the RHtest results, Graphical examination, coincidence of known ENSO or localized precipitation (Karki et al., 2017a).

3.4 Methodology

3.4.1 ClimPACT2

The ClimPACT2 software updates ClimPACT which was based on the RClimDEX software developed by the WMO CCl/WCRP/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI). ClimPACT2 is an R software package for calculating the 34 core ET-SCI indices, and additional non-core ET-SCI indices (Lisa Alexander & Herold, 2016). ClimPACT2 provides useful indices for application in Health, Agriculture and Food Security, and Water Resources and Hydrology Sectors. The software provides three methods for computing indices using text files containing station data : (1) graphical user interface; (2) to batch process multiple station text files in parallel; and (3) calculating indices from netCDF data (Lisa Alexander & Herold, 2016). The development of these ClimPACT2 sector specific indices have made a significant contribution to climate change discussions in the IPCC assessment reports (Lisa V. Alexander, 2016).

ClimPACT2 was written in R-programming, R is available as Free Software under the terms of the Free Software Foundation's GNU General Public License in source code form (see **http://www.r-project.org/**). Users familiar with the RClimDEX1 software will notice some similarities in the output of ClimPACT2 GUI. This is because ClimPACT2 was developed using the basic code from climdex.pcic2 which was modeled after RClimDex. This means that the same simple data quality control procedure is implemented along with a bootstrapping procedure to determine climatological percentile thresholds.

3.4.2 Computation and calculation of precipitations indices

After the quality control and homogeneity test, the daily precipitation data from 23 stations were load for the indices calculation using Climpact2. ClimPACT2 was used to calculate the core and non-core ET-SCI selected precipitation indices presented in Table 2, and all indices are found in the (Alexander & Herold, 2016). The core and non-core ET-SCI sector specific indices were tested for statistical significance at 99.9%, 99%, 95% and 90% confidence intervals, using MAKSENS excel template developed by (Salmi et al., 2002) and assumed statistically significance above a 95% confidence interval. And slope was categorized into three classes including significant, positive non-significant and negative non-significant. List and definitions of the indices used in this study are presented in Table 2.

Table 2 Definitions of the indices used in the study

Index	Descriptive name	Definition	Units	Sectors
PRCPTOT	Annual total wet day precipitation	Annual total precipitation in wet days	mm	AFS, WRH
RX1day	Max-1-day precipitation amount	Annual maximum 1-day precipitation	mm	
RXd-day[a]	User defined consecutive days precipitation amount	Annual maximum consecutive d-day precipitation	mm	H, AFS, WRH
RX5day	Max-5-day precipitation amount	Annual maximum consecutive5-day precipitation	mm	
SDII	Simple daily intensity index	Ratio of annual total precipitation divided by the number of wet days in the year	mm/day	
Rnnmm[a]	Number of customized rain days	Annual count of days when the precipitation ≥nnmm	Days	
R10mm	Number of heavy precipitation days	Annual count of days when the precipitation ≥10mm	Days	
R20mm	Number of very heavy precipitation days	Annual count of days when the precipitation ≥20mm	Days	AFS, WRH
R95p	Very wet days	Annual sum of daily precipitation > 95 percentile	mm	
R99p	Extremely wet days	Annual sum of daily precipitation > 99 percentile	mm	
R95pTOT	Precipitation fraction due to very wet days	$100 \times R95p/PRCPTOT$	%	AFS, WRH
R99pTOT	Precipitation fraction due to extremely wet days	$100 \times R99p/PRCPTOT$	%	AFS, WRH
CDD	Consecutive dry days	Maximum number of consecutive days when PR<1mm	Days	H, AFS
CWD	Consecutive wet days	Maximum number of consecutive days when PR ≥ 1mm	Days	

Note: H= health, AFS= Agriculture and food security, WRH= water Resources and Hydrology, a = User-defined indices, RX d-day is calculated as maximum consecutive 3 days precipitation and Rnnmm calculated as number of wet days (R≥1mm)

Source: (Alexander et al., 2013; Alexander & Herold, 2016)

3.5 Significance test and trend analysis

3.5.1 Mann-Kendall Test

The Mann-Kendall test is a non-parametric test for identifying trends in time series data. The test compares the relative magnitudes of sample data rather than the data values themselves (Gilbert, 1987). The Mann-Kendall Test is used to determine whether a time series has a monotonic upward or downward trend. It does not require that the data be normally distributed or linear. It does require that there is no autocorrelation

The Mann-Kendall test is applicable in cases when the data values X_i of a time series can be assumed to obey the model

$$X_{i=f(t_i)+\varepsilon_i} \qquad (1)$$

Where, $f(t)$ is a continuous monotonic increasing or decreasing function of time and the residuals ε_i can be assumed to be from the same distribution with zero mean. It is therefore assumed that the variance of the distribution is constant in time.

We want to test the null hypothesis of no trend, Ho, i.e. the observations xi are randomly ordered in time, against the alternative hypothesis, H1, where there is an increasing or decreasing monotonic trend. In the computation of this statistical test MAKESENS exploits both the so-called S statistics given in Gilbert (1987) and the normal approximation (Z statistics). For time series with less than 10 data points the S test is used, and for time series with 10 or more data points the normal approximation is used.

The number of annual values in the studied data series is denoted by n. Missing values are allowed and n can thus be smaller than the number of years in the studied time series.

The Mann-Kendall test statistic S is calculated using the formula

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k), \qquad (2)$$

Where, x_j and x_k are the annual values in years *j* and *k*, *j* > *k*, respectively, and

$$sgn\left(x_j - x_k\right) = \begin{cases} 1 & if\ x_j - x_k > 0 \\ 0 & if\ x_j - x_k = 0 \\ 1 & if\ x_j - x_k < 0 \end{cases} \tag{3}$$

If n is 9 or less, the absolute value of S is compared directly to the theoretical distribution of S derived by Mann and Kendall (Gilbert, 1987). In MAKESENS the two-tailed test is used for four different significance levels α: 0.1, 0.05, 0.01 and 0.001. At certain probability level H_0 is rejected in favour of H1 if the absolute value of S equals or exceeds a specified value $S\alpha/2$, where $S\alpha/2$ is the smallest S which has the probability less than $\alpha\ /\ 2$ to appear in case of no trend. A positive (negative) value of S indicates an upward (downward) trend.

The minimum values of n with which these four significance levels can be reached are derived from the probability table for S as follows.

Significance level (α)	**required *n***
0.1	≥ 4
0.05	≥ 5
0.01	≥ 6
0.001	≥ 7

The significance level 0.001 means that there is a 0.1% probability that the values xi are from a random distribution and with that probability we make a mistake when rejecting H_0 of no trend. Thus, the significance level 0.001 means that the existence of a monotonic trend is very probable. Respectively the significance level 0.1 means that there is a 10% probability that we make a mistake when rejecting H_0.

If *n* is at least 10 the normal approximation test is used. However, if there are several tied values (i.e. equal values) in the time series, it may reduce the validity of the normal approximation when the number of data values is close to 10.

First the variance of S is computed by the following equation which takes into account that ties may be present:

$$VAR(s) = \frac{1}{8}\left[\mathrm{n(n-\ 1)(2n+\ 5)} - \sum_{\mathrm{p=1}}^{\mathrm{q}} t_p(\mathrm{t_p}-1)(2\mathrm{t_p}+2\mathrm{t\ _p}) \right] \qquad (4)$$

Here q is the number of tied groups and t_p is the number of data values in the p^{th} group.

The values of S and VAR(S) are used to compute the test statistic Z as follows

$$Z_q = \begin{cases} \frac{s-1}{\sqrt{VAR\ (s)}} & if\ s > 0 \\ 0 & if\ \ s = 0 \\ \frac{s+1}{\sqrt{VAR(s)}} & if\ s < 0 \end{cases} \qquad (5)$$

The presence of a statistically significant trend is evaluated using the $Z_q$value. A positive (negative) value of Z indicates an upward (downward) trend. The statistic Z has a normal distribution. To test for either an upward or downward monotone trend (a two-tailed test) at α level of significance, H_0 is rejected if the absolute value of Z is greater than $Z_{1-\alpha/_2}$ where $Z_{1-\alpha/_2}$ is obtained from the standard normal cumulative distribution tables. In MAKESENS the tested significance levels α are 0.001, 0.01, 0.05 and 0.1.

3.5.2 Sen's Slope estimator

To estimate the true slope of an existing trend (as change per year) the Sen's nonparametric method is used. The Sen's method can be used in cases where the trend can be assumed to be linear. This means that $f(t)$ in equation (1) is equal to

$$f(t) = Qt + B \qquad (6)$$

Where, Q is the slope and B is a constant

To get the slope estimate Q in equation (6) we first calculate the slopes of all data value pairs

–

$$Q_i = \frac{x_j - x_k}{j-k} \qquad (7)$$

Where x_j and x_K are the data value in the tile j and k (j>k),

If there are n values x_j in the time series we get as many as $N = n(n-1)/2$ slope estimates Qi. The Sen's estimator of slope is the median of these N values of Q_i.The N values of Q_i are ranked from the smallest to the largest and the Sen's estimator is

$$Q = Q_{[(N+1)/2]} \qquad if\ N\ is\ odd$$

Or,

$$Q = \frac{1}{2}\left(Q_{[N+2]} + Q_{[(N+1)/2]}\right), \qquad if\ N\ is\ even \qquad (8)$$

Q sign reflect the data trend reflection, while its value indicates the steepness of the trend.

A 100(1-α) % two-sided confidence interval about the slope estimate is obtained by the nonparametric technique based on the normal distribution. The method is valid for *n* as small as 10 unless there are many ties.

The procedure in MAKESENS computes the confidence interval at two different confidence levels; α = 0.01 and α = 0.05, resulting in two different confidence intervals

The confidence interval about the tile slope can be defined by

$$C_{\alpha} = Z_{1-\alpha/2}\sqrt{VAR(S)} \qquad (9)$$

Where, VAR(S) has been defined in equation (4), and $Z_1 - \alpha/2$ is obtained from the standard normal distribution

Next $M_1 = (N - C_\alpha)/2$ and $M_2 = (N - C_\alpha)/2$ are computed. The lower and upper limits of the confidence interval, Q_{min} and Q_{max}, are the $M1^{th}$ largest and the $(M_2+1)^{th}$ largest of the N ordered slope estimates Q_i. If M_1 is not a whole number the lower limit is interpolated. Correspondingly, if M_2 is not a whole number the upper limit is interpolated. To obtain an estimate of B in equation (6) the n values of differences $X_i - Q_{t_i}$ are calculated. The median of these values gives an estimate of B (Sirois, 1998). The estimates for the constant B of lines of the 99% and 95% confidence intervals are calculated by a similar procedure.

3.6 Spatial Analysis

Interpolation methods estimate the values in un-sampled locations. ArcGIS statistical analyst has the capability to apply many types of spatial interpolation to point data. There are a number of interpolation methods available (Lam, 1983) but one of the most frequently used interpolation method in GIS is Kriging. Ordinary kriging method was used for the spatial analysis of seasonal, and precipitation indices characteristics over the basin in ArcGIS platform (Zimmerman et al., 1999).

3.7 Extreme Precipitations Indices

The Expert Team on Sector-specific Climate Indices (ET-SCI) related to daily precipitation characteristics were analyzed. A full list of indices are found in (Alexander & Herold, 2016). The studied indices were divided into 5 categories as adapted from (Alexander et al., 2006; Zhang et al., 2011), and are described below.

3.7.1 Percentile-based indices

Very wet days (R95p)

The very wet days (R95p) is total amount of rainfall from very wet days (annual sum of daily precipitation PR> 95th percentile). Percentile based precipitation extreme indices were calculated using the baseline reference period of 1981-2010. Let RR_{wj} be the daily precipitation amount on a day in the 1980-2018 period. If W represents the number of wet days in the period, then:

$$R95\,P_j = \sum_{w=1}^{W} RR_{wj.}\ where\ RR_{wj} > RR_{wn}95$$

Extremely wet days R99p

The extremely wet days (R99p) is the total amount of rainfall from very wet days (annual sum of daily precipitation PR>99th percentile). R99p were calculated using the baseline reference period of 1981-2010. Let RR_{wj} be the daily precipitation amount on a wet day $w(RR \geq 1.0mm)$ in period j and let $RR_{wn}99$ be the 99th percentile of precipitation on wet days in the 1981-2010 period. If W represents number of wet days in the period, then:

$$R99\, P_j = \sum_{W=1}^{W} RR_{wj} \text{ where } RR_{wj} > RR_{wn}99$$

Contribution from very wet days (R95pTOT)

The R95pTOT is the fraction of total wet-day rainfall that comes from very wet days (100*r95p/PRCPTOT)

Contribution from extremely wet days (R99pTOT)

The R99pTOT is the fraction of total wet-day rainfall that comes from extremely wet days (100*r99p/R99pTOT)

3.7.2 Absolute indices

The absolute indices represented maximum or minimum values of weather parameters within a year. The absolute precipitation indices are maximum 1-day precipitation amount (RX1day), maximum 3 days precipitation amount (RX3day) and maximum 5 days precipitation amount (RX5day)

Maximum 1-day precipitation amount (RX1day)

The RX1day is the maximum amount of rainfall that falls in one day. Let RR_{ij} be the daily precipitation amount on day i in period j. Then maximum 1-day values for period j are:

$$Rx1day_j = max(RR_{ij})$$

Rx3day (RXdday) (user defined consecutive days PR amount)

The RX3day is the maximum amount of rainfall that falls in consecutive three days. Let RR_{kj} be the precipitation amount for the 3-day interval ending k, period j. Then maximum 5-day values for period j are:

$$Rx3day_j = \max(RR_{kj})$$

Maximum 5-day precipitation total (Rx5day)

The RX5day is the maximum amount of rain that falls in five consecutive days. Let RR_{kj}be the precipitation amount for the 5-day interval ending k, period j. Then maximum 5-day values for period j are:

$Rx5day_j = max(RR_{kj})$

3.7.3 Threshold Indices

These are the number of days at precipitation value falls above or below the fixed threshold, including number of wet days (R1mm), number of heavy precipitation days (R10mm) and number of very heavy precipitation days (R20mm).

Number of heavy precipitation days (R10mm)

The R10mm is the annual count of days when precipitation is ≥ 10mm. Let RR_{ij}be the daily precipitation amount on day i in period j. Count the number of days where:

$RR_{kj} \geq 10\ mm$

Number of very heavy days (R20mm)

The R20mm is the annual count of days when precipitation is ≥ 20mm. Let RR_{ij}be the daily precipitation amount on day i in period j. Count the number of days where:

$RR_{ij} \geq 20mm$

Rnmm : (R1mm) wet days

The R1mm (WD) is the annual count of days when precipitation ≥ 1mm. Let RR_{ij}be the daily precipitation amount on day i in period j. If nnrepresents any reasonable daily precipitation value then, count the number of days where:

$RR_{ij} \ \geq nnmm$

3.7.4 Duration indices

The precipitation duration indices are the periods of excessive wetness or dryness. Precipitation duration indices includes, the consecutive dry days (CDD) and consecutive wet days (CWD).

Consecutive dry days (CDD)

The CDD is the length of the longest dry spell in a year. Let RR_{ij}be the daily precipitation amount on day j in period j. Count the largest number of consecutive days where:

$$RR_{ij} < 1mm$$

Consecutive wet days (CWD)

The CWD is the longest wet spell in a year. Let RR_{ij}be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where:

$$RR_{ij} \geq 1mm$$

3.7.5 Other Indices

Annual total wet-day precipitation (PRCPTOT)

The PRCPTOT is the annual sum of precipitation from days ≥ 1mm. Let RR_{ij}be the daily precipitation amount on day i in period i. If I represents the number of days in j, then

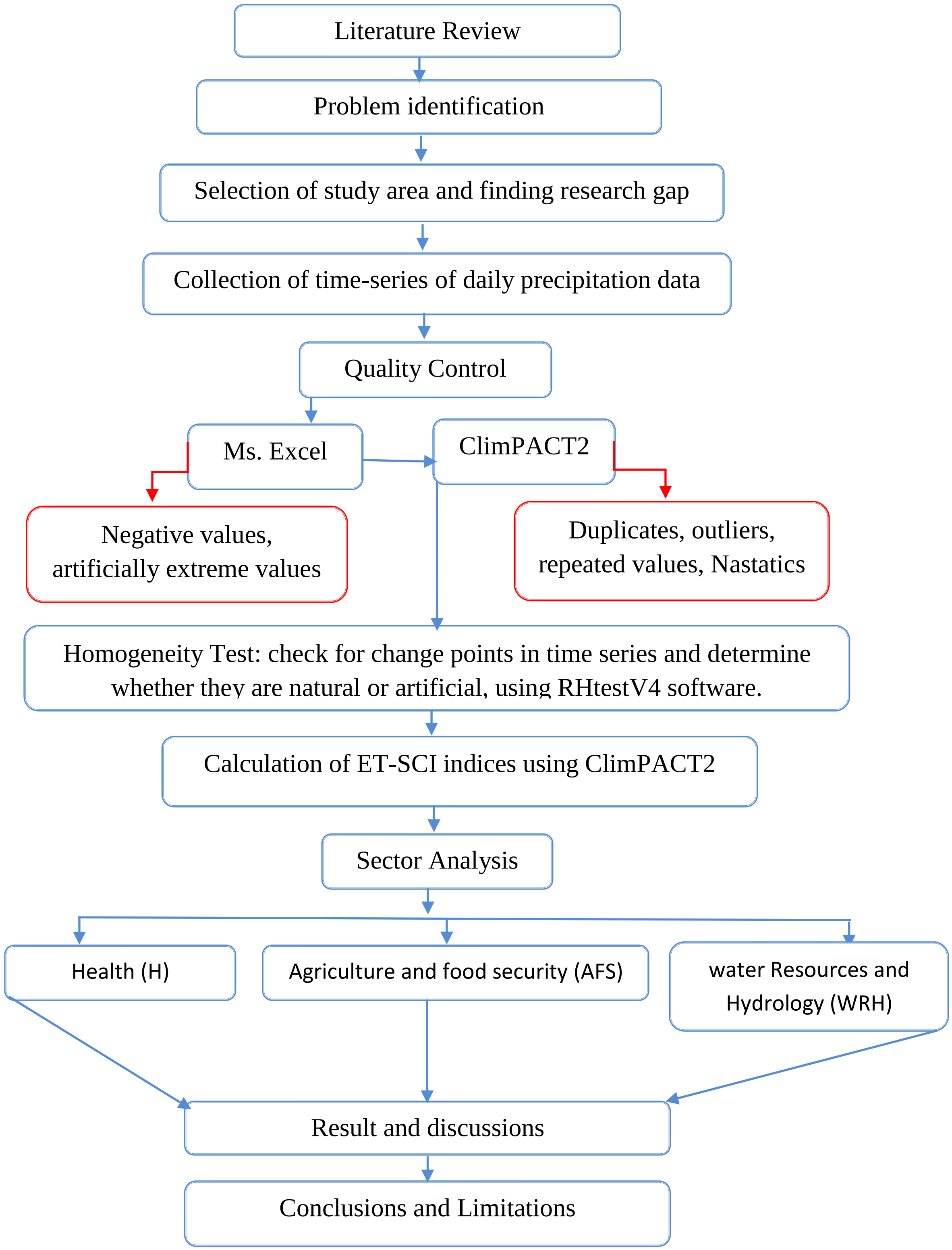
$$PRCPTOT_j = \sum_{i=1}^{I} RR_{ij}$$

Simple daily intensity index (SDII)

The SDII is the ratio of annual total precipitation divided by the number of wet days (when the total precipitation ≥ 1.0 mm) Let RR_{ij}be the daily precipitation amount on wet days, $w(RR \geq 1mm)$ in period j. If w represents number of wet days in j, then:

$$SDII_j = \frac{\sum_{W=1}^{W} RR_{wj}}{W}$$

3.8 Research Design



Chapter 4

Result and discussion

4.1 Precipitation characteristics over the basin

The average annual precipitation in the Narayani river basin ranged from 270 mm to 5401 mm. The middle mountain receives the maximum amount of precipitation whereas the high Himalaya receives the minimum amount of rainfall (Figure 4). July is the highest precipitation month for all regions and august is the second highest precipitation month for Terai, Siwalik, Middle mountain and high mountain regions but September is the second highest precipitation month for high Himalaya. November is the lowest precipitation month for the regions, expect high Himalayas. December is the lowest precipitation month for high Himalaya. Narayani river basin received 78.9 % of total annual precipitation in monsoon season. The contribution from post-monsoon, winter and pre-monsoon precipitation are 3.68%, 3.125%, and 14.26% respectively.

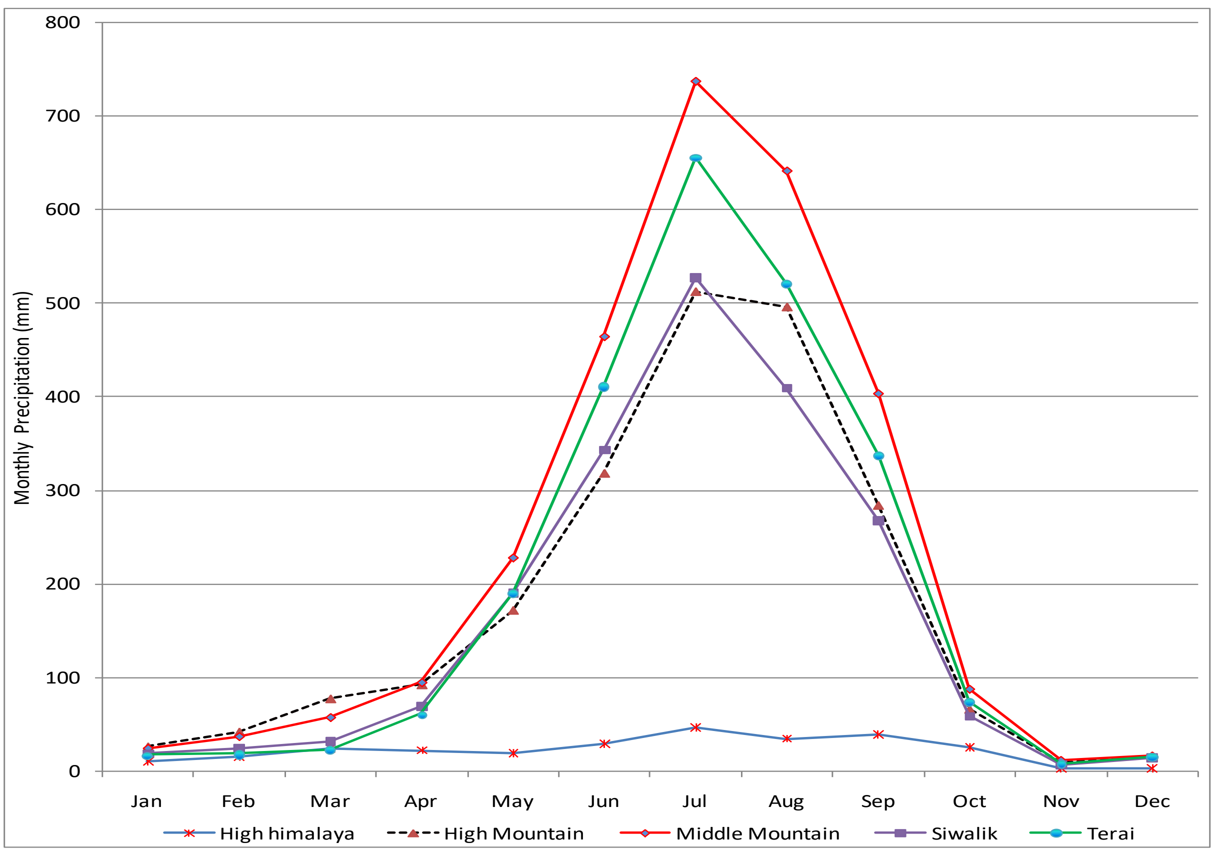


Figure 4: Monthly averaged precipitation in different regions of the Narayani river basin

4.2 Distribution and trend in seasonal precipitation

4.2.1 Winter

The distribution pattern of winter precipitation is presented in Figure 7. The winter precipitation was found in the range of 28mm (Jomsom) to 158mm (Siklesh) with considerable diagonally increasing pattern from south eastern to North West up to central part of the basin then decreased pattern was observed. The minimum winter precipitation was observed at the two corners of the basin i.e, north western and south eastern part of the basin. The distribution pattern of winter precipitation represent that the central part of the basin received maximum precipitation than other part of the basin at winter seasons.

The winter precipitation decreased on average -0.71 mm $year^{-1}$ which is presented in Table 4, and spatial distribution of winter trend and magnitude is presented in Figure 26.Overall, most of the station shows the negative trend. The winter precipitation is decreased at 20 stations (4 statistically significant) and increased at 2 stations (1 statistically significant) and only one stations shows the no trend in winter precipitation. Overall, winter precipitation is decreased at maximum rate at the central part of the basin (middle mountain), decreased with minimum rate at southern part of the basin (siwalik and indo gangetic plain) and increased at the northern west part of the basin (high mountain and high himalayas). The increasing maximum trend was observed at jomsom station with magnitude 0.89mm per year (significantly) and decreasing trend with higher magnitude was observed at pokhara airport with magnitude -1.68mm per year (significantly).

4.2.2 Pre-monsoon

The distribution pattern of pre-monsoon precipitation shows that the increasing pattern with increasing elevation up to central part and then decreasing at western part of the basin, but unclear distribution pattern was observed at eastern part of the basin. Figure 8 clearly shows that the central part of the basin received maximum pre-monsoon precipitation than other parts, and south western and north part of the basin received the minimum precipitation.

The trend of pre-monsoon precipitation is presented in Figure 27 and Table 4, which indicates that the pre monsoon precipitation is increased on average 0.93mm per year. The pre monsoon precipitation is increased insignificantly at 17 stations and decreased insignificantly at 6 stations, no any significant trend was observed. The increasing trend with higher magnitude was observed at musikot station with 4.20 mm per year and maximum decreasing trend was observed at Bandipur station with magnitude -2.81mm per year. All the station at the Terai and High Himalaya regions shows the increasing trend, mixed pattern was observed at other part of the basin.

4.2.3 Monsoon

The distribution pattern of monsoon precipitation is shown in Figure 9. The distribution pattern of monsoon precipitation is nearly similar with distribution pattern in pre-monsoon seasons. Monsoon precipitation ranges from 148mm (Jomsom station) to 4605mm (Lumle station) which indicates that the central part received maximum precipitation at monsoon seasons. 78.9% of the total annual precipitation was received in the monsoon seasons.

The monsoon precipitation is decreased on average -2.16mm per year (Table 4). Overall, most of the stations shows negative trend (Figure 28). The monsoon precipitation is increased at 6 stations and decreased at 17 stations (1 significant). All the stations at the Terai and Siwalik regions shows the decreasing trend, whereas high Himalaya shows the increasing trend. Mixed pattern of increasing and decreasing pattern was observed at Middle mountain and high mountain regions. In overall, north-west part of the basin shows the positive trend and all the stations at the south and east part of the basin shows the negative trend. This result indicates that the southern part of the basin will receive less precipitation in future and the precipitation in northern part at high altitude will receive more monsoon rainfall in upcoming years.

4.2.4 Post-monsoon

The distribution pattern of post-monsoon precipitation is presented in Figure 10. The post monsoon precipitation is ranges from 28mm (Jomsom) to 224mm (Lumle). The post monsoon precipitation is almost same as the winter precipitation in Jomsoom station. Figure 10 show that the post monsoon precipitation is decreases from central part of the basin toward north and south in most part of the basin but reverse pattern was observed in the eastern part of the basin. In overall the Lumle and its surrounding area receives maximum and Jomson, Ridi Bazzar and dhunibesi area receives minimum precipitations in post monsoon seasons. The trend of post-monsoon precipitation is presented in Table 4 and Figure 29. The post-monsoon precipitation is decreased on average -0.18mm per year. The post-monsoon precipitation is decreased at 17 stations (1 statistically significant) and increased at 6 stations. The maximum increasing trend was observed at the Pokhara airport stations with magnitude 2.36mm per year and decreasing trend was observed at the Balewa Girwari station with magnitude -1.6mm per year. All the stations located in the Terai, Siwalik, high mountain and high Himalaya shows the downward trend whereas mixed pattern of increasing and decreasing trend observed at middle mountain regions. Most of the stations at the central part of the basin shows the increasing trend. Only one station Chisapani Gadi shows the significant decreasing trend with magnitude -0.89mm per year.

4.3 Spatial distribution of maximum (annual and 1 day) Precipitation

The ever-recorded maximum annual precipitation is found in the range of 408mm to 6310mm (Figure 11), which is strength at the central part of the basin and lowest at the northern part of the basin (leeward side of the Annapurna-Machhapuchare range). The maximum annual 1-day precipitation over the period 1980-2018 is shown in Figure 12. The ever recorded 1-day precipitation is ranges from 87mm (water equivalent) at high elevated area (Jomsom and its surrounding) to 516mm at low land (Terai and siwalik). which shows that the maximum 1 day precipitation is strength at the southern part of the basin, while southern part received the minimum annual precipitation than the central part of the basin, this result indicates that the southern part of the basin is more vulnerable to extreme precipitation related disasters, such as flooding which is also indicated by (Eckstein et al., 2018)

4.4 Spatial distribution of extreme precipitation indices

Annual extreme precipitation indices were calculated, for better understanding, the indices were divided into five broad categories.

1. percentile-based indices (R95p, R95p TOT, R99p, R99p TOT)

2. Absolute indices (RX1day, RX3day, RX5day)

3. Threshold indices (R10mm, R20mm, R1mm)

4. Duration indices (CDD, CWD)

5. Other indices (PRCPTOT, SDII)

The average values of these indices for each station was calculated and further analyzed. The spatial distribution of these indices is shown in Appendix A.

4.4.1 Percentile-based indices

Percentile based indices covers the precipitation over the certain long-term percentile. Percentile based precipitation extreme indices were calculated using the baseline reference period of 1981-2010, and the results are presented in appendix A. The percentile based extreme precipitation indices were: very wet days (R95p TOT) and extremely wet days (R99p TOT) and these indices represent the amount of precipitation falling above the 95^{th} and 99^{th} percentile respectively. The total annual precipitation from heavy rain days for Narayani basin was found in the range of 60 to 1181 mm each year (Figure 13) and contribution from very wet days R95p TOT was found in the range 18% to 27% Figure 14. The total annual precipitation from very heavy rain days R99p was found in the range of 23 to 337mm each year Figure 15. The maximum R95p was found in the central part of the basin and minimum R95p was found in the north western part of the basin but the contribution from 95^{th} percentile is quite different. The R95p TOT is maximum at the southern part of the basin 24 to 27 % and minimum at the northern part of the basin 18-19%. It clearly shows that the distribution pattern of R95p TOT is decreased with increasing elevation (Figure 14)

4.4.2 Absolute indices

The absolute indices represent maximum or minimum values of weather parameters within a year. The absolute precipitation indices are maximum 1-day precipitation amount (RX1day), maximum 3 days precipitation amount (RX3day) and maximum 5 days precipitation amount (RX5day).the spatial distribution of RX1day, RX3day and RX5day are presented in Figure16, Figure 17, Figure 18 respectively. The maximum 1- day, 3-day and 5-day precipitation was found in the range of 35 to 209mm, 51 to 359mm and 56 to 486mm respectively each year. The maximum 1 day precipitation was intense at the low land (Balewa Girwari and surrounding station) and central part of the basin (lumle and surrounding station). But the RX3day and RX5day shows almost similar distribution pattern. These indices are intense at the central, central west and eastern west part of the basin. It indicates that the lowland region in the southern part of the basin is much more vulnerable to flood-related disasters like; loss of life and properties. This result is strongly supported by some previous research works by Eckstein et al., (2018) and Karki et al., (2017b).

4.4.3 Threshold indices

These are the number of days at precipitation value falls above or below the fixed threshold, including number of wet days (R1mm), number of heavy precipitation days (R10mm) and number of very heavy precipitation days (R20mm). The wet days are found in the range of 46 (jomsom) to 182 (siklesh) days each year Figure 21. The number of heavy precipitation and very heavy precipitation was found in the range of 7 (jomsom) to 111 (lumle) days (Figure 19) and 2 (jomsom) to 80 (lumle) days (Figure 20) respectively. The distribution of number of heavy precipitation days shows that the increasing pattern with increasing elevation up to the central part of the basin and then decreasing with increasing with elevation (expect south eastern part of the basin). The central part of the basin (or Middle Mountain) around Lumle and Pokhara said to be the pocket area concerning the concentration of all these indices but its south and northwest parts seem to have a lower frequency of heavy rainfall. The increase in the frequency of threshold indices could possess some serious impact on the Middle Mountain region, landslide as a major and agriculture losses are secondary.

4.4.4 Duration indices

The precipitation duration indices are defined as the periods of excessive wetness or dryness. Precipitation duration indices includes, the consecutive dry days (CDD) and consecutive wet days (CWD). The CDD is the length of the longest dry spell in a year while the CWD is the longest wet spell in a year. The distribution of consecutive dry days is shown in Figure 22 and distribution of consecutive wet days is presented in Figure 23. The CDD and CWD are found in the range of 43 to 86 and 4 to 48 respectively. The area with highest number of consecutive dry days is the southern (expect Tamghas and Hetauda N.F.I) and west northern part of the basin, while the central part of the basin with the minimum number of consecutive dry days. Likewise, consecutive wet days are strength at the central part of the basin and less at the southern and western north part of the basin. There is no clear pattern of distribution of CDD and CWD with elevation. It is clear that in the southern part including Terai and Siwalik region of the basin numbers of consecutive dry days were highest and seem to be decreased northward by the Middle Mountain (MM). It indicates how the agricultural hub of the Narayani river basin gets dominated by maximum dry days. It is interesting to note down that some part of High Himalaya (HH) in western part around Jomsom possesses high frequency of CDD than the central and eastern belt. The study of the nearby river basin in eastern Nepal also shows that the HH area was comparatively drier than any other parts, similar result was obtained by Subba et al., (2019)

4.4.5 Other indices

It includes the indices of annual precipitation total (PRCPTOT) and simple daily intensity index (SDII). The distribution pattern of PRCPTOT is presented in Figure 24, and distribution pattern of SDII is presented in Figure 25. The PRCPTOT and SDII are found in the range of 265 to 5394mm and 6 to 32 mm/day respectively. The simple daily intensity index is intense at the central and central south part of the basin, while the southern part of the basin receive less precipitation but simple daily intensity index is nearly equal with the central part of the basin which receive the maximum precipitation, this indicates that the precipitation in the central southern part is concentrated within the short period of time.

4.5 Trend in extreme precipitation indices

The result of the trend analysis of precipitation extreme are presented in Table 3, and spatial distribution of precipitation extreme and magnitude over the Narayani basin are presented in appendix A.

4.5.1 Percentile based indices

Percentile based indices covers the precipitation over the certain long-term percentile. The trends in precipitation on very wet days R95p is presented in Table 3 and Figure 30.The annual total precipitation on very wet days R95p (precipitation amount >95th percentile) decreased on average by -0.05mm per year. This is consistent with the result reported by Devkota & Bhattarai, (2018). R95p increased at 9 stations (1 statistically significant) and non-significant negative trend at 14 stations. Maximum positive trend was observed at Syangja station with magnitude 8.75mm per year and minimum trend was observed at Jomsom station with magnitude -0.19mm per year. Only one station (Late) shows the statistically positive trend with magnitude 4.11 mm per year. The precipitation fraction due to very wet days (R95pTOT) increased on average 0.02% per year Figure 31, Table 3). The trend of R95pTOT shows non-significant positive at 14 stations and negative at 9 stations. The precipitation on extremely wet days (R99p) increased on average by 0.32mm per year. All the stations situated at the Terai shows the downward trend of R99p Figure 32. R99p is increased significantly at Late stations by 3.96mm per year. This results is partially consistent with the result study by Baidya et al., (2008) and Shrestha et al., (2017).

4.5.2 Absolute indices

These indices represent the maximum or minimum values within a seasons or year. Maximum 1-day precipitation RX1day, maximum 3-day precipitation RX3day and maximum 5 day precipitation RX5day all are absolutes indices.

The maximum 1-day precipitation (RX1day) increased on average by 0.11mm per year. RX1day increased at 11 stations (1 statistically significant) and decreased at 12 stations (1 statistically insignificant) presented in Figure 33. Maximum positive trend was observed at pokhara airport station with magnitude 1.19mm per year (statistically significant) and minimum trend was observed at khudi bazaar station with magnitude -0.90mm per year (statistically significant). On average RX1day is increased over the basin, which is consistent with Baidya et al., (2008),Devkota & Bhattarai, (2018), but decreased, most of the stations at northern part of the basin which is consistent with Sigdel & Ma, (2017). Maximum 1 day precipitation is increased at all the stations of Terai regions and decreased at high Himalaya, and mixed pattern of increasing and decreasing trend observed at other part of the basin, this is consistent with the results reported by Karki et al., (2017b). The maximum consecutive 3-day precipitation (RX3day) increased on average by 0.16mm per year. RX3day increased at 13 stations and decreased at 10 stations (2 statistically significant) represented in Figure 34. Maximum positive trend was observed at Balewa Girwari station with magnitude 1.72mm per year and negative trend was observed at Chapkot station with magnitude -1.83mm per year.

The maximum consecutive 5 day precipitation (RX5day) increased on average by 0.04mm per year, which is consistent with (Baidya et al., 2008; Shrestha et al., 2017) but magnitude is different. RX5day increased at 12 stations (no statistically significant) and decreased at 11 stations (1 statistically significant) presented in Figure 35. Maximum positive trend was observed at Syangja station with magnitude 2.07mm per year and minimum was observed at Chapkot station with magnitude -2.43mm per year. All the absolute indices Shows the upward trend at Terai regions, which indicates that more flooding event will occur in this region. on average the absolute indices RX1day, RX3day and RX5 shows the upward trend, similar result was observed by the Zhan et al., (2017), over the Hindu Kush Himalaya. These absolute indices are mostly increased in low lands of the Terai region and thus bringing about rainfall related hazards like floods, soil degradation with inundation and may cause the possible impacts on agriculture and livelihood.

4.5.3 Threshold indices

These are the number of days at precipitation value falls above or below the fixed threshold. The trend of wet days is presented in Figure 38, the total annual wet days WD (PR <1mm) decreased on average by -0.19 days per year. WD increased at only 5 stations (2 statistically significant), decreased at 17 stations (8 statistically significant) and one station shows no trend (Khairani tar station). The stations above the 2000m (high Himalaya and high mountain) shows the positive trend, similar trend was observed by Karki et al., (2017). This indicates that the higher altitude becomes more wetter than previous years and 78.3% of the stations shows the negative trend below 2000m. This result shows that in most part of the basin wet days are decreased.

The trend of heavy precipitation days (R10mm) is presented in Figure 36, the total number of heavy precipitation days (R10mm) decreased on average -0.09 days per year. R10mm increased at 6 stations (1 statistically significant) and decreased at 17 stations (5 statistically significant). The stations above 2000m (high Himalaya and high mountain) shows the positive trend expect Kakani station. Similar trend was observed by Karki et al., (2017).The maximum increasing trend was observed at musikot station by 0.41 days per year (statistically significant) and decreasing trend was observed at Bandipur station by -0.48 days per year (statistically significant).

The trend of very heavy precipitation days (R20mm) is presented in Figure 37, the total number of very heavy precipitation days (R20mm) increased on average 0.01 days per decade. The R20mm increased at 7 stations (1 statistically significant) and decreased at 16 stations (5 statistically significant). All the stations situated at the eastern part of the basin shows the negative trend and there is a mix pattern of increasing and decreasing trend in other part of the basin. The maximum increasing trend was observed at Musikot station by 0.68 days per year (statistically significant) and decreasing trend was observed at Ridi bazaar by -0.26 (statistically significant). These results are partially consistent with Baidya et al., (2008); Shrestha et al., (2017). These results suggest that in addition to Terai most of the Middle Mountain and Siwalik range moderate to heavy rainfall events are decreasing, while in High Mountain and Himalaya region the events seem to be increasing.

4.5.4 Duration indices

These indices signify the wetness or dryness in the climate. The consecutive dry days and consecutive dry days are duration indices.

The trends of consecutive dry days (CDD) and consecutive wet days (CWD) is presented in Figure 39 and Figure 40 respectively. The maximum number of consecutive dry days CDD (when the precipitation < 1.0 mm) increased on average by 0.56 days per year. The trends of consecutive dry days are presented in fig Figure 39. CDD increased at 21 stations (4 statistically significant) and decreased at only 2 stations (statistically insignificant). Consecutive dry days are decreased at Jomsom (High Himalaya) station. The maximum number of consecutive wet days CWD (when the precipitation ≥ 1.0mm) decreased on average by -0.02 days per year. CWD is increased at 8 stations (2 statistically significant) and decreased at 15 stations (4 statistically significant), which is presented in Table 3. All the stations above the 2000m shows the increasing trend and other stations below 2000m shows the mixed pattern of increasing or decreasing trend. Increasing trend of CDD and decreasing trend of CWD linked with the livelihood of the people in the area, which affect the agriculture activities and may cause drought and floods. These increasing trends of CDD and decreasing trends of CWD below 2000masl during the last 4 decades correlate much with the recent droughts events throughout the country identified by (Dahal et al., 2016). The increasing trend of CDD and decreasing trend of CWD may affect the crop yield, cause wildfire by prolonged drought, and also the health-related problem by increasing of dust particles in the air within the basin.

4.5.5 Other indices

The other indices included the annual total wet day precipitation (PRCPTOT) and simple daily intensity index (SDII). The PPRCPTOT is the sum of daily precipitation in wet days (precipitation $\geq$1.0 mm) and SDII is the annual total precipitation divided by the number of wet days (PRCP $\geq$1.0 mm).

The trend of total wet day precipitation (PRCPTOT) is presented in Figure 41. The PRCPTOT decreased on average by –2.25mm per year. PRCPTOT is increased at 8 stations (2 statistically significant) and decreased at 15 stations (1 statistically significant). Maximum increased trend was observed at musikot station by 15.93 mm per year (statistically significant) and decreased at Ridi Bazzar station by -13.86 mm per year. The wet days precipitation is increased at Jomsom and nearer station late (significant), this indicates increasing pattern of precipitation in northwestern part of the basin. There is decreasing trend of PRCPTOT at all the stations situated in the eastern part of the basin and mixed pattern of increasing and decreasing trend was observed at other part of the basin.

The simple daily intensity index (SDII) indicates the intensity of precipitation in wet days, trends of SDII is presented in Figure 42. The SDII increased on average by 0.02 mm/day. SDII is increased at 14 stations (3 statistically significant) and decreased at 9 stations (1 statistically significant). Maximum increased trend was observed at Balewa Girwari station by 0.26 mm/day and decreased trend was observed at Chapkot station by -0.11 mm/day. SDII is increased at all the stations of Terai regions (2 statistically significant), decreased at all the stations of high-mountain and high Himalaya and mixed pattern of increasing and decreasing pattern was observed at other part of the basin. This result indicates that the precipitation is leading toward more intense (concentrated within short period of time) in Terai regions than other part. Overall increased pattern of SDII indicates that the precipitation is concentrated within short period of time. This is consistent with the result reported by Karki et al., (2017b); Shrestha et al., (2017).

4.6 Annual total wet day precipitation (PRCPTOT)

Figure 5 shows that the average annual total wet day precipitation across the 23 precipitation stations in the Narayani river basin from 1980 to 2018. The long-term wet day precipitation shows that the decreasing trend by -2.099 mm per year which may be corelate with the serious impact on agriculture, food security, water Resources and Hydrology. The decreasing pattern of PRCPTOT may indicate that the basin is leading towards the drought events and may seriously impact on agriculture. This result is consistent with the result indicated by Dahal et al., (2016).

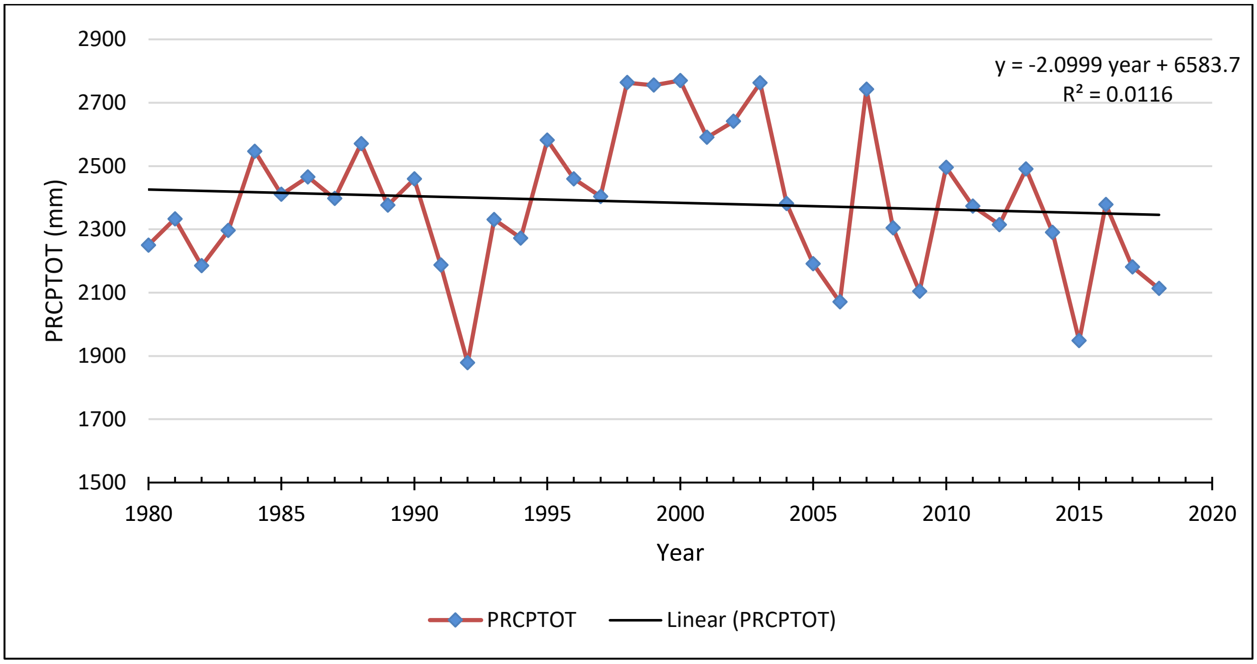


Figure 5: Annual total wet day precipitation (PRCPTOT) across the Narayani river basin, Nepal

4.7 Total stations with different trend features

The percentage of stations with different trends features presented in Figure 6, which shows 91% of the stations shows the increasing pattern of consecutive dry days, among them 17.4% of stations shows the significantly increasing trend and only 8.7% of the stations shows the insignificant downward trend of consecutive dry days whereas CWD, R1mm R10mm, R20mm, shows decreasing trend at most of the stations. This indicates that the normal precipitation days are in decreasing trend at most of the stations. CWD, R1mm, and PRCPTOT increased significantly at 8.7% of the stations and there is significantly increasing trend of R10mm, R20mm, R95p, R99p, R99ptot, and RX1day at 4.3% of the stations. SDII is increased at 61% of the stations (at 13% significantly), whereas about 65% of the stations shows downward trend of PRCPTOT (4.3% significantly). At 4.4% of the stations, R1mm and R95pTOT Shows no trend. Winter precipitation is decreased at 65% of the stations (4.3% significantly) and increased at 8.6% of the stations (4.3 significantly). Pre-monsoon precipitation is increased at 73.9% of the stations and decreased at 26.1% of the station. Monsoon and post-monsoon precipitation is decreased at 64% of the stations (4.3 significantly) and decreased at 26% of the stations. This result shows that, at most of the stations there is increasing trend of pre-monsoon precipitations and decreased at most of the stations in other seasons.

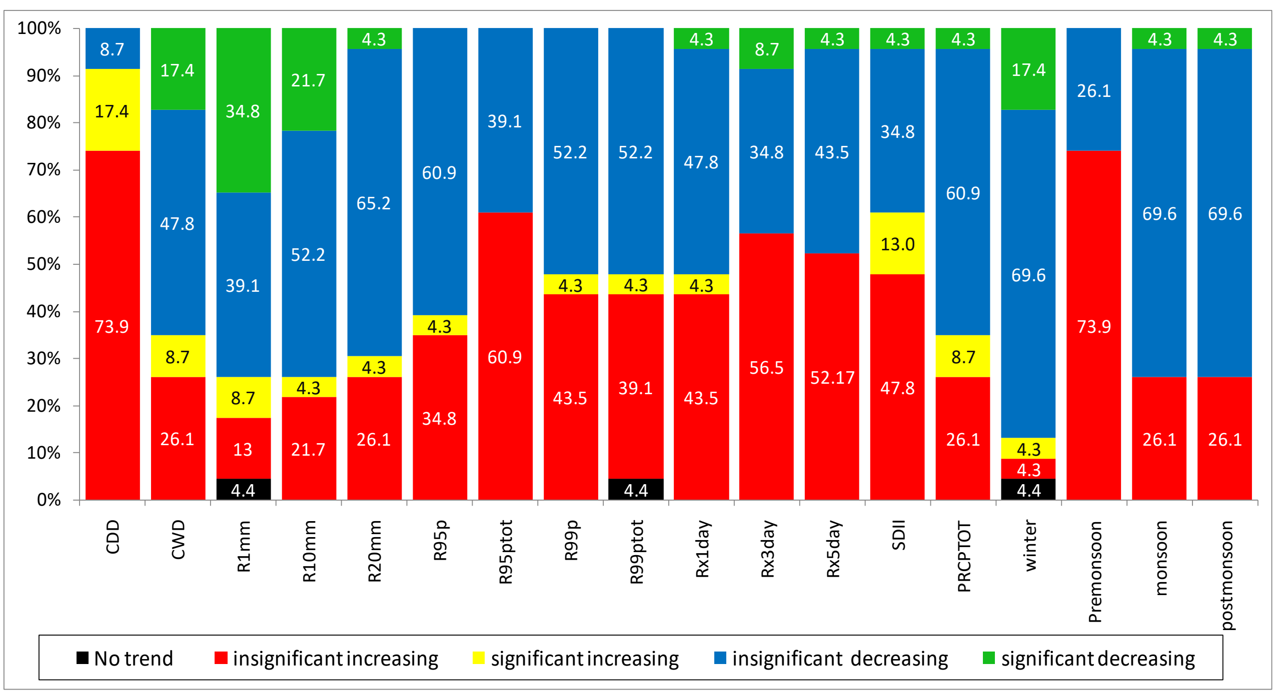


Figure 6: percentage of total stations with different trend features in the Narayani basin

Table 3: Trends in annual precipitation indices 0ver the Narayani basin

Region	Index No	CDD	CWD	R1mm	R10mm	R20mm	R95p	R95ptot	R99p	R99ptot	Rx1day	Rx3da	Rx5day	SDII	PRCPTOT
H H	601	-0.25	0	**0.77**	0	0	-0.19	-0.25	0	0	-0.02	-0.23	-0.21	-0.03	1.94
H M	607	0.03	**0.24**	**0.86**	0.03	0	**4.11**	0.23	**3.96**	**0.27**	0.73	0.76	0.88	-0.01	**5.65**
	1007	0.00	**0.41**	0.16	0.00	-0.07	-5.82	-0.18	-0.23	0.00	-0.37	-0.98	-0.93	-0.06	-6.69
M M	824	0.20	-0.24	-0.30	-0.04	0.15	-1.56	-0.04	-0.78	-0.06	0.11	-0.44	-1.32	0.05	1.68
	904	0.58	-0.12	-0.13	**-0.37**	-0.17	-1.55	0.08	0.00	0.00	-0.07	0.65	1.33	-0.06	-5.64
	814	0.13	**0.33**	-0.25	-0.09	0.00	5.17	0.10	3.00	0.06	0.44	1.64	0.27	0.08	0.31
	613	0.55	**-0.31**	**-0.29**	0.00	-0.06	0.32	0.03	0.00	*0.00*	-0.03	-0.15	-0.20	0.03	-1.20
	725	0.94	-0.08	**-0.50**	**-0.14**	**-0.10**	-1.05	0.00	0.00	0.00	-0.33	-0.48	-1.15	0.03	-6.97
	722	**1.56**	0.06	**-0.46**	**0.41**	**0.68**	4.14	0.08	0.00	0.00	0.22	0.22	0.22	**0.22**	**15.93**
	1038	0.53	-0.06	-0.03	-0.09	0.00	-2.55	-0.13	0.00	-0.02	-0.56	-0.52	-0.59	-0.02	-3.36
	808	0.30	0.08	-0.23	**-0.48**	-0.08	-3.36	-0.01	0.00	0.00	-0.40	-0.27	-1.33	-0.11	-10.30
	805	**1.00**	0.13	0.10	-0.10	-0.06	8.75	0.32	0.24	0.01	1.06	1.37	2.07	0.04	3.52
	807	0.67	-0.05	-0.46	0.00	0.00	1.20	0.05	0.00	0.00	-0.07	1.58	1.41	0.10	-1.39
	804	0.38	-0.10	**-0.33**	**-0.30**	-0.13	-0.72	0.00	2.12	0.07	**1.19**	0.57	0.59	0.01	-6.81
	802	0.46	-0.20	-0.21	-0.11	0.11	-2.32	-0.03	-1.04	-0.03	**-0.90**	-1.16	-1.47	0.01	-3.45
S	815	0.51	0.00	*0.00*	0.00	-0.10	-0.37	0.04	0.00	0.00	-0.21	0.41	0.58	-0.08	-7.28
	726	0.82	-0.04	**-0.50**	-0.20	0.00	1.23	0.14	0.00	0.00	0.22	0.26	-0.25	0.05	-4.95
	906	0.78	**-0.15**	**-0.35**	-0.05	-0.06	2.67	0.16	0.00	0.00	0.52	0.51	0.94	0.06	-1.38
	810	0.30	0.00	0.06	-0.13	-0.04	-3.36	-0.09	0.00	-0.02	-0.56	**-1.83**	**-2.43**	-0.11	-6.62
	701	**1.05**	0.00	**-0.47**	**-0.42**	**-0.26**	-5.07	-0.13	0.00	0.00	-0.16	**-1.60**	-1.43	**-0.09**	**-13.86**
T	704	0.89	**-0.13**	**-1.00**	**-0.18**	-0.03	2.18	0.13	0.00	0.00	0.66	1.72	1.69	**0.26**	-2.10
	706	0.41	-0.05	**-0.50**	0.23	0.15	-2.49	-0.11	0.00	0.00	0.43	0.37	1.01	**0.16**	0.44
	902	**1.06**	**-0.16**	-0.33	0.00	0.12	-0.55	0.04	0.00	0.00	0.52	1.15	1.20	0.07	0.87
	Average	0.56	-0.02	-0.19	-0.09	0.00	-0.05	0.02	0.32	0.01	0.11	0.16	0.04	0.02	-2.25
Station with + ve trend		21	8	5	6	7	9	14	11	10	11	13	12	14	8
Station with - ve trend		2.00	15	17.00	17.00	16.00	14.00	9.00	12	12	12.00	10.00	11.00	9.00	15.00
station with 0 trend		0.00	0	1.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	0.00	0.00
stations with significant + trend		4.00	2	2.00	1.00	1.00	1.00	0.00	1	1	1	0	0	3	2.00
Stations with significant - trend		0.00	4	8.00	5.00	1.00	0.00	0.00	0	0	1	2	1	1	1.00
% of + trend stations		91.30	34.78	21.70	26.10	30.40	39.10	60.9	47.8	43.44	47.8	56.5	52.2	60.9	34.78
% 0f - trend Stations		8.70	65.2	78.30	73.90	69.60	60.90	39.1	52.2	52.2	52.2	43.5	47.8	39.1	65.20
% of no trend stations		0.00	0	4.34	0.00	0.00	0.00	0.00	0	4.34	0	0	0	0	0.00
		Bold with black numbers indicates statistically significant at 5 %						**italic indicates no trend**							

HH (High Himalaya), HM (High Mountain), MM (Middle mountain), S (Siwalik), T (Terai)

Table 4: Trends in Seasonal precipitation over the Narayani basin

Region	Index No	Winter	Pre-monsoon	monsoon	Post-monsoon
HH	601	**0.89**	1.21	1.28	-0.13
HM	607	0.18	2.42	3.95	-0.03
	1007	-0.44	1.31	-6.21	-0.45
MM	824	-1.09	1.79	0.15	0.16
	904	-0.50	-0.81	-4.43	**-0.89**
	814	-0.88	1.33	0.48	0.58
	613	-0.84	1.97	-1.93	0.08
	725	-1.04	1.43	-6.01	-0.82
	722	-0.45	4.20	11.62	-0.75
	1038	*0.00*	-0.16	-1.41	-0.54
	808	-1.09	-2.81	-5.38	-0.40
	805	**-1.26**	0.76	4.96	0.18
	807	**-1.43**	0.34	0.27	0.10
	804	**-1.68**	0.26	-6.05	2.36
	802	-1.13	-0.01	-0.28	0.75
S	815	-0.96	-1.94	-4.83	-0.25
	726	-0.40	1.64	-6.72	-0.23
	906	-0.79	1.15	-0.55	-0.33
	810	-0.66	1.65	-6.72	-0.48
	701	-0.79	-0.60	**-12.88**	-0.30
T	704	**-1.17**	2.02	-7.00	-1.60
	706	-0.25	2.37	-2.07	-0.25
	902	-0.58	1.81	-0.01	-0.84
	Average	-0.71	0.93	-2.16	-0.18
Station with + ve trend		2.00	17.00	6.00	6.00
Station with - ve trend		20.00	6.00	17.00	17.00
station with 0 trend		1.00	0.00	0.00	0.00
stations with significant + trend		1.00	0.00	0.00	0.00
Stations with significant - trend		4.00	0.00	1.00	1.00
% of + trend stations		8.70	73.90	26.10	26.10
% 0f - trend Stations		87.00	26.10	73.79	73.79
% of no trend stations		4.30	0.00	0.00	0.00

Bold with Black numbers indicates statistically significant at 5 %, italic indicates no trend

HH (High Himalaya), HM (High Mountain), MH (Middle mountain), S (Siwalik), T (Terai)

Chapter 5

Conclusions and Limitations

5.1 Conclusions

The study analyzes spatial distribution and trends in extreme daily precipitation indices in Narayani river basin. Trends in 14 indices recommended by the ET-SCI were calculated for the period 1980-2018 using ClimPACT2 software. From the analysis it is clear that precipitation extremes over the Narayani basin are increasing. The main findings can be summarized as follows.

- ❖ The spatial distribution of seasonal precipitations shows that the precipitation is strength at central part of the basin and July is the highest precipitation month for all regions. Basin received 78.9 % of total annual precipitation in monsoon season. Pre-monsoon precipitation is increased at most of the stations and decreased in other seasons at most of the stations.

- ❖ The ever recorded 1-day precipitation is ranges from 87mm (water equivalent) at high elevated area (Jomsom and its surrounding) to 516mm at low land (Terai and siwalik). This shows that the maximum 1-day precipitation is strength at the southern part of the basin, which also indicates that the southern part of the basin is more vulnerable to flooding events.

- ❖ The annual total precipitation on very wet days R95p (precipitation amount >95th percentile) decreased on average by -0.05mm per year, but the precipitation fraction due to very wet days (R95pTOT) increased on average 0.02% per year. The precipitation on extremely wet days (R99p) increased on average by 0.32mm per year.

- ❖ All the absolute indices such as RX1day, RX3day and RX5day Shows the upward trends. The maximum 1 day precipitation (RX1day) increased on average by 0.11mm per year and increased at all the stations of Terai regions and decreased at high Himalaya. This result indicates the southern part of the basin is more vulnerable to flood and intense precipitation events. RX3day and RX5day increased on average 0.16mm and 0.04mm per year respectively.

- The wet days (PR <1mm) are decreased at all the stations below 2000m, which indicates that, middle mountain, Siwalik and Terai region leading towards drier conditions. The total number of heavy precipitation days (R10mm) and very heavy precipitation days decreased on average -0.09 and 0.01 days per year. Maximum increasing trend of R10mm and R20mm was observed at Musikot station.

- The consecutive dry days (CDD) increased on average by 0.56 days per year. CDD increased at 21 stations (4 statistically significant) and decreased at only 2 stations (statistically insignificant). Consecutive dry days are decreased at Jomsom (High Himalaya). The maximum number of consecutive wet days (CWD) decreased on average by -0.02 days per year, all the stations above 2000m shows upward trend in CWD and decreased at most of the stations below 2000m. Increasing trend of CDD and decreasing trend of CWD linked with the livelihood of the people in the area, which affect the agriculture activities and may cause drought.

- PRCPTOT in High Himalaya exhibits a positive trend (1.94 mm y-1) while in the Siwalik range it was decreased by -6.82 mm y-1. There is a decreasing trend of PRCPTOT at all four stations (Hetauda, Chisapani-Gadi, Dhunibesi, Kakani) situated in the eastern part of the basin with the range of -1.38 to -6.69 mm y-1. It suggests that there may be a possible impact on the overall agriculture facilities and food security including water scarcity in the eastern belt of the basin

5.2 Limitation of the study

The extreme precipitation was limited by the incompleteness of the data and wide spread stations at high altitude. Due to lack of sufficient number of meteorological stations, especially in high altitude regions, the robustness of finding about the extreme precipitation may affect the study. Thus, more meteorological station at high altitude of the basin is recommended.

References

Alexander, L., Yang, H., & Perkins, S. (2013). ClimPact. Indices and software. World Climate Programme. *New South Wales University of Technology. 52p*.

Alexander, Lisa, & Herold, N. (2016). *ClimPACT2: Indices and software*.

Alexander, Lisa V. (2016). Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond. *Weather and Climate Extremes*, *11*, 4–16.

Alexander, Lisa Victoria, Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G., Haylock, M., Collins, D., Trewin, B., & Rahimzadeh, F. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres*, *111*(D5).

Authority, N. E. (2008). *Nepal Electricity Authority Fiscal Year 2007/08—AYear in Review*. Kathmandu.

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

Bajracharya, S. R. (2009). Glacial lake outburst floods risk reduction activities in Nepal. *Asia-Pacific Symposium on New Technologies for Prediction and Mitigation of Sediment Disasters, Japan Society of Erosion Control Engineering (JSECE), Tokyo, Japan*, 18–19.

Bajracharya, S. R., & Shrestha, B. R. (2011). *The status of glaciers in the Hindu Kush-Himalayan region*. International Centre for Integrated Mountain Development (ICIMOD).

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

Cannarozzo, M., Noto, L. V., & Viola, F. (2006). Spatial distribution of rainfall trends in Sicily (1921–2000). *Physics and Chemistry of the Earth, Parts A/B/C*, *31*(18), 1201–1211.

Cao, L., & Pan, S. (2014). Changes in precipitation extremes over the "Three-River Headwaters" region, hinterland of the Tibetan Plateau, during 1960–2012. *Quaternary International*, *321*, 105–115. https://doi.org/10.1016/j.quaint.2013.12.041

Climate breaks multiple records in 2016, with global impacts. (2017, March 20). World Meteorological Organization. https://public.wmo.int/en/media/press-release/climate-breaks-multiple-records-2016-global-impacts

Dahal, N., Shrestha, U. B., Tuitui, A., & Ojha, H. R. (2019). Temporal changes in precipitation and temperature and their implications on the streamflow of Rosi River, Central Nepal. *Climate*, *7*(1), 3.

Dahal, P., Shrestha, N. S., Shrestha, M. L., Krakauer, N. Y., Panthi, J., Pradhanang, S. M., Jha, A., & Lakhankar, T. (2016). Drought risk assessment in central Nepal: Temporal and spatial analysis. *Natural Hazards*, *80*(3), 1913–1932.

Dangal, R. (2015). Nepal Disaster Report 2015. *The Government of Nepal, Ministry of Home Affairs and Disaster Preparedness Network-Nepal: Kathmandu, Nepal*.

Dankers, R., & Hiederer, R. (2008). *Extreme Temperatures and Precipitation in Europe: Analysis of a High-resolution Climat Change Scenario*. Citeseer.

Dawadi, B., Liang, E., Tian, L., Devkota, L. P., & Yao, T. (2013). Pre-monsoon precipitation signal in tree rings of timberline Betula utilis in the central Himalayas. *Quaternary International*, *283*, 72–77.

Devkota, D. C., Gosai, K. R., & Devkota, D. (2017). Economic impact analysis of current climate change variability and future impacts in agricultural sector of Nepal. *Nepal Journal of Environmental Science*, *5*, 49–56.

Devkota, R. P., & Bhattarai, U. (2018). Assessment of climate change impact on floods from a techno-social perspective. *Journal of Flood Risk Management*, *11*, S186–S196.

Dhakal, C. K., Regmi, P. P., Dhakal, I. P., Khanal, B., & Bhatta, U. K. (2013). Livelihood vulnerability to climate change based on agro ecological regions of Nepal. *Glob J Sci Front Res*, *13*, 47–53.

Dhital, M. R., Khanal, N., & Thapa, K. B. (1993). *The role of extreme weather events, mass movements, and land use changes in increasing natural hazards: A report of the.... causes of the recent damages incurred in South-central Nepal during 19-20 July 1993*.

Donat, M. G., Lowry, A. L., Alexander, L. V., O'Gorman, P. A., & Maher, N. (2016). More extreme precipitation in the world's dry and wet regions. *Nature Climate Change*, *6*(5), 508–513.

Easterling, D. R., Meehl, G. A., Parmesan, C., Changnon, S. A., Karl, T. R., & Mearns, L. O. (2000). Climate extremes: Observations, modeling, and impacts. *Science*, *289*(5487), 2068–2074.

Eckstein, D., Hutfils, M.-L., & Winges, M. (2018). *Global Climate Risk Index 2019: Who suffers most from extreme weather events? Weather-related Loss Events in 2017 and 1998 to 2017*. Germanwatch Nord-Süd Initiative eV.

Field, C. B. (2014). *Climate change 2014–Impacts, adaptation and vulnerability: Regional aspects*. Cambridge University Press.

Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the intergovernmental panel on climate change*. Cambridge University Press.

Gilbert, R. O. (1987). *Statistical methods for environmental pollution monitoring*. John Wiley & Sons.

Howard, M. J., Brillman, J. C., & Burkle, F. M. (1996). Infectious disease emergencies in disasters. *Emergency Medicine Clinics*, *14*(2), 413–428.

Huang, R., Zhu, H., Liang, E., Grießinger, J., Dawadi, B., & Bräuning, A. (2019). High-elevation shrub-ring δ18O on the northern slope of the central Himalayas records summer (May–July) temperatures. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *524*, 230–239.

Karki, R., Schickhoff, U., Scholten, T., & Böhner, J. (2017a). Rising precipitation extremes across Nepal. *Climate*, *5*(1), 4.

Karki, R., Schickhoff, U., Scholten, T., & Böhner, J. (2017b). Rising precipitation extremes across Nepal. *Climate*, *5*(1), 4.

Karki, R., Talchabhadel, R., Aalto, J., & Baidya, S. K. (2016). New climatic classification of Nepal. *Theoretical and Applied Climatology*, *125*(3–4), 799–808.

Khanal, N. R. (1999). Study of landslide and flood affected area in Syangja and Rupandehi districts of Nepal. *Unpublished Report Submitted to Mountain Natural Resources Division, International Center for Integrated Mountain Development, Kathmandu*.

Klein Tank, A. M. G., Peterson, T. C., Quadir, D. A., Dorji, S., Zou, X., Tang, H., Santhosh, K., Joshi, U. R., Jaswal, A. K., & Kolli, R. K. (2006). Changes in daily temperature and precipitation extremes in central and south Asia. *Journal of Geophysical Research: Atmospheres*, *111*(D16).

Lam, N. S.-N. (1983). Spatial interpolation methods: A review. *The American Cartographer*, *10*(2), 129–150.

Liang, E., Dawadi, B., Pederson, N., Piao, S., Zhu, H., Sigdel, S. R., & Chen, D. (2019). Strong link between large tropical volcanic eruptions and severe droughts prior to monsoon in the central Himalayas revealed by tree-ring records. *Science Bulletin*, *64*(14), 1018–1023.

Manandhar, S., Pandey, V. P., & Kazama, F. (2012). Hydro-climatic trends and people's perceptions: Case of Kali Gandaki River Basin, Nepal. *Climate Research*, *54*(2), 167–179.

Manton, M. J., Della-Marta, P. M., Haylock, M. R., Hennessy, K. J., Nicholls, N., Chambers, L. E., Collins, D. A., Daw, G., Finet, A., & Gunawan, D. (2001). Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998. *International Journal of Climatology*, *21*(3), 269–284.

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., & Noda, A. (2007). *Global climate projections*.

MoHA, Dpn. N., & UNDP, O. (2009). *Nepal Disaster Report: The hazardscape and Vulnerability*. Jagadamba Press.

Multi-agency report highlights increasing signs and impacts of climate change in atmosphere, land and oceans. (2020, March 9). World Meteorological Organization. https://public.wmo.int/en/media/press-release/multi-agency-report-highlights-increasing-signs-and-impacts-of-climate-change

Nepal Disaster Report 2013—Nepal. (n.d.). ReliefWeb. Retrieved February 1, 2020, from https://reliefweb.int/report/nepal/nepal-disaster-report-2013

Nepal disaster report 2019 | PreventionWeb.net. (n.d.). Retrieved February 1, 2020, from https://www.preventionweb.net/publications/view/69000

Nyaupane, G. P., & Chhetri, N. (2009). Vulnerability to Climate Change of Nature-Based Tourism in the Nepalese Himalayas. *Tourism Geographies*, *11*(1), 95–119. https://doi.org/10.1080/14616680802643359

Panthi, J., Dahal, P., Shrestha, M., Aryal, S., Krakauer, N., Pradhanang, S., Lakhankar, T., Jha, A., Sharma, M., & Karki, R. (2015). Spatial and temporal variability of rainfall in the Gandaki River Basin of Nepal Himalaya. *Climate*, *3*(1), 210–226.

Rai, M. (2007). Climate change and agriculture: A Nepalese case. *Journal of Agriculture and Environment*, *8*, 92–95.

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., & Srinivasan, J. (2007). Climate models and their evaluation. In *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC (FAR)* (pp. 589–662). Cambridge University Press.

Salmi, T., Määttä, A., Anttila, P., Ruoho-Airola, T., Amnell, T., & Maatta, A. (2002). *Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates: The Excel template application MAKESENS*.

Shen, L., Lu, L., Hu, T., Lin, R., Wang, J., & Xu, C. (2018). *Homogeneity Test and Correction of Daily Temperature and Precipitation Data (1978–2015) in North China* [Research Article]. Advances in Meteorology. https://doi.org/10.1155/2018/4712538

Shrestha, A. B., & Aryal, R. (2011). Climate change in Nepal and its impact on Himalayan glaciers. *Regional Environmental Change*, *11*(1), 65–77. https://doi.org/10.1007/s10113-010-0174-9

Shrestha, A. B., Bajracharya, S. R., Sharma, A. R., Duo, C., & Kulkarni, A. (2017). Observed trends and changes in daily temperature and precipitation extremes over the Koshi river basin 1975–2010. *International Journal of Climatology*, *37*(2), 1066–1083.

Shrestha, M. L. (2000). Interannual variation of summer monsoon rainfall over Nepal and its relation to Southern Oscillation Index. *Meteorology and Atmospheric Physics*, *75*(1–2), 21–28.

Shrestha, M. S., Artan, G. A., Bajracharya, S. R., Gautam, D. K., & Tokar, S. A. (2011). Bias-adjusted satellite-based rainfall estimates for predicting floods: N arayani B asin. *Journal of Flood Risk Management*, *4*(4), 360–373.

Sigdel, M., & Ma, Y. (2017). Variability and trends in daily precipitation extremes on the northern and southern slopes of the central Himalaya. *Theoretical and Applied Climatology*, *130*(1–2), 571–581.

Sirois, A. (1998). A brief and biased overview of time series analysis or how to find that evasive trend. *WMO Report*, *133*, 14–18.

Subba, S., Ma, Y., & Ma, W. (2019). Spatial and temporal analysis of precipitation extremities of Eastern Nepal in the last two decades (1997–2016). *Journal of Geophysical Research: Atmospheres*, *124*(14), 7523–7539.

Talchabhadel, R., Karki, R., Thapa, B. R., Maharjan, M., & Parajuli, B. (2018). Spatio-temporal variability of extreme precipitation in Nepal. *International Journal of Climatology*, *38*(11), 4296–4313. https://doi.org/10.1002/joc.5669

Wang, X. L. (2008). Penalized maximal F test for detecting undocumented mean shift without trend change. *Journal of Atmospheric and Oceanic Technology*, *25*(3), 368–384.

Wang, X. L., & Feng, Y. (2013). Climate Research Division Atmospheric Science and Technology Directorate Science and Technology Branch, Environment Canada Toronto, Ontario, Canada. *Ontario, Canada*, *17*.

Yadav, R. R. (2011). Long-term hydroclimatic variability in monsoon shadow zone of western Himalaya, India. *Climate Dynamics*, *36*(7–8), 1453–1462.

Zhan, Y.-J., Ren, G.-Y., Shrestha, A. B., Rajbhandari, R., Ren, Y.-Y., Sanjay, J., Xu, Y., Sun, X.-B., You, Q.-L., & Wang, S. (2017). Changes in extreme precipitation events over the Hindu Kush Himalayan region during 1961–2012. *Advances in Climate Change Research*, *8*(3), 166–175.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B., & Zwiers, F. W. (2011). Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(6), 851–870.

Zimmerman, D., Pavlik, C., Ruggles, A., & Armstrong, M. P. (1999). An experimental comparison of ordinary and universal kriging and inverse distance weighting. *Mathematical Geology*, *31*(4), 375–390.

Appendix A

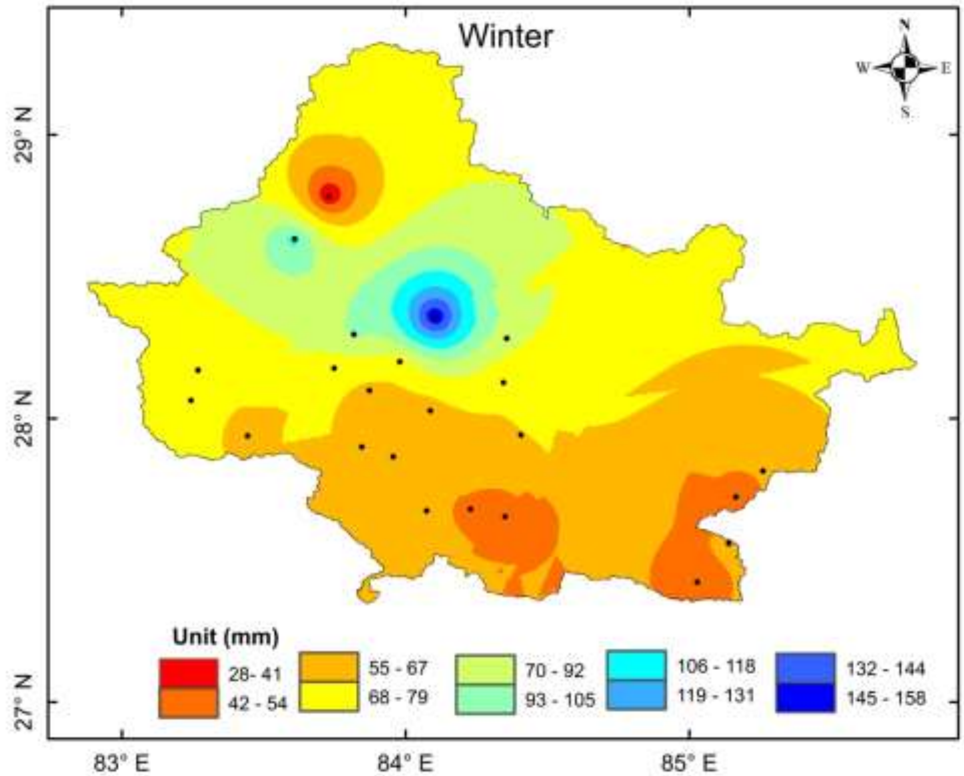


Figure 7: Winter precipitation

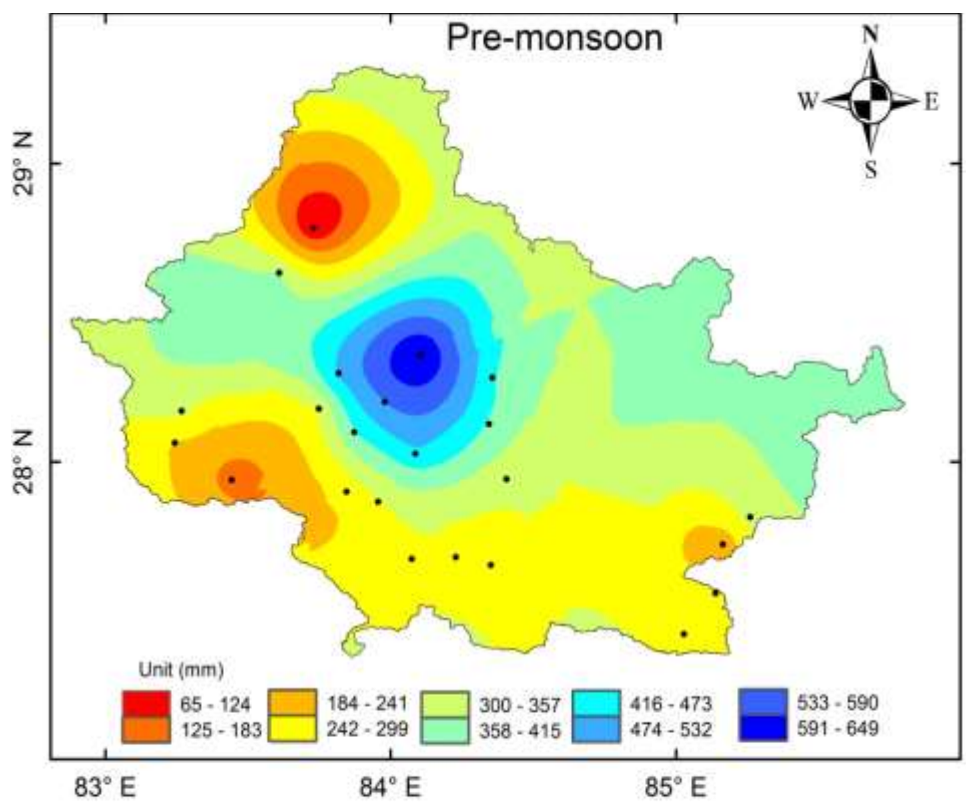


Figure 8: Pre-monsoon precipitation

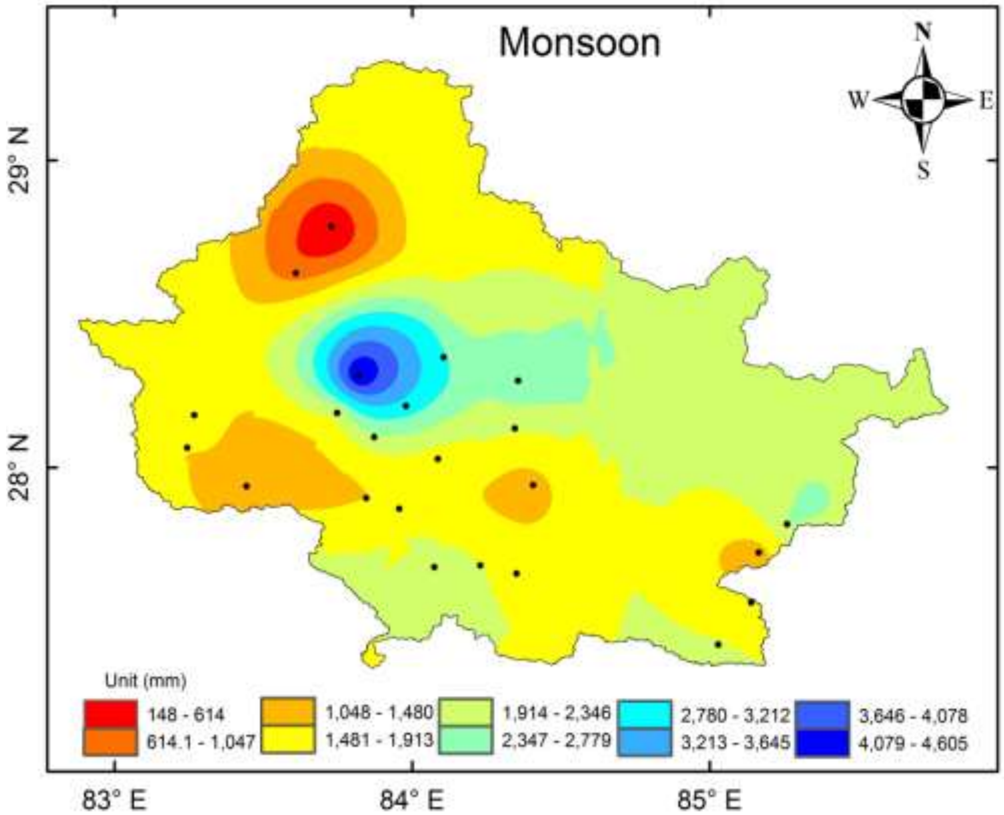


Figure 9: Monsoon precipitation

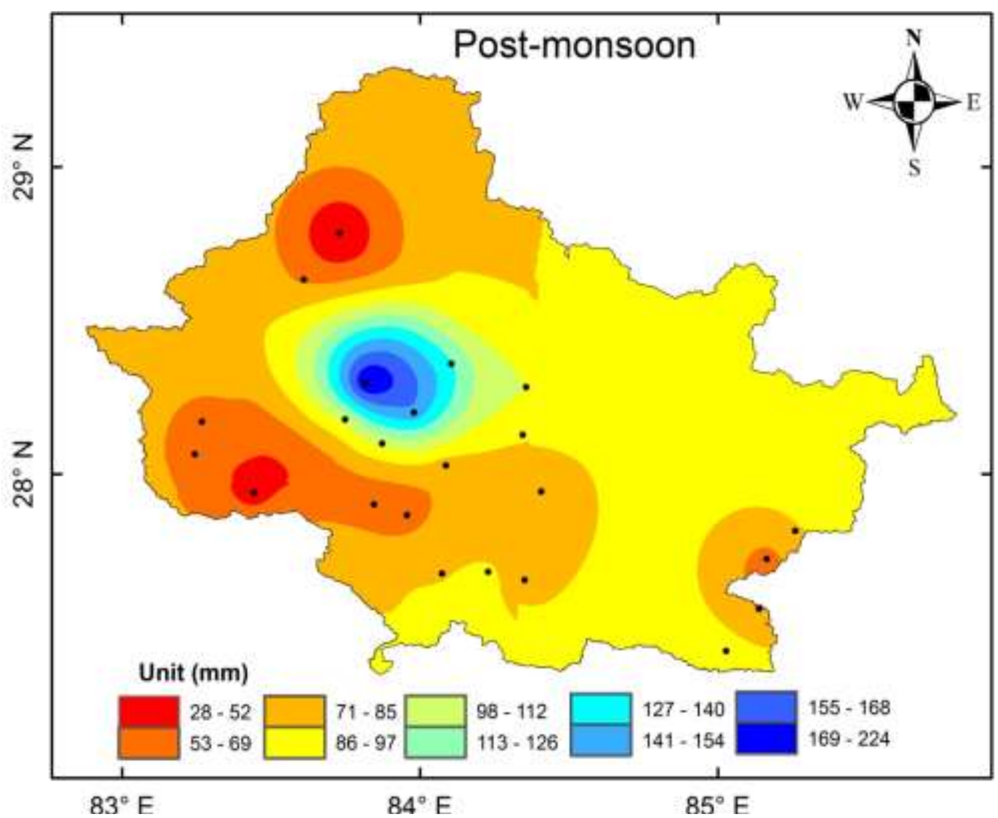


Figure 10: post-monsoon precipitation

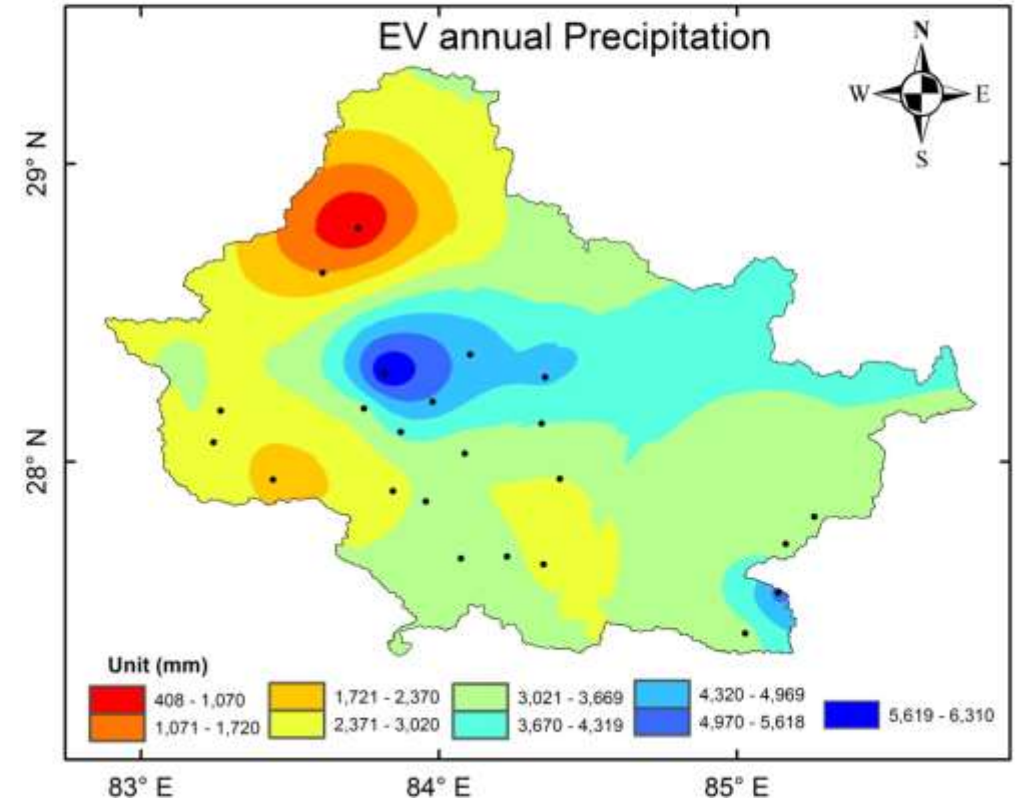


Figure 11: Ever recorded annual precipitation

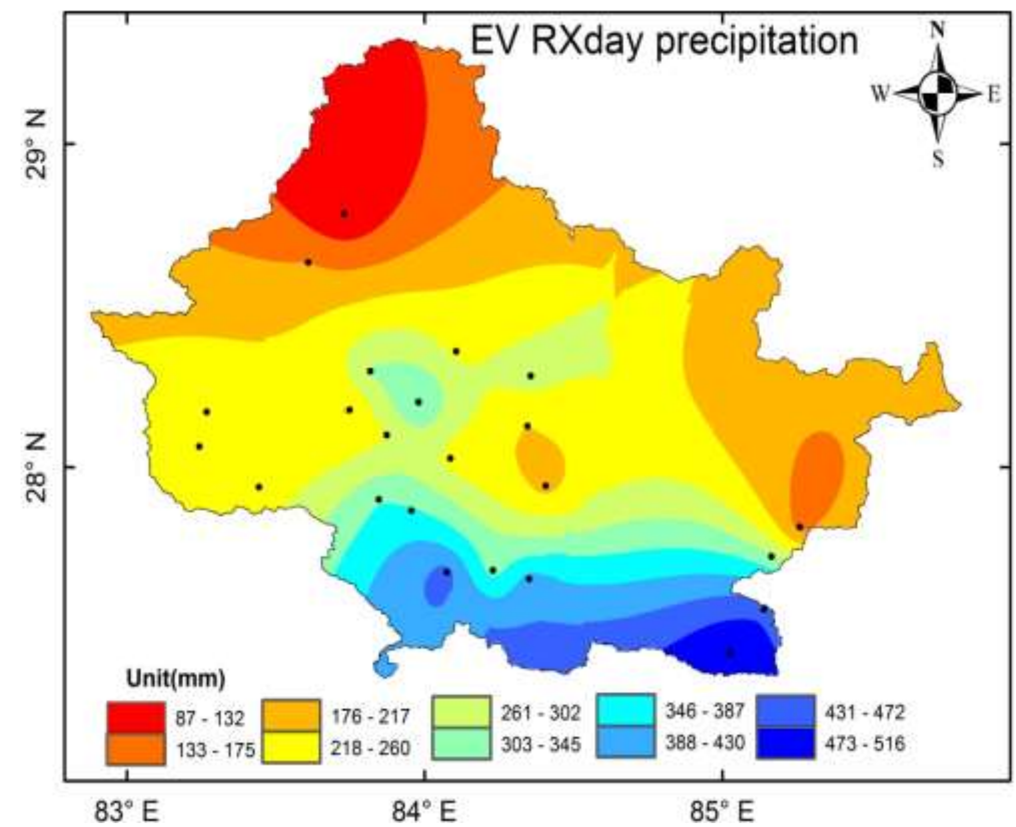


Figure 12: Ever recorded maximum one day precipitation

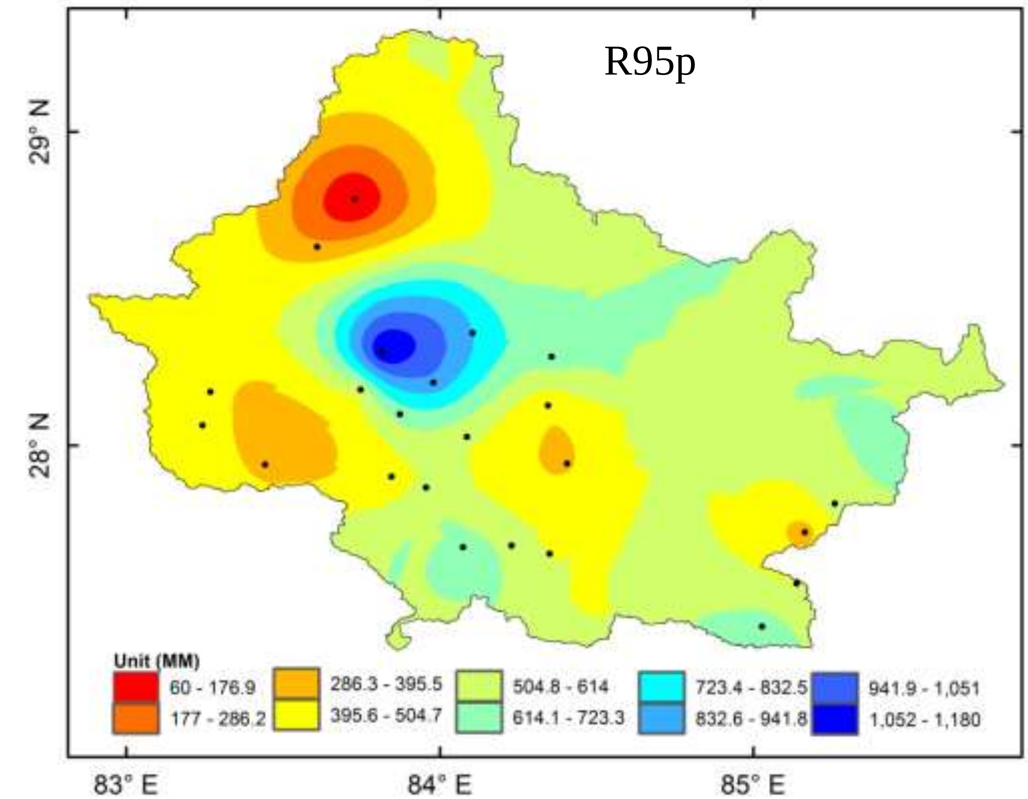


Figure 13: Annual sum of daily precipitation > 95 percentile

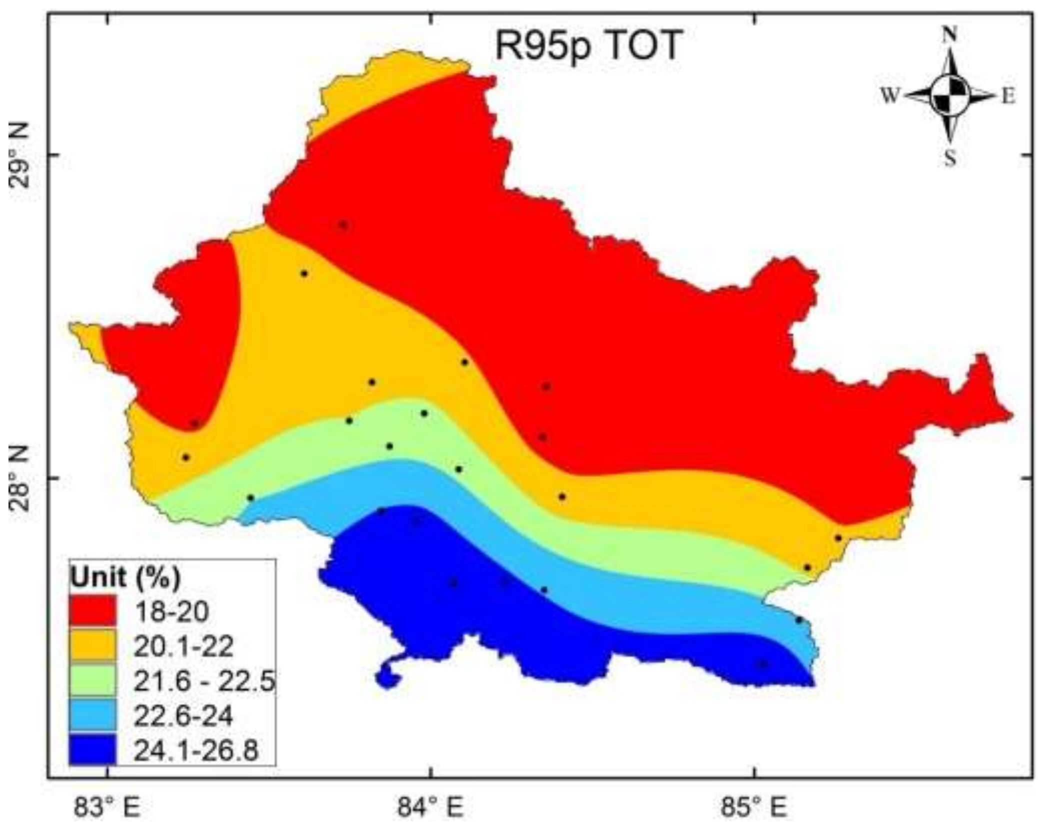


Figure 14: Contribution from 95 percentile precipitation

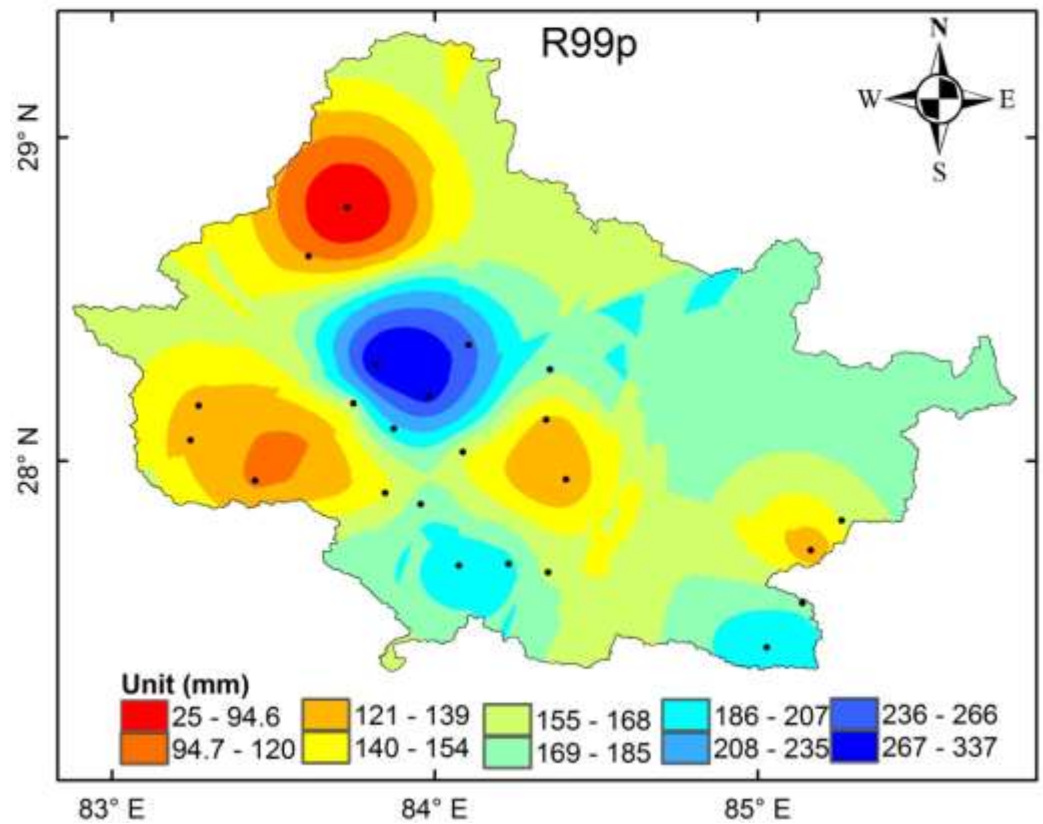


Figure 15: Annual sum of daily precipitation > 99percentile

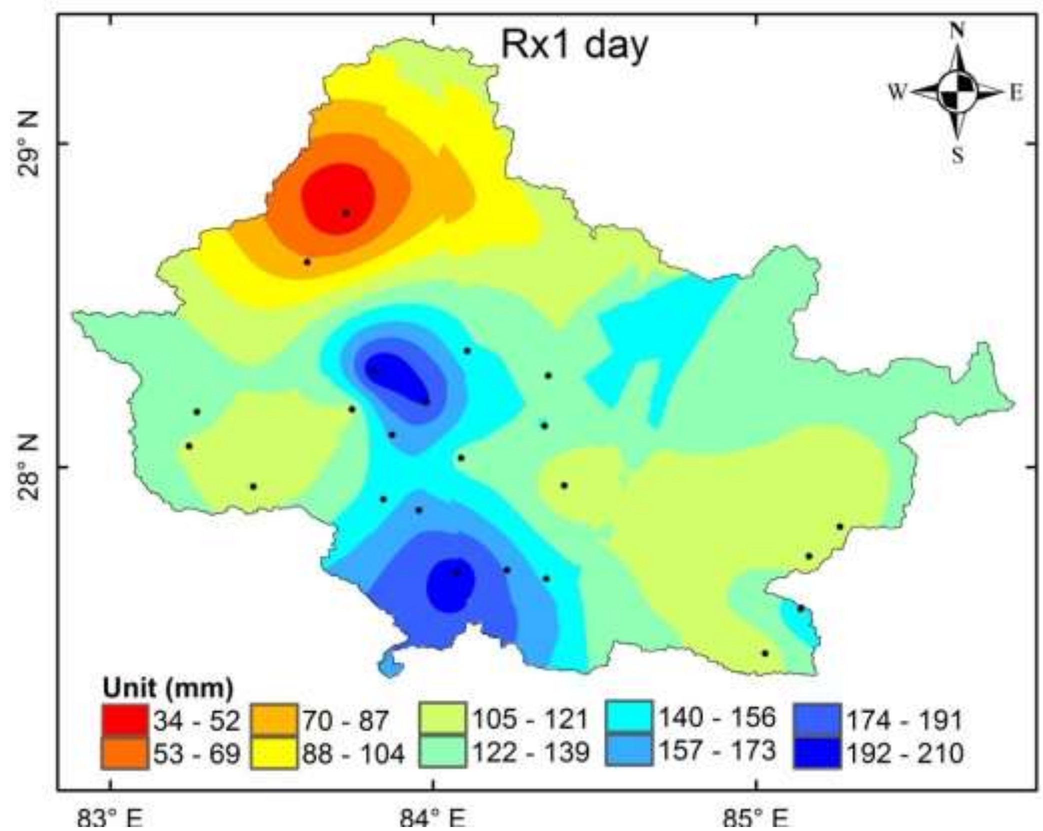


Figure 16: Annual maximum 1-day precipitation

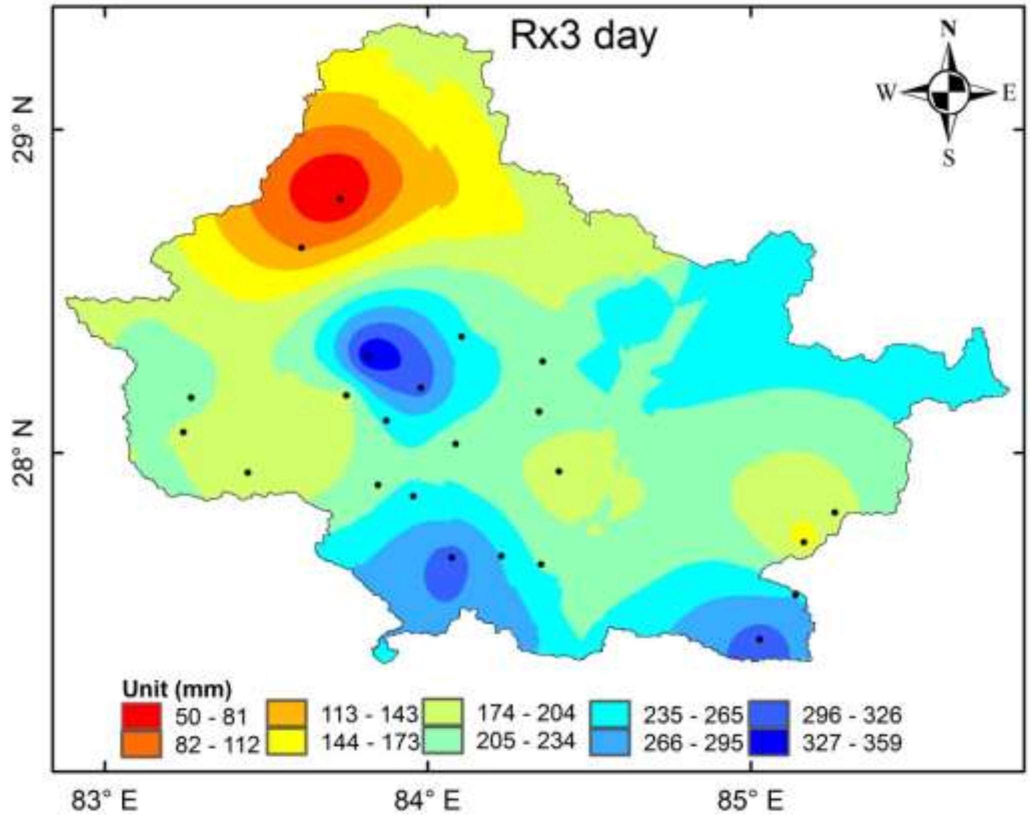


Figure 17: Annual maximum consecutive 3-day precipitation

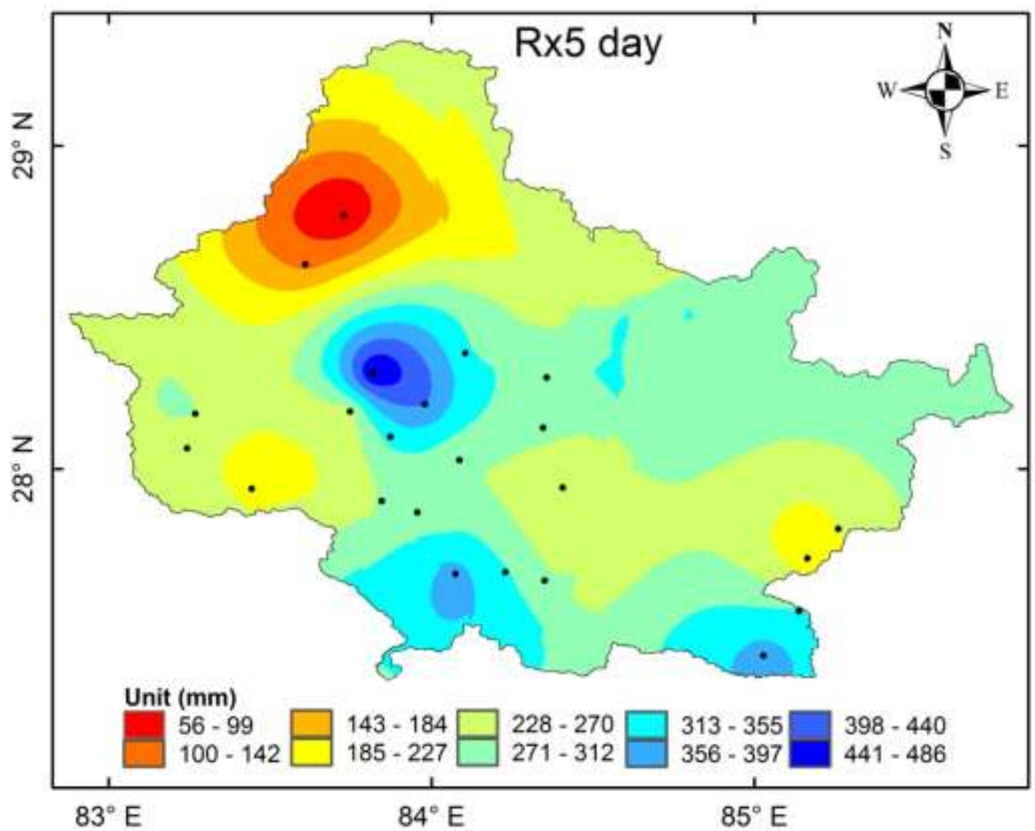


Figure 18: Annual maximum consecutive 5-day precipitation

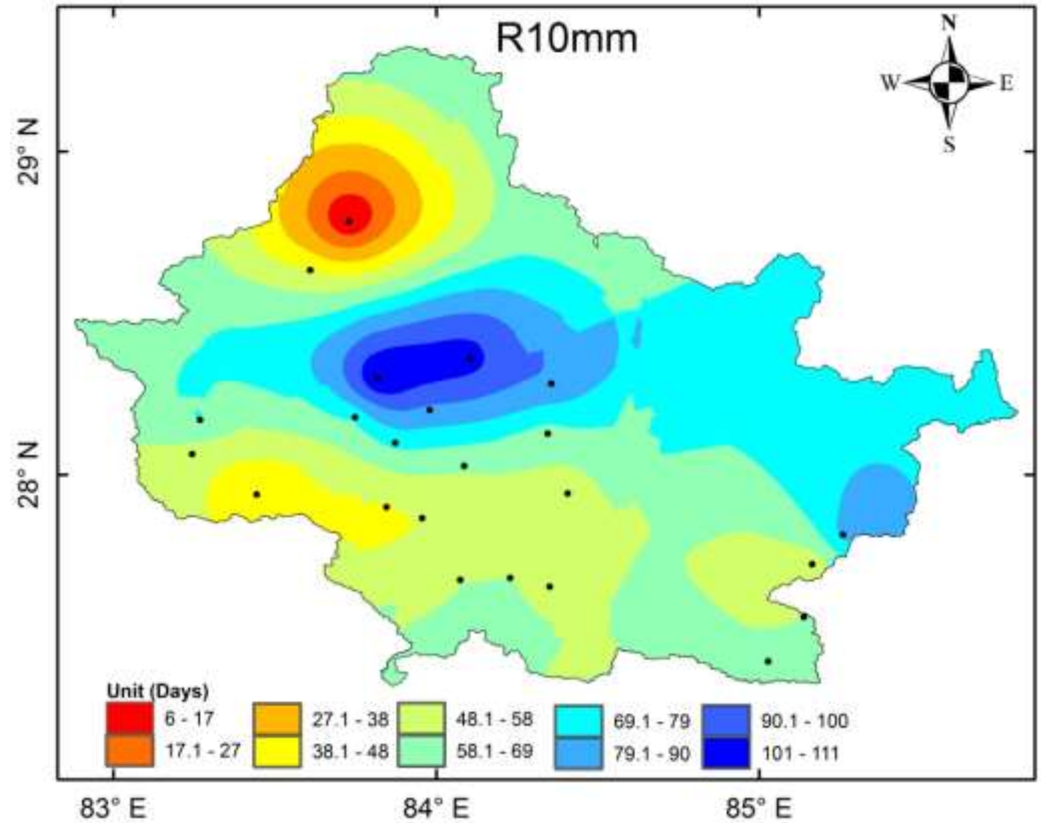


Figure 19: Annual count of days when the precipitation ≥10mm

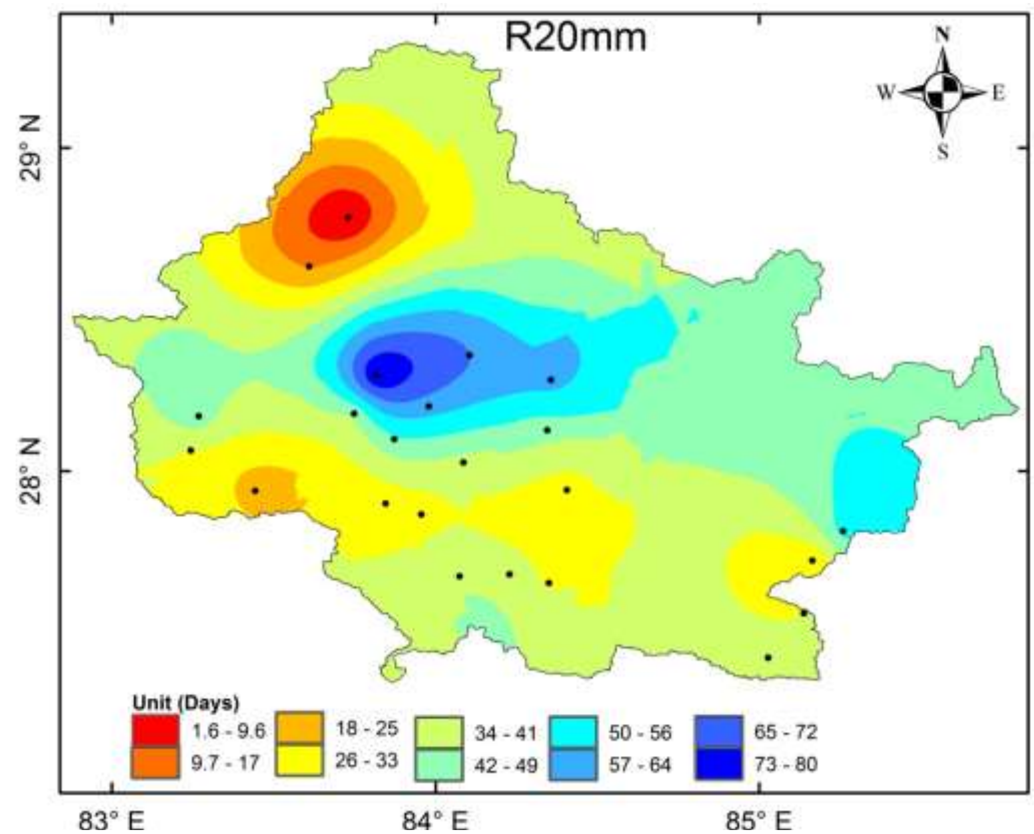


Figure 20: Annual count of days when the precipitation ≥20mm

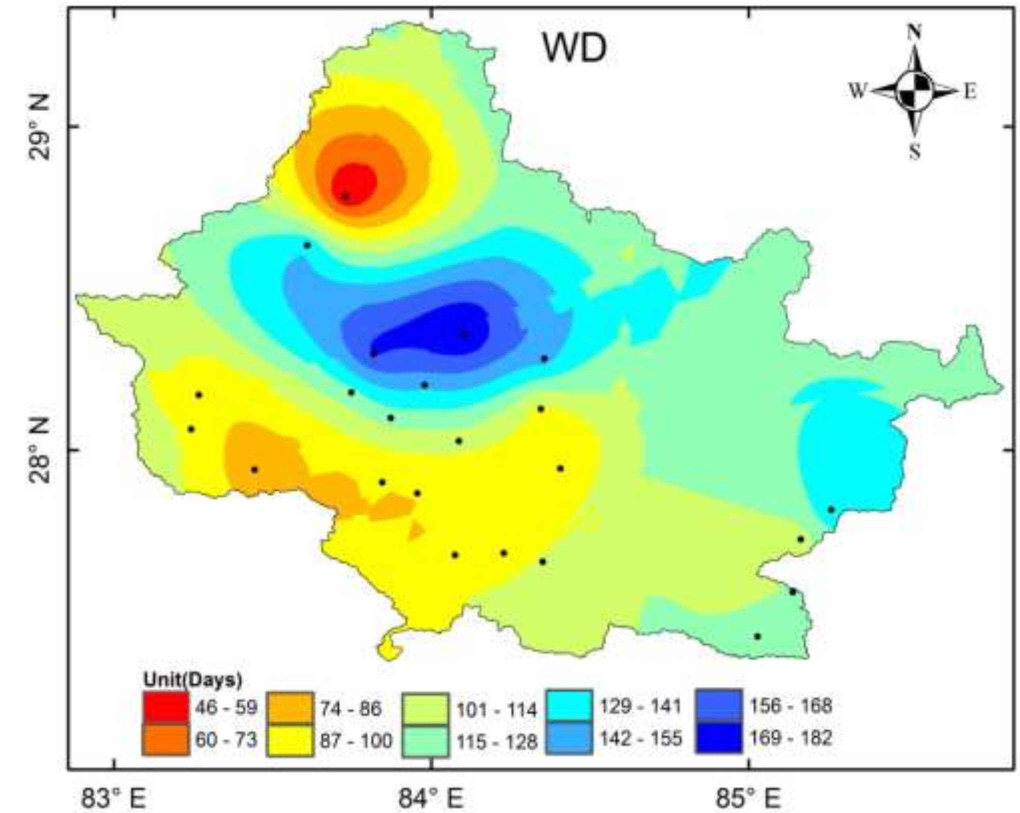


Figure 21: Annual count of days when the precipitation ≥1mm

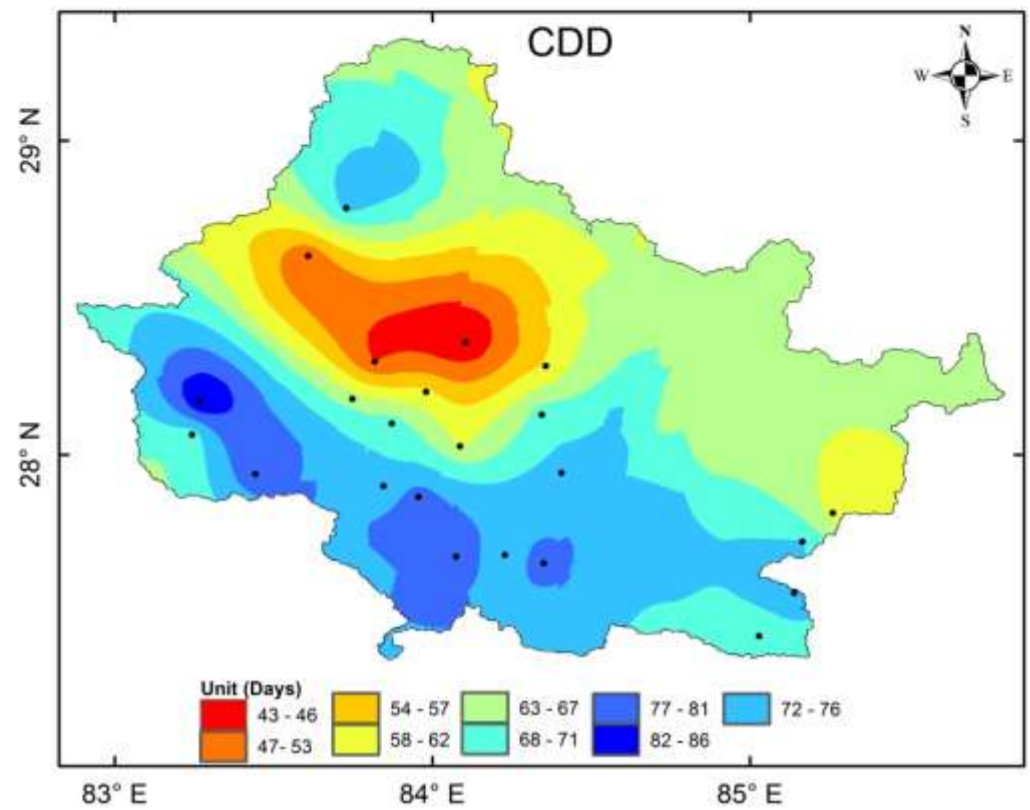


Figure 22: Maximum number of consecutive days when PR<1mm

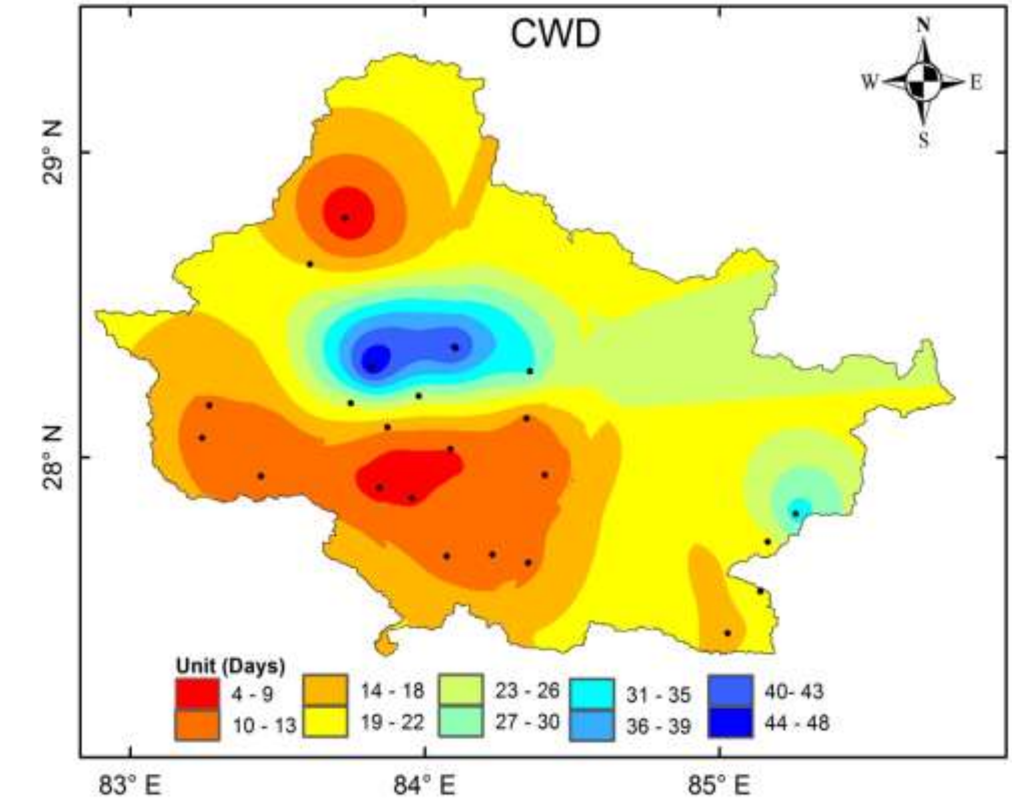


Figure 23: Maximum number of consecutive days when PR ≥ 1mm

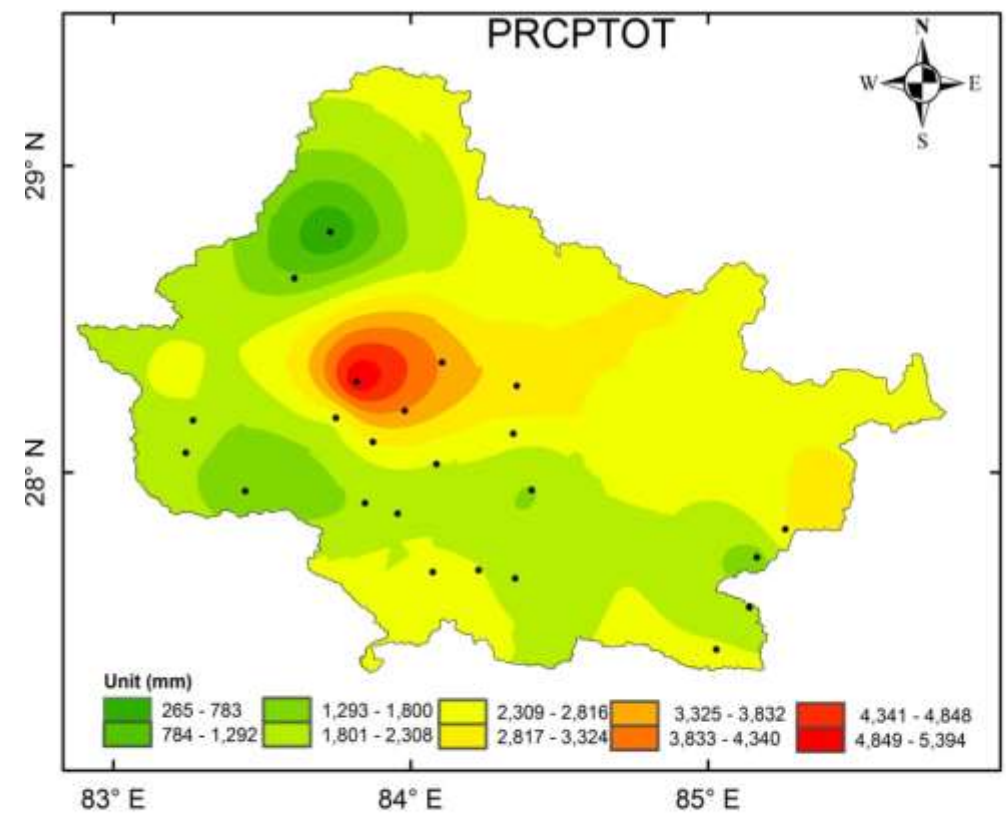


Figure 24: Annual total precipitation in wet days

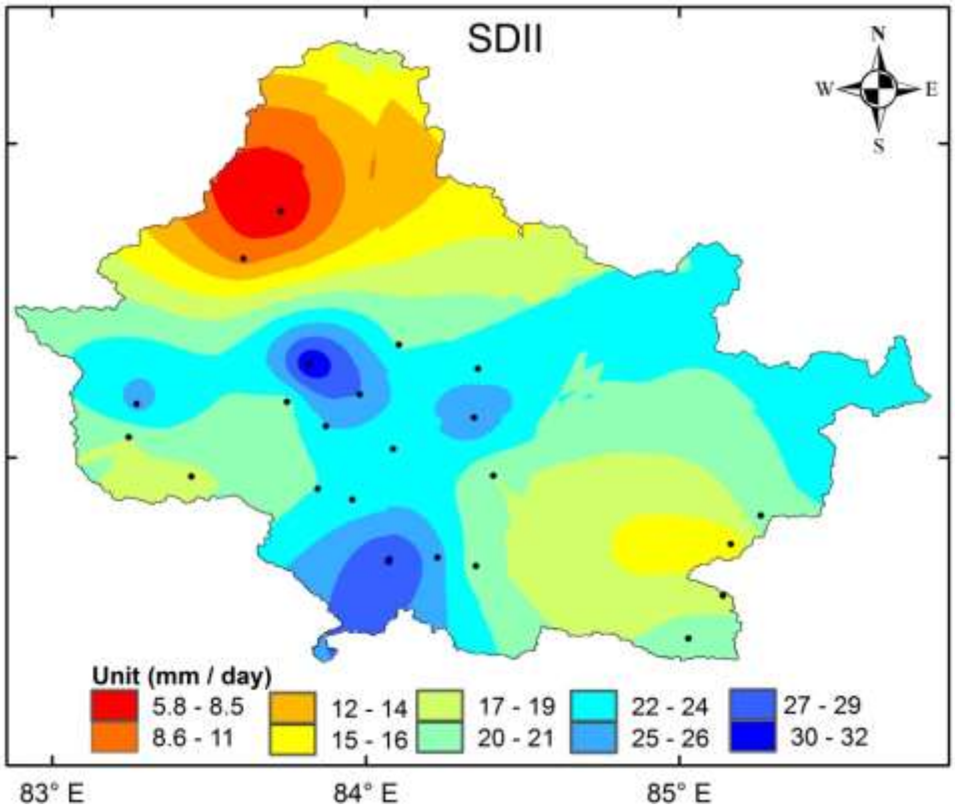


Figure 25: Ratio of annual total precipitation divided by the number of wet days in the year

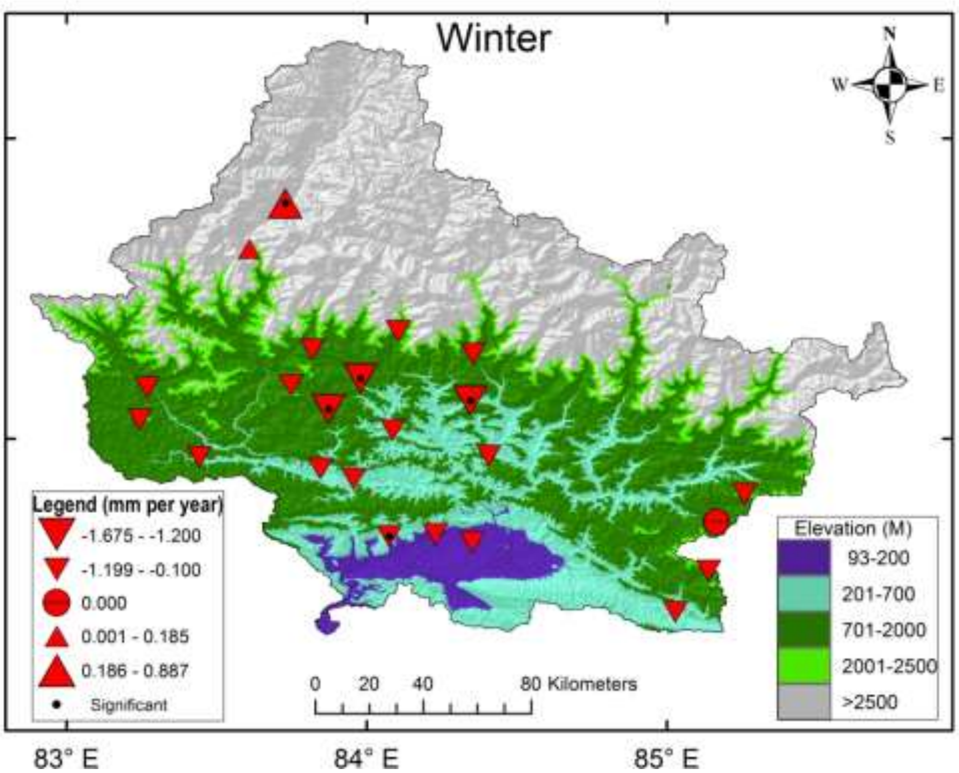


Figure 26: Trends in winter precipitation

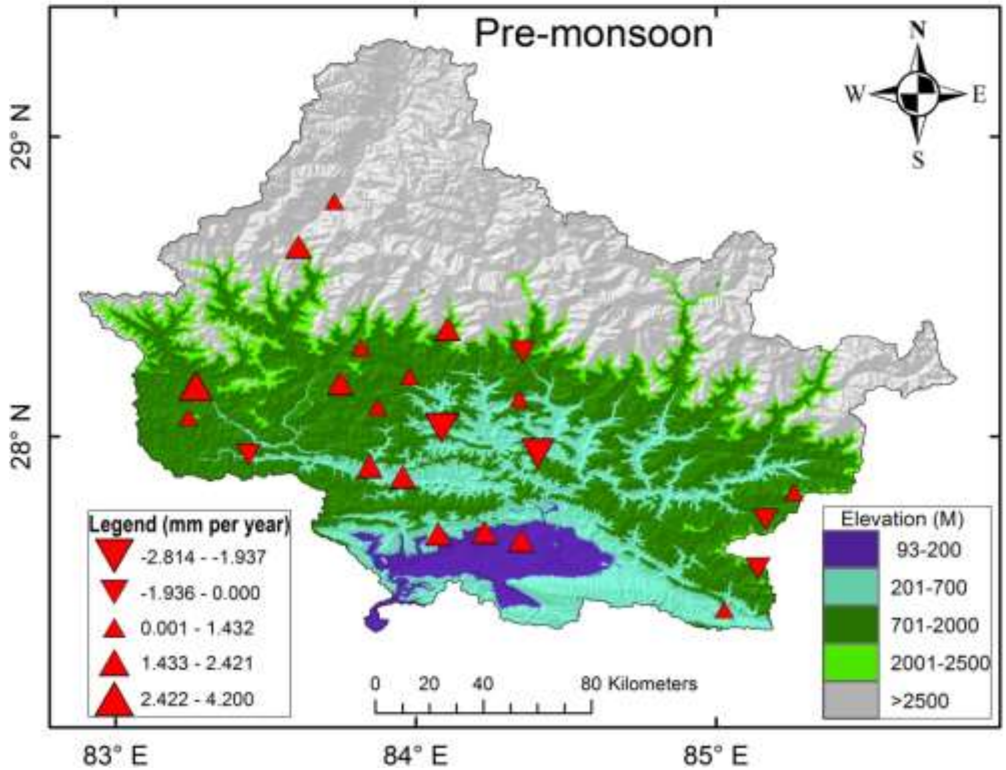


Figure 27: Trends in pre-monsoon precipitation

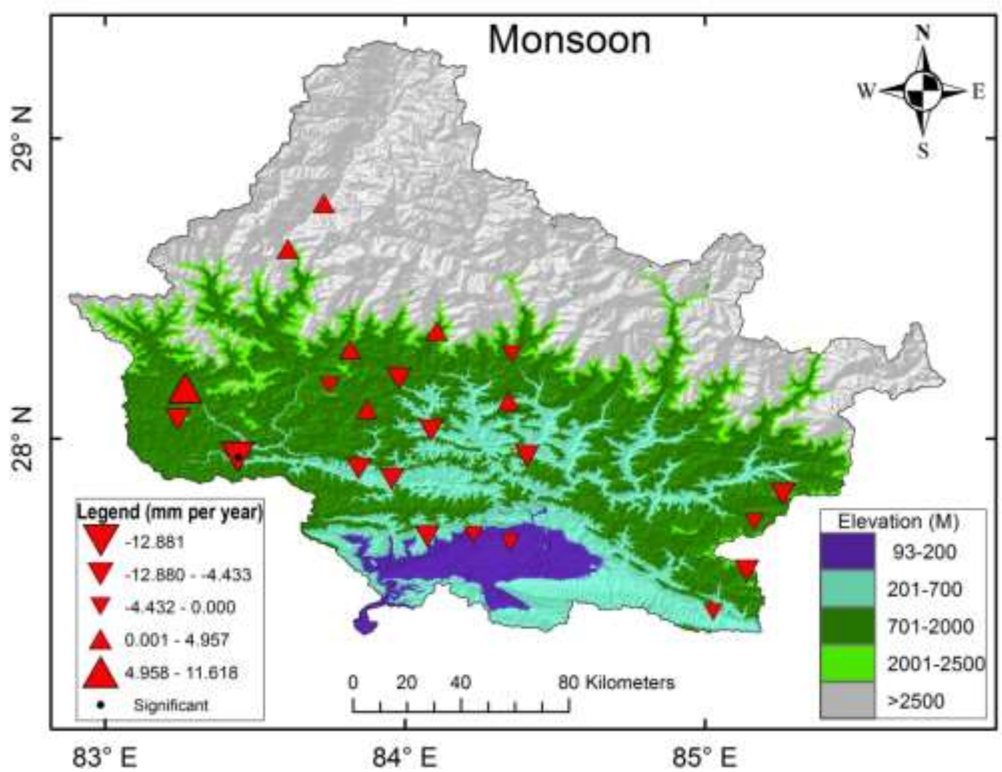


Figure 28: Trends in monsoon precipitation

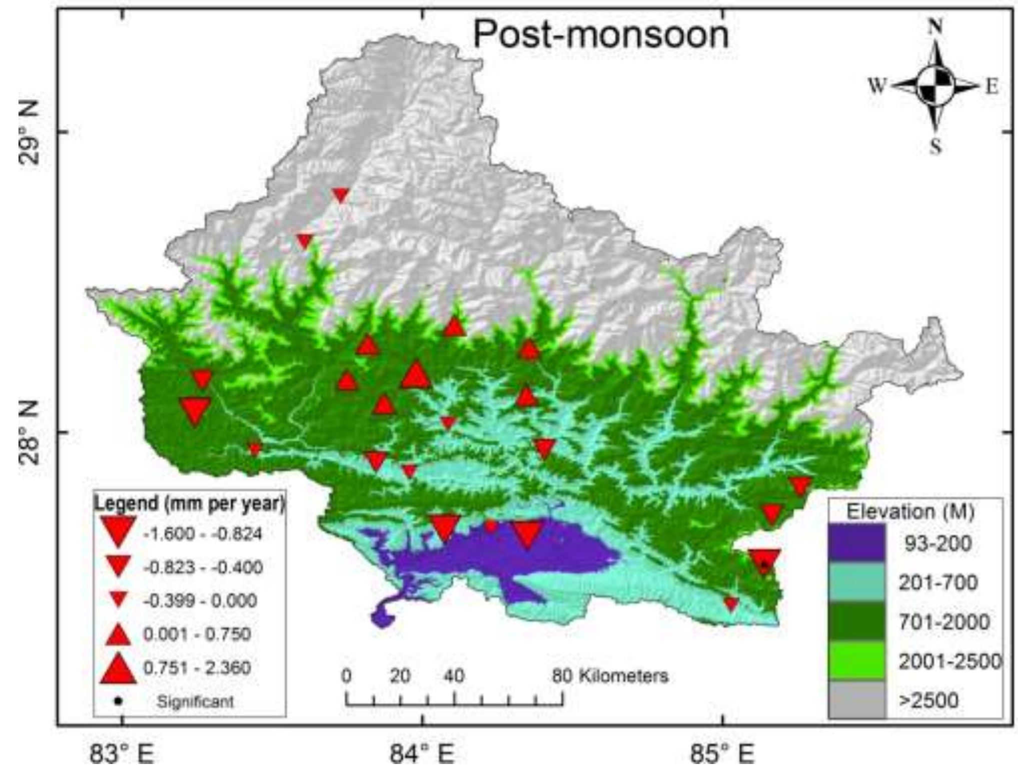


Figure 29: Trends in post-monsoon precipitation

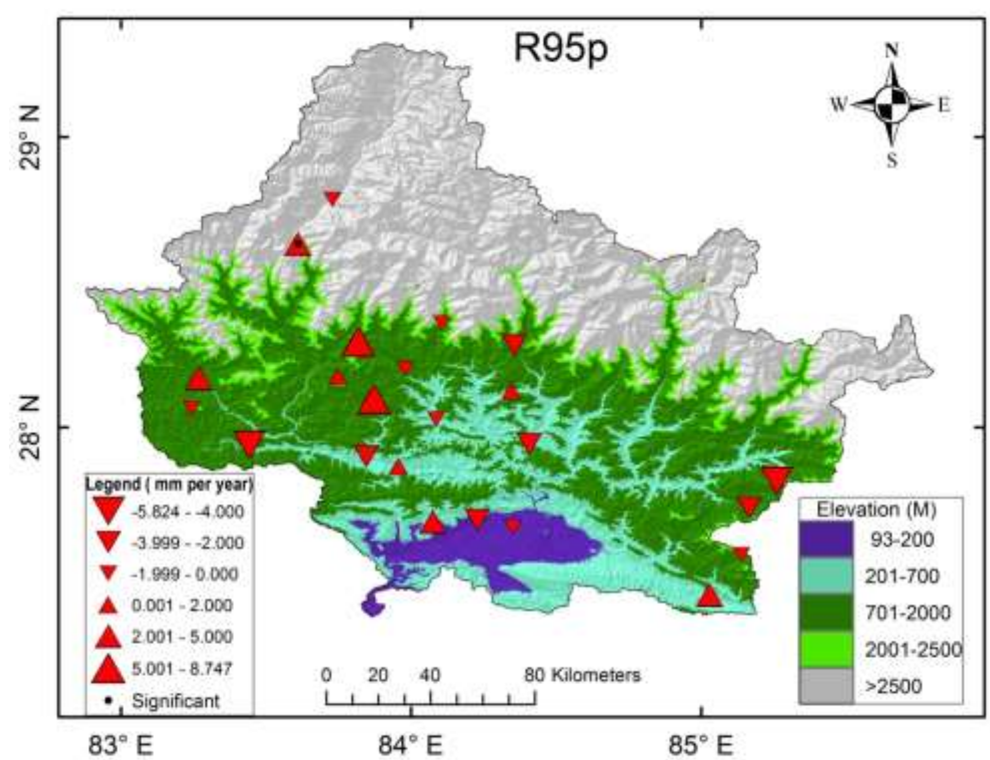


Figure 30: Trends in annual sum of daily precipitation > 95 percentile

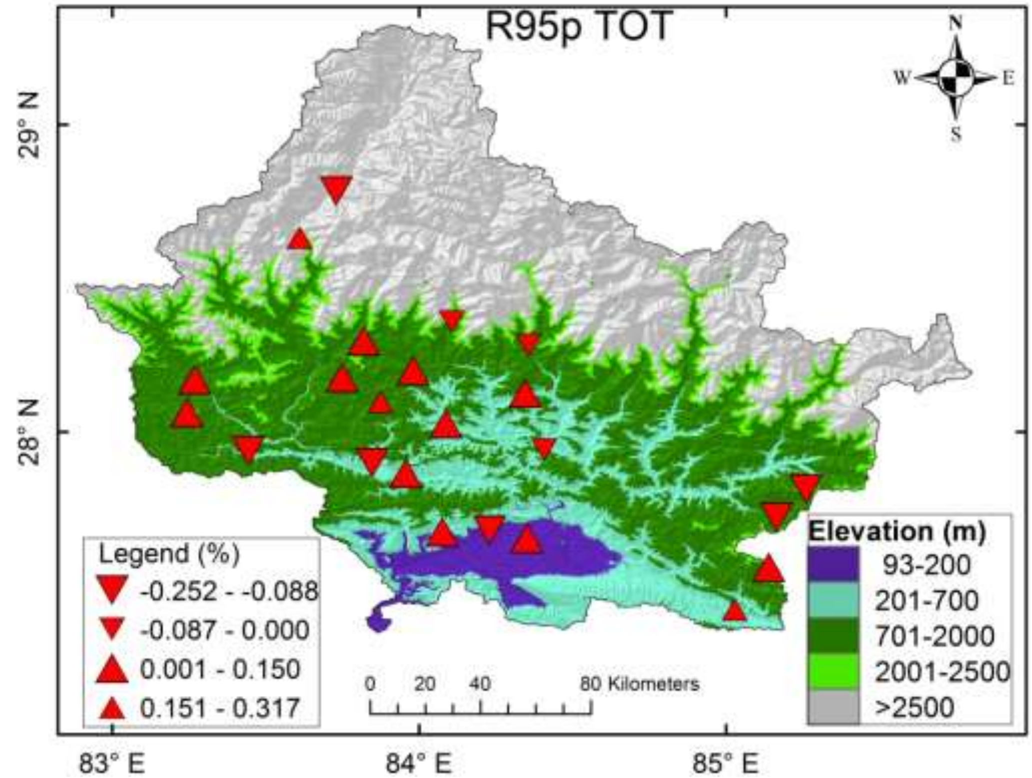


Figure 31: Trends in contribution > 95 percentile

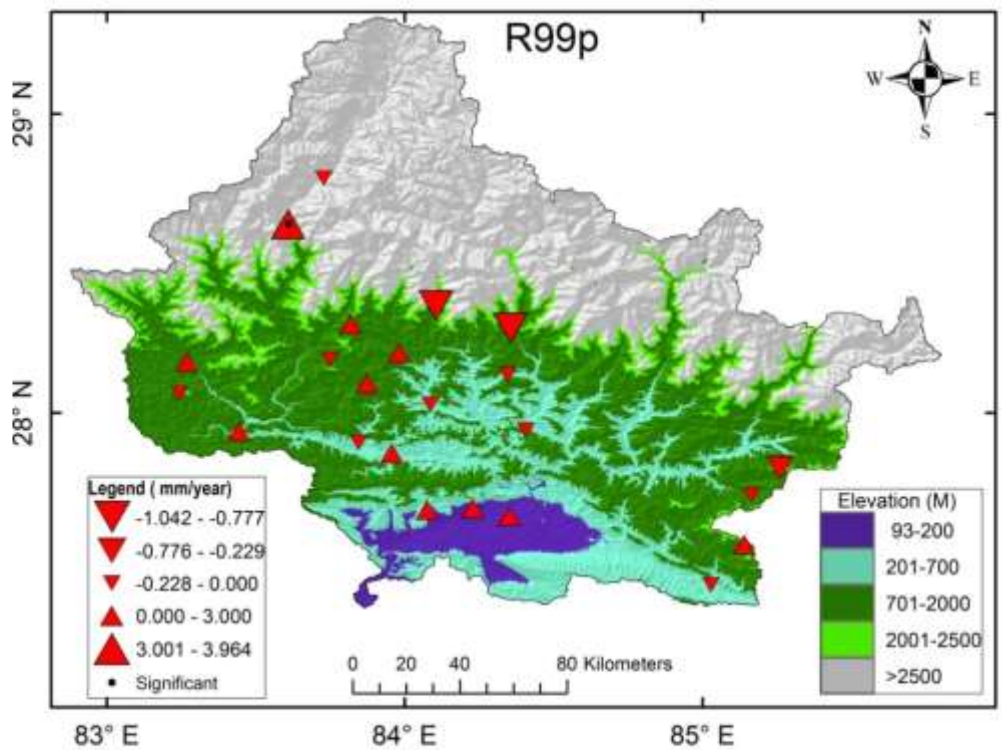


Figure 32: Annual total precipitation > 99 percentile

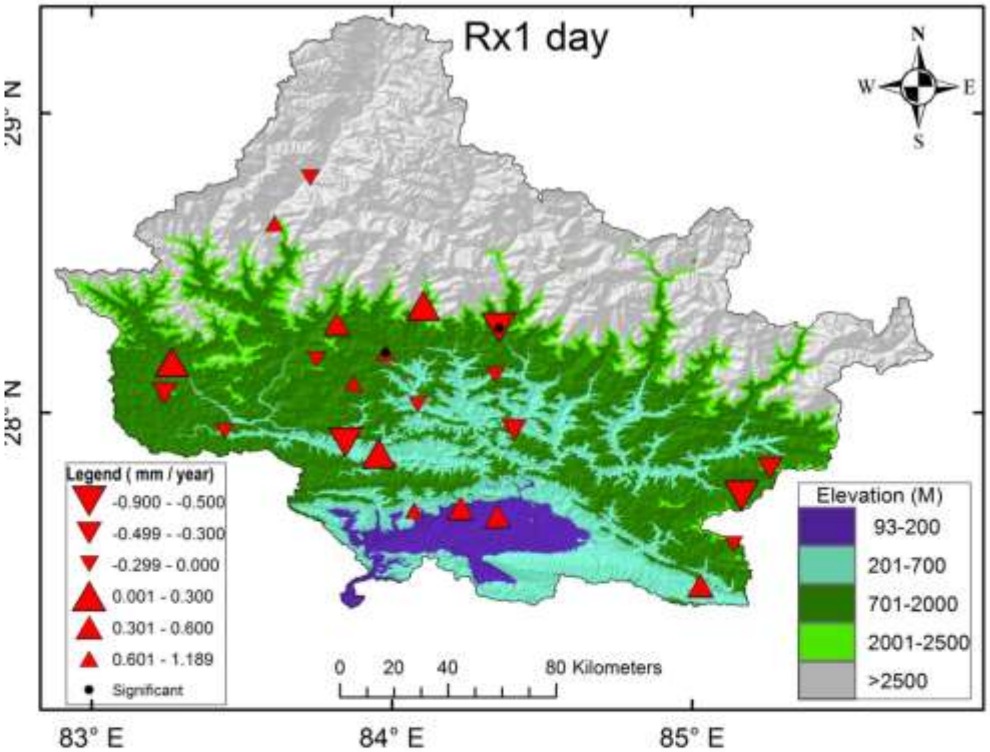


Figure 33: Trends in annual maximum 1-day precipitation

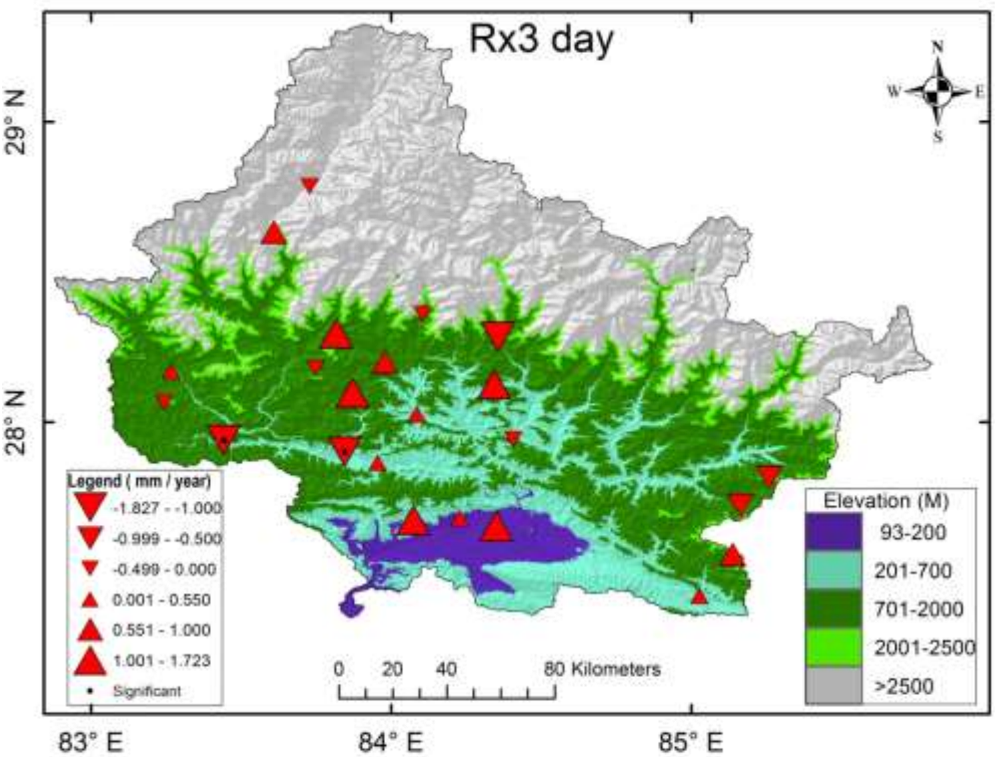


Figure 34: Trends in annual maximum 3-day precipitation

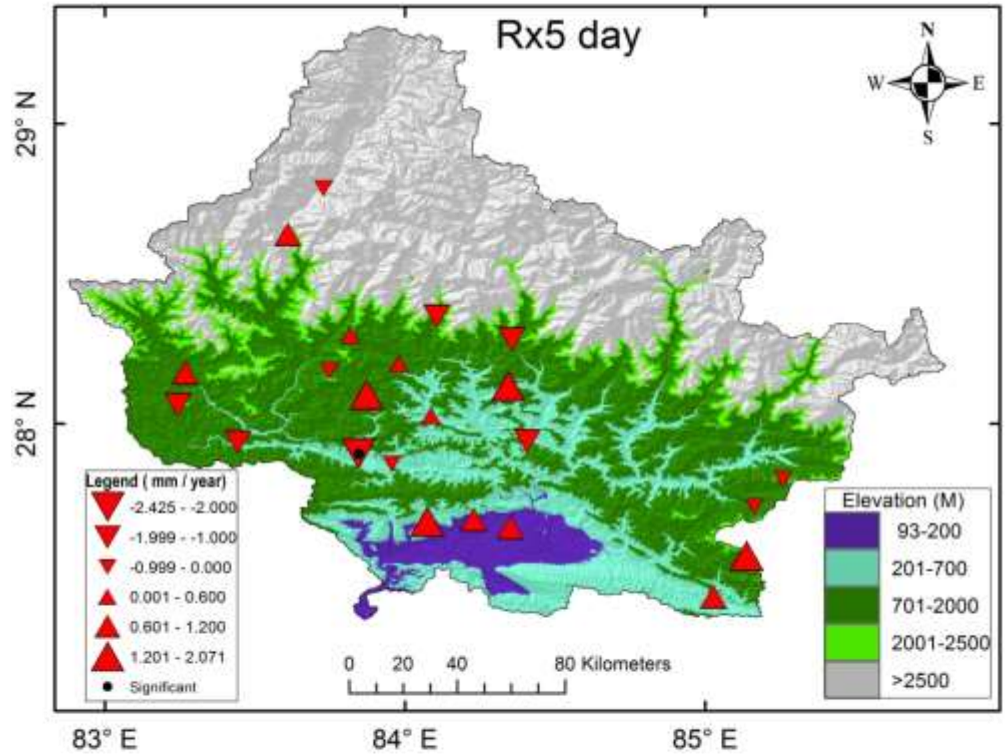


Figure 35: Trends in annual maximum consecutive5-day precipitation

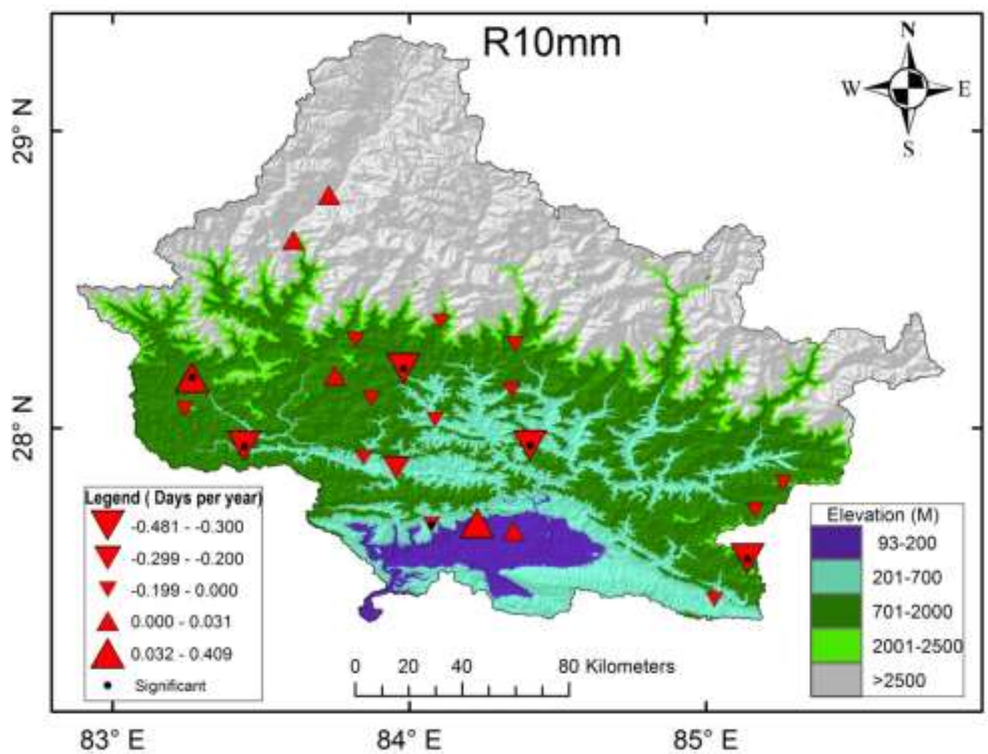


Figure 36: Trends in annual count of days when the precipitation ≥10mm

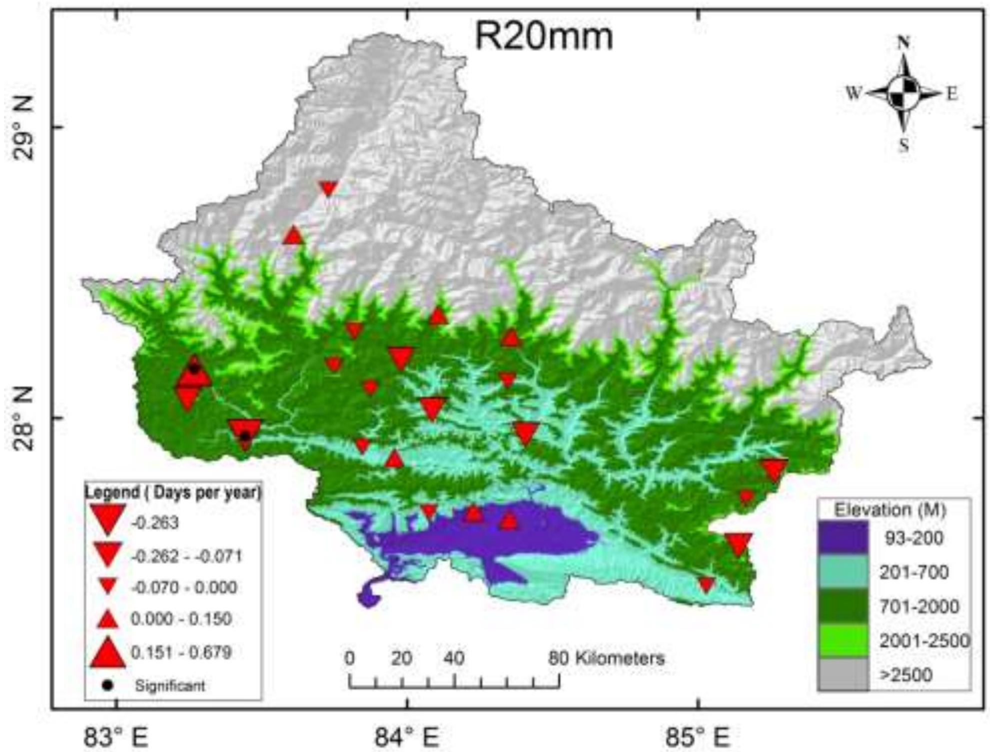


Figure 37: Trends in annual count of days when the precipitation ≥20mm

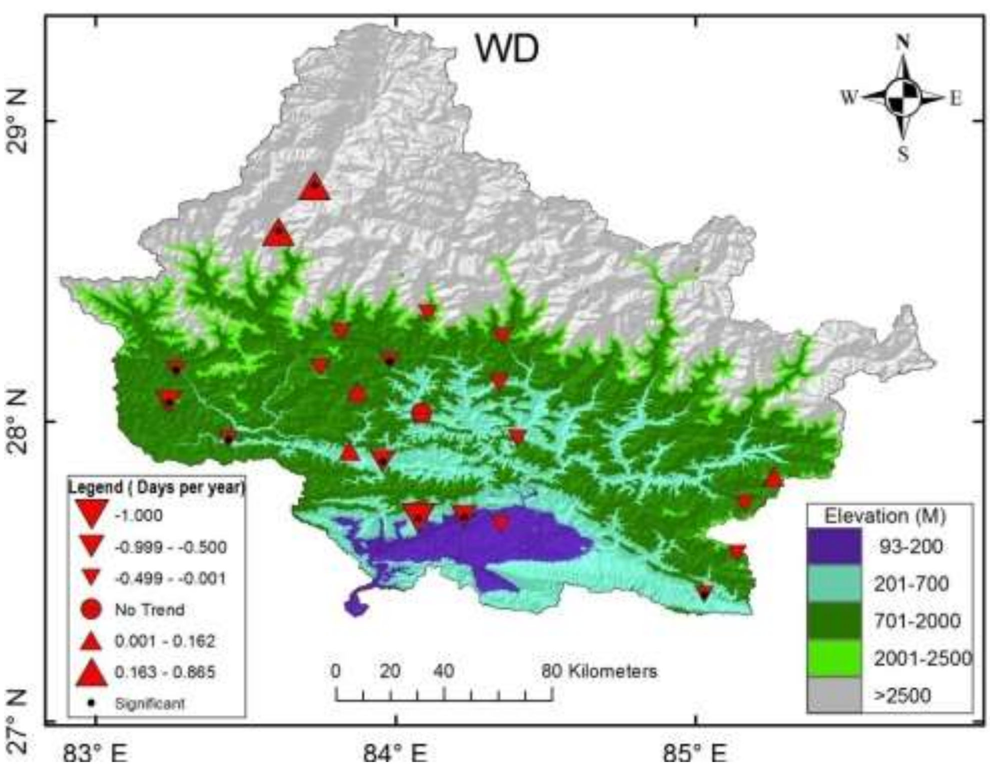


Figure 38: Trends in annual count of days when the precipitation ≥1mm

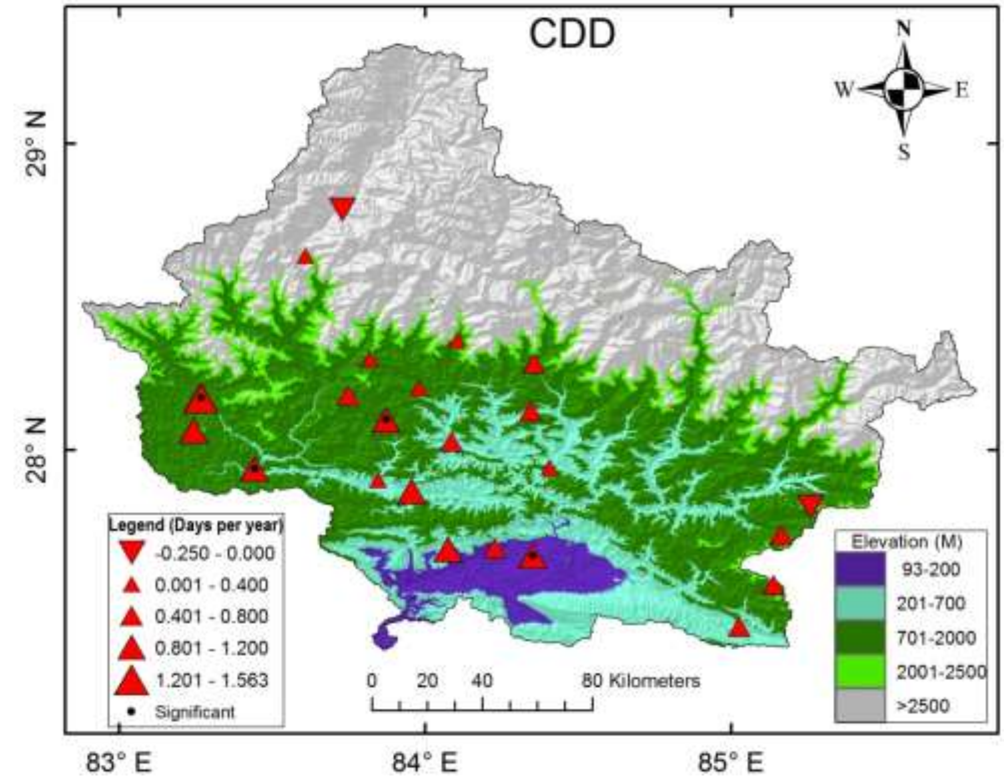


Figure 39: Trends in maximum number of consecutive days when PR<1mm

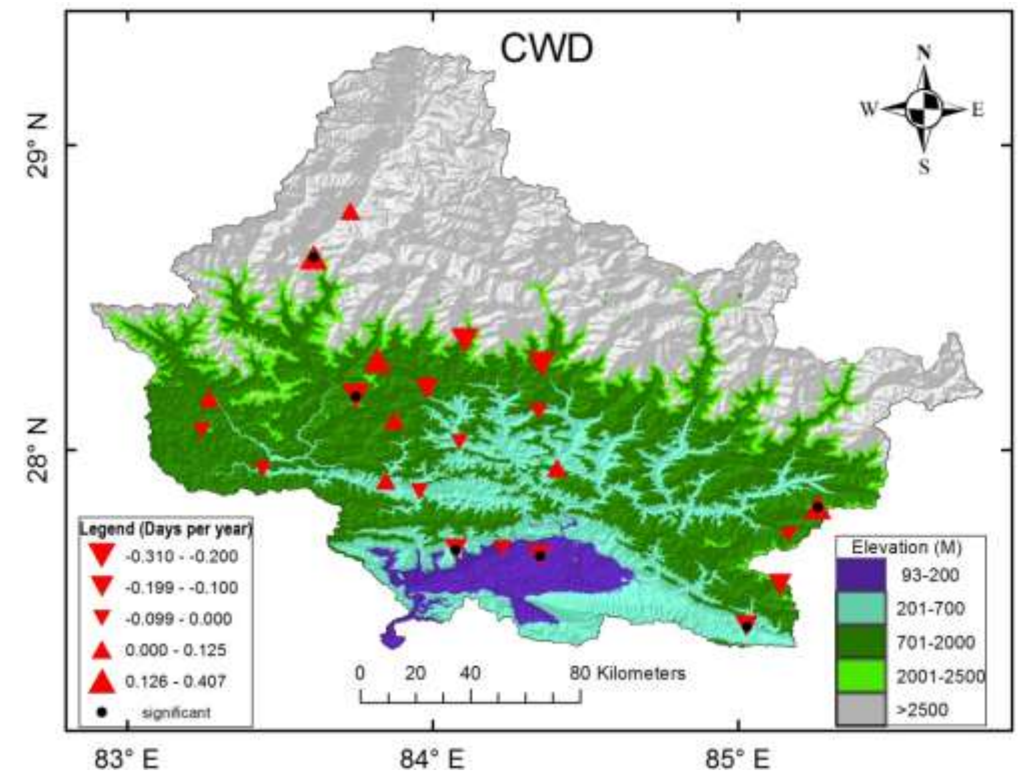


Figure 40: Trends in maximum number of consecutive days when PR ≥ 1mm

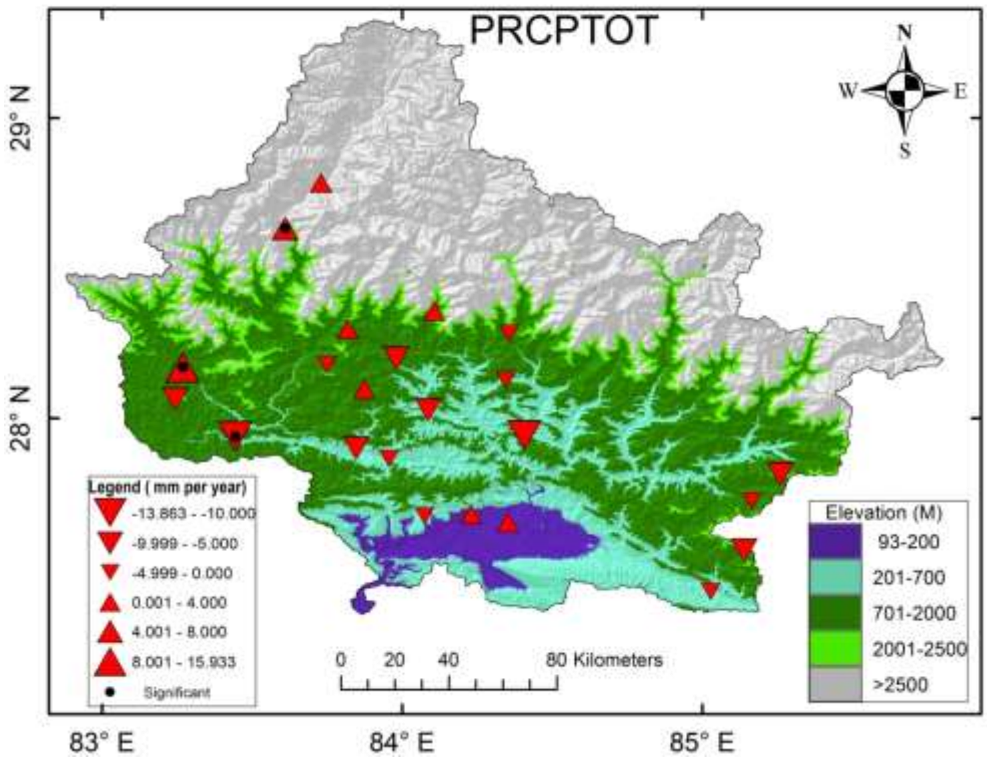


Figure 41 : Trends in annual total precipitation in wet days

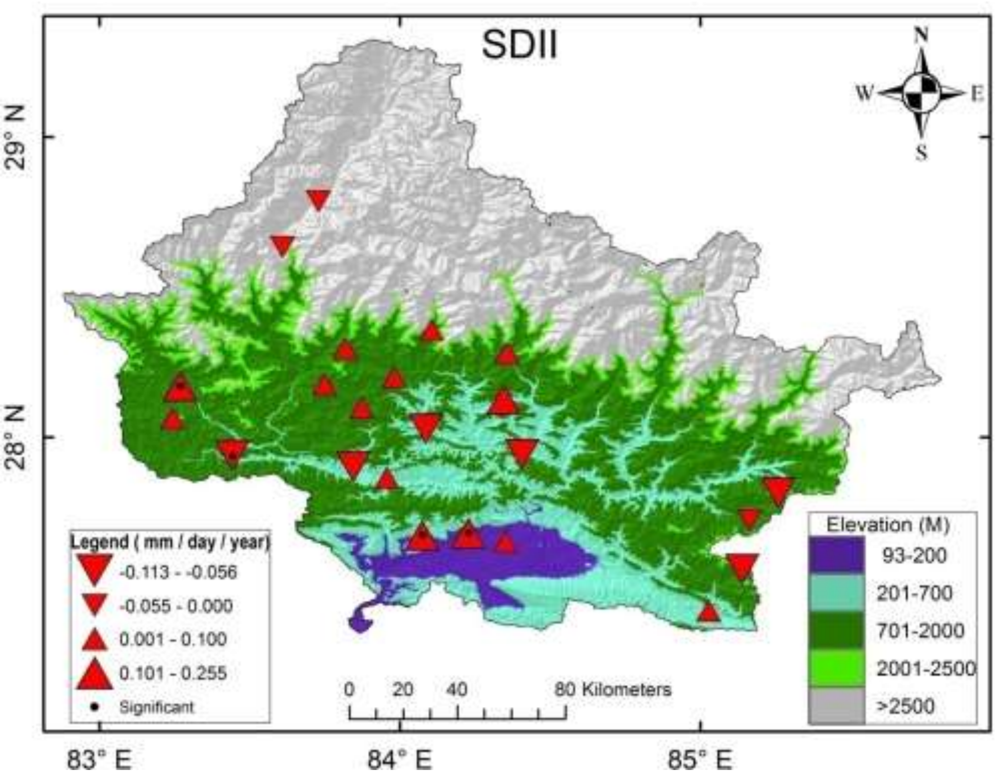


Figure 42: Trends in ratio of annual total precipitation divided by the number of wet days in the year